DETECTION AND EARLY WARNING OF LIGHTNING AND EXTREME STORM EVENTS IN KWAZULU-NATAL, SOUTH AFRICA

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based at the Centre for Water Resources Research (CWRR), in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. This work forms part of the uMngeni Resilience Project, funded by the Adaptation Fund, which is a partnership between the Department of Environment, Forestry and Fisheries, the South African National Biodiversity Institute, the uMgungundlovu District Municipality and the University of KwaZulu-Natal's Centre for Transformative Agricultural and Food Systems. The research was financially supported by the Durban Research Action Partnership (DRAP) and the eThekwini Municipality as well as the National Research Foundation.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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DECLARATION 1: PLAGIARISM

I, Maqsooda Mahomed, declare that:

(i) the research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) this thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) this thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this thesis is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the references sections.

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DECLARATION 2: PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part of and/or include research presented in this thesis (including publications submitted and published, giving details of the contributions of each author to the research and writing of each publication). Some minor editorial differences may exist between the published papers and the thesis chapters. A list of presentations for the research is also presented.

Publication 1 (Chapter 2) is published as:

Mahomed, M, Clulow, AD, Strydom, S, Savage, MJ and Mabhaudhi, T. 2021. Lightning monitoring and detection techniques: progress and challenges in South Africa. *South African Journal of Science*, 117(1/2). https://doi.org/10.17159/sajs.2021/7020.

This manuscript is a review, highlighting the advances in lightning monitoring and detection, along with the major lightning detection challenges facing South Africa and including the relevance to rural communities. The review of relevant literature and content was conducted by M, Mahomed. Advice on paper structure and content were provided by AD, Clulow, S, Strydom, MJ, Savage and T, Mabhaudhi. Final editing was also provided by the co-authors and anonymous reviewers of the publication. The publication was written in its entirety by M, Mahomed and all results, figures, tables and graphs were produced by the same, unless otherwise stated within the text of the paper.

Publication 2 (Chapter 3) is currently under review:

Mahomed, M, Clulow, AD, Strydom, S, Mabhaudhi, T and Savage, MJ. 2020. Assessment of a ground-based lightning detection and near real-time warning system in the rural community of Swayimane, KwaZulu-Natal, South Africa. *Weather, Climate and Society*.

In this manuscript, a near real-time lightning warning system was developed and assessed to improve lightning detection on a local scale for rural communities in South Africa. The data reported on are based on *in-situ* field measurements, acquired from a remote server located at the University of KwaZulu-Natal. A team of researchers and a technician were required for the site-selection, set-up and maintenance of the instrumentation, due to its remote locality. The team members are co-authors or have been acknowledged in the text. M, Mahomed was actively involved in the collection of data and was assisted by AD, Clulow, who wrote the datalogger programs. Advice regarding the interpretation of the data and structuring of the research presented within the paper, was provided AD, Clulow, S, Strydom, T, Mabhaudhi and MJ, Savage. The review of relevant literature, methodological design and data analysis for this paper was undertaken by M, Mahomed. The publication was written in its entirety by M, Mahomed and all results, figures, tables and graphs were produced by the same, unless otherwise stated within the text of the paper.

Publication 3 (Chapter 4) is in preparation for submission to *Atmosphere* with authors:

Mahomed, M, Clulow, AD, Gijben, M, Strydom, S, Savage, MJ, Mabhaudhi, T and Chetty, KT. 2020. An evaluation of a community-based lightning warning system against the South African Lightning Detection Network.

The data reported on are based on window-period, *in-situ* field measurements and long-term monitoring. M, Mahomed was actively involved in the collection and analysis of the community, ground-based early warning lightning dataset. Supplementary data used in this study pertaining to the South African Lightning Detection Network was obtained from the South African Weather Service through M, Gijben. Advice regarding the interpretation of the data and structuring of the research presented within the paper, was provided by AD, Clulow, M, Gijben, S, Strydom, MJ, Savage, T, Mabhaudhi and KT, Chetty. The review of relevant literature, methodological design and data analysis for this paper was undertaken by M, Mahomed. The publication was written in its entirety by M, Mahomed and all results, figures, tables and graphs were produced by the same, unless otherwise stated within the text of the paper.

Publication 4 (Chapter 5) is in preparation for submission to *Weather and Climate Extremes* with authors:

Mahomed, M, Gijben, M, Clulow, AD, Strydom, S, Savage, MJ, Chetty, KT and Mabhaudhi, T. 2020. A supercell tornado event on 12 November 2019 in KwaZulu-Natal, South Africa: Radar, mesoscale perspectives and lightning correlations.

Data collection for this publication was conducted by M, Mahomed with support from M, Gijben. M, Gijben was responsible for the South African Lightning Detection Network's data products as well as the radar scans used in this manuscript. Advice regarding the interpretation of the data and structuring of the research presented within the paper, was provided by M, Gijben, AD, Clulow, S, Strydom, MJ, Savage, KT, Chetty and T, Mabhaudhi. The review of relevant literature, methodological design and data analysis for this paper was undertaken by

M, Mahomed. The publication was written in its entirety by M, Mahomed and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper.

Presentations:

The * in each presentation, indicates my role to be the corresponding author.

Mahomed M*, Clulow AD and Mabhaudhi T. 2018. The development of a near real-time environmental early warning system towards increasing climate resilience and adaptive capacity in South Africa. *International Data Week 2018*. Gaborone International Convention Centre (GICC), Gaborone, Botswana, 05-08 November 2018. (Chapter 3).

Mahomed M*, Clulow AD and Mabhaudhi T. 2018. The development of a near real-time environmental early warning system towards increasing climate resilience and adaptive capacity in South Africa. *Proceedings of the ACCESS 4th DST National Global Change Conference*, 6. Bolivia Estate, Polokwane, South Africa, 03-06 December 2018. (Chapter 3).

Mahomed M*, Clulow AD, Mabhaudhi T and Chetty KT. 2018. The development of a near real-time environmental warning system towards increasing climate resilience and adaptive capacity of rural communities in South Africa. Project Coordinating Committee of the uMngeni Resilience Project. uMgungundlovu District Municipality (uMDM) Council Chamber, 242 Langalibalele Street, Pietermaritzburg, South Africa, 10 September 2018. (Chapter 3).

Mahomed M*, Clulow AD, Mabhaudhi T and Chetty KT. 2019. The development of a near real-time environmental warning system towards increasing climate resilience and adaptive capacity of rural communities in South Africa. Durban Research Action Partnership (DRAP) for

Biodiversity, Climate and People, student inception workshop. Paradise Valley Nature Conservation, Durban, South Africa, 02 August 2019. (Chapters 2 and 3).

Mahomed M*, Clulow AD, Mabhaudhi T and Chetty KT. 2019. The development of a near real-time environmental warning system towards increasing climate resilience and adaptive capacity of rural communities in South Africa. *Proceedings of the 35th Annual Conference of the South African Society for Atmospheric Sciences (SASAS)*. Riverside Sun, Vanderbijl Park, Gauteng, South Africa, 8-9 October 2019. (Chapters 3 and 4).

Mahomed M*, Clulow AD, Mabhaudhi T and Chetty KT. 2019. The development of a near real-time environmental warning system towards increasing climate resilience and adaptive capacity of rural communities in South Africa. DRAP Year-end Research Symposium: Global Environmental Change Programme (GEC) 2019. Paradise Valley Nature Conservation, Durban, South Africa, 19 November 2019. (Chapters 3 and 4).

Mahomed M*, Clulow AD, Mabhaudhi T and Chetty KT. 2019. The development of a near real-time environmental warning system towards increasing climate resilience and adaptive capacity of rural communities in South Africa. Climate Smart Technologies Workshop. South African Local Government Association (SALGA) offices, Durban, South Africa, 11-12 March 2020. (Chapters 3 and 4).

Mahomed M*, Clulow AD, Mabhaudhi T and Chetty KT. 2020. The development of a near real-time environmental warning system towards increasing climate resilience and adaptive capacity of rural communities in South Africa. *The 8th International Lightning Detection Conference*

(ILDC) and International Lightning Meteorology Conference (ILMC) [Abstract Online]. Vaisala, Vantaa, Finland. (Chapter 3).

Mahomed M*, Clulow AD, Mabhaudhi T and Chetty KT. 2020. Detection and early warning of lightning and extreme storm events in KwaZulu-Natal, South Africa. DRAP Year-end Research Symposium: Global Environmental Change Programme (GEC) 2020. [Online]. 23 November 2020. (Chapters 3, 4 and 5).

Mahomed M, Clulow AD, Chetty KT and Mabhaudhi T. 2020. The development of a near real-time environmental warning system towards increasing climate resilience and adaptive capacity of rural communities in South Africa. College of Agriculture, Engineering and Science- 2020 Postgraduate Research and Innovation Symposium (PRIS). [Online]. 10-11 December 2020. (Chapters 3, 4 and 5).

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EXECUTIVE ABSTRACT

South Africa is particularly vulnerable to climate variability and change and its associated impacts, due to the country's dependency on climate-sensitive economic sectors and the prevailing high levels of poverty. The poor typically have limited opportunity, are generally uneducated and ill-equipped, and hence are disproportionately affected by the negative impacts of climate variability and change, as they are found to be less adaptive in their employment and housing.

Climate model observations from past studies have shown that South Africa has already experienced a warming trend, which is likely to continue in the future with uncertain changes in mean annual rainfall and air temperature. These projections are of significant concern as they point towards an increased risk of extreme climate-driven events, which include but are not limited to, wild fires, flash floods, droughts, severe thunderstorms and increased lightning activity. Lightning is a life-threatening severe weather phenomenon that can result in damage to infrastructure, economic losses, physical injury and loss of life (human and livestock). The complex phenomenon of lightning is sometimes accompanied by extreme weather such as hail, high wind speeds and heavy rainfall. The damaging characteristics of lightning are a result of the heat that is generated by the current caused by electrical potential differences. Climate change projections, of an anticipated increase in lightning activity, are an added concern for a country such as South Africa, as it is already considered a lightning prone country, with prevailing high levels of poverty and low adaptive capacity, resulting in many individuals being exposed to the threat of lightning.

South America, Africa, Asia, North America and Oceania are ranked amongst the lightning hotspots in the world, whilst South Africa has one of the highest incidences of lightning-related

injuries and deaths in comparison to the rest of the world. Technological advances have contributed towards improving lightning detection and monitoring activities in many countries. South Africa has made considerably more progress in the field of lightning research than other African countries and possesses one of the three ground-based lightning detection networks in the southern hemisphere. However, despite these developments, rural communities in South Africa, and indeed in the African continent, remain vulnerable to lightning because there is no dissemination of warnings within communities at present, amongst other reasons. Contrastingly, lightning incidence itself may also be a valuable variable that could be used to monitor climate change and severe weather changes since it is associated with storm-related phenomenon and can be monitored over large distances.

Since the impact of climate change in Africa is more negatively proportioned than elsewhere on the globe, developing countries like South Africa are therefore more likely to face the brunt of climate change. Thus, the monitoring and predictive capacity of lightning incidences on a local scale for developing countries in particular requires attention. Considering this statement as a point of departure, the overall aim of this thesis was to investigate the possibility of reducing the vulnerability of lightning threat of rural communities within South Africa to lightning and to better understand the use of lightning for severe weather prediction in South Africa.

This research involved conducting detailed literature investigations into the advances made in the monitoring and detection of lightning. Particular emphasis was given to the major lightning detection challenges facing South Africa, including the impact on rural communities. These investigations highlighted the need to determine the most effective way to utilise existing monitoring networks but with warning dissemination to rural communities. The research also presented valuable insights into the lack of literature pertaining to lightning detection and monitoring within rural communities across the world. No literature exists on determining effective approaches to communicate lightning data, threats and advance warnings in a manner appropriate for rural communities.

Consequently, a community ground-based near-real time lightning warning system (NRT-LWS) to detect and disseminate lightning threats and alerts in a timeous and comprehensible manner for rural communities in South Africa was developed in this study. The NRT-LWS was installed in the rural community of Swayimane, KwaZulu-Natal, South Africa. The system consisted of an electrical field meter and a lightning flash sensor with warnings disseminated via audible (siren) and visible alarms (beacon lights) on-site. A remote server was responsible for the issuing of short message services (SMS) and email alerts, making it an automated observation, measurement and warning dissemination system. Since the system operates automatically, it minimizes the potential for human error in its operation. In the event of GSM (Global System for Mobile communication) network failure, the audible and visible alarm systems remain in place to alert the surrounding community in the case of a lightning warning. The system’s monitoring and warning capacity can improve the preparedness of rural communities to lightning thus mitigating losses.

The NRT-LWS showed its capability as a risk-based warning system through the provision of NRT information for a variety of environmental conditions (emerging storm/potential lightning threat risks). This information can be beneficial to farmers, community members, municipal officials and disaster risk management agencies with measurable thresholds upon which actions can be initiated. In addition to being an NRT warning system, the meteorological conditions are automatically stored and published on a web page for public access. Poor network signals in the rural community was an initial challenge delaying data transmission to the central server until rectified using multiple network providers. However, the independence of the system allowed lightning warnings to be disseminated to the community through the audible and visible alarm systems on site despite network failures. In addition to disseminating reliable warnings timeously, the system was also found to be beneficial in characterizing lightning events with two above-normal lightning events examined in detail.

Despite South Africa possessing one of the three ground-based lightning detection networks in the southern hemisphere, the South African Lightning Detection Network (SALDN) is only operational at a national level with no warnings disseminated to rural communities. It has the capability to disseminate lightning data to a local level, however, this has not been implemented and rural communities still do not receive timely warnings of potentially dangerous thunderstorms. In an attempt to understand the capabilities of the SALDN and the NRT-LWS, and to bridge the gap between the SALDN and rural communities, a systematic evaluation on the performance of the NRT-LWS using the existing national network was conducted. The research therefore provides the first insights on the use of the SALDN at a local level as well as provides context to researchers who aim to better understand lightning occurrence at a local level.

In the 12-month validation of the NRT-LWS against the SALDN, both measured a similar temporal distribution in lightning and produced a correlation coefficient of 0.95. The NRT-LWS was capable of capturing the seasonal and diurnal variations in lightning activity, which revealed that maximum lightning activity occurred during summer, and that the majority of the lightning activity was concentrated in the later stages of the day relating to the influence and variation in solar heating on lightning incidences. Comparative analyses between the lightning flashes and the electric field discharges displayed that for most instances the NRT-LWS and the SALDN detected flashes simultaneously. The SALDNs average peak current parameter for two studied lightning events was found to constitute an indicator for the Detection Efficiency (DE) of the study area. The storm DE indicated a 100% DE at close-alert categories, with the DE decreasing with distance. Despite the fact that the two systems did not target exactly the same discharges, the lightning activity was adequately captured by the NRT-LWS, further emphasizing that the NRT-LWSs data are a reliable source of information with the potential to identify and disseminate lightning threats at local scales.

Lightning data were also investigated to provide early warnings for extreme weather phenomena on a local scale for South Africa. A supercell tornado event that occurred on 12th November 2019, within the vicinity of the newly developed NRT-LWS was analysed. The use of total and cloud-to-ground lightning data was assessed as a precursor to tornadoes and for severe weather in South Africa. The development and structure of the tornado event at a localized level using a suite of nowcasting data from remote sensing tools such as the METEOR 600S S-band Doppler radar and the Meteosat-11 satellite, as well as available observed data for the event, including weather station data and a synopsis of weather systems was analysed.

To demonstrate the use of lightning data to support decision making and to nowcast severe convection, the study examined the concurrent trends in both total (NRT-LWS) and cloud-to-ground (SALDN) lightning within the same supercell tornado event, using the internationally developed 2σ lightning jump algorithm. The most obvious and distinguishing feature of the supercell event, indicated by both datasets, was the rapid increases in flash rate followed by a dramatic decline, signalling the tornado at the ground. The total lightning system was found to be more beneficial than the cloud-to-ground network, providing a lead time of 33 minutes to the event. The research demonstrated that total lightning activity can be a useful observation that indicates the need to issue a warning as well as providing a greater lead-time over radar for local scales in South Africa.

The 2σ jump algorithm showed promise for the detection of severe weather using lightning trend data for South Africa. The algorithm also demonstrated the potential to provide warnings for a tornadic supercell thunderstorm using lightning data on a local scale. The results elucidate a need to develop an operational total-lightning jump algorithm for nowcast operations on local scales in South Africa and to correlate the lightning jump alerts to the South African Weather Service (SAWS) severe thunderstorm warning to evaluate lead time and accuracy. This is a significant contribution and enhancement of the understanding of lightning as a short-term predictor to severe storms and as a precursor to severe weather (including tornadoes and supercell events) for local scales in South Africa. Additionally, the synergistic effects of combining lightning data with radar and satellite data were found beneficial in supporting the early detection of convection.

The thesis throughout clearly documents and highlights the invaluable contributions that can be gained from this first-ever community early warning system in South Africa, especially towards building the resilience of rural communities and small-scale farmers towards mitigating the impacts of climate-driven risks and the associated projected increase in lightning activity. Prior to this, there was a dearth of information focussing on advancing lightning warnings within rural communities, which is now provided in this thesis. This research has not only provided avenues to expand knowledge and understanding of lightning occurrence at a local scale, but also for monitoring and providing early warnings for severe weather phenomena using lightning at local scales in South Africa. The thesis documents the first results of an internationally developed lightning jump algorithm for South Africa. Although uncertainties in the 2σ algorithm for use in South Africa could not be verified, due to the lack of research on lightning jump algorithms in South Africa, this preliminary study may be considered as an invaluable contribution towards the use of lightning data to nowcast tornadoes, supercells and severe weather on a local scale for South Africa. Knowledge from this study can help future South African operational forecasters identify what to look for in lightning datasets for severe weather events in order to nowcast with improved accuracy. An increased sample dataset and longer-term monitoring of storms may allow for a more robust understanding of different thunderstorm types and their associated lightning characteristics.

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LIST OF SYMBOLS

R^2	Coefficient of determination
°C	Degrees Celsius
t_i	Issuing of alert
t_s-t_i	Lead time of the alert
t_0	Lightning jump
t_p	Peak lightning rate time
σ	Sigma
t_s	Time of severe weather

LIST OF ABBREVIATIONS

ACLENet	African Centres for Lightning and Electromagnetics Network
AIM	Agrometeorological Instrumentation Mast
AWS	Automatic Weather Station
BUFR	Binary Universal Form for the Representation of meteorological data
BWER	Bounded Weak Echo Region
CAT	Central African Time
CC	Cloud-To-Cloud/Inter-Cloud
COL	Cut-off Low-pressure System
CG	Cloud-to-Ground
CIGRÉ	International Council on Large Electric Systems
CPM	Convective Permitting Models
CPS	Central Processing System
CRR	Convective Rainfall Rate
CSIR	Council for Scientific and Industrial Research in South Africa
CS 110	Campbell Scientific Electric Field Meter
DE	Detection Efficiency
D’RAP	Durban Research Action Partnership
E-Field	Electrical Field
EFM	Electric Field Meter
ELF	Extremely Low Frequency (3–3000 Hz)
ELPA	Earthing and Lightning Protection Association
EMP	Electromagnetic Pulse
EUCLID	European Cooperation for Lightning Detection

EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EWS	Early Warning System
FALLS	Fault Analysis and Lightning Location System
FPP	Fujita-Pearson Scale
GA	Global Atmosphere
GII	Global Instability Index
GLD360	Global Lightning Dataset
GLM	Geostationary Lightning Mapper
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
GPRS	General Packet Radio Services
GSM	Global System for Mobile Communication
H-Field	Magnetic Field
HRAC	High-Resolution Annual Climatology
HRIT	High Rate Information Transmission
HRV	High Resolution Visible
IC	Intra-Cloud
ILDC	International Lightning Detection Conference
IP	Internet Protocol
IR	Infrared
KZN	KwaZulu-Natal
LDN’s	Lightning Detection Networks
LEO	Low Earth Orbit
LF	Low Frequency
LIGHTS	Lightning Interest Group for Health, Technology and Science

LIS	Lightning Imaging Sensor
LPATS	Lightning Positioning and Tracking System
LTE	Long-term Evolution
LTI	Lightning Threat Index
LWS	Lightning Warning System
MDF	Magnetic-Direction-Finding
MPEF	Meteorological Product Extraction Functions
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Seas Systems Command
NEERI	National Electrical Engineering Research Institute
NGO’s	Non-Governmental Organisations
NLDN	National Lightning Detection Network
NOAA	National Oceanic and Atmospheric Administration
NPO	Non-Profit Organisations
NRT	Near Real-Time
NWC SAF	Nowcasting Satellite Application Facility in support to Nowcasting and very Short-Range Forecasting
NWP	Numerical Weather Prediction
OTD	Optical Transient Detector
RDT	Rapidly Developing Thunderstorm
RF	Radio Frequency
RGB	Red-Green-Blue
RH	Relative Humidity

811	RII	Regional Instability Indices
812	SA	South Africa
813	SAIEE	South African Institute of Electrical Engineers
814	SALDN	South African Lightning Detection Network
815	SANBI	South African National Biodiversity Institute
816	SEVIRI	Spinning Enhanced Visible and Infrared Imager
817	SAWS	South African Weather Service
818	SG/SG 000	Strike Guard
819	SMS	Short Message Services
820	SUMO	Software for the Utilization of Meteosat Outlook
821	TCP	Transmission Control Protocol
822	TGFs	Terrestrial Gamma Ray Flashes
823	TITAN	Thunderstorm Identification, Tracking and Nowcasting algorithm
824	TLEs	Transient Luminous Events
825	TOA	Time-Of-Arrival
826	TRMM	Tropical Rainfall Measuring Mission
827	UKMO	United Kingdom Meteorological Office
828	UKZN	University of KwaZulu-Natal
829	UM	Unified Model
830	UMDM	uMgungundlovu District Municipality
831	URP	uMngeni Resilience Project
832	USA	United States of America
833	USD	US Dollars
834	UTC	Coordinated Universal Time
835	VCUT	Vertical Cut

836	VHF	Very High Frequency
837	VIS	Visible
838	VLF	Very Low Frequency (3–30 kHz)
839	VM	Virtual Machine
840	WER	Weak Echo Region
841	WMO	World Meteorological Organization
842	WWLLN	World-Wide Lightning Location Detection Network
843	WV	Water Vapour

CHAPTER 1: INTRODUCTION

1.1 Rationale for the research

1.1.1 Background

Lightning is recognisably one of the most frequently occurring geophysical phenomenon (Dwyer and Uman, 2014). Despite lightning being a familiar phenomenon, it still remains poorly understood. This is primarily due to the random and complex occurrence of lightning in space and time as well as the wide range in time variation. The significant time variation ranges from tens of nanoseconds for several individual processes to nearly a second for the total discharge, and its obscuration is often caused by the thundercloud that produces it (Dwyer and Uman, 2014; Cooper *et al.,* 2016; Gomes, 2017). Nevertheless, there has been more than a century of research conducted on the physics and the phenomenology of lightning with some issues still requiring answers. On a daily basis, lightning is known to cause injury, fatalities and economic losses across the world (Holle *et al.,* 1999; Holle, 2008; Gomes, 2017; Cooper and Holle, 2019c). An overview of recent topics regarding lightning research and protection are presented by Rakov and Rachidi (2009), Cooper and Holle (2012), Cooper *et al.,* (2016), Gomes (2017) and Cooper and Holle (2019c), amongst others. Modelling and observations on lightning discharges, the electromagnetic fields of lightning, the effects of lightning together with lightning protection as well as the occurrence of lightning in conjunction with lightning detection networks are amongst the recent topics.

1.1.2 Overview of lightning in South Africa

A country such as South Africa experiences lightning frequently, however, not as much as the equatorial parts of Africa and South America, but is still considered a lightning-prone country

(Gijben, 2012; Cooper *et al.,* 2016; Cooper and Holle, 2019c). South Africa is known to have a rich history of lightning research, however, it lacks research locally on lightning related clinical and pathological effects (Blumenthal *et al.,* 2012). Early lightning work can be traced back to the 1920s, when the first electric field measurements were made by physicists Drs Schonland and Malan (also considered to be the founding members of the Council for Scientific and Industrial Research in South Africa [CSIR]) (Blumenthal *et al.,* 2012).

On average, between 1.5 and 8.8 deaths per million per year are lightning related deaths in South Africa (Blumenthal *et al.,* 2012; Gijben, 2012; Cooper *et al.,* 2016; Gomes, 2017; Cooper and Holle, 2019c). The aforementioned is said to be about four times higher than the global average and the country's insurance claims resulting from lightning deaths and damages amount to more than R500 million per year equivalent to approximately R32 million USD per year (November 2020) (Gijben, 2012).

1.1.3 Overview of the effects of lightning on humans, animals and the environment

Lightning is one of the noteworthy yet underestimated hazards to people, animals and infrastructure. It poses a severe risk to almost all facets of society and the environment. Lightning results in injury and death to humans and livestock, produces fires as well as damage to infrastructures, power lines, electrical systems and communication systems (Dlamini, 2009; Blumenthal *et al.,* 2012; Gijben, 2012; Trengove, 2015; Gomes, 2017; Cooper and Holle, 2019a). Globally, approximately 24,000 deaths per annum are reportedly caused by lightning strikes (Holle *et al.,* 1999; Blumenthal *et al.,* 2012; Gomes, 2017; Bhavanadhar *et al.,* 2018). This indicates that each year lightning causes more deaths globally than any other natural phenomenon or event (Blumenthal *et al.,* 2012). Along with lightning fatalities, lightning injuries also deserve specific mention as they range from being mild to severe (disabling people)

(Cooper *et al.,* 2016), with developing countries reporting a higher number of severe injuries than developed countries (Cooper, 2012). This may be due partly to fewer available fully enclosed, metal-topped vehicles, the lack of lightning-safe structures, myths and belief systems, a lack of awareness regarding the dangers and precautions of lightning, unavailability and delays in receiving proper medical treatment, affordability concerns (e.g. unable to afford lightning protection systems), a high rate of labour intensive subsistence farming/agriculture, population density, amongst others (Cooper *et al*., 2016; Gomes 2017). Severe injuries may render people incapable of returning to school or work, disrupting normal lives and in some cases may even lead to the impoverishment of families (Cooper, 1998). Lightning itself is a current source caused by electrical potential differences due to the flow of current, whilst the damage results from the heat that is generated by the current (Blumenthal *et al.*, 2012).

Additionally, significant economic losses attributed with lightning are significant for those involved in game farming, forestry and crop farming as lightning-induced fires can cause severe destruction (Blumenthal *et al.,* 2012; Price, 2013). Cooper and Holle (2019a) provide a comprehensive discussion on the economic damage, resulting from lightning that exist amongst the various sectors. Amongst the direct and indirect economic losses that results from lightning, a direct lightning strike can ignite fires, cause explosions, power outages as well as result in the detachment or fragmentation of objects that can fall injuring individuals (Gomes, 2017). While, indirect damage may include permanent to temporary damage to electrical and electronic equipment, data transmission losses, computing downtime, loss of workers due to injury or death, amongst others (Gomes 2017; Cooper and Holle, 2019a). In South Africa, many people residing in rural settlements and those who work outdoors are particularly vulnerable to lightning strikes (Cooper *et al.,* 2016; Gomes, 2017; Cooper and Holle, 2019c).

Furthermore, several cultural complications have also been associated with lightning strikes (and thunder) in South Africa, which include mythical association with lightning. Some indigenous South Africans have religious and traditional beliefs that lightning may be directed to strike someone, and that significant personality changes ensue after a lightning strike, and that it could be a sign of God's anger (Dlamini, 2009; Blumenthal *et al.*, 2012; Trengove, 2015; Cooper *et al.*, 2016; Cooper and Holle, 2019c). Such beliefs still exist and some hinder the necessity to take precautionary measures thereby increasing the risk and effects of lightning injury (Dlamini, 2009; Cooper *et al.*, 2016).

Apart from the damaging effects of lightning, lightning is also regarded as an indicator for convective activity in climatology (Price, 2013), as it is related to storm phenomenon such as, hail, gusts, tornadoes and rainfall. It is one aspect of severe storms that can be monitored continuously, and from great distances. Therefore, lightning can be a valuable tool to monitor and provide early warning for severe weather, as well as keep track of significant climate parameters and overall, the earth's climate system (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). Furthermore, the earth is also impacted by lightning through additional beneficial uses, which include maintaining an electrical balance on earth by producing negatively charged electrical currents that react with the positively charged ground (Changnon, 1985). Lightning is also necessary for the purpose of nitrogen fixation by nitrogen oxides (produced by lightning), which is essential for the manufacture of natural fertilizers that can be absorbed by plants (Leigh, 2002). Nitrogen oxides are also a major source of ozone, which is a crucial gas found in the atmosphere, protecting the planet from the harmful ultraviolet rays of the sunlight (Jasaitis *et al.*, 2016).

1.1.4 Climate change and lightning

During the past decade, a growing body of research has emerged due to increasing concerns about the impacts of climate change. These impacts are a result of changes in weather patterns that are expected to lead to an increase in the frequency and extent of natural disasters such as floods, heat waves, droughts and thunderstorms. Globally, climate change research has indicated that lightning patterns and intensity are predicted to alter with some studies indicating that global warming will increase overall lightning activity (Blumenthal *et al.,* 2012; Romps *et al.,* 2014). The anticipated increase in the occurrence of lightning is likely to mean more danger for society, infrastructure and the environment. The impacts of these natural disasters are likely to be more significant at a local level due to the lack of adaptive capacity due to existing developmental challenges, such as low levels of education and primary health care and low incomes, amongst others (Turpie and Visser, 2013, Ziervogel *et al*., 2014, Chersich and Wright, 2019). Plans for these and other impacts, may put considerable strain on local municipalities and governments. Rural communities and local municipalities will need to find appropriate and efficient ways of developing resilience to climate change through adaptation measures.

South Africa is particularly vulnerable to climate change because of its dependence on climate-sensitive economic sectors and the prevailing high levels of poverty (Turpie and Visser, 2013, Ziervogel *et al*., 2014, Chersich and Wright, 2019). The poor, typically have limited opportunities, and consequently, are disproportionately affected by the negative impacts of climate change, as they are less adaptive in their employment and housing. Several provinces, including KwaZulu-Natal have already been highlighted as being negatively affected by climate change in South Africa (Turpie and Visser, 2013). Additionally, climate change is one of the major challenges constraining smallholder agriculture in sub-Saharan Africa because of extreme weather conditions associated with climate variability (Turpie and Visser, 2013, Serdeczny *et al*., 2017). In a study by Evert and Gijben (2017), the lightning ground stroke density for South Africa ranged between 4 to 66 km^{-2} y^{-1}, while the province of KwaZulu-Natal was between 15 to 66 km^{-2} y^{-1}, based on the 11 year (1 March 2006 to 1 March 2017) lightning ground stroke density map for Southern Africa. Despite maximum lightning activity already being detected and present over the eastern parts of the South Africa (particularly KwaZulu-Natal and Mpumalanga), climate models predict increasing lightning activity (Prein *et al*., 2015, Romps *et al*., 2014) as the climate becomes warmer and drier, despite the atmosphere becoming more stable (Price, 2009). These intricate relationships indicate less rainfall attributed with more lightning, similar to drier climates with high and intense thunderstorm activity (Price, 2009). These projections raise concern for the rural poverty-stricken communities of South Africa, as they do not possess the resources to adapt to a potentially higher lightning incidence. Thus, a new urgency to better understand the atmosphere and threat of lightning develops, along with the need for developing “robust” or “resilient” or “adaptive” responses to reduce vulnerability in South Africa, particularly for the rural areas. Through detection and understanding lightning occurrences, crucial information regarding the intensity of convection, can also be obtained.

1.1.5 Motivation for the study

A poorly understood natural phenomenon such as lightning coupled with a magnitude great enough to cause catastrophic destruction to infrastructure, livelihoods, as well as injury and even death, highlights the need to further investigate lightning in South Africa. Excluding the damage to infrastructure, up to 100 lightning-related fatalities annually in South Africa (Blumenthal *et al.,* 2012), further adds importance to conducting a study on such a phenomenon.

Along with South Africa’s high levels of poverty and low adaptive capacity, those individuals that reside in rural areas are often found outdoors due to work activities such as small-scale subsistence farming, herding livestock, mining, tending to land or walking in the open to reach their destinations (Cooper *et al.*, 2016; Gomes 2017; Cooper and Holle, 2019c). Consequently, these individuals become most prone to lightning related risks. Risk even exists indoors as rural people live in houses that have no 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 ground (Cooper *et al.*, 2016; Gomes, 2017; Cooper and Holle, 2019c). Rural housing may also have thatched roofs or newspaper to insulate the roof, both of which can easily be set alight by lightning, preventing even the healthiest individual from escaping the threat of lightning (Cooper, 2012; Cooper and Holle, 2012; Gomes, 2017). Furthermore, a lack of lightning safe-shelters, few available fully-enclosed metal-topped vehicles, unavailability/delays in medical treatment, a lack of awareness on the dangers and precautions of lightning as well as a lack to accessible and easy to understand early warnings further expose rural areas in South Africa and in other developing countries to the threat of lightning (Cooper *et al.*, 2016; Gomes, 2017; Cooper and Holle, 2019b). In addition, South Africa has a very diverse population with different people from different cultural backgrounds having different traditions, beliefs and myths regarding lightning, which hinders necessary precautionary measures being adopted.

Climate change projections are an added concern as they indicate an increased risk of climate-driven events (Brooks 2013; Singh *et al*., 2017), including increased lightning activity (Price 2009; Romps *et al.*, 2014). Price (2009) discusses a prevailing positive relationship between lightning activity and surface temperatures with climate models supporting an approximate 10% increase in lightning activity for every 1 K in global warming. In a study by

Ziervogel *et al*., (2014) climate change was highlighted as a key concern in South Africa with an observed increased in the frequency of extreme rainfall events and increases in mean annual temperatures by at least 1.5 times compared to the observed global average of 0.65°C over the last five decades. Climate change projections of increases in lightning activity will pose an added concern for a lightning prone countries such as South Africa (Price 2009; Romps *et al.*, 2014). The increase in these extreme events are the realities bringing harm to human communities and the natural world, which countries have to prepare, plan and deal with (Ringler *et al.,* 2013). Since a developing country such as South Africa has a large proportion of the population living in poverty, an added danger will prevail in their lives with an increase in lightning incidence. Children represent more than a third of South Africa's population and are one of the social groups most vulnerable to climate change (UNICEF, 2011). The nature of their vulnerability is multidimensional, shaped largely by physical, social, and emotional changes which are further intensified by children's heightened sensitivity to negative or high-impact events. Additionally, wider development pressures affecting the country also need to be considered, including challenges such as population changes, high levels of poverty and inequality, and rapid urbanisation in relation to climate change. UNICEF (2011) has initiated a new study that calls for policy makers to focus on children in addressing climate change. Children have a right to be involved in the planning of mitigation and adaptation strategies as effective participation by children on climate change issues can feed into and strengthen policy and national response.

In order to reduce the high risk South Africa's rural communities are exposed to, plans and measures need to be implemented to improve the detection of lightning within rural communities. If implemented through the education system, it will assist them in preparing for lightning safety. Teachers and schools are ill-equipped to teach children about lightning and rural communities lack the resources and knowledge needed to assist them against the dangers of lightning. Promoting lightning safety tips and guidelines to follow in order to minimise the number of lightning related injuries and deaths at a school level would have a wide reaching benefit. This study therefore involved developing and researching a near real-time lightning warning system, with the capability of displaying early warning information for a variety of environmental conditions within the teaching and learning environment of a rural school.

Since lightning can result in injury and death, the need for continued scientific and technological advancement, dissemination of knowledge and public awareness is crucial. Apart from early warning systems for monitoring and detection, lightning occurrence data have also become a useful variable for detecting climate change and providing early warning for severe weather such as flash floods, hail storms and tornadoes. Studies over the last few decades have researched the relationships between meteorological factors and lightning and have shown lightning to produce greater lead times for severe weather warnings. Consequently, this study will also attempt to demonstrate the use of lightning data (e.g., rates) as a useful lightning-based severe weather warning decision support tool for South Africa. This is a preliminary study and a first study of its kind in South Africa, to illustrate the benefit of using lightning data as a precursor to severe weather (a super-cell event) on a local scale in South Africa, indicating the novelty of this study.

Lightning alerts, stressing lightning awareness and safety and diffusing some of the cultural beliefs, while addressing the socio-economic imbalances may save lives. Building regulations and standards need to be considered and implemented to determine the lightning risk. These are strategies that have been discussed and mentioned in various studies such as Dlamini (2009) and Stano (2012), however, no studies prior to this have focussed on the implementation. This clearly highlights the significance of this research and the importance of the need for a near real-time lightning warning system (NRT-LWS) and for assessing the use of lightning under a changing climate to support decision making, during severe weather conditions in South Africa. By using participatory research methodologies, as well as community-based adaptation planning, adaptation will become an iterative co-learning process. The findings of this study will also be beneficial to other rural areas within South Africa.

1.2 Research question

Is the NRT-LWS capable of increasing the climate resilience and adaptive capacity of rural communities in South Africa by providing warnings and alerts in a timeous manner as well as, providing accurate lightning data at a local level to monitor lightning activity, track thunderstorms and severe weather phenomena?

1.3 Aims and objectives

This section will detail the main aims of the research project and identify the objectives that need to be completed to accomplish the main aim. Hence, the objectives are steps towards completing the overall research study aim.

1.3.1 Research aims

The overall aim of this study was to investigate the possibility of reducing the vulnerability of lightning threat of rural communities within South Africa (as epitomised by the Swayimane community), and to better understand the use of lightning for severe weather prediction in South Africa.

1.3.2 Objectives

Considering the overall aim of the study, the thesis is divided into four parts, which progressively documents existing, and innovative approaches, which are intended to fulfil the following specific objectives;

i. review of relevant literature on the history and development of lightning as well as on the different techniques that exist to detect and monitor lightning occurrence;
ii. develop and implement a NRT-LWS to reduce the vulnerability of lightning threat and the impacts of climate-driven risks and the associated projected increase in lightning activity for rural communities;
iii. employ a multi-disciplinary approach, using existing lightning systems data and automatic weather station (AWS) data in conjunction with the developed NRT-LWS to quantify lightning and thunderstorm activity within the study area;
iv. assess the use of lightning to predict severe weather by investigating if there was evidence of a lightning jump as a precursor to a tornado event within the vicinity of the study area.

Considering the importance of the need for building adaptive capacity and empowering community members, officials and municipalities to understand, prepare and better their livelihoods within the domain of a changing climate and projected increases in lightning activity, research that may assist is essential.

While existing ground-based lightning detection networks and space-based lightning sensors provide an opportunity to acquire such information. These techniques, however, have limitations in terms of providing information at a local scale and in near real-time to rural communities and schools with adequate time to react, plan and prepare for lightning. Communication systems that translate space-based lightning detection into a community warning are not available in South Africa at this present time.

Given these limitations, a study was undertaken by using a Campbell Scientific electric field meter (CS 110) and a strike guard (SG 000) lightning warning system. The tasks undertaken to achieve the above-mentioned objectives are included in the following hypothesis (*H*) and sub-objectives (*O*), which were tested in Chapter 3.

H_0: The selected NRT-LWS comprising of the Campbell Scientific Inc. electric field meter (CS 110) and strike guard (SG 000) are able to adequately detect, measure and warn based on lightning activity within the study area, as well as alert the community within sufficient time to react appropriately

O1: Identify and apply a short-message-service to the early LWS to alert officials, authorities and the community

O2: Apply and evaluate the approach of the Agrometeorological Instrumentation Mast (AIM) system's website to publish, store and communicate lightning data

O3: Evaluate the performance of the NRT-LWS to detect lightning through the assessment of storms and above normal lightning events within the study area

O4: Identify limitations associated with the NRT-LWS and evaluate potential solutions to address these limitations

Once the aforementioned objectives were achieved and the ability of the NRT-LWS to adequately detect, warn and communicate lightning data within the study area was confirmed, comparisons between the NRT-LWS against South Africa's existing lightning detection network were undertaken in the study. As previously mentioned, there remains a fair degree of uncertainty regarding the ability of the early warning systems to detect lightning activity. Consequently, the following hypothesis and sub-objectives were tested in Chapter 4.

H_0: The ground-based LWS is able to detect lightning reliably and accurately as the country's existing national lightning network

O5: Compare and assess the NRT-LWS against the South African Lightning Detection Network (SALDN)

O6: Utilise statistical techniques to identify the capability of the LWS to detect the occurrence of lightning versus the capability of SALDN at a local level

Once the performance of the ground-based NRT-LWS was evaluated, a methodology to understand, detect and predict severe convective activity/thunderstorm climatology using the LWS lightning climatology was investigated. The following hypothesis and sub-objectives were tested in Chapter 5.

H_0: The NRT-LWS in conjunction with meteorological nowcasting data may be used in determining the severity and onset of convective development, as well as for the supply of short-term forecasts of convective storms

O7: Utilise moisture parameters from the AWS together with the LWS's flashes and electrical field to detect the occurrences of potential thunderstorms

O8: Utilise available data for nowcasting to detect an extreme weather event

O9: Analyse the diurnal cycle of lightning activity during an active thunderstorm

O10: Utilise a statistical lightning jump algorithm to identify the capability of using lightning data from the LWS to provide early warnings for extreme weather phenomena

1.4 Structure of the thesis

Figure 1.1 provides an overview of the structure of the thesis, showing the approach that was followed to achieve the overall aim of the study. In order to place each chapter in context of the overall thesis, Figure 1.1 is repeated at the beginning of each chapter, with the relevant parts of the figure addressed in the following chapter, highlighted in grey. The thesis is structured as a series of research papers, which have been published, are in press, submitted or are intended for submission, following the approach that has been accepted by the University of KwaZulu-Natal. As recommended by the University of KwaZulu-Natal's thesis guidelines, the referencing style for each of the research papers conforms to the journal in which the paper was published, to which it has been submitted or will be submitted.

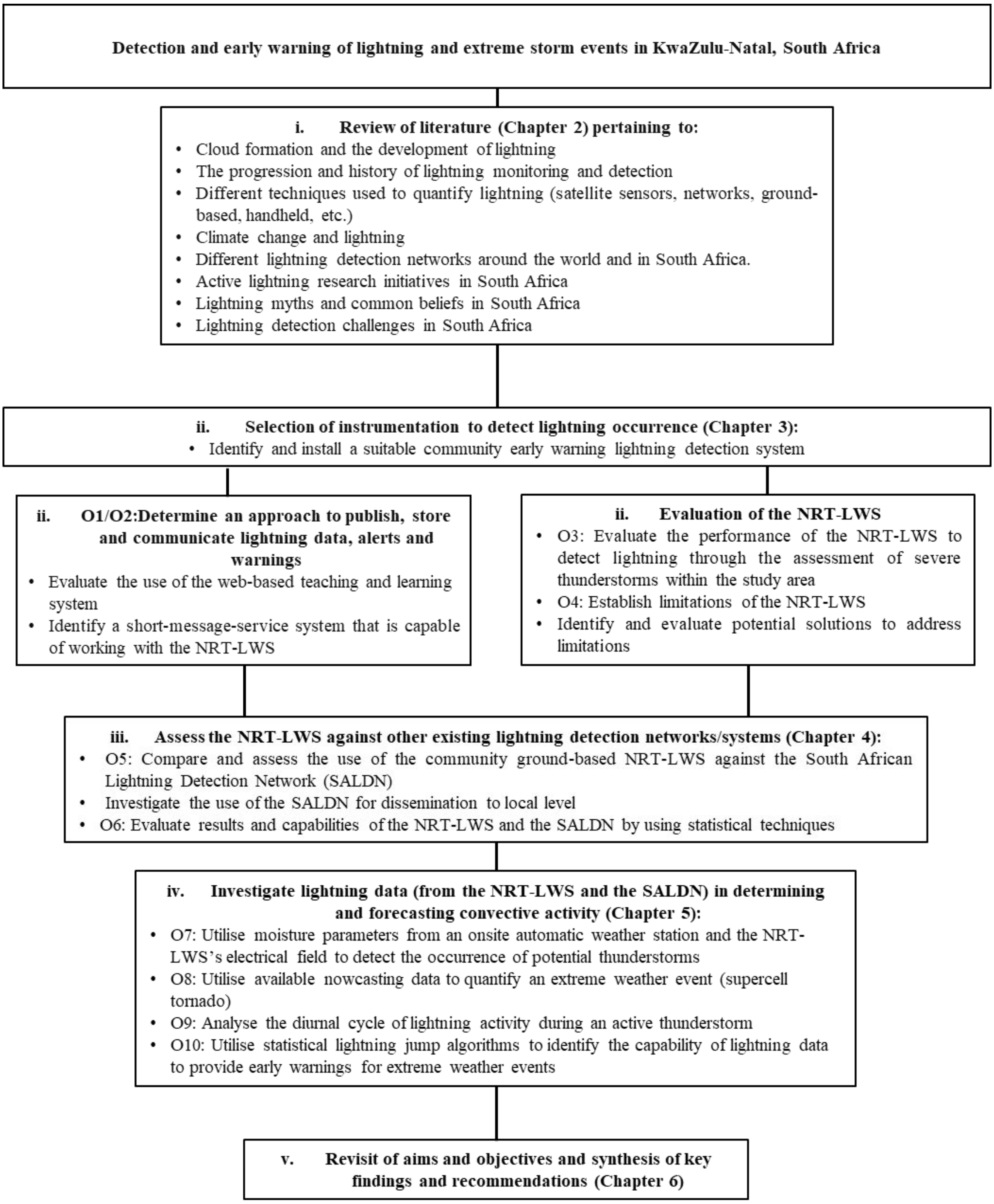

Figure 1.1 A conceptual framework of the study.

Chapters 2 to 5 inclusive of this thesis have been written for publication, with each chapter consisting of its own introduction, methodology, results, discussion and conclusion sections.

The description and application of the NRT-LWS (Chapter 3) is central to the remaining chapters. While every effort was undertaken to ensure that each chapter was presented as an independent investigation, some overlap within the thesis is inevitable, usually when describing study sites or equipment and datasets. Each chapter is outlined below.

Chapter 2 presents a literature review that outlines the importance of lightning as a natural hazard and a safety risk. The chapter discusses the history and development of lightning research. The chapter also details the developments of research in the field of lightning across the world but narrows down specifically to South Africa. In addition, the different techniques that exist to monitor and detect lightning is discussed. The purpose of this chapter is to provide an overview on the existing research undertaken in the field of lightning, to highlight the advances in lightning detection over the years and to outline existing challenges and knowledge gaps, which this research seeks to remedy.

Chapter 3 is devoted to documenting the development of the NRT-LWS within a rural community in South Africa. It provides an understanding on the instrumentation that make up the system and describes the terminology as well as the levels/classification in the alarm states that are used to warn against the threat of lightning. The structure and process of the LWSs communication and warning status dissemination system is also included. Data from the NRT-LWS is utilized in the chapter to report on the early warning system’s detection and warning capability, along with characterising lightning activity in the study area. The chapter also addresses the challenges associated with implanting early warning systems such as the NRT-LWS, in rural communities.

Chapter 4 focuses on further investigating the performance of the NRT-LWS through a systematic evaluation on the performance of the system using the existing national network, known as the South African Lightning Detection Network (SALDN). Since, the SALDN is currently only operational at a national level, this chapter also investigates and demonstrates the potential benefits of the SALDN if warning dissemination could be achieved at a local level.

Chapter 5 provides insight into the use of lightning data as a precursor to severe weather, and especially as a tool for assessing tornado climatology in South Africa. An objective lightning jump algorithm was used to examine concurrent trends in both total and cloud-to-ground lightning within the same severe thunderstorm, which led to a supercell tornado event. This chapter also illustrates the synergistic effects of combining lightning, radar and satellite data to support the early detection of atmospheric convection.

Chapter 6, the final chapter, integrates and synthesizes the work. The aims and objectives of the research outlined in this chapter are revisited. Key findings, limitations and future research possibilities, relating to the various methodologies that were adopted to fulfil the aim and objectives of this thesis are also discussed.

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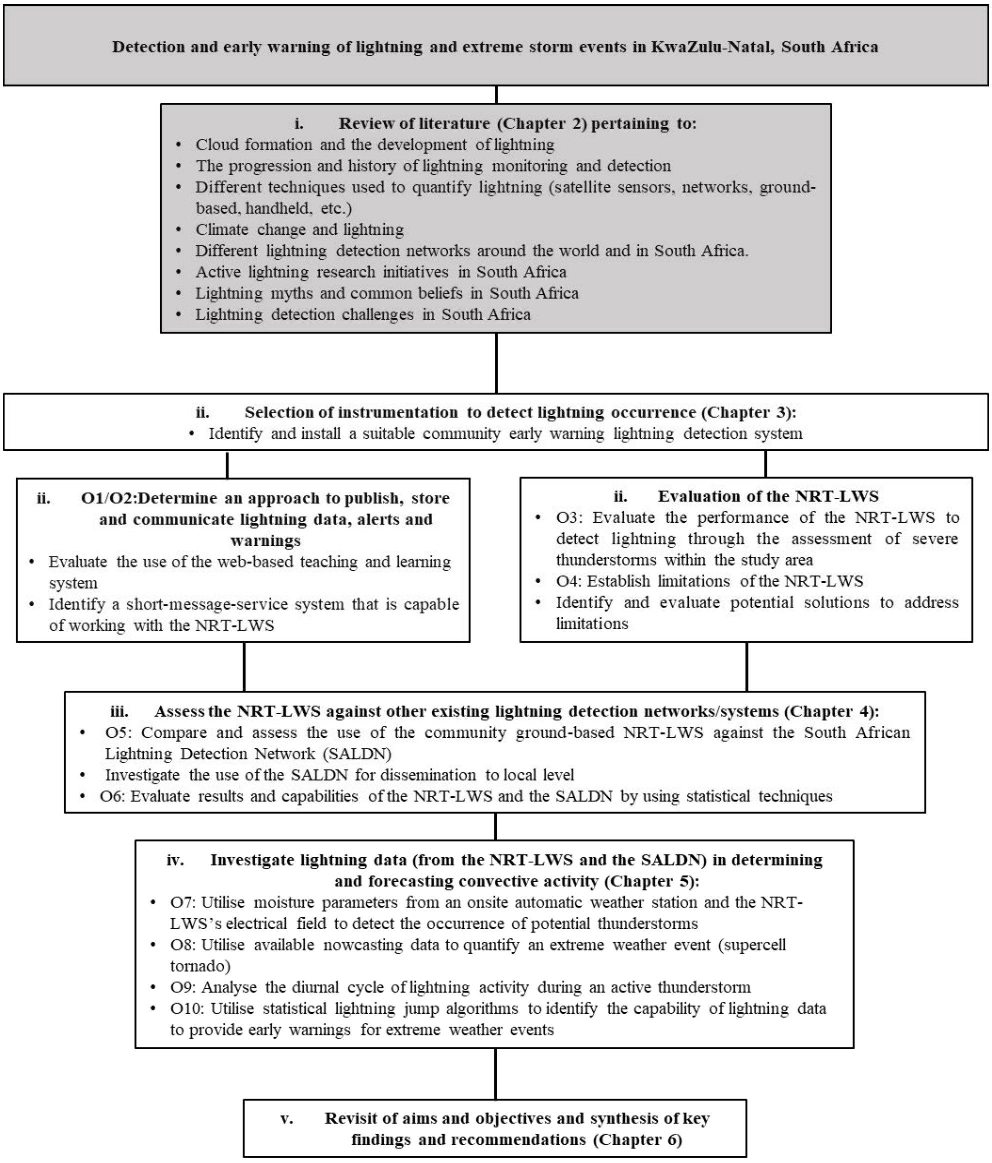
Lead into Chapter 2: Provides evidence and sets the scene for the development of a ground-based NRT-LWS at a local scale. The following literature review chapter introduces the phenomenon of lightning, reviews existing lightning detection and monitoring techniques as well as the recent developments in lightning research. The chapter also includes sufficient fundamental background information on the area/topic of study to support the aims and objectives of this thesis.



CHAPTER 2: LIGHTNING MONITORING AND DETECTION TECHNIQUES: PROGRESS AND CHALLENGES IN SOUTH AFRICA (PAPER 1)

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2.1 Abstract

Globally, lightning causes significant injury, death and damage to infrastructure annually. South America, Africa, Asia, North America and Oceania are amongst the lightning hotspots in the world, whilst South Africa has one of the highest incidences of lightning-related injuries

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and deaths in comparison to the rest of the world. The latest available lightning detection techniques and technologies are reviewed and include current research being conducted in South Africa and South Africa's lightning detection challenges. Technological advances have contributed towards improving lightning detection and monitoring activities in many countries. South Africa has made considerably more progress in the field of lightning research than other African countries and possesses one of the three ground-based lightning detection networks in the Southern Hemisphere. However, despite these developments, rural communities in South Africa, and indeed in the African continent, remain vulnerable to lightning, the occurrence of which is predicted to increase with climate change. A large proportion of the population of African countries resides in rural areas, where citizens participate in subsistence farming, and built infrastructure is not lightning safe. The study recommends a call for the integration of indigenous and scientific knowledge as well as for the development of a participatory early warning system. Investigations into determining the most effective way to utilise existing monitoring networks but with warning dissemination to rural communities are also required. Lastly, future research on the development of lightning-safe rural dwellings or shelters especially in lightning prone areas are needed.

Keywords: *climate change; extreme weather; lightning activity; rural communities*

2.2 Significance

- Climate change projections of increases in lightning incidence highlight an increased risk for vulnerable communities.
- There is a lack of literature focussing on lightning detection within rural communities.

- Technological advancements now allow for better dissemination of lightning information and early warning within rural communities.
- The South African Lightning Detection Network (SALDN) is operational at a national level; however, there is no dissemination at a local level.
- There are currently no recommended design guidelines for informal dwelling and no safety protocols for rural communities.

2.3 Introduction

Lightning is one of the most frequently occurring geophysical phenomenon.[1] Despite lightning being a familiar and researched phenomenon, it still remains poorly understood. This is primarily due to the spontaneous spatial and temporal occurrence of lightning. There has been more than a century of research conducted on the physics and the phenomenology of lightning and yet some processes still require further in-depth research.[1-2] Lightning is complex and is sometimes accompanied by extreme weather such as hail, extreme wind gusts and heavy rainfall.[3-4] According to Blumenthal *et al*.[3], apart from incidental catastrophes and disasters, lightning strikes result in more deaths than any other natural event or phenomenon. In South Africa, the number of lightning deaths is about four times higher than the global average.[5] Although various studies report disparate lightning-related fatalities, the actual number may be higher since many injuries and deaths are often unreported.[6-7]

It is expected that extreme weather and the occurrence of lightning will also increase with climate change.[8] A study by Ziervogel *et al*.[8], discusses climate change as a key concern in South Africa with an observed increased in the frequency of extreme rainfall events and increases in mean annual temperatures by at least 1.5 times compared to the observed global average of 0.65°C over the last five decades. Africa has already experienced a warming trend, which is likely to continue in the future.[9] These climate change projections become an added concern for developing African countries that are already prone to lightning occurrences. Climate models support the positive correlation between lightning and global temperatures.[10] A study by Romps *et al*.[11] modelled the frequency of lightning strikes across the continental USA and predicted that lightning strike rates will increase significantly due to increases in global average air temperature. However, there is uncertainty regarding the expected changes in spatial distribution of lightning with climate change. Since climate change is intricately linked to almost all facets of society, developing countries are more likely to face the brunt of climate change due to their low adaptive capacity. Thus, monitoring and prediction of lightning incidences on a local scale for developing countries requires attention.

Lightning incidence itself may be a valuable variable that could be used to monitor climate change and severe weather changes.[7] There are now reliable ways for monitoring global and regional lightning activity in near real-time.[7] The ease of monitoring lightning across the globe using ground-based networks is frequently advocated. This makes lightning an attractive indicator for tracking changes in severe weather.[12] Climate models predict increasing lightning activity as the climate becomes warmer and drier, despite the atmosphere becoming more stable.[10] These relationships indicate reduced rainfall, which may result in increased lightning incidence.[10]

Lightning has already been recognised as an important research topic on the African continent. Gijben[13] presents a review of the historical and current instrumentation used for the detection of lightning activity over South Africa. However, with an increase in the accessibility of detection methods and systems, it is important to re-evaluate their application in the South African context. Consequently, the objective of this review is to highlight the advances in lightning monitoring and detection, along with the major lightning detection challenges facing South Africa, including the relevance to rural communities.

2.4 Approach

The review assesses the latest lightning detection techniques and technologies used globally and includes an updated review of the progress and challenges in lightning detection with a focus on South Africa. A detailed summary of South Africa's current lightning research initiatives as well as future endeavours towards improving South Africa's lightning detection at a local/community-level is highlighted. A mixed-methods approach was used, which included qualitative and quantitative inputs towards exploring existing lightning detection methods and investigating South Africa's current state of lightning detection. The focus was on the specific challenges facing South Africa, with respect to community-level lightning detection to provide feasible recommendations.

The first section (*cf.* History of Lightning Detection) of the review establishes the context for the study and provides an overview of the historical and current status of lightning detection at a global and national level. The second section (*cf.* Existing Lightning Detection Techniques and Systems) discusses the lightning detection techniques and systems currently available and provides details on the three common types of lightning detection systems used globally. The third section (*cf.* Lightning Detection in South Africa) details South Africa's approach towards lightning detection and includes existing lightning related research organisations and institutions. This is followed by a discussion on lightning detection in South Africa at a community/local-level (*cf.* Community-level Lightning Detection) and provides information on lightning detection systems that are appropriate for use at a community level. The fifth section (*cf.* Lightning Detection Challenges in South Africa) details the lightning detection challenges in South Africa, which is due to poor infrastructure at a community level, as well as belief systems and a lack of education. This is followed by recommendations towards dealing with these challenges. Lastly, the review concludes by highlighting the gaps in South Africa's lightning detection approach, suggesting where future research should be focussed.

2.5 History of lightning detection

2.5.1 Internationally

Lightning has been associated with God's anger up to the Middle Ages until the natural interpretation of attributing lightning to collisions between clouds by René Descartes began in the 17th Century.[14] In 1746 Benjamin Franklin showed that lightning was electrical.[1] Franklin's well-known kite experiment in 1752 was a critical breakthrough in scientific research that showed that lightning was electrical.[1-2,6]

In the late nineteenth century, photography and spectroscopy became available as diagnostic techniques utilized for lightning research in England, Germany, and the USA.[1,13] Investigations used time-resolved photographic techniques to identify individual "strokes" comprised of a lightning discharge to ground and the "leader" that precedes the first strokes. In 1900, the double-lens streak camera was invented in England by Boys[15]. In the 1930's and after, Boys' double-lens camera was used in South Africa to study CG (between a cloud and ground) lightning.[16] Pockels[19-21] in Germany made the first lightning current measurements. Pockels analysed the residual magnetic field induced in basalt rock by nearby lightning currents and was able to estimate the values of those currents. Studies by Boys[15]; Schonland[16]; Proctor[17]; Proctor *et al*.[18]; Pockels[19]; and Uman[22] further elaborated on lightning photography and spectroscopy, while the early history of lightning photography and spectroscopy was comprehensively reviewed by Uman[23].

The modern era (21st century) of lightning research dates back to work by Wilson in England,[24] which investigated remote, ground-based electric field measurements. It was only about 20 years ago that Transient Luminous Events (TLEs) and high-energy phenomena (runaway electrons, X-rays, and gamma rays including the Terrestrial Gamma Ray Flashes (TGFs) observed on orbiting satellites) were discovered and are still the subject of intensive present-day research.[1]

2.5.2 Nationally (South Africa)

In South Africa, lightning-related research can be traced back to the 1920s when Schonland and Malan, founding members of the Council for Scientific and Industrial Research (CSIR), pioneered the first electric field measurements in South Africa.[3] Much of the lightning research in South Africa was then continued and produced by Schonland and others during the 1930s.[25] The CSIR has continued to maintain its lightning research activities, and from the 1960s has actively participated in the development and testing of lightning detection equipment through the National Electrical Engineering Research Institute (NEERI) in Pretoria, and in cooperation with CIGRÉ (International Council on Large Electric Systems).[3]

In recent years, prominent South African institutions, including the South African Weather Service (SAWS), the University of Witwatersrand and the University of KwaZulu-Natal (UKZN) have made significant contributions to the field of lightning research. The University of Witwatersrand has led research on lightning medicine (keraunomedicine)[3] and lightning myths[26] whereas, the nowcasting and forecasting of lightning threats[5] as well as the use of lightning to track the development of thunderstorms[27] in the country has been documented by the SAWS. A recent study by Gijben *et al*.[5] developed a new lightning threat index (LTI) for South Africa by using numerical weather prediction to enable forecasts of lightning threats. A study by Clulow *et al*.[28] conducted at the UKZN illustrated the use of ground-based lightning early warning systems for areas not covered by continent-wide lightning locating systems. These recent research studies and activities show the relevance of lightning through the ongoing advances in lightning research in South Africa.

2.6 Existing lightning detection techniques and systems

Existing lightning detection systems vary in terms of their spatio-temporal characteristics and identifying a suitable system for an application can therefore be complex (Figure 2.1; Table 2.1). Detection systems have different capabilities in terms of warning dissemination. Handheld detection systems for example have no dissemination capabilities and are spatially restricted, while national network systems have been integrated with global warning systems (i.e. the World-Wide Lightning Detection Network) and cover large areas (Figure 2.1).

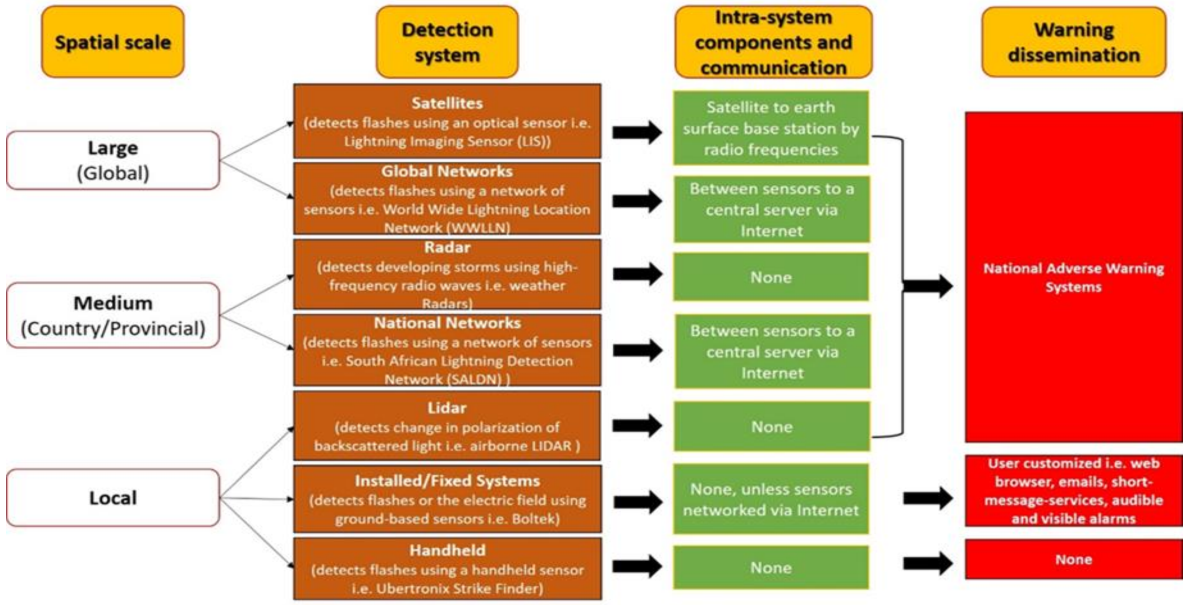

Figure 2.1 The spatial characteristics of the existing lightning detection systems and their associated warning and alert dissemination capabilities.

Radiation that is emitted from lightning forms the basis of lightning detection and lightning location. During the lightning process, electromagnetic and acoustic radiation is generated in various forms, which include radio emission (occurs in the form of short pulses), optical radiation (emitted by thermal radiation of the hot lightning channel) and acoustical radiation (mainly observed by humans).[6,29]

During the last 50 years, various lightning mapping systems have been developed, operating in various frequency ranges and bandwidths. Ground-based detection systems using multiple antennas, space/satellite-based systems and mobile systems using a direction and a sense antenna in the same location are currently the three common types of lightning detection systems globally.[29] The most commonly used techniques remain the ground- and space-based lightning detection networks.[31] These networks are continuously improving and their data are growing in importance for scientists and operational weather forecasters.

Table 2.1 A list of present-day lightning detection options (Kithill[30]).

Present-day lightning detectors	**Generalized description**
Radio frequency (RF) detectors	Measure past energy discharges from lightning and can determine the approximate distance and direction of the threat
Inferometers	Multi-station devices, more costly than RF detectors and employed for research purposes requiring a skilled operator
Network systems	Multiple ground-based RF sensors are networked to determine location of lightning over large spatial scales (i.e. continent or country scale)
Electric field mill/meters (EFM)	A pre-lightning sensor that measures the potential gradient (voltage) changes of the Earth's electric field (cloud voltages) and reports changes as predetermined thresholds to lightning breakdown values. They consist of a narrow reporting range and false alarms may occur from various sources such as dust storms. More importantly, the electric field changes rapidly before a strike, which is useful for early warning.
Optical monitors	Detect light flashes from cloud-to-cloud lightning that typically precedes cloud-to-ground lightning
Hybrid designs	Consists of a combination of the aforementioned technology designs such as RF and EFM sensors
Meteorological information services	Includes meteorological subscription services usually sourced from a network system

2.6.1 Satellite/Space-based

Tracking thunderstorms and assessing cyclone intensification become important challenges in weather prediction for remote regions where surface observations and radar systems are not available. Significant advances in the understanding of global distribution and frequency of lightning have been made possible by the different types of satellite-borne lightning detectors.[32] Two primary satellite sensors that have been widely used include the National Aeronautics and Space Administration (NASA) Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS) on board the Tropical Rainfall Measuring Mission (TRMM) satellite.[10,29,33] The OTD and the LIS are both low Earth orbit (LEO) instruments, capable of detecting optical pulses from lightning flashes, during both day and night. However, they do not accurately separate CG and cloud lightning incidence. Additionally, the majority of these satellites such as the LIS are polar-orbiting satellites, restricting spatio-temporal coverage. They are also incapable of providing near real-time lightning monitoring, detection and warning.[32]

The OTD was operational from May 1995 until March 2000 with a spatial resolution of 8 km, while LIS, with a 4 km spatial resolution, was active from November 1997 to 2015.[34] The OTD and LIS systems were critically assessed, providing guidance on the applicability for research use and instruction for new instrument design.[33-37] A merged global lightning 0.5° resolution dataset composed of the individual LIS and OTD orbits is freely available online (http://lightning.nsstc.nasa.gov/data/data_lis-otd-climatology.html).[38] The LIS-OTD climatology is the most accurate depiction of total lightning across the planet to date and is named the High-Resolution Annual Climatology (HRAC) database.[39]

The new generation series of GOES-R (Geostationary Operational Environmental Satellites) carrying a Geostationary Lightning Mapper (GLM) was launched in November 2016 and has been deployed in a geostationary orbit to continuously detect lightning activity over America and its adjacent ocean region in the Western Hemisphere.[40] The GLM is an optical sensor that detects total lightning (in-cloud, cloud-to-cloud and cloud-to-ground) activity over the Western Hemisphere.[41] The GLM delivers lightning measurements similar to those of LIS but provides continuous lightning detection.[41] This GLM will be able to provide high-quality data for forecasting severe storms and convective weather but only over the Western Hemisphere.[41]

EUMETSAT plan to launch the Meteosat Third Generation (MTG) operational meteorological satellite in 2021 with an onboard lightning imager operating on a continuous basis covering the entire MTG disk (including the entire African continent). It is expected to deliver near real-time information on total lightning for the purpose of supporting nowcasting of severe weather warnings and monitoring deep convection.[32] The development of such modern lightning detection instrumentation has been driven by a variety of practical needs and applications as well as research needs.[42]

2.6.2 Ground-based lightning detection networks (LDN's)

Ground-based global lightning observation networks are based on the Schumann resonance method.[10,43] As a result of the narrow time scale (sub-millisecond to millisecond) and the large spatial scales associated with the lightning current, the majority of the energy in the radiated spectrum is contained in the Extremely Low Frequency (ELF 3–3000 Hz) and Very Low Frequency (VLF 3–30 kHz) bands.[4] Further details on these different frequency ranges are given by Cummins *et al*.[44]

Electromagnetic waves disseminate at ELF and VLF frequencies, by being reflected from the ground and from the conducting layer of the atmosphere known as the ionosphere, and in this manner, they can travel large distances around the Earth.[4] The low loss propagation of sferics (typically 2–3 dB/1000 km) allow measurements to be conducted spatially from their source locations within the ionosphere waveguide. This makes networks of ELF/VLF sensors particularly useful in long-range severe weather monitoring applications, compared to weather radars. Weather radars use microwave – frequency radar beams that are blocked by mountainous regions when locating the presence of storms over several kilometres.[4]

According to Mayekar *et al.*[4], a low-frequency lightning receiver forms a part of a node/sensor that captures electromagnetic radiation emitted by lightning. Several such nodes/sensors are distributed across a certain geographical area (to form a network), which rely on the use of either time-of-arrival (TOA)[29,42,44] or magnetic direction-finding (MDF)[29,42] techniques to detect lightning. The digitized data are sent to a central processing system (CPS), which processes these data to calculate the lightning signal characteristics such as peak current, polarity and source location. Finally, the CPS sends this information to a user/display software.

Examples of regional LDNs include the South African Lightning Detection Network (SALDN) in South Africa,[13] the European Cooperation for Lightning Detection (EUCLID)[29] and the National Lightning Detection Network (NLDN) in the USA.[42,45] Regional LDNs operate with sensors spaced relatively close to each other (e.g. the SALDN consists of 24 sensors spread across South Africa),[5] providing regional coverage of total lightning with high detection efficiency. These networks, however, do not provide information over oceanic regions or remote locations where no sensors are installed.[40] Over the years, long-range detection networks have also been developed to enable global coverage and real-time lightning detection, but with a lower detection efficiency than short-range detection networks and satellite detection systems.[40] Global LDNs consist of sensors separated by thousands of kilometres. Examples of global LDNs include the Global Lightning Dataset (GLD360)[46] and the World-Wide Lightning Location Network (WWLN).[47] These sensors detect mainly CG with regional LDNs also detecting a small fraction of IC (cloud to itself) lightning.[5]

In 2003, an innovative lightning location network, "Blitzortung Lightning" was established. This network is a worldwide, real-time, community collaborative network. The network monitors magnetic field (H-field) and electrical field (E-field) emissions from lightning strikes and has a set of servers in Europe to correlate the Time-Of-Arrival at detectors vs GPS-time to locate strikes.[48] A real-time, online map is available, displaying strike information for North America. The web application notifies users via email, SMS or URL-call when lightning is detected within their area. Strikes are colour coded to show how recent they are. Currently, coverage is biased towards the largest clusters of lightning detectors, across Europe, USA and Australia, whilst Africa, Asia and South America remain devoid of detectors.

2.6.3 Handheld/Mobile

Handheld lightning detectors allow users the opportunity to buy a detector easily from a retail store and self-setup instead of having to pay for a service or for lightning information. The cost for these devices varies according to the accuracy and design of the equipment. Such lightning detection instrumentation typically has limitations and the value of these portable devices requires consideration. They detect mostly the intensity of the electromagnetic pulse (EMP)[49] and are generally unable to detect cloud-to-cloud lightning (which usually precedes CG strikes), which is critical in recognizing an approaching storm. Additional limitations include, but are not limited to, poor detection ranges, inability to determine direction or location of a lightning strike as well as interferences from other EMP-emitting devices (such as electrical equipment, fluorescent lights, appliances and even car engines), which may result in either missed strikes or false alarms. Examples of popular hand-held devices include the Ubertronix Strike Finder (Ubertronix, Inc. San Antonio, Texas, USA), designed to record lightning strikes during the day and night by using an infrared sensor and microcontroller-based technology,[50] while other manufacturers include the ThunderBolt Storm Detector (Stormsytems, Tampa, Florida, USA), SkyScan lightning detector (Extreme Research Corporation, Port Richey, Florida, USA) and the INO Weather Pro portable weather station (INO Technologies, Louisville, Colorado, USA).

2.7 Lightning detection in South Africa

2.7.1 Current lightning detection system

The SAWS had no role in measuring lightning activity prior to 2005.[51] The major power utility of South Africa, Eskom, had operated a network of six Lightning Position and Tracking System (LPATS) lightning detection sensors.[52] Before this, the CSIR operated a lightning detection network of 400 lightning flash counters and was the first institution to produce a lightning flash density map for South Africa.[51]

Over the recent years, the detection of lightning occurrences in South Africa has been undertaken by the South African Lightning Detection Network (SALDN), which is operated by the SAWS.[5] In 2005, SAWS purchased a Vaisala (LS 7000 and LS 7001, Helsinki, Finland), lightning detection network, making South Africa one of only three countries in the southern hemisphere to operate such a network, with the others being in Brazil and Australia.[51] The network provided SAWS with its first opportunity to explore lightning and also to provide lightning information to the public.[13] The network eventually consisted of 24 sensors across the country.[5]

2.7.2 Lightning research initiatives

In recent years, the University of Witwatersrand has participated in lightning research in South Africa and has been a key role player in the development of a multi-disciplinary interest group called Lightning Interest Group for Health, Technology and Science (LIGHTS).[3] LIGHTS has been successfully running since 2015, contributing, disseminating and sharing vital information regarding lightning and lightning research in South Africa and within the broader African lightning community. The African Centres for Lightning and Electromagnetics Network (ACLENet) is a pan-African network of Centres that is dedicated to reducing infrastructure damage, injury and mortality resulting from lightning across Africa.[53] It operates as a not-for-profit and non-governmental organization with national centres in Zambia, Malawi, Kenya and South Africa. The network consists of several research and technical advisors that are internationally recognised and serve voluntarily to advise ACLENet on education, research and grant proposals, mentor African researchers, supervise graduate studies and promote ACLENet worldwide. Their website is designed to be user-friendly and can be translated online into Arabic, French, Portuguese, Spanish and Swahili. The network gathers and presents media articles about lightning injuries and deaths caused by lightning and are listed by country. The Earthing and Lightning Protection Association (ELPA) is also a significant contributor towards the standard of safety in the South African lightning and protection industry. ELPA offers certification of qualified designers, installers and inspectors, with recognition by the University of Witwatersrand, the South African Institute of Electrical Engineers (SAIEE) amongst others.[54] LIGHTS, ACLENet and Eskom, are among the collaborating institutions. ELPA has been established as an NPO of voluntary membership. The University of Zambia has also recently contributed towards the academic knowledge regarding lightning in Africa and has opened an MSc and PhD program in high voltage, electromagnetic compatibility, lightning studies and protection.[53]

In addition to the SALDN disseminating lightning warnings across South Africa at a national scale via media broadcasts, a few other initiatives exist for alerting South Africans to possible threats from lightning. One such example is the WeatherBug application. WeatherBug is a mobile application brand owned by GroundTruth, a company based in New York City.[55] This mobile application provides near real-time lightning detection and provides alerts via the application. WeatherBug uses data from the Total Lightning Network (run by Earth Network) together with the users' mobile phone's GPS location.[56] The Total Lightning Network dates back to 2009, with most sensors initially existing in the United States. The network now covers areas of North and South America, Africa, Asia, Europe and Australia. AfricaWeather (Lone Hill, Sandton, South Africa) is another example of a mobile application disseminating lightning warnings to South Africans. It is the only South African built application with lightning and storm detection capability (AfricaWeather 2019).[57] The application provides basic free content (daily weather notices), while advanced features (including lightning proximity and lightning data) require a paid subscription. The online storm-tracking tool allows individuals to identify the location, intensity and time of recorded lightning strikes. AfricaWeather monitors the country's grounded lightning strikes using the Earth Networks (Germantown, Maryland, USA) Total Lightning Network.[57] Information is disseminated to numerous schools and golf courses across South Africa with a siren and spinning strobe light that is installed and maintained through a paying subscription. This is utilized as a visual confirmation of the danger condition with SMSs being sent to a list of specified contacts.

2.8 Community-level lightning detection in South Africa: A new approach

Despite great strides being made in detecting lightning throughout the world, including South Africa, there still remain a high number of lightning fatalities in many rural communities within developing countries such as South Africa. According to media articles and reports, several of these lightning fatalities occur whilst rural people are still present inside their homesteads. However, there is still a lack of literature focussing on lightning detection within rural communities. Furthermore, no literature exists on determining effective approaches to communicate lightning data, threats and advance warning in a manner appropriate for rural communities, as well as information on how to reduce lightning damage in rural dwellings. Such information is vital to assess risk knowledge as part of early warning systems, which is accounted for in the dissemination aspects to build response capabilities that will enable mitigation.

Based on the detection and warning systems reviewed, there are a number of community-level, automated possibilities available for South Africa that are appropriate for high-risk lightning areas. The first is that the national lightning detection network (SALDN) supply areas with lightning warnings using the method employed by AfricaWeather. The second option includes a local measurement system, consisting of a single sensor/node. Numerous types of local measurement systems exist and continue to evolve. Examples of these standalone systems include the Boltek (Port Colborne, Ontario, Canada) lightning detection systems and the Campbell Scientific (Logan, Utah, USA) lightning warning systems. These systems are not only capable of detecting lightning strikes but are also capable of monitoring the electric field changes by using an Electric Field Meter (EFM) and providing warnings before the first lightning strike takes place. These systems are, however, expensive but there are more cost-effective lightning flash sensors now included with some basic weather stations. The ATMOS41 by the METER Group (Pullman, Washington, USA) features a lightning strike counter with distance categories, as well as other meteorological sensors. A third approach includes identifying lightning prone communities using the SALDN and installing lightning rods to divert the lightning pathway from dwellings.

Currently, in South Africa, the SALDN is operating at a national level and has the capability of disseminating the lightning data to a local level. However, this has not been implemented and rural communities continue to lack cognisance of the dangers of lightning. This remains a significant gap within lightning detection research in South Africa and a dire need exists to bridge the gap between the SALDN and rural communities.

2.9 Lightning detection challenges in South Africa

People residing in South Africa's rural areas are often outdoors due to work activities such as subsistence farming and livestock herding. Such individuals are the most prone to facing lightning related risks.[26] The houses in rural communities are commonly not well-earthed and provide little protection against lightning. Consequently, some of the lightning deaths occur whilst people are inside their homes. Many rural structures do not contain metal plumbing, electrical wiring or reinforcing steel that provides a pathway for a lightning current to be grounded.[26] Rural dwellings also do not have proper interior flooring, which increases the risk, since many deaths are due to ground currents of nearby lightning strikes, rather than direct strikes. Furthermore, rural housing often has thatched roofs or newspaper to insulate the roof, both of which are a fire risk.[26] Rural areas therefore lack lightning-safe shelters, leaving communities vulnerable to the threat of lightning. The economic implications and feasibility of building lightning-safe houses and structures as well as the installation of lightning detectors in high lightning risk areas requires further investigation. Investigation specifically into developing lightning-safe shelters are the key priorities which includes projects to fund and develop lightning safe shelters (such as schools, community halls, as well as lightning safe houses, etc.). This is urgently needed in South Africa where funders to support such initiatives are required. There also appears to be no design criteria for establishing lightning-safe rural dwellings which is a critical need in South Africa.

Several cultural beliefs have been associated with lightning strikes (and thunder) in South Africa, which include mythical association. Some indigenous South Africans have religious and traditional beliefs that lightning may be directed to strike someone, and that significant personality changes ensue after a lightning strike, and that it could be a sign of God's anger.[3,26,58] Such myths still exist and some hinder the necessity to take precautionary/mitigation measures thereby increasing the risk of lightning injury.[58] This calls for the integration of selected relevant indigenous and scientific knowledge into educational packages that are relevant to rural community inhabitants.

The review of techniques shows that over recent years, various lightning detection systems have evolved, however, the warnings are not disseminated well to rural communities. Various practical constraints such as poor network signals, a lack of knowledge and the cost of smartphones and data, are prohibitive to the success of such lightning detection systems. Consequently, rural communities continue to remain vulnerable to lightning threats.

2.10 Way forward and recommendations

Significant progress on South Africa's national lightning detection and monitoring has been achieved. Despite these advances, local level research and more specifically the vulnerability of rural communities to lightning incidence/threats requires further attention as rural communities continue to live without any lightning warning. The proposed way forward for improving lightning detection on a local scale is through a system with monitoring and predictive capacity to improve the detection of lightning occurrences and assist rural communities in preparing for lightning through risk knowledge and near real-time/early warning systems is ultimately needed. This can be achieved through the communication and dissemination of alerts in a timeous and comprehensible manner in languages that are understood within specific communities. Building lightning-safe rural dwellings and shelters is also required as well as transformative adaptation. It has been shown that in rural areas using participatory research methodologies, as well as community-based adaptation planning, adaptation can become an iterative co-learning process and facilitate transformative adaptation through the integration of indigenous knowledge with science-based systems. An opportunity therefore exists for bridging the gap between the existing SALDN and rural communities.

To raise awareness of lightning, a national lightning awareness week should be introduced to coincide with that run internationally to promote the magnitude of risks associated with lightning and how to minimize risks, especially in rural communities.

2.11 Conclusions

The current study provides a synthesis on the development and detection of lightning activity internationally and at a local level (South Africa). There are different lightning detection systems available, varying in their spatial scale, detection and dissemination capability. The literature revealed significant and ongoing advances in detection methods, mainly using satellites but that the vulnerability of rural communities in countries like South Africa remains a challenge. This is mainly due to the dissemination of lightning warnings. The SALDN continues to accurately detect lightning activity at a national level but warnings are not disseminated to a local scale. Also, if warnings were disseminated at a local scale, there are few available lightning safe shelters/dwellings in rural areas.

Myths and beliefs regarding lightning in rural areas also continue to remain a challenge in South Africa and hinder necessary precautionary measures. The national school education system needs to include lightning safety and the role of cultural beliefs associated with lightning. Education around lightning safety, the development of lightning safety protocols/guidelines and the involvement of multiple stakeholders, from community members, government extension officers and NGO’s are required.[58]

2.12 Acknowledgements

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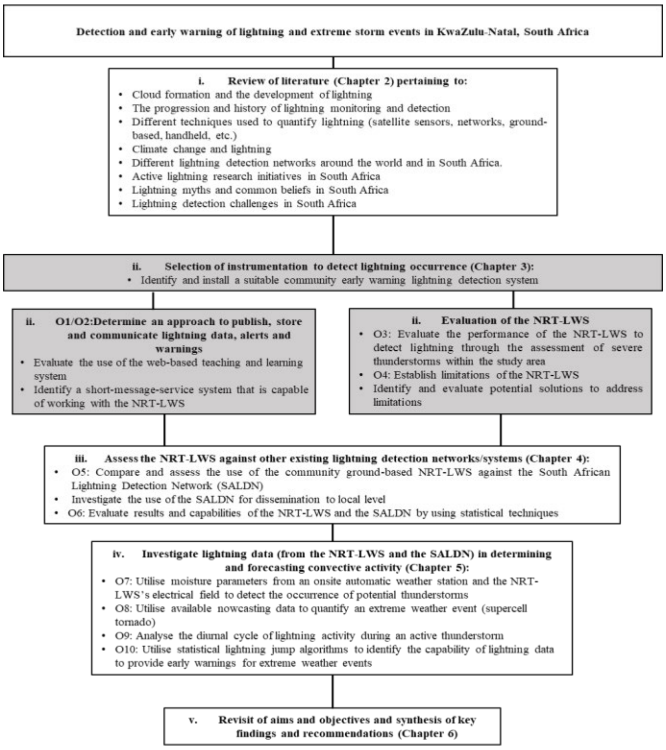
Lead into Chapter 3: While previous studies on the detection and monitoring of lightning activity in South Africa has displayed and achieved significant progress over the years with the aid of technological advances, rural communities in South Africa continue to remain vulnerable to lightning. Literature has revealed that the vulnerability of rural communities to lightning incidence in African countries, including South Africa remain poorly understood, are a subject of debate and remains a challenge. Clearly, more efforts to detect, monitor and disseminate lightning activity information within a timely and easy to comprehend manner at a local level is required. Consequently, the objective of Chapter 3 was to select, implement and evaluate an appropriate local-level early warning lightning detection system for rural communities, determine an effective approach to store, publish and communicate the data and alerts, as well as evaluate the system's performance.



CHAPTER 3: ASSESSMENT OF A GROUND-BASED LIGHTNING DETECTION AND NEAR REAL-TIME WARNING SYSTEM IN THE RURAL COMMUNITY OF SWAYIMANE, KWAZULU-NATAL, SOUTH AFRICA (PAPER 2)

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3.1 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

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and awareness, as well as a poorly developed infrastructure increases 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 timeous and comprehensible manner within Swayimane, KwaZulu-Natal, South Africa. The system comprised 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 14h00 and 21h00) coinciding with learners 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 was 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 timeously.

Keywords: *climate change; decision support; emergency preparedness; lightning; nowcasting*

3.2 Significance statement

Thunderstorms and more specifically lightning, are a life-threatening severe weather phenomenon that can result in damage to infrastructure, physical injury and loss of life (human and livestock) (Dlamini 2009; Blumenthal 2012; Gijben 2012; Trengove 2015). South Africa's lightning mortality rate is said to be four times higher than the global average (Hill 2006). 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.

3.3 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, amongst 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 either 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, amongst 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 to agriculture and forestry sectors (Price 2013). Cooper and Holle (2019b) further elaborate on the economic damages that occur amongst 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 view lightning (thunder) in great awe and to be associated with traditional and religious beliefs (Dlamini 2009; Cooper *et al*. 2016; Cooper and Holle 2019a). In developing countries, many people are also not aware of lightning-induced human hazards, since most incidents occur in remote locations that lack media coverage, whilst a prevailing high illiteracy rate, poverty, lack of protection shelters and other factors are also responsible for the high vulnerability amongst 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 hotspots 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 km^{-2} yr^{-1}) 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 amongst the rural population is due to the lack of lightning-safe structures, fewer available fully enclosed, metal-topped vehicles, a lack of awareness regarding 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 labour intensive subsistence farming/agriculture, population density, amongst 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).

Since a developing country like South Africa has a large proportion of the population living in poverty, an added danger will now prevail in their lives. Climate change projections of increases in lightning activity will pose an added concern the lightning prone country, South Africa (Price 2009; Romps *et al*. 2014). South Africa is particularly vulnerable to climate change impacts due to the prevailing high levels of poverty, 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 tracking severe weather and warning of lightning risks can be made 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 Eskom (South Africa's electricity public utility) operated Lightning Positioning and Tracking System (LPATS) 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 a greatest risk of being killed or injured by lightning (Trengove and Jandrell 2015). Whilst lightning fatalities are generally highlighted, some studies have emphasized lightning injury as being of equal, if not more, concerning (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 even prevent the healthiest individual from escaping (Cooper 2012; Cooper and Holle 2012; Gomes 2017). Furthermore, rural houses may also contain stored flammable materials which 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), whilst 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 regarding lightning around the world and in South Africa.

Communities, workers, learners and schools in rural areas are also found to lack knowledge regarding 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 nor fully enclosed metal-topped vehicles (Cooper *et al*. 2016, Cooper and Holle 2019a), and may not understand how to avoid the danger or even afford lightning protection systems due to socio-economic factors, affordability costs, literacy rates, amongst others (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 to investigate the possibility of 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) towards 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.

3.4 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 (Figure 3.1). 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 hotspots in South Africa (DEA 2013). This is largely owing to the already observed warmer climate 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, which 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 to 14 flashes km^{-2} y^{-1}, based on the 11 year (1 March 2006 to 1 March 2017) 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).

3.4.1 Climate

Swayimane lies within the subtropical costal climate zone with average air temperatures of between 16°C to 18°C (Matungul 2000). The region receives approximately 500-800 mm per annum of rainfall and is characterized by fog in the wet season (uMngeni Resilience Project 2014; Khumalo 2016). Anticipated increases in the frequency and severity of dry spells, as well as intense rainfall is likely to result in brief periods of flooding, threatening food security and long-term livelihoods for the community (uMngeni Resilience Project 2014).

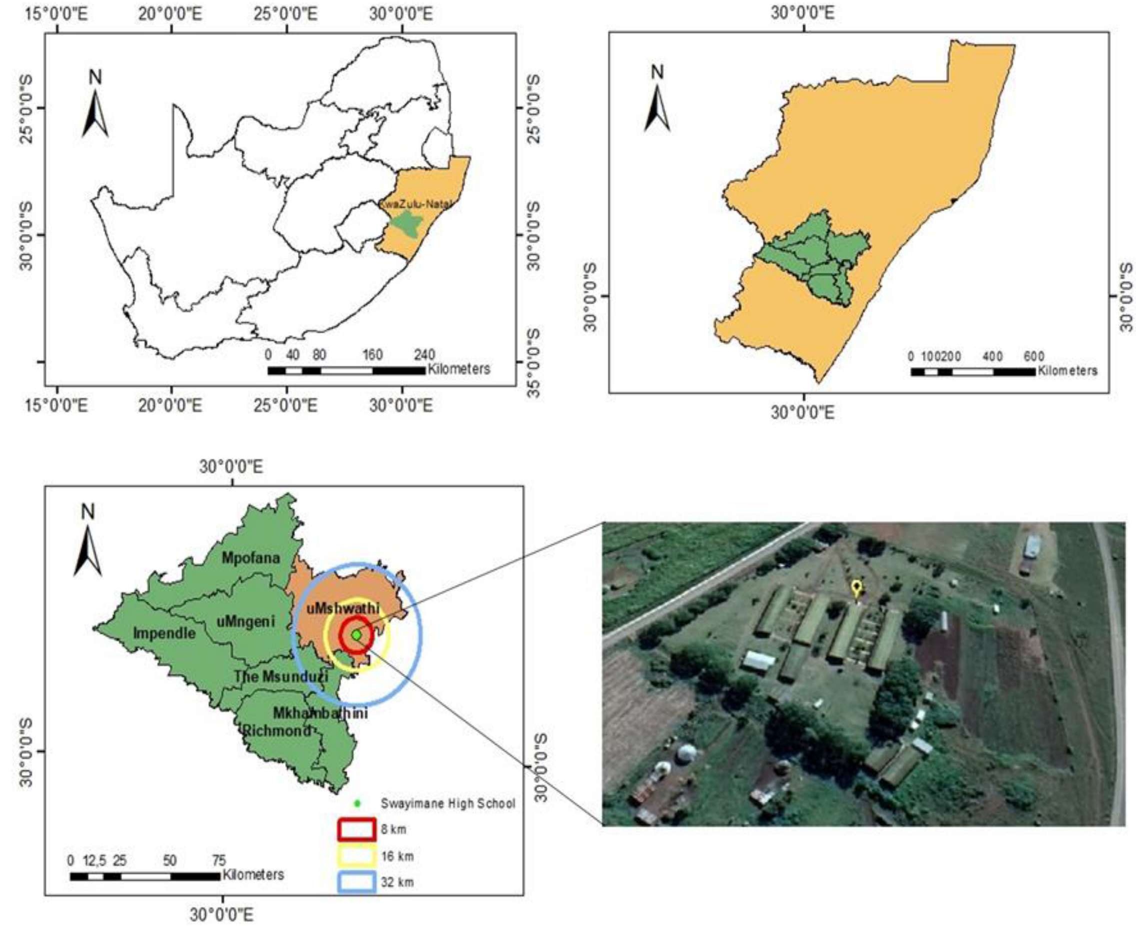

Figure 3.1 The Swayimane High School study site located in the Swayimane community of the uMshwathi Local Municipality in KwaZulu-Natal, South Africa. The red, yellow and blue circles represent the three warn state categories/radius values for which the study area is defined.

3.5 Data and methodology

3.5.1 Lightning warning and notification system

A NRT-LWS was installed at the Swayimane High School in Swayimane on the 2nd February 2018 (Figures 3.1 and 3.2). 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 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 (V m^{-1}) was measured (accuracy within 5%) by a downward-facing Electric Field Meter (CS110, Campbell Scientific Inc., Logan, Utah, USA) positioned at a height of 4.05 m above the ground surface. A clear sky with dry conditions value of approximately -80 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 (SG000, Strike Guard, Wxline, Tucson, Arizona, USA) 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 seconds, two events are detected, the most significant one (closest) will be reported as a flash. Individual lightning strokes are therefore not accumulated. These discharges detected include intra-cloud (IC) and inter-cloud (CC) flashes as well as cloud-to-ground (CG) strikes. Rodger and Russel (2002) describe a lightning flash as an entire lightning discharge whereas the pulses in a flash are known as strokes. Therefore, one lightning flash can be made up of multiple lightning strokes. On the other hand, a lightning strike refers to a lightning discharge that hits the ground. 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 towards 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 fibre-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.

Figure 3.2 The Lightning Warning System (LWS) located at the Swayimane High School, Swayimane. The CS110 Electric Field Meter, the SG000 lightning flash sensor, the siren and strobe beacon lights are visible from the inset image.

One-second measurements from both sensors were recorded with averages or totals calculated every 1-minute, every 5-minutes and every hour (see Section 3.5.2 systems design for details). The 1-minute data were used in all interpretations within this manuscript while the 5-minute 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, 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) (Supplementary Figure 3.1).

Further details regarding the instrumentation used are available at 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 V m^{-1} (Caution) and 2000 V m^{-1} (Alarm) electric field magnitudes were used according to the Naval Seas Systems Command (NAVSEA) and the National Aeronautics and Space Administration (NASA) Launch Pad Lightning Warning System as thresholds to guide the activation of the three states (Clulow *et al*. 2018). The absolute electric field measurements (one- and ten-minute running averages) were used in conjunction with SG000 measurements (flashes detected as they occur) to ascend into higher warning states (Table 3.1) and to descend to lower warning states (Table 3.2) (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 3.1), 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, whilst level 3 accounts for flashes detected within 16 km and/or electric field magnitudes of > 2000 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, and 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-minute duration for the flashes is based on the National Oceanic and Atmospheric Administration (NOAA) 30/30 rule, instructing people to remain in a sheltered area for 30 minutes 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 one-second, one-minute and five-minute data outputs were conducted over a 12-month period to assess the electric field levels and the occurrence of lightning flashes. The 12-month (02 February 2018 until 02 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 temporal behaviour 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 (section 3.6). All times in this Chapter are reported in Central African Time (CAT [UTC +2 hrs]).

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).

Table 3.1 Interpretation of data from the electric field meter and strike guard in respect to understanding the increase of warning levels from 2 to 4.

Increasing with warning states

State	**Beacon colour**	**Electric field meter**	**Strike guard**
2= Caution	Yellow	One-minute running average of the absolute electrical field are > 1000 V m^{-1}	Flash detected within a 32 km radius
3= Alarm and Siren	Red	One-minute running average of the absolute electrical field is > 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

Table 3.2 Interpretation of data from the electric field meter and strike guard in respect to understanding the decrease of warning levels from 3 to 1.

	State	Beacon colour	Electric field meter	Strike guard
Decrease in warning state	3 to 2 = Caution	Yellow	One- and ten-minute running averages of the absolute electrical field are < 1000 V m^{-1}	No flash detected within a 16 km radius for 30 minutes
	2 to 1= All Clear	Blue	One- and ten-minute running averages of the absolute electrical field are < 500 V m^{-1}	No flash detected within a 32 km radius for 30 minutes

3.5.2 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-minute facilitated by Campbell Scientific Africa (Pty) Ltd (Logan, Utah, USA), through a call-back service to a server computer located at the University of KwaZulu-Natal (UKZN) (Figure 3.3). 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-Watt 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 through the Web Publisher.

Email and short message service (SMS) warnings were initiated from the VM when values exceeded certain thresholds as illustrated in Table 3.1. 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 councillor, 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 on the web page, which were easily downloaded from which seasonal trends could be analysed. LWS data were accessible via http://agromet.ukzn.ac.za:5355/Sw_lws/index.html (Supplementary Figure 3.2). A large screen (56-inch 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 (Supplementary Figure 3.3).

The warning system operated automatically, minimising the potential for human error. Initially, due to 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.

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 the NRT screen at the school could operate, a LTE (Long-term Evolution) 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-VDC (Direct Voltage Current) 24 A h battery (with 220 VAC [Alternating Current Voltage]) was used for the CS110 and SG000, with a capability of operating for approximately 24 hours on the battery supply. In order to monitor the SG000 communication and failures, an IP (Internet Protocol) 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.

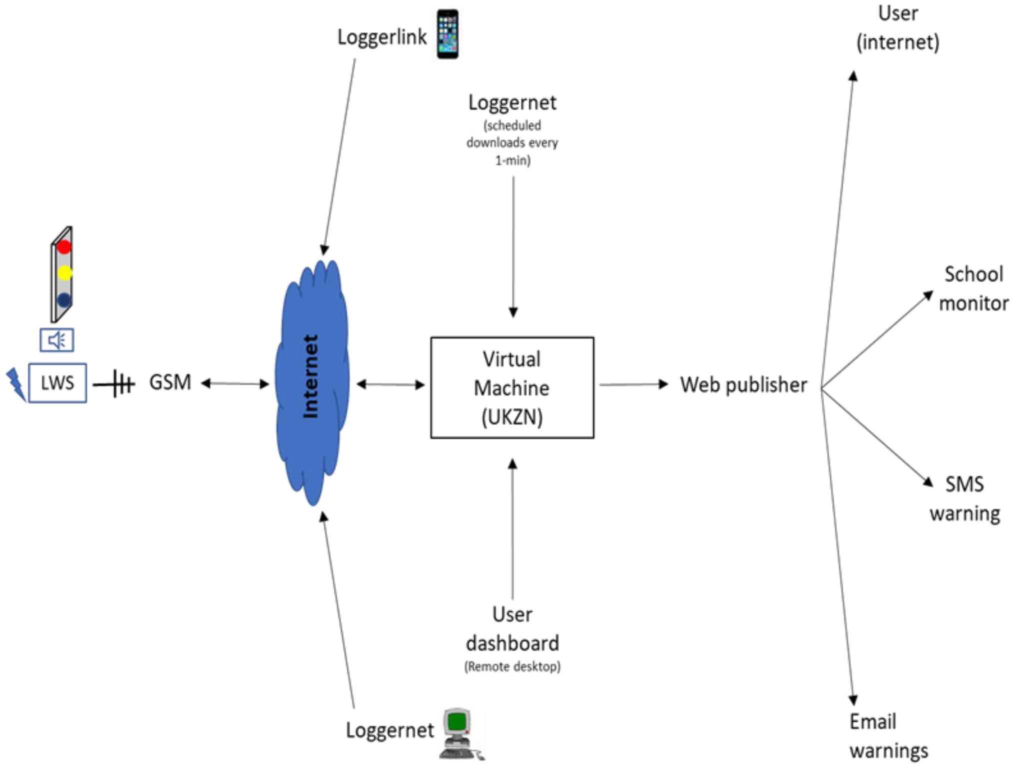

Figure 3.3 Structure of the LWSs communication and warning status dissemination system.

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). 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 3.1).

3.5.3 Automatic weather station

An automatic weather station (AWS) was also installed at the Swayimane High School in March 2016 (Supplementary Figure 3.4). 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 (TR252I, Texas Electronics Inc., Dallas, Texas, USA), air temperature and relative humidity (Vaisala HC2S3 L), barometric pressure (CS106, Cambbell Scienfitic), solar irradiance (LI-200SA, LI-COR, Lincoln, Nebraska, USA), wind speed and direction (Model 05103, R.M. Young, Transverse City, Michigan, USA) as well as a solar panel (for back-up power supply). Measurements were made every 10 s with statistical summaries output as hourly and daily data from the datalogger (CR3000, Campbell Scientific). Data are freely available on the web page and was accessible via http://agromet.ukzn.ac.za:5355/Sw_weather/index.html (Supplementary Figure 3.5).

The sensors were installed in accordance to the World Meteorological Organisation (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 (CS650, Campbell Scientific) at depths 0 cm, 15 cm and 30 cm and a dielectric leaf wetness sensor (Meter Group, Inc., Pullman, USA).

3.6 Data analysis and results

3.6.1 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 to February 2019, is illustrated in Figure 3.4. 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 10h00 CAT to a maximum in the mid-afternoon (approximately 16h00 CAT), which decreased from approximately 20h00 in the evening (Figure 3.4). 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 14h00 and 21h00. The period between 02h00 and 09h00 had the least lightning activity.

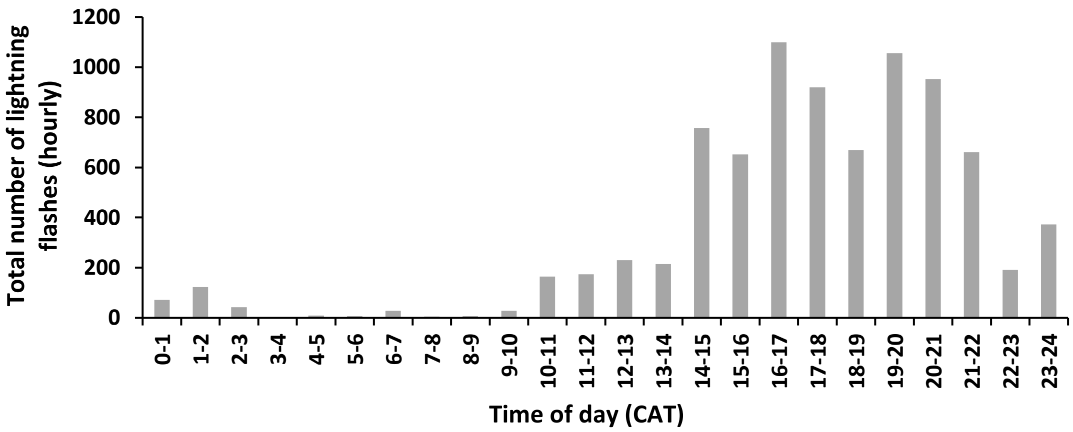

Figure 3.4 Diurnal cycle of lightning for the study period (February 2018 to February 2019), expressed as a count of the hourly totals summed over all three warn category detection ranges. Time corresponds to Central African Time (CAT).

3.6.2 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) (Figure 3.5). 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 state 3 to state 4 was 36. The remaining number of escalations from 2 to 4 totalled 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 (13h00-22h00) before decreasing. Escalations were at a minimum during the early morning hours until midday (00h00-12h00). There were no escalation events observed between 03h00-04h00. The increases in escalation events that occurred from 13h00 to 22h00 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 Figure 3.5, were reached less frequently during the morning hours, than the afternoon and evening. Furthermore, the highest states were quite often reached between 13h00-02h00, with the peak occurring between 18h00-19h00, coinciding with the period when many people will be returning home from their daily routines.

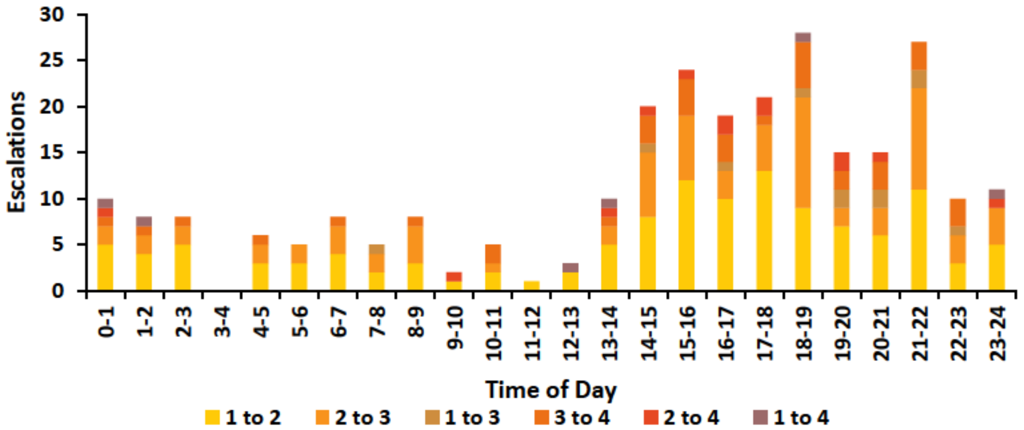

Figure 3.5 Annual total diurnal variation in event states displayed as stacked bars.

3.6.3 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 3.3). The strike guard was solely responsible for 57.6% of the escalations to an alarm state 2, whilst 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 3.1); 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 that occurred without the EFM and SG thresholds having being 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, amongst 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 analysed for each alarm state at every 1 minute interval.

Table 3.3 Percentage of escalations per alarm state observed by the dual sensor system (SG and EFM). Warnings without any detected local lightning activity is represented by false alarm escalations.

Reason for	**Alarm State Escalations**		
Escalation	2	3	4
SG	57,6	45,6	100
EFM	37,8	43,7	N/A
Both	4,5	10,7	N/A
False alarm	0	0	0

3.6.4 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 (Figure 3.6). 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 2018/2019 (5965.2 hours – 95.8%) was spent in alarm state 1 (All Clear) (Table 3.4). Total time spent in alarm state 2 (Watch) was 53.2 hours, 49.8 h in alarm state 3 (Warning) and 60.0 h in alarm state 4. It should be noted, 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 minutes (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 due to a communication failure, while the remaining fault period was due to low battery voltages.

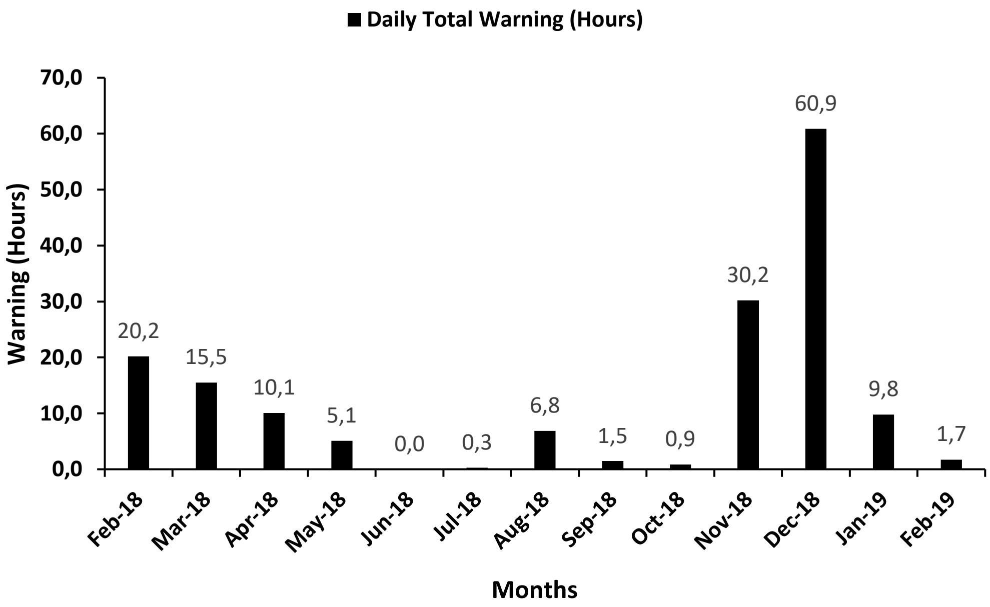

Figure 3.6 Monthly total warning duration in hours for 2018/19 for alarm states.

Table 3.4 The total and percentage of time spent in states 0 to 4 for February 2018 to February 2019.

	Alarm state				
	0	**1**	**2**	**3**	**4**
Hours	97,1	5965,2	53,2	49,8	60,0
%	1,6	95,8	0,9	0,8	1,0

3.6.5 Lightning event assessment

3.6.5.1 Lightning data

A lightning event was identified from the time the system entered a warning state of 3, lasting until the system had exited and approached a warning state of 1. Two specific lightning events were assessed to provide insight into the systems performance and to confirm that SMS warnings were being delivered timeously. They were identified as periods exhibiting above-normal lightning activity based on the number of flashes within a lightning event. The measured rainfall data were obtained from the onsite AWS. Of these two events, the strongest electrical activity occurred on 03rd February 2019, with 260 lightning flashes and 21.4 mm of rain (Table 3.5). The event with fewer lightning flashes occurred on the 20th November 2018, with 117 lightning events and 6.4 mm of rainfall.

In the 9-hour long lightning event on the 20th November 2018 (Figure 3.7), a large, negative electric field at approximately 13h58 was the initial cautionary trigger, causing an alarm state of 2 and thereafter an alarm state of 3 (warning, at 14h00). Within a few minutes (at 14h07), lightning flashes within 16 km of the study site were detected. Approximately 24 minutes after the first strike was detected, a strike within the 8 km warn category was observed (14h31). Over the following seven hours, 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 minutes in alarm conditions (> 1), the atmospheric electric field magnitude increased rapidly to a peak of over 6500 V m^{-1} (Figure 3.7). During the entire duration there were numerous flashes detected within the span of a few minutes, whilst 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 seven hours (approximately 21h35), however the atmospheric electric field only stabilised two hours later (approximately 23h44) allowing the system to trigger an All Clear.

In the second event, a 2-hour long lightning event (20h00-22h00) followed 7-hours after a brief period of early to mid-afternoon lightning activity on the 03th February 2019 (Figure 3.8). The large, negative electric field detected at 12h57 resulted in an escalation to an alarm state of 2 (caution). At 13h19, 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 (13h00-14h00), 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 20h00 and 22h00 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-hour period of which 137 were detected within 8 km, 49 within 16 km and 74 within 32 km (Figure 3.8). Again, flash frequency diminished first (approximately 21h50) and thereafter the atmospheric electric field diminished to around -60 V m^{-1} and stabilized (approximately at 23h38). Of the SG and EFM triggers, the EFM kept the alarm in a warning state well beyond 2 hrs (2.11 hrs) after the flash warning had ceased.

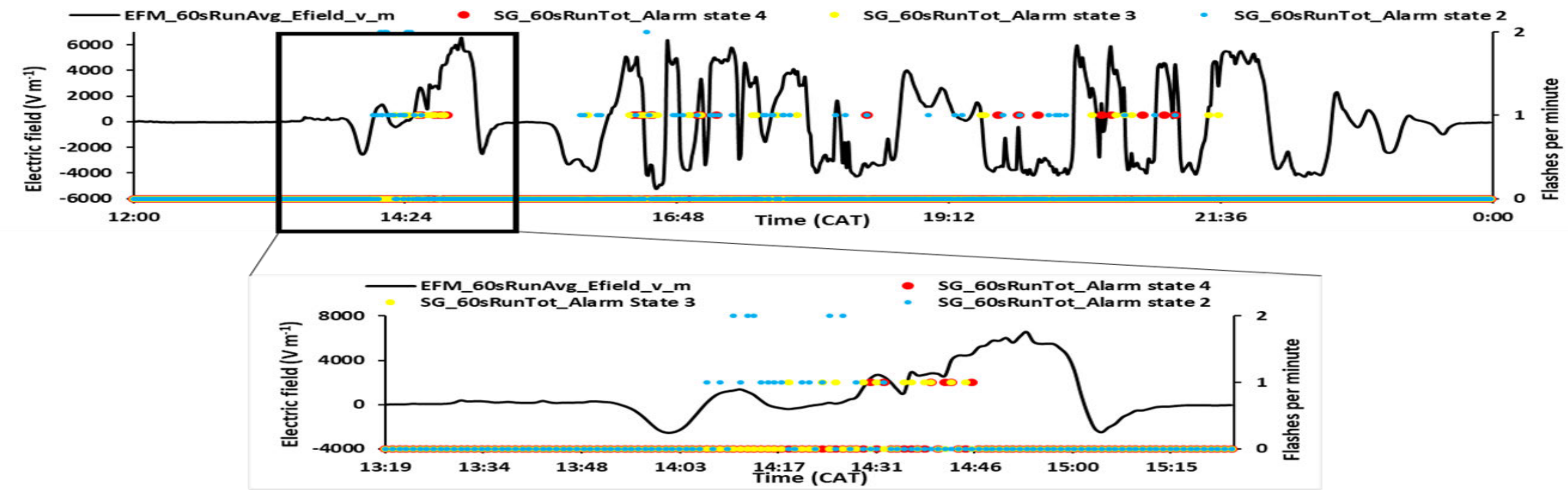

Figure 3.7 Temporal progression of the lightning event that occurred on the 20th November 2018 with observed fluctuations in the atmospheric electric field detected by the CS110 sensor on the primary y-axis. The secondary y-axis denotes the lightning flashes detected by the SG000 sensor and the alarm 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 min detected within the lightning event.

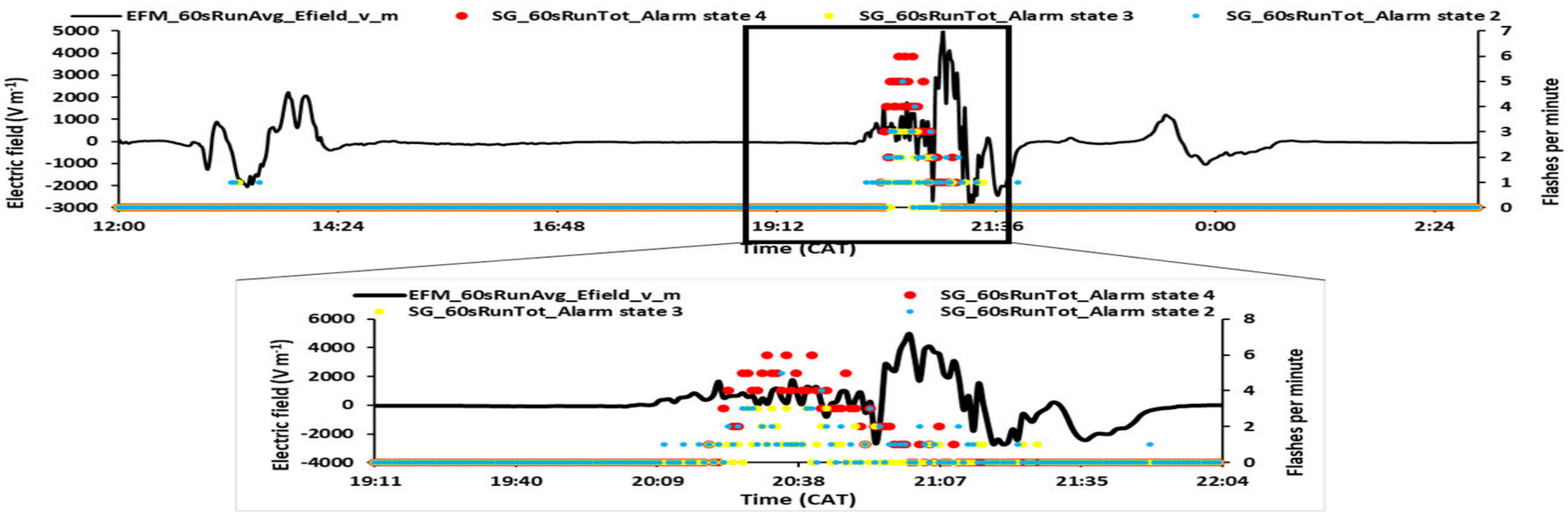

Figure 3.8 As in Figure 3.8 for a lightning event on 3rd February 2019.

Table 3.5 Lightning and rainfall data from two lightning events observed in Swayimane.

Day	Rainfall (mm)	Warning state category (Flashes detected)			Total number of flashes	Storm duration (hrs)
		4	3	2		
20/11/2018	6,4	60	33	24	117	9
03/02/2019	21,4	137	49	74	260	2

3.6.5.2 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.

In order to evaluate the SMS alert system, the timestamp of the SMSs were compared to the EFM and SG data recorded for the above-mentioned observed lightning events using 5-min outputs for illustrative purposes. On the 20th November 2018 (Figure 3.9) and the 3rd February 2019 (Figure 3.10), 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.

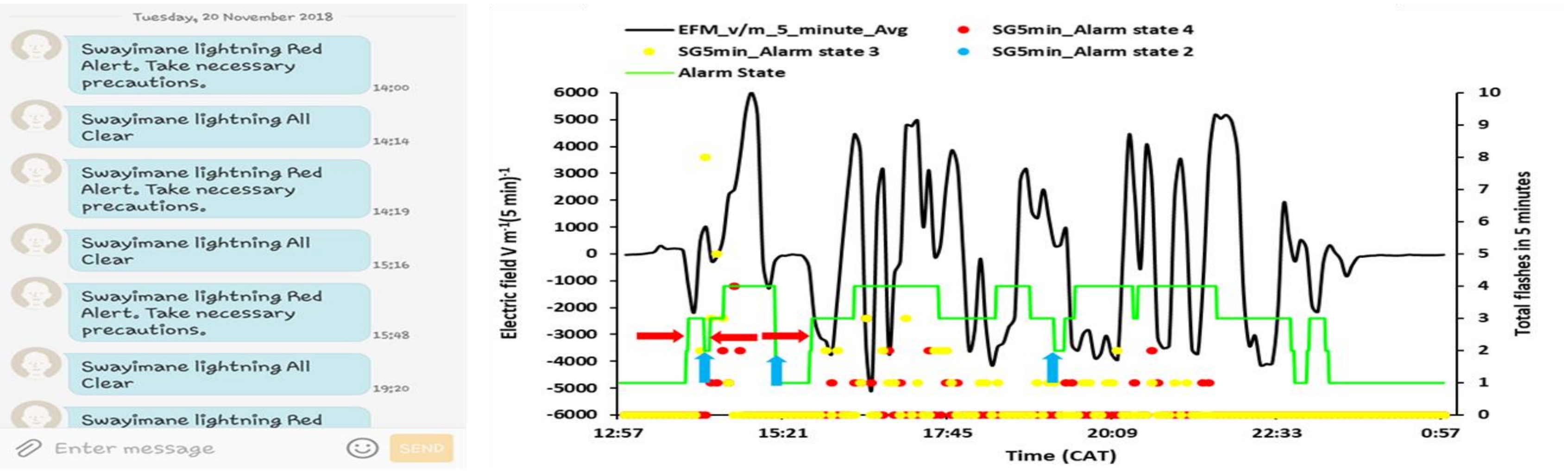

Figure 3.9 A comparison between the SMS alerts (red arrows-warning SMSs, blue arrows-all clear SMSs) and the recorded fluctuations in the atmospheric electric field detected by the CS110 sensor on the primary y-axis and lightning flashes detected by the SG000 sensor on the secondary y-axis at 5 minutes increments for a lightning event on 20th November 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 to 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 SMS's.

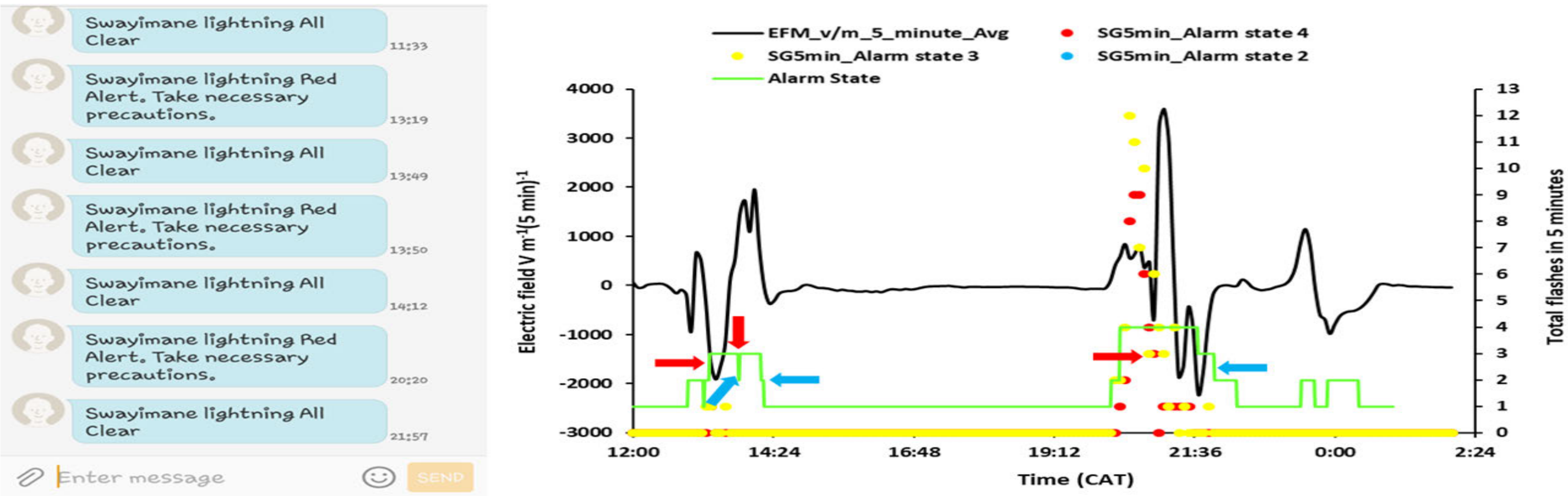

Figure 3.10 As in Figure 3.9 for a lightning event on 3rd February 2019.

For both lightning events the SMSs were received timeously based on the trigger conditions (Figures 3.9 and 3.10). 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 the 20th November 2018, the warning state was entered and exited over 4 times, whereas, for the lightning event on the 3rd 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.

3.7 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 3.4) when compared to an alarm state of 1. These results may elucidate that the community and school is 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 over-warning.

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), amongst 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 Figure 3.4, the diurnal cycle of lightning activity for the study site exhibited most lightning during the period between 09h00 and 23h00 as also indicated by Gijben (2016), with peak activity between 14h00 and 21h00. Results are also in agreement with Collier *et al*. (2006) who determined that peak lightning occurred at 17h00 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 mid-afternoon, and thereafter, decreasing towards the late evening and early morning hours. 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 14h00 to 21h00, during which learners 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 unware 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.

Whilst 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 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. The verification was based on any indication of storm weather (such as sudden decreases in air temperature or pressure, high relative humidity, high wind speeds, etc.). 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 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) compared to 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 towards 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 towards 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 EFM’s may not be early warning systems as observing lightning within a close proximity of a site does not provide an “early” warning. It may also be worthwhile noting that since EFM’s are strongly influenced by local conditions (Harrison and Nicoll 2018), in some instances the local field may tend to rise very rapidly just before a flash and may be a challenge in providing a sufficient/ adequate warning lead time to take the necessary precautions.

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 analysed 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 between 5000 and 6000 V m^{-1}. This result is in agreement with

Madhulatha *et al*. (2013), which discusses electric field intensity's greater than 2000 V m^{-1} are recognised 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 whilst the atmospheric electric field took longer to stabilise 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 personnel are alerted during the onset of lightning and signalled when the threat has completely passed.

Several past studies have also investigated the relationship between lightning activity and rainfall to understand the behaviour of storms. Studies by Kane 1993; Soula and Chauzy 2001; Seity *et al*. 2001; Gungle and Krider 2006 and Xu *et al*. 2010, amongst others reported on a close link between lightning and convective storms. Maximum rainfall was found to coincide with the highest concentration of lightning flashes (specifically CG flashes) (Kane 1993; Soula and Chauzy 2001), and most lightning was observed to occur when a storm is mature (De

Coning *et al.* 2015). Of the two lightning events assessed in the current study, the event on the 3rd 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 (Figure 3.11). Since a point-based rain gauge measurement was analysed in the study, further research between the study's lightning events with a more spatially representative rainfall distribution is required.

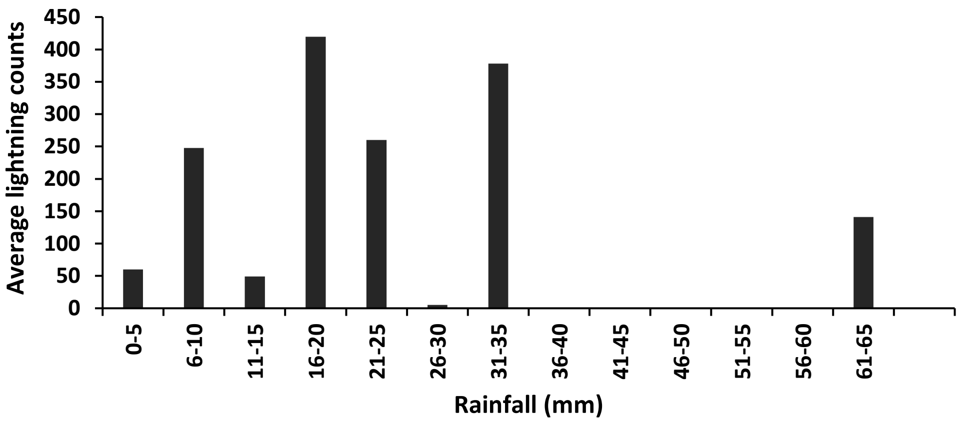

Figure 3.11 Rainfall (mm) categories versus the average lightning counts for lightning events in each of these categories from 02 February 2018 until 02 February 2019. The rainfall measurements were sourced from the onsite automatic weather station for analysis with the lightning warning system. The total lightning counts and rainfall amounts were compared for all lightning events within the study period.

The lightning event on the 20th November 2018 was further observed to have entered and exited warning thresholds rapidly, whereas the lightning event on the 3rd 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 that may have occurred, since lightning occurrence and detection was not verified in the study, the reliability of the system to disseminate warnings when lightning was detected and vice versa, as well as ensuring that the desired thresholds were met 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 regarding the warning status.

Based on 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. Whilst 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 EFM's could be useful for disseminating email and SMS's 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 SMS's could be mimicked for use over larger spatial scales, which could prove to be an invaluable contribution towards 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 learners, while the audible and visible alarms contributed to the safety of the school learners and nearby areas, which include a community hall, clinic and taxi rank

3.8 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 quite 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 are 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. It should be noted 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 ≥ 60%) were some of the maintenance required as well as a scheduled calibration and internal battery change of the SG000 after approximately four years.

The purpose of this research focussed 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:

- 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, amongst others.

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 which 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, the vulnerability assessment and risk mitigation remains 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 endeavours to ensure successful implementation of the system, for the people, within the community will continue and include on-going research within the theme of community education/involvement, seeking answers towards to the following:

- 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 behaviour of individuals change;

- what are the community's social and cultural perspectives regarding 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 to 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, amongst others.

3.9 Conclusions

In South Africa, lightning is a significant threat with a mortality rate four times greater than the global average of between 0,2 and 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 to a local scale.

A 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 learners 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, minimising 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 hours 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 incidence occurred between 14h00 to 21h00 when learners are exiting the school grounds and many people are returning home and hence out in the open. Additionally, at night individuals are asleep and unware 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 analysed and SMS warnings were being delivered timeously 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 towards 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 counsellor. 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 realised. Hence, it is recommended that sufficient resources be allocated to interact with the surrounding communities on the issue of lightning and lightning warning.

Future endeavours towards 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, installing necessary 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.

Finally, despite lightning systems providing reliable warnings, the community response to the warnings is complex as 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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3.11 Data availability statement

The data analysed during the current study are openly available at 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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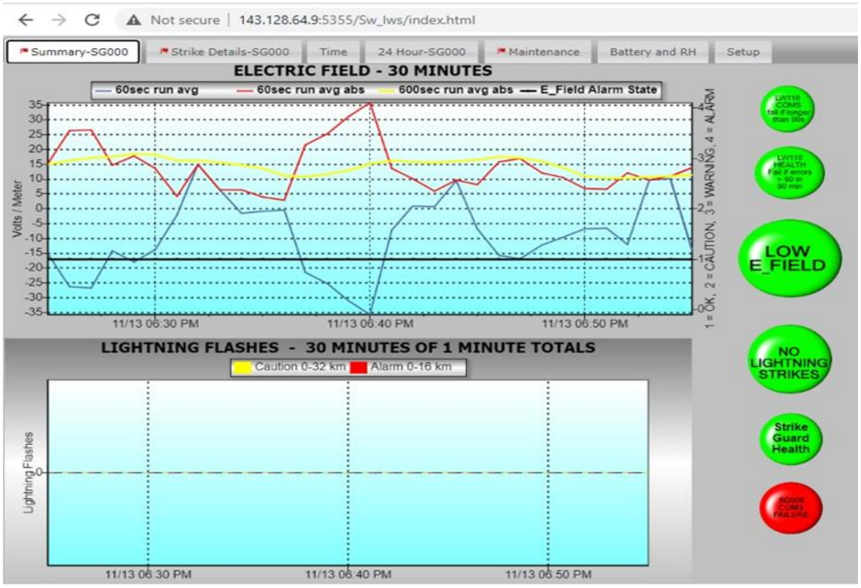
3.13 Supplementary material

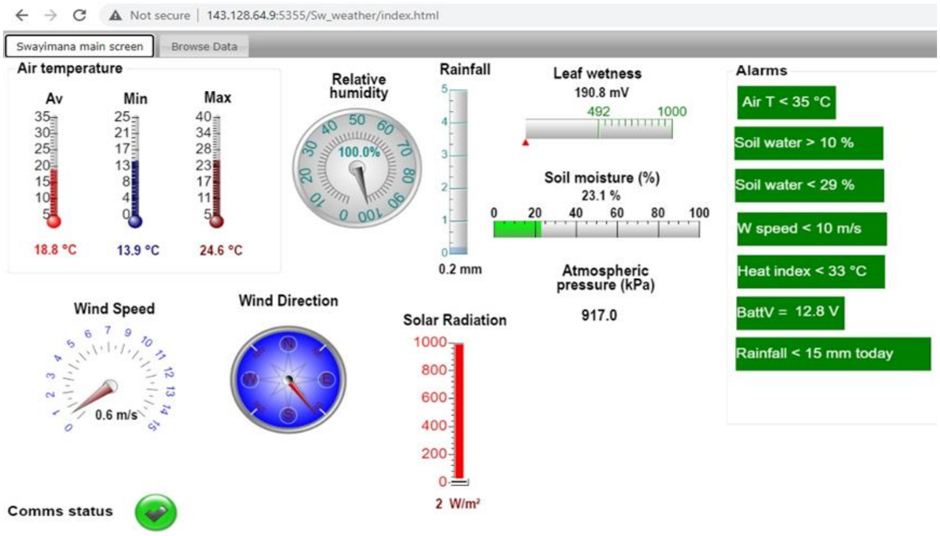
Supplementary Figure 3.1 The NRT-LWS located on the outside of one of the school buildings. The audible and visible alarm systems are visible to the surrounding community, benefitting a nearby taxi rank, a community hall and a clinic.



Supplementary Figure 3.2 A screenshot of the NRT-LWS's web-page, which can be accessed at http://agromet.ukzn.ac.za:5355/Sw_lws/index.html. Data are freely available on the web page and can easily be downloaded.

Supplementary Figure 3.3 The 56-inch monitor that was installed inside a secure metal housing within the corridors of the school. This screen displays the NRT-LWS and climatic data for teaching and learning purposes at school.

Supplementary Figure 3.4 The onsite automatic weather station that is also located at the Swayimane High School, at a distance of approximately 200 m from the lightning warning system.



Supplementary Figure 3.5 A screenshot of the automatic weather station's web-page, which can be accessed at http://agromet.ukzn.ac.za:5355/Sw_weather/index.html. Data are freely available on the web page and can easily be downloaded.

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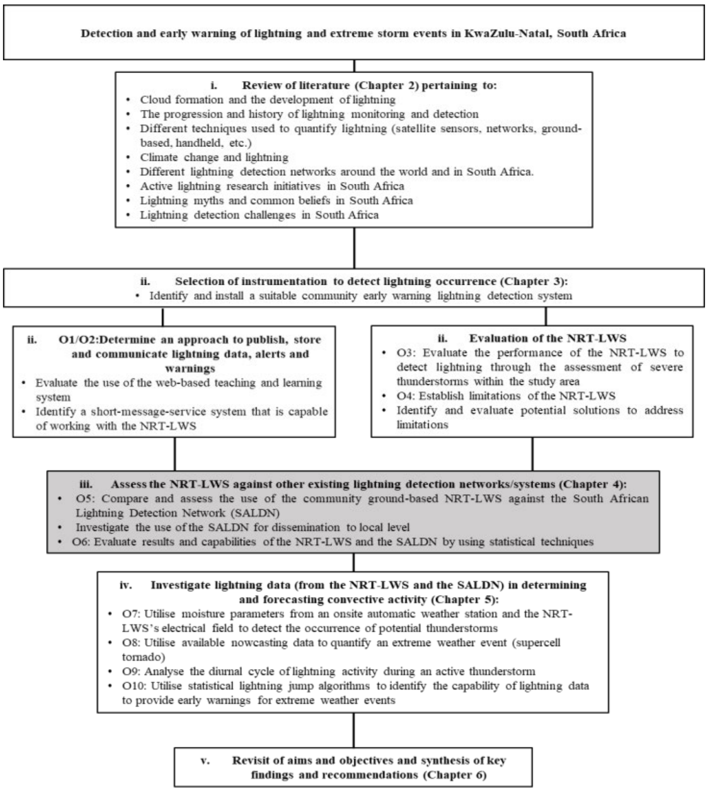
Lead into Chapter 4: The findings of the previous chapter have demonstrated the potential of the NRT-LWS to disseminate warnings timeously thereby, providing the community with a system that offers reliable warnings to lightning danger and to mitigate the risk of losses. The system was also found capable of characterising lightning activity in the area. However, the detection characteristics of this ground-based system required further investigation. Consequently, the objective of Chapter 4 was to assess the NRT-LWS against other existing LWSs. The SALDN is an existing and available lightning data source for South Africa and was extracted for the study area. Hence, a systematic evaluation on the performance of the system using the existing national network was undertaken. Furthermore, since the SALDN is currently only operational at a national level, this chapter also provided the first insights on the use of the SALDN at a local level.



CHAPTER 4: AN EVALUATION OF A COMMUNITY, GROUND-BASED NEAR REAL-TIME LIGHTNING WARNING SYSTEM BASED ON THE SOUTH AFRICAN LIGHTNING DETECTION NETWORK'S OBSERVATIONS (PAPER 3)

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* Referencing adheres to format of Atmosphere.

4.1 Abstract

An experimental lightning early warning system was developed to provide timeous, accessible and comprehensive near-real time (NRT) lightning alerts and warnings for a rural community in South Africa. The aim was to evaluate the performance of this community-based system in Swayimane, KwaZulu-Natal, using the existing national network, known as the South African Lightning Detection Network (SALDN). A validation of the NRT lightning warning system (NRT-LWS) flash count against the SALDN produced a correlation coefficient of 0.95. The NRT-LWS captured the seasonal and diurnal variation in lightning activity, which revealed that maximum lightning activity occurred during summer, and that the majority of the lightning activity was concentrated in the latter stages of the day (between 14:00 to 21:00 CAT) due to the influence and variation of solar heating on lightning incidences. The SALDN average peak current parameter was found to constitute a useful indicator for the Detection Efficiency (DE) of the study area. The NRT-LWS DE indicated a 100% DE at close alert categories, with the DE decreasing with distance and was observed to be storm dependent. This study provides insights into the use of the SALDN at a local level in KwaZulu-Natal and shows that the NRT-LWS data was a reliable source of information with the potential to identify and disseminate lightning threats at local scales.

Keywords: *electric field; flashes; storms; weather*

4.2 Introduction

Since the 1980's, lightning detection systems data have been studied to investigate temporal and spatial lightning distribution patterns (Schulz *et al*. 2005). Ground- and space-based lightning detection networks remain the most sought after and commonly used lightning detection techniques (Rudlosky 2014). These networks are continuously improving their capability to detect optical and radiometric emissions from lightning. As the existing and projected danger of lightning increases and the variety of users expands, it becomes increasingly important to understand the detection and performance capabilities of these networks. Stand-alone, ground-based lightning detection systems have high detection efficiencies (DE) as they are limited to a defined area, while ground-based lightning networks provide excellent geographical coverage (Thompson *et al*. 2014). In addition to monitoring and detecting lightning activity, these systems also provide operationally useful information to support decision making for severe weather including tornados (Goodman 1990, Schultz *et al*. 2009, Liu and Heckman 2011, Farnell *et al*. 2017). In some thunderstorms, sudden increases in lightning flash rates precede severe weather at the ground due to a combination of the thunderstorms strong updraft leading to the appearance of an ice phase which provides the necessary separation of charge and an electric field (Liu and Heckman 2011, Farnell *et al*. 2017). Despite the existence of such systems, their comparative performance and applicability is not well documented at a local or community level.

On an average annual basis, lightning injures hundreds of people with the actual number of lightning related injuries and deaths being far greater, as many deaths in developing countries are often underreported (Frisbie *et al*. 2013, Cooper and Holle 2009b). Rural communities across the world face the greatest risk to lightning threats due to poor lightning safe infrastructure, fewer fully enclosed, metal-topped vehicles, myths and belief systems, socio economic factors, a lack of awareness on the dangers of lightning and a lack of participatory early warning systems, amongst others (Gomes 2017; Cooper *et al*. 2016; Cooper and Holle 2019a). South Africa is regarded as having a lightning mortality rate that is four times higher than the global average (Blumenthal *et al*. 2012). South Africa possesses one of three ground-based lightning detection networks in the Southern Hemisphere, the South African Lightning Detection Network (SALDN) (Gijben 2012). However, warning dissemination to rural communities is limited.

Recently an experimental community-based early warning system was installed to provide a low cost, timeous, easily accessible and in a comprehensive manner, lightning alerts and warnings for a rural community in South Africa. Consequently, the aim of this study was to investigate the performance of this ground-based, community-focussed lightning warning system (NRT-LWS) in Swayimane, KwaZulu-Natal, South Africa. This was required to enable its data to be used appropriately to increase public safety as well as for research and operational applications at a local scale. The NRT-LWS data was compared with standards such as efficient lightning flash detection, meaningful flash density detection and minimal false detection, amongst others as discussed in Jacobson *et al*. (2006). This study also compares the NRT-LWS data with the SALDN data, and the ability of the SALDN in its detection capability for the provision of warning dissemination at a local level (rural community). To the best of our knowledge, this is the first time the SALDN will be assessed at a local level.

4.3 Data sources

4.3.1 Community ground-based near real-time lightning warning system

The NRT-LWS was installed in the rural community of Swayimane (Ward 8), situated approximately 65 km east of Pietermaritzburg within the province of KwaZulu-Natal, South Africa. The NRT-LWS used two sensors to detect the threat of lightning and has been in operation since February 2018. The atmospheric electric field magnitudes (V m^{-1}, with an accuracy of ~5%) were measured by an Electric Field Meter (CS110, Campbell Scientific Inc. (CSI), Logan, Utah, USA), detecting the presence of nearby electrified clouds that are capable of producing lightning discharges, within a maximum effective detection radius of 40 km. A lightning flash sensor (SG000, Strike Guard, Wxline, Tucson, Arizona, USA) was also installed together with the electric field meter. The SG000 receives and processes optical and radio emissions of lightning discharges within 0-32 km of the sensor. The discharges include intra-cloud (IC) and cloud-to-cloud/inter-cloud (CC) flashes as well as cloud-to-ground (CG) strikes. The SG000 sensor does not differentiate between flashes and strikes, hence, the term 'flashes' with respect to the NRT-LWS will also include strikes. In addition, it detects multiple stokes as a single flash.

The LWS used a GSM (global system for mobile communication) modem (Sierra Wireless) for communication of data every one-minute, facilitated by Campbell Scientific Africa (Pty) (Ltd) through a call-back service to a server computer located at the University of KwaZulu-Natal (UKZN). The server is a virtual machine on the UKZN network responsible for scheduling the download of data (Loggernet, CSI) and publishing (CSI webserver) the data to a web page. Data are freely available on the web page, which can easily be downloaded and accessed via http://agromet.ukzn.ac.za:5355/Sw_lws/index.html. Warnings were initiated when values exceeded thresholds set by the user. Warnings are displayed on the website and emails and/or short-message services are sent to individuals or groups indicating warning levels.

One-second measurements from both sensors of the NRT-LWS are recorded by the datalogger (CSI, CR1000) with averages or totals calculated every one-minute, every five-minutes and hourly. In addition, the NRT-LWS also has an audible (siren) and visible (strobe beacons) alarm system. A single remote alarm system with strobe lights/beacons indicated the lightning warning status (CSI, RA110). Three possible states or categories were chosen to represent the measurements of the atmospheric electric field magnitudes 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 is no existing universal warning criteria for the electric fields. As stated by Clulow *et al*. (2018), the 1000 V m^{-1} (Caution) and 2000 V m^{-1} (Alarm) of the electric field were used according to the Naval Seas Systems Command (NAVSEA) and the National Aeronautics and Space Administration (NASA) Launch Pad Lightning Warning System as thresholds to guide the activation of the three states, along with the strike guard warning states.

A level 4 was also added to the measurement system, which considers flashes only (does not account for the atmospheric electric field magnitudes) within the 8 km radius of the system. Hence, the alarm state 4 is for a level 3 and 4, but the alarm state 4 only represents the lightning flashes detected within 8 km of the study site.

4.3.2 South African Lightning Detection Network (SALDN)

In this study, lightning data from the SALDN operated by the South African Weather Service (SAWS) were used to compare with data from the community-based NRT-LWS. The SALDN is a Vaisala (Helsinki, Finland) lightning detection network comprising of 24 strategically located sensors across South Africa, and with one sensor located in Swaziland (Vaisala LS 7000 and LS 7001). The sensors are designed to detect CG lightning but is also capable of detecting up to 50% of IC lightning depending on the location of the sensors and the distances between, as well as the number of sensors participating in the detection of the IC lightning. In 2005, SAWS purchased and installed the network making South Africa one of only three countries in the southern hemisphere to operate such a network (Gijben 2012). A contemporary lightning climatology for South Africa was developed using 5 years of data (2006-2010) by Gijben (2012) and is further updated annually (Gijben *et al*. 2016).

The distribution of the 25 stations (Fig. 4.1) that form the SALDN enables the network to detect lightning flashes with a greater than 90% prediction detection efficiency (DE) and with a less than 0.5 km median location accuracy over most of the country (Gijben 2012; Gijben *et al*. 2016). The SALDN sensors detect electromagnetic signals emitted by lightning discharges by means of a combination of time of arrival and magnetic direction-finding methods (Gijben 2012). These sensors operate at very low and low frequency ranges to ensure that the sensors detect CG lightning flashes. The combined technology employed in the SALDN requires that at least two sensors detect a lightning flash but on average about 5 to 9 sensors usually detect a single flash. Three or more sensors are required when the time of arrival and magnetic direction-finding methods are used individually.

Rodger and Russel (2002) describe a lightning flash as an entire lightning discharge whereas the pulses in a flash are known as strokes. Therefore, one lightning flash can be made up of multiple lightning strokes. The peak current of the initial stroke is used to record the lightning flash data by setting the peak current of the flash to be the same as the peak current of the initial stroke (Gijben 2012). Raw data recorded by the sensors are sent to the network control centre at the SAWS headquarters in Centurion, where a central analyser processes the data. These data are stored in a database and can be retrieved by the Fault Analysis and Lightning Location System (FALLS) software package from Vaisala (Gijben, 2012). Within this software package, there is an option to extract either lightning flash data or lightning stroke data from the database, and for the purpose of this study, only flash data were analysed to be comparable with the SG000 sensor. The system is able to provide CG lightning stroke location (longitude and latitude), time of incident (date and GPS time within milliseconds), polarity of the stroke, amplitude of that stroke and other information critical to that stroke. The SALDN adopted a similar approach to that used by the National Lightning Detection Network (NLDN) in the United States of America and those of other national lightning detection networks that use similar technologies to discard positive lightning strokes with peak currents less than 10 kA. The same approach was followed by SAWS as it appears that over 90% of all positive events less than 10 kA are IC or CC and most positive events above 20 kA are CG strokes (based on a video validation in Texas) (Krider 1980, cited by Schulz *et al*. 2005). However, recently, the threshold value of 10 kA has been changed to 15 kA (Gijben 2012). Comprehensive descriptions of this network are provided by Evert and Schulze (2005), Gill (2008, 2009) and Gijben (2012, 2016).

Figure 4.1 Location of the 25 Vaisala sensors showing the SALDN coverage across South Africa (Gijben 2019).

4.4 Data sample and methodology

The NRT-LWS evaluation includes data from 1 March 2018 to 31 March 2019. This information was used together with the SALDN's dataset to patch/infill the NRT-LWS dataset as well as for assessing the performance of the community ground-based NRT-LWS. There were periods of missing data from September 2018 to December 2018 due to poor GSM network signals within the research area affecting the data downloads. September and October 2018 had considerably more missing days than November and December 2018. However, despite these poor network signals which resulted in communication failures and the subsequent data loss, the onsite audible and visible alarm systems remained in place to alert the surrounding community. As a result of this initial communication failure and data loss concern, the use of an LTE (long-term evolution) and GSM modem using multiple network providers were used to rectify the communication concerns.

Since the SG000 records individual lightning strokes as a single lightning flash/discharge and therefore as one event, coincident lightning data from the SALDN had to be identified to be able to compare lightning charges detected by the NRT-LWS with the SALDN. The approach that was used to determine which events were coincident events entailed establishing a time/space window within which an event detected by both networks was regarded as the same event. The choice of the time/space window size was arbitrary and chosen depending on data characteristics. In this study, the time window served as the primary parameter of identification of coincident events. The SALDN has a time resolution of milliseconds, hence for comparison with the NRT-LWS (resolution of a minute), all millisecond SALDN flashes were converted to minute-based values. Consequently, the lightning discharges reported by the two systems within the same minute and within the same spatial buffer ranges were considered coincident lightning.

The SALDN CG dataset was available to the study and were extracted from 1 February 2018 to 24 April 2019 within three warn/alert range categories (8, 16 and 32 km) around the Swayimane area (30.663302°, -29.486330°). However, for the purpose of this study, data from the 1 March 2018 to 31 March 2019 were analysed. The data were extracted from the normally stored CG database using the Fault Analysis and Lightning Location Software. The NRT-LWS dataset was infilled with the SALDN's dataset for a period of 67 days for the missing periods within September 2018 to December 2018 and thereafter used to obtain relevant information regarding the monthly and seasonal variations, and the temporal distributions of lightning activity within the research area.

4.5 Results and discussion

4.5.1 Infilling using the South African Lightning Detection Network data

Before the NRT-LWS dataset could be infilled, a relationship between the SALDN and the NRT-LWS for all three alert range categories was observed to determine the correlation between the datasets (Figure 4.2). The comparison was undertaken during a lightning event that occurred on the 3 February 2019. A time series was plotted to visually interpret and compare the performance of the datasets. The community based NRT-LWS temporal behaviour was well correlated with the SALDN dataset. The NRT-LWS flashes dataset followed the general trend of the SALDN flash data (Figure 4.2). There were however slight differences between the datasets. The NRT-LWS slightly underestimated lightning activity compared to the SALDN. This underestimation was apparent within the 16 km and more so within the 32 km buffer ranges. The potential sources attributed to this underestimation may be as a result of the DE of both systems as well as due to the NRT-LWS being a single-point sensor. Table 4.1 show the results of classical statistical indicators (P-value, R^2 and Pearson's correlation) that were used to evaluate the comparison between the SALDN and the NRT-LWS. The one-minute datasets produced R^2 values between 0.3 to 0.6, while one-minute datasets that were averaged into five-minute datasets had R^2 values ranging between 0.5 to 0.9. The Pearson correlation coefficient for the lightning event was between 0.6 to 0.8 for both one-and five-minute datasets. P-values for the correlation for all three warn categories were < 0.05. While the R^2 and Pearson values that were obtained were found to be satisfactory to good, low P-values were obtained indicating a close relationship between both datasets. Hence, any errors or differences between the datasets may be as a result of the differences in the detection capability of both systems. Following the results from the correlation, the SALDN data were used to patch missing NRT-LWS data.

The SALDN flash dataset was also utilized to obtain lightning flash density maps for the three spatial range categories and to determine the DE of the NRT-LWS. The NRT-LWSs DE was calculated as a percentage by dividing the number of NRT-LWS flashes that were coincident with the SALDN event to the total number of SALDN flashes, as suggested by Jacobson *et al*. (2006) and Abarca *et al.* (2010). The DE is the estimated percentage of detected flashes out of every hundred flashes that actually take place in reality (Evert and Schulze 2005). It is therefore assumed that the SALDN is the ground truth (with a DE of 100%). As stated by Abarca *et al*. (2010), this assumption may result in an overestimation of the SALDN DE proportional to the departure of the NRT-LWS DE from 100%, or an underestimation of the NRT-LWS DE proportional to the number of flashes missed by the NRT-LWS and captured by the SALDN.

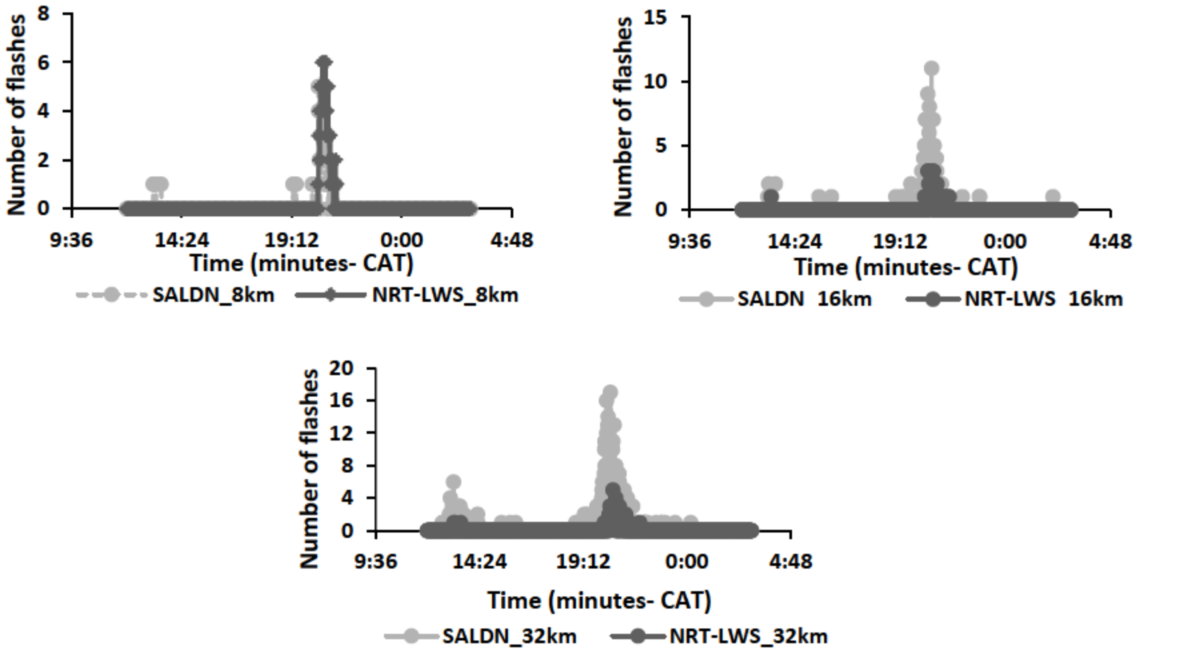


Figure 4.2 A time series analysis for the SALDN and the NRT-LWS datasets in which CAT refers to Central African Time.

Table 4.1 Statistical comparison between the SALDN and the NRT-LWS (3 February 2019).

Range	Comparative datasets	Pearson correlation statistics	R^2	P-value	Pearson correlation statistics	R^2	P-value
		One-minute datasets			Five-minute datasets		
8 km	SALDN and LWS 110	0.8	0.6	2.9E-176 (0.0)	0.9	0.9	1.6E-81 (0.0)
16 km	SALDN and LWS 110	0.7	0.4	1.6E-114 (0.0)	0.9	0.8	1.8E-69 (0.0)
32 km	SALDN and LWS 110	0.6	0.3	2.9E-74 (0.0)	0.7	0.5	2.7E-31 (0.0)

4.5.2 Ground-based monthly and seasonal distributions of lightning flash density

A total of 13458 flashes was recorded by the NRT-LWS over a 12-month period from March 2018 to March 2019 for the study site. The NRT-LWS displayed a clear summer peak in lightning activity (Figure 4.3), with December 2018 receiving the highest monthly total of 5584 lightning flashes, which resulted in it being the most active month on record. The winter months (June to August) experienced little to no lightning activity (Figure 4.3), with no lightning flashes detected for June and July and only six flashes in total for August and over the entire three-month period.

In comparison to the NRT-LWS (13458 flashes), a total of 25032 flashes was detected by the SALDN over the three warn/alert range categories (8, 16 and 32 km) from the NRT-LWS. Despite much higher values for lightning flash density deduced from SALDN data, the overall lightning characteristics were similar from both systems: a clear summer peak in lightning activity (Figure 4.3), with December 2018 showing the highest activity and minimal lightning activity during the winter season. Large differences in lightning activity from austral summer to winter is highlighted in Figure 4.4.

However, despite the correlation in the data, the NRT-LWS consistently underestimated the number of lightning flashes compared to the SALDN. The underestimation was most visible during the summer period when flash counts were higher and thus, the differences, larger. The potential sources of underestimation may be attributed to the DE of the systems. The greater number of detected lightning flashes by the SALDN compared to the NRT-LWS may be the result of a better detection efficiency of the SALDN at greater distances as well as the ability of the SALDN to detect the occurrence of lightning activity to the milliseconds. For the NRT-LWS, more than one lightning flash within a second is regarded as a single flash. The NRT-LWS is also a point-based sensor which may explain the underestimation at greater distances. Additionally, both systems detect different types of lightning. The SALDN normally stored CG dataset was used whilst the NRT-LWS dataset does not differentiate between cloud-to-cloud (IC) and CG lightning, hence the total lightning dataset was utilised. Therefore in this study, the SALDN has a bias and we would expect the accumulative lightning count to be lower.

The correlation between the data from the SALDN and the NRT-LWS was further determined by a Pearson correlation coefficient. A Pearson correlation coefficient of 0.95 was computed between both lightning datasets and the relationship was found to be statistically significant. A p-value of < 0.05 and a Nash-Sutcliffe efficiency index of 0.62 were found.

Overall, the correlation between the two distributions validates the representativeness of the observations by the NRT-LWS in terms of detection compared to the SALDN.

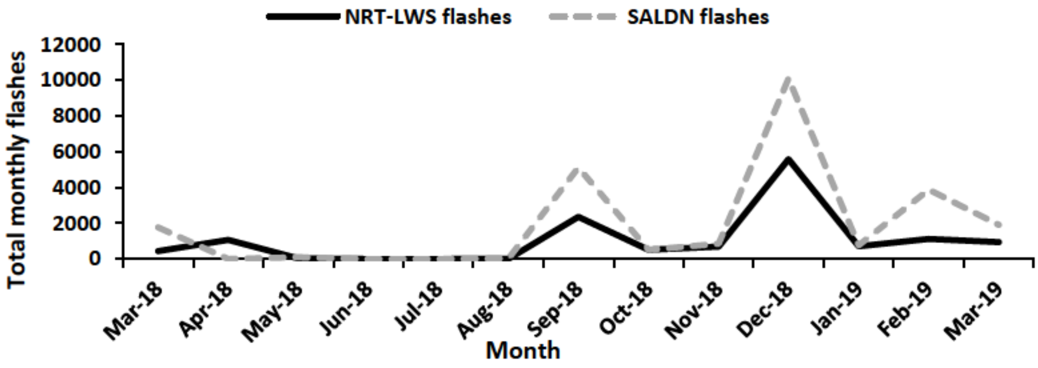


Figure 4.3 Distribution of the total monthly flashes for all three warn states (8, 16 and 32 km) over the study period, March 2018 to March 2019.

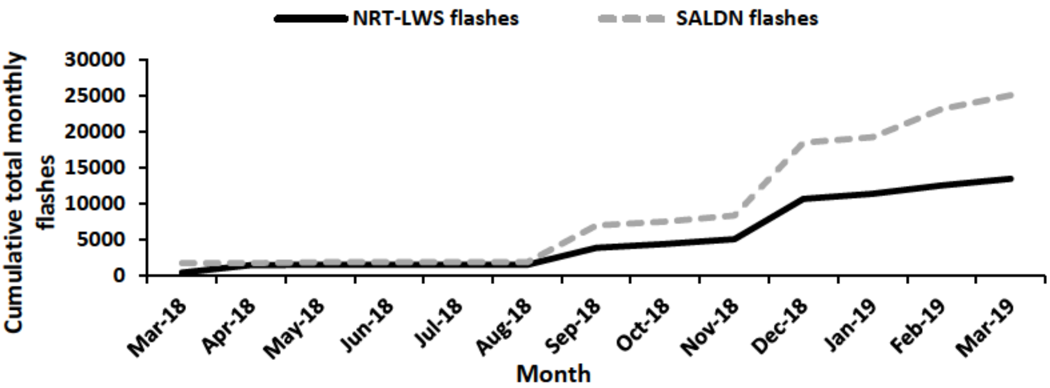


Figure 4.4 Distribution of the cumulative total monthly flashes for all three warn states (8, 16 and 32 km) over the study period from March 2018 to March 2019.

The total monthly counts of lightning flashes that was detected by the NRT-LWS and the SALDN for the entire study period was further distributed amongst the three different warn/alert spatial categories (8, 16 and 32 km), as illustrated in Figure 4.5. A total of 1922 flashes was detected within the 8 km range, 2585 flashes for the 16 km range and 8951 flashes within the 32 km range by the NRT-LWS. Whereas, the SALDN recorded a total of 1309 flashes within the 8 km range, 4578 flashes for the 16 km range and 19145 within the 32 km range.

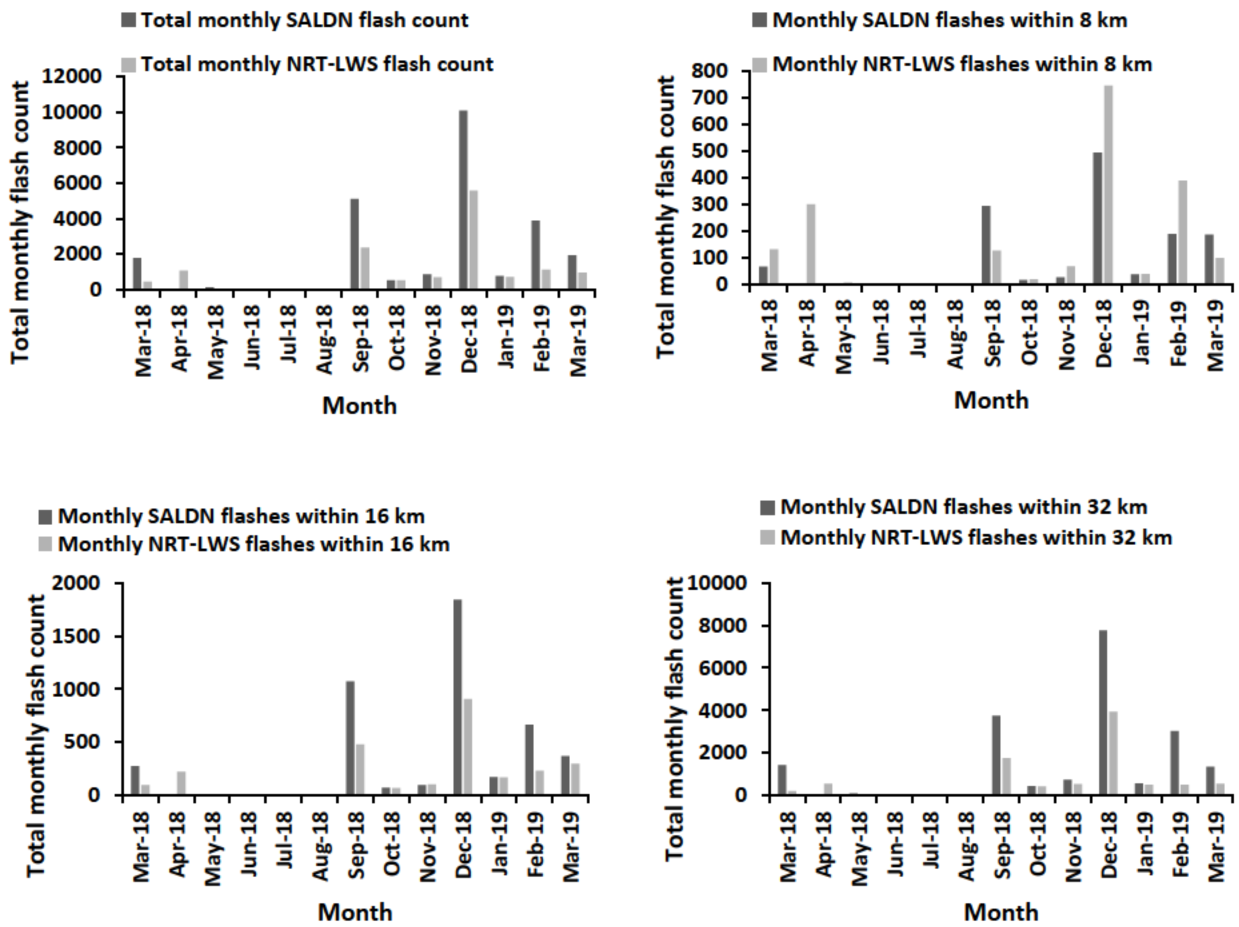


Figure 4.5 Monthly distributions of total daily lightning flashes separated for the three warn categories (within the 8 km, 16 km and 32 km ranges) from February 2018 to January 2019.

4.5.2.1 Seasonal flash distribution

An analysis of seasonal lightning flash distribution using the NRT-LWS data was carried out. The period February to April and November to December coincide with the austral summer season and October to March, the period of intense thunderstorm activity. However, for analysis purposes, autumn was taken as 1 March 2018 to 31 May 2018, winter as 1 June 2018 to 31 August 2018, spring as 1 September 2018 to 30 November 2018 and summer as 1 December 2018 to 28 February 2019. The total number of flashes and the percentages for each season are given in Table 4.2.

Table 4.2 The number of flashes per season for the study period.

Season	Calendar dates	Number of flashes	Percentage of total
Autumn	1 March to 31 May	1534	12,26
Winter	1 June to 31 August	6	0,05
Spring	1 September to 30 November	3563	28,47
Summer	1 December to 28 February	7411	59,22
Total		12514	100

As stated by Bhavika (2007), the beginning of the cool and dry seasons is labelled as Autumn. This season accounts for 12.30% of all lightning flashes for the study period. April had a high incidence of lightning, accounting for 7.95% of the total lightning within the season. According to Bhavika (2007), the atmosphere begins to stabilize during this season and thus, leads to a decrease in lightning activity.

The winter season is characterized by a clear rapid decline in overall lightning activity, with only 0.05% of the total number of lightning flashes for the study period. The findings from Bhavika (2007) indicate that the atmospheric circulation features during winter are situated towards the north resulting in atmospheric stability and low relative humidity. Additionally, high-pressure systems dominate the country in winter causing subsidence and accompanying clear skies, with the systems situated closer to the coast of South Africa picking up less moisture as they move more towards the interior. Consequently, the lightning that occurs in this season is mainly as a result of frontal systems since convection is suppressed by the deficit of moisture during the winter period.

Lightning distribution during the spring season clearly shows the transition from the winter season with minimal lightning activity to gradual increase in spring. Spring accounts for 28.50% of total lightning, with an increase in lightning activity as the season progresses. September had a high incidence of lightning during this season accounting for 17.50% of the total lightning. Convective activity in this season develops as circulation features move southwards, resulting in an influx of moisture (Bhavika 2007), and surface air temperatures gradually increase and become favourable for thunderstorm activity (Christian *et al*. 2003).

The summer season was characterized by peaks in lightning activity and lightning flashes generally increase dramatically in this season in the country (Bhavika 2007, Collier *et al*. 2006, Blakeslee *et al*. 2014). In this study period, this season accounted for 59.20% of total lightning, with December having the highest flash density (41.50%). These results agree with the findings by Christian *et al*. (2003) and Bhavika (2007). Christian *et al*. (2003) discussed the influence of surface air temperature resulting in spring and summer being most conducive to thunderstorm activity. According to Bhavika (2007), the high occurrence of lightning activity during this season is as a result of the summer movement of air masses and circulation features that migrate to the south of the continent. Winds associated with the Indian Ocean high collect moisture as they migrate towards the continent bringing in an influx of humid air from the east (Tyson and Preston-Whyte 2000). This enhances convection over the eastern coastline, whereas the north eastern part of the region is influenced by the south eastern trade winds. This influx of moisture coupled with instability and orographic uplift result in enhanced thunderstorm activity towards the eastern and north eastern half of the country (Bhavika 2007).

Overall, the monthly seasonal variations in lightning flashes indicate a clear seasonality (summer/wet months). The spring, summer and autumn months experience considerably more lightning than the winter months, which may be due to higher amounts of available moisture that consequently aid in the development of thunderstorms during the convective season (Frisbie *et al*. 2013). Lightning activity reached its highest level during the summer period owing to the thermodynamic conditions favourable for lightning generation. As discussed by Gill (2008), the distribution of lightning appears to be closely linked to the location of the interior trough in summer and to the passage of mid-latitude synoptic systems in winter. Winter months accounted for the least number of lightning occurrences. As land begins to warm in spring, convection begins to switch from sea to land and by early summer unstable conditions prevail and increased lightning activity occur. Thus, lightning activity can be used as an effective predictor for seasonal change and cases with more intense convective precipitation.

Ninety-nine percent of all the detected flashes occurred during spring through to early autumn. This illustrates that changes that occur seasonally in spring for example, such as an increase solar irradiance and the resulting increase in surface air temperature and the diurnal heating of surface air, are conducive in modulating convection and therefore for the formation of thunderstorms.

4.5.2.2 Seasonal diurnal variation in lightning activity

The diurnal pattern in lightning flashes were analysed per season for the study site. The diurnal activity for autumn indicates a variable distribution (Figure 4.6) with no lightning activity observed during the early morning hours from 00:00 to 9:00 CAT (Central African Time) and during late evening from 21:00 to 23:00 (Figure 4.6). Lightning activity was detected from 10:00-20:00 with a peak in the late afternoon between 15:00-16:00. The afternoon peak in lightning activity may be as a result of the sun heating the ground, causing updrafts which reach subfreezing altitudes due to the correct vertical structure of the atmosphere and hence, lightning is formed.

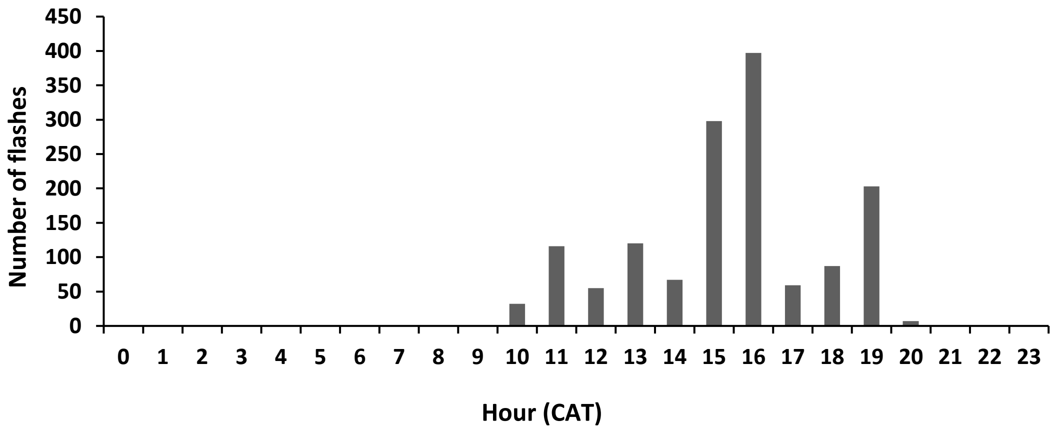


Figure 4.6 Autumn seasonal diurnal variation in lightning activity for the study site.

During winter, lightning activity occurred mostly from 07:00 to 13:00, with the lowest levels of lightning flashes occurring around 07:00 and a peak at 10:00. Lightning activity was also detected at 01:00 and 23:00. There was no lightning activity observed throughout the remaining hours of the day (Figure 4.7). The morning peak agrees with findings from Bhavika (2007) that winter lightning is not sensitive to solar heating and thus frontal activity is the dominant process driving thunderstorm development in this season.

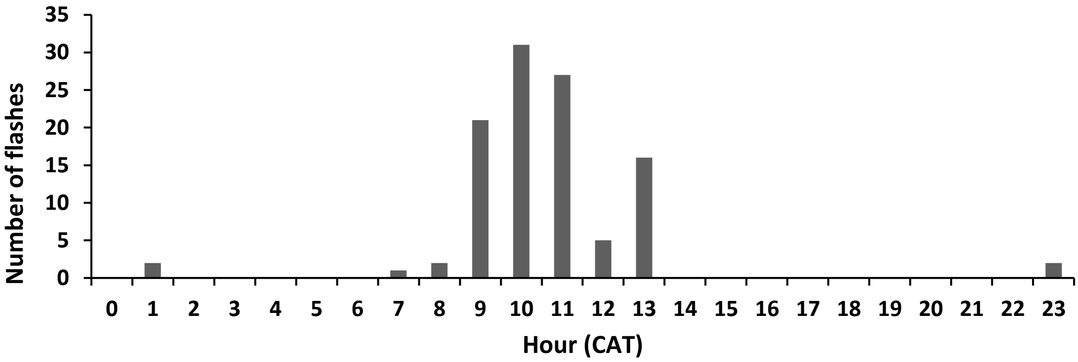


Figure 4.7 Winter seasonal diurnal variation in lightning activity for the study site.

Spring diurnal variation shows active lightning occurrences between 12:00 to 23:00 (Figure 4.8). Lightning activity was low between 0:00-11:00 with a complete absence of lightning from 5:00 to 8:00. Peak lightning activity occurred at 14:00 and 23:00. These results again display a distribution to afternoon peaks corresponding to solar radiation and thermal accumulation. Lightning activity peaks during the early afternoon and late evening may be attributed to an influx of humid air and high solar energy levels carried through from the afternoon.

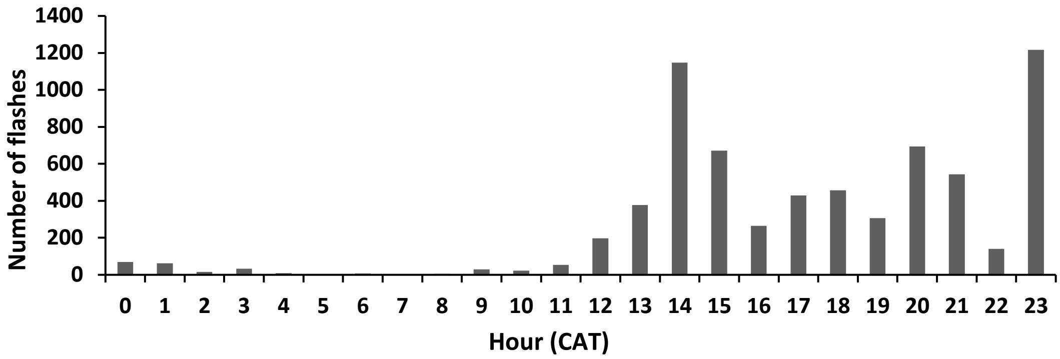


Figure 4.8 Spring seasonal diurnal variation in lightning activity for the study site.

The summer diurnal distribution of lightning activity, which displays lightning occurrences mainly between 10:00 and 23:00 is similar to spring but with an earlier start in the mornings (Figure 4.9). Minimal lightning activity occurred during the remaining hours. Maximum activity occurred at 18:00. These results again may indicate that summertime lightning activity may be modulated by the diurnal cycle of solar heating and surface air temperature.

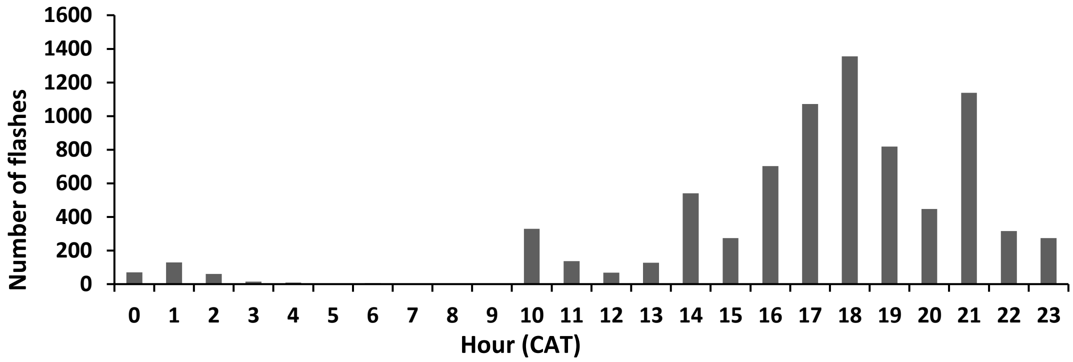


Figure 4.9 Summer seasonal diurnal variation in lightning activity for the study site.

Overall, the effects of diurnal heating were observed in the data particularly for the summer and autumn seasons. The seasonal diurnal variation analysis revealed that thunderstorms/lightning activity is related to an increased thermodynamic instability, which typically occurs in the later stages of the day, as observed by Collier *et al.* (2006), Bhavika (2007) and Yang *et al*. (2020). The annual distribution of lightning activity was observed to be dominated by the spring, summer and autumn months. Thus, the annual average diurnal patterns reflect maximum activity during mid-afternoon, with a decrease towards the late evening and early morning hours. The results were also in agreement with Blakeslee *et al*. (2014), who found a peak in the diurnal lightning activity toward late evening or early morning hours during summer. This is also in agreement with the development of convective thunderstorms over South Africa in the late afternoon and early evening (Tyson and Preston-Whyte 2000). Results obtained in this study are also consistent with results obtained from the World-Wide Lightning Location Network (WWLLN) (Collier *et al*. 2006) and with findings by Bhavika (2007) which indicated that peak lightning activity over land occurs during the late afternoon decreasing towards the late evening.

4.5.2.3 Temporal distribution of lightning flashes and atmospheric electric field discharges

The escalations depicted by the temporal distribution of the electric field and the lightning flashes were as a result of the electric field and/or strike guard thresholds being met. The absolute electric field magnitudes, measured by the Electric Field Meter (EFM), generally remained below 1000 V m^{-1} during the winter months of June and July with the exception of a few instances towards end of July and in August where the electric field exceeded the 2000 V m^{-1} threshold and triggered an alarm state of 3 and 4 (Figure 4.10). During the lightning season, the electric field fluctuated as high as 6569 V m^{-1} (August), 5960 V m^{-1} (September), 5960 V m^{-1} (December) and 6569 V m^{-1} (November).

An alarm and electric field state of zero represents a fault in the system. This occurred several times for the EFM state during one-minute intervals with a total of 2940 times for the EFM field state (49 hours or 2.04 days), while 7500 times for the alarm state (125 hours or 5.21 days). These errors mainly occurred during system maintenance check-ups and when the operating system was being updated.

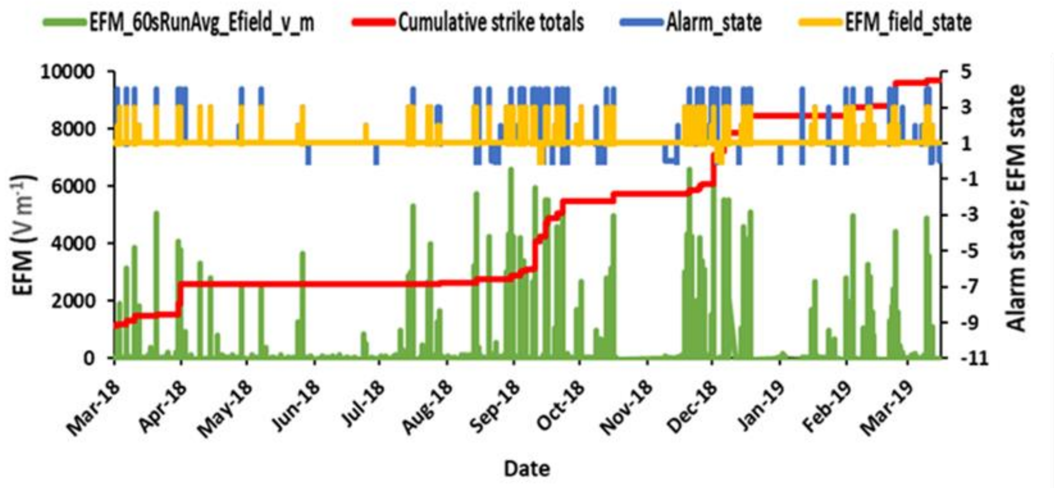
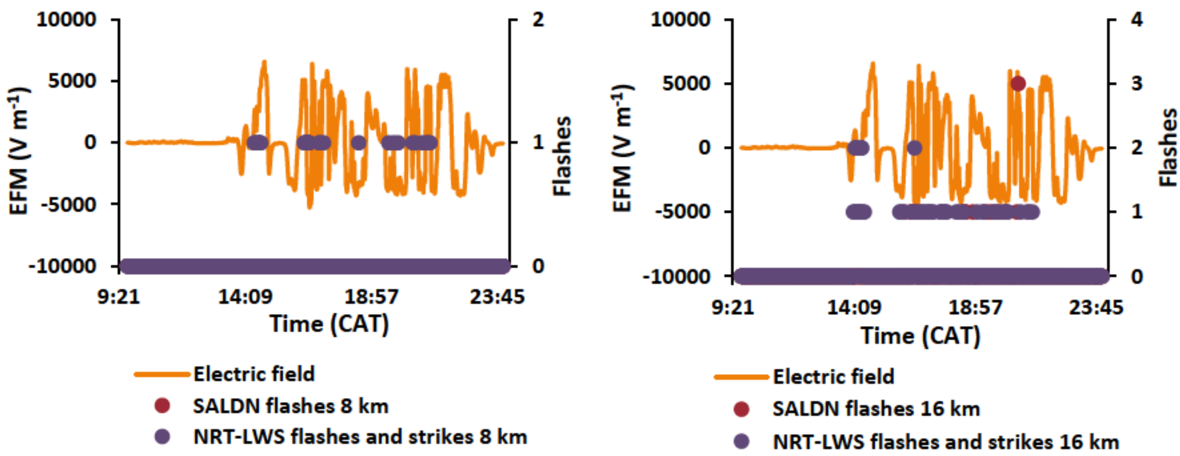


Figure 4.10 Annual variations in the average 60 seconds atmospheric electric field measurements and cumulative strike totals (includes 8, 16 and 32 km warn categories).

<u>4.5.2.4 Comparative analyses between lightning flashes and electric field magnitudes</u>

The detected lightning flashes by the SALDN and the NRT-LWS, for two specific lightning events on the 20th November 2018 and 3rd February 2019, were compared to the NRT-LWSs electric field magnitudes. These lightning events were identified amongst the above-normal lightning events as well as were observed to be extensive in their spatial extent within the three warn state categories of 8, 16 and 32 km. The analyses were undertaken to assess the correlation and performance between the detected lightning flashes by the SALDN, the NRT-LWS flashes and the change in the EFM by the NRT-LWS.

At closer distances (8 to 16 km), the NRT-LWS detected more lightning flashes than the SALDN (Figure 4.11). At greater distances (16 to 32 km) the SALDN was able to detect more flashes than the NRT-LWS (Figure 4.12). The comparison of flashes detected by the two systems with the EFM is better illustrated in Figure 4.12: whenever an increase or peak in the atmospheric EFM occurs, flashes were detected by the SALDN. More importantly, the time the lightning flashes are detected by the SALDN is in synchronization with those flashes detected by the NRT-LWS.



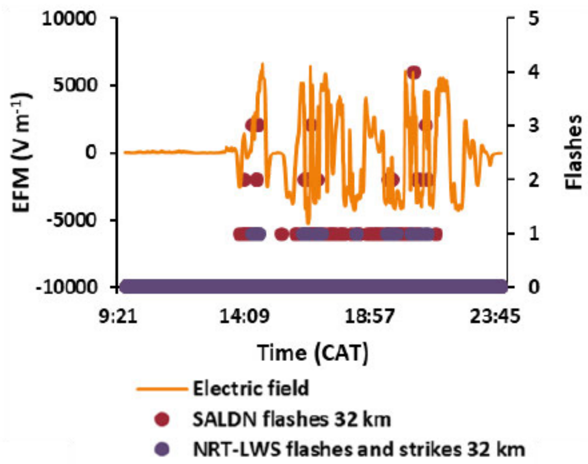
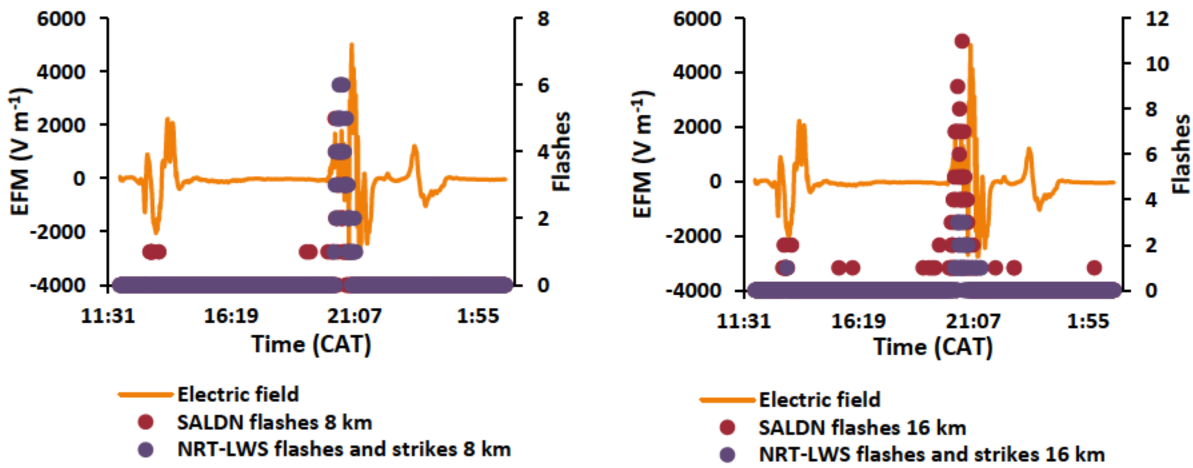


Figure 4.11 A comparative analysis between the atmospheric electric field magnitudes (EFM, V m^{-1}) and the detected lightning activity by the NRT-LWS and the SALDN during a lightning event on 20th November 2018 for the 8, 16 and 32 km radius.



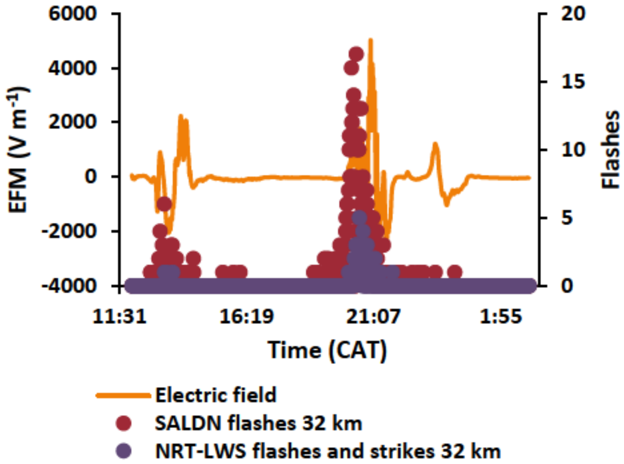


Figure 4.12 A comparative analysis between the atmospheric electric field magnitudes (EFM, V m^{-1}) and the detected lightning activity by the NRT-LWS and the SALDN during a lightning event on 3rd February 2019 for the 8, 16 and 32 km radius.

4.5.3 South African Lightning Detection Network's polarity and peak current distribution analysis

The distribution of positive and negative polarity lightning flashes for the three different warn categories using the SALDN's data are shown in Figure 4.13. In respect to CG lightning activity, downward positive CG flashes only constitute about 10% of all ground flashes (Hazmi *et al*. 2017). In this study, results showed that the negative lightning flashes dominated throughout the study period for the Swayimane research site, accounting for 92.9% of the total lightning flashes whereas, positive lightning flashes were limited to 7.1%, in agreement with Hazmi *et al*. (2017).

In the early years of lightning detection systems, it was observed that the ratio of negative to positive flashes increases during summertime (Orville *et al*. 2011). In Swayimane, there is a clear observed increase in the number of negative flashes during the summer months (Figure 4.13). Tables 4.3 and 4.4 provide a summary of the monthly lightning flash polarity counts and statistics.

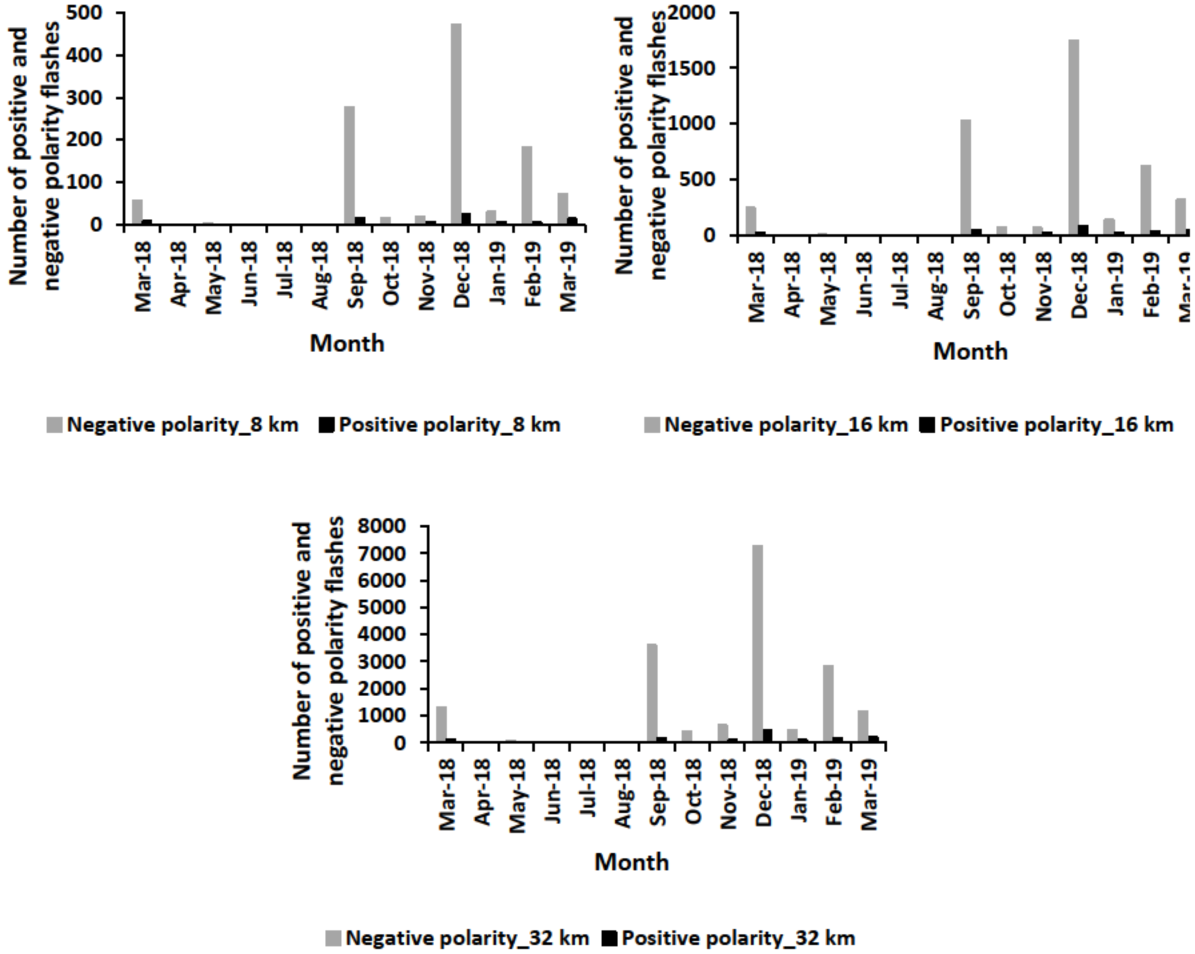


Figure 4.13 The distribution of the monthly counts of positive and negative flashes recorded by the SALDN for the 8, 16 and 32 km radius.

The distribution of the SALDN estimated peak current for the study period is shown in Figure 4.14. It should be noted that flashes with currents less than 10 kA were not utilized in the analysis (as discussed in Section 2.2).

Negative and positive flashes exhibited current amplitudes mainly less than 50 kA. The amplitudes/peak currents that had the majority of values greater than 50 kA were found to be mainly from the positive flash peak current distributions. These results were once again in agreement with Hazmi *et al*. (2017), who stated that one of the properties of positive lightning flashes are known to be high peak currents, which lead to more damage to electric power and telecommunication systems than negative lightning flashes. The highest mean percentages kA (peak kilo ampere) and median peak currents were detected during the summer months (Table 4.3).

Table 4.3 Monthly negative lightning flash polarity statistics.

	Negative flashes					
Month	**8 km**		**16 km**		**32 km**	
	Percentage (%)	**Median (kA)**	**Percentage (%)**	**Median (kA)**	**Percentage (%)**	**Median (kA)**
March 2018	3.8	-10.0	4.9	-11.5	6.5	-12.0
April 2018	0.0	0.0	0.0	0.0	0.0	0.0
May 2018	0.2	-19.0	0.2	-11.0	0.3	-10.0
June 2018	0.0	0.0	0.0	0.0	0.0	-13.0
July 2018	0.0	0.0	0.0	0.0	0.0	0.0

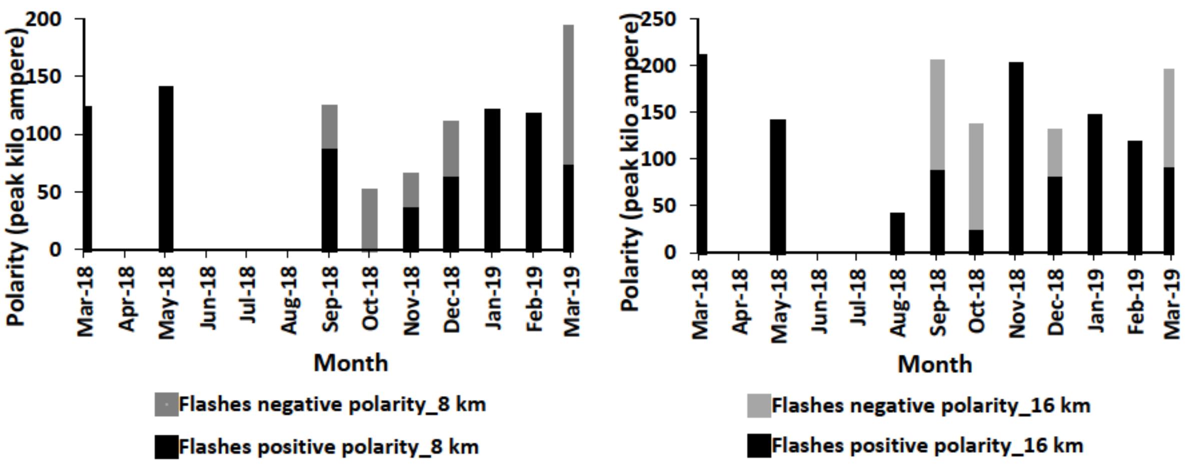
August 2018	0.0	0.0	0.1	-12.5	0.1	-12.0
September 2018	29.4	-15.0	28.5	-15.0	23.0	-14.0
October 2018	1.1	-6.0	2.1	-18.0	2.8	-17.0
November 2018	1.4	-9.5	1.3	-10.0	3.5	-13.0
December 2018	39.8	-14.0	40.6	-13.0	40.2	-12.0
January 2019	1.4	-7.0	2.6	-7.0	2.0	-7.0
February 2019	14.0	-13.0	12.1	-12.0	15.3	-13.0
March 2019	8.9	-12.5	7.7	-14.0	6.3	-12.0

Table 4.4 Monthly positive lightning flash polarity statistics.

	Positive flashes					
Month	**8 km**		**16 km**		**32 km**	
	Percentage (%)	**Median (kA)**	**Percentage (%)**	**Median (kA)**	**Percentage (%)**	**Median (kA)**
March 2018	13.8	21.0	12.0	18.0	9.7	16.0
April 2018	0.0	0.0	0.0	0.0	0.0	0.0
May 2018	5.6	135.0	2.4	15.0	1.9	18.5
June 2018	0.0	0.0	0.0	0.0	0.0	0.0
July 2018	0.0	0.0	0.0	0.0	0.0	0.0
August 2018	0.0	0.0	0.7	30.0	0.4	22.0
September 2018	20.6	20.0	13.1	16.0	9.5	15.0
October 2018	0.0	0.0	0.4	15.0	0.4	14.5
November 2018	4.9	19.0	10.6	23.0	9.5	22.0

December 2018	18.3	14.0	20.6	14.0	29.7	14.0
January 2019	8.5	17.5	10.0	14.0	6.2	14.0
February 2019	8.1	17.0	13.3	21.0	14.5	17.0
March 2019	20.2	32.5	16.8	22.0	18.0	23.0

For the respective warn/alert categories of 8, 16 and 32 km, the average peak currents for negative polarity was 17.1, 17.1 and 16.5 kA respectively, and for positive polarity were 27.5, 26.3 and 25.3 kA respectively (Figure 14). The aforementioned statistics displayed a sequence whereby the lower peak values were obtained for the furthest warn category. Therefore, as the warn category distance increased, the peak parameter decreased. This possibly indicated that the DE of the SALDN is better with distance for lower average peak current values, assuming a uniform distribution lightning polarity across the wider area. The behaviour of this parameter was further analysed in Table 4.5. This average peak current parameter constituted an indicator and an indirect approach to the DE of the SALDN within the study area (Diendorfer 2009).



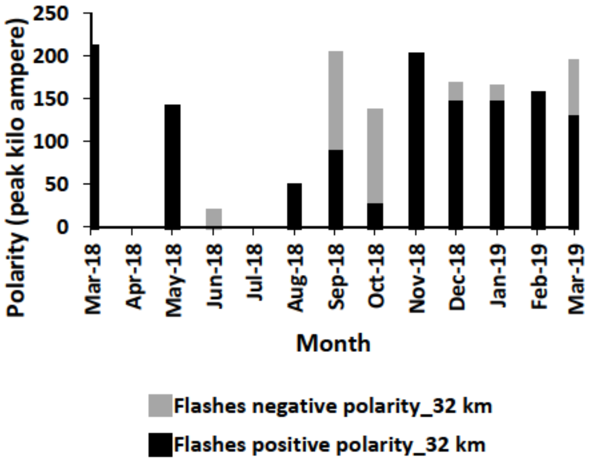


Figure 4.14 The distribution of the SALDN's lightning flashes by peak current for the study period at the 8, 16 and 32 km radius.

4.5.4 Lightning detection efficiency

As a way to test the ability of the NRT-LWS to capture the lightning discharge activity on the synoptic and meso-scales, the DE of the SALDN and the NRT-LWS was carried out for the two specific lightning events.

The method proposed by Jacobson *et al*. (2006) and used by Abarca *et al*. (2010) to evaluate the statistical proportionality of the discharge detection between the SALDN and the NRT-LWS was applied. Some proportionality is expected given the confinement of the overall electrical discharge activity, regardless of its type. Some proportionality is also expected because of the overlap between the two systems in the detection of CG flashes with strong currents. However, since the two systems detect different aspects of lightning activity (the SALDN focuses mainly on CG flashes, whereas the NRT-LWS has a tendency to detect stronger flashes regardless of their type), it is not expected that the networks are fully proportional.

The DE of the NRT-LWS flashes was calculated directly as the percentage of NRT-LWS flashes that had a SALDN flash coincident event. Interestingly, the largest number of coincidences between the SALDN and the NRT-LWS was at a close range (DE of the NRT-LWS is 100% within 8 km) (Table 4.5). At greater warn distances, the NRT-LWS tends to underestimate the number of detected flashes compared to the SALDN. This underestimation ranges between 13.0% to 46.5%, which may be dependent on the intensity of the lightning or storm event. As a result, the NRT-LWS reports more flashes at closer distances, whilst the SALDN reports more flashes at greater distances. Furthermore, the reduction in the DE of the SG000 at greater distances may explain the sensors maximum detection range of 32 km and hence, the chosen 8 and 16 km warn state categories based on the National Weather Service's "Flood Watch" and "Flood Warning" forecasts.

The SALDN is able to detect lightning with a high degree of spatial certainty/reliability compared to the NRT-LWS. The SALDN makes use of multiple sensors to detect lightning with the sensors sparsely distributed and separated distances of the order of thousands of kilometres. Each lightning flash is detected by at least two sensors, but on average about 5 to 9 sensors for the study area. The discrepancy may be a manifestation of the bias the SALDN has towards local scale/level. Another factor contributing to the NRT-LWS not detecting as many flashes as the SALDN at greater distances could be due to the window period and the differences in the types of lightning discharges both systems detect. Overall, the agreement between the spatial and temporal distributions of both lightning datasets shows that despite the lower DE of the NRT-LWS at greater distances, the NRT-LWS is capable of detecting nearby lightning activity, which is the greatest threat to the community.

Table 4.5 Summary of performance characteristics of the NRT-LWS evaluated using the SALDN.

	20-Nov-18			**03-Feb-19**		
Characteristics	**SALDN**	**NRT-LWS**	**DE (%)**	**SALDN**	**NRT-LWS**	**DE (%)**
8 km flashes	4	24	100	80	137	100
16 km flashes	21	33	100	206	49	23.4
32 km flashes	129	60	46.5	568	74	13

Lastly, the strong temporal correlation suggests that despite the two systems not targeting the same discharges, the lightning activity is well captured by the NRT-LWS. It confirms that the NRT-LWS data are a source of information with the potential to identify lightning threats at local scales. The strong correlation indicates that the lightning activity detected by both systems was very often occurring at the same time, although possibly not coincident events.

4.5.4.1 Lightning ground flash density maps

Spatial lightning flash density maps for all recorded CG lightning by the SALDN were generated using GIS for the study site located within the uMshwathi local municipality. The lightning flash density map for the 20th November 2018 lightning event is displayed in Figure 4.15, whereas Figure 4.16 displays the lightning density map for the 3rd February 2019 lightning event at the three different alert ranges. The high lightning count illustrated by the maps highlight the community's vulnerability within the area.

An advantage of utilizing the SALDN lies in the location accuracy of the detected lightning, which allow for a greater understanding and analysis around the intensity and spatial extent of storms. Furthermore, this can be beneficial towards the identification of areas that have slightly higher lightning density that surrounding areas and may therefore require prioritization for access to lightning warnings or early warning systems in the future. For future studies and risk analyses, these maps produced using the SALDN can be incorporated with a multitude of other parameters to develop a better understanding of the behaviour of lightning for different local areas in South Africa.

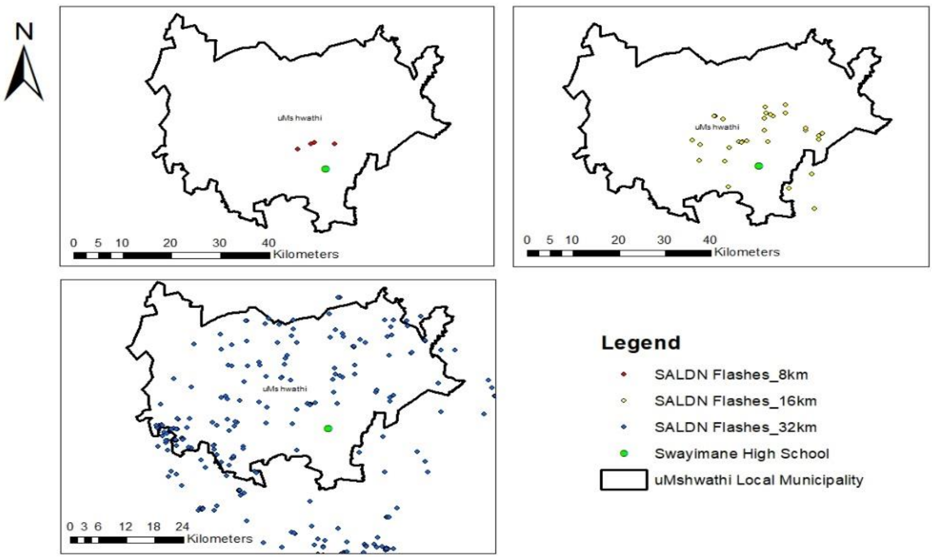


Figure 4.15 The lightning density map for the 20th November 2018 generated for all recorded CG lightning by the SALDN at three warn/alert ranges.

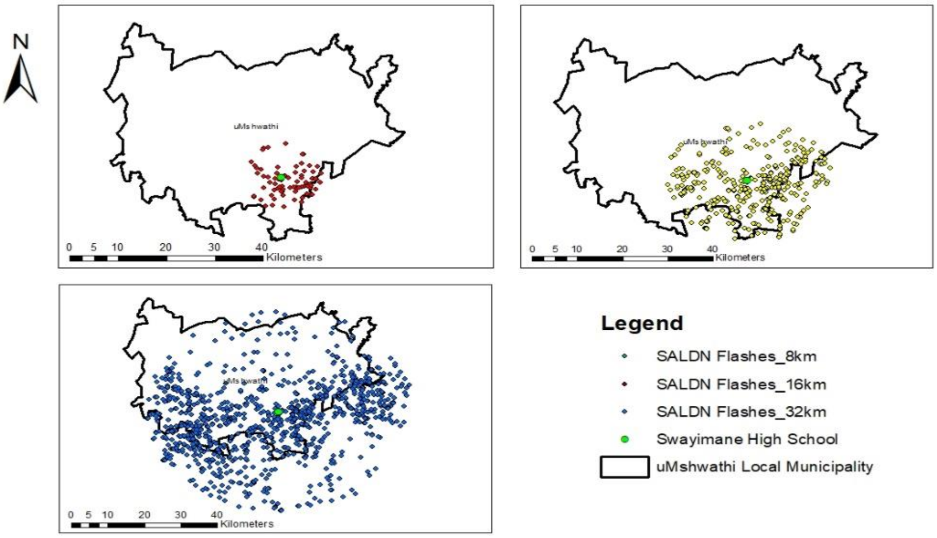


Figure 4.16 The lightning density map for the 3rd February 2019 generated for all recorded CG lightning by the SALDN at three warn/alert ranges.

4.6 Conclusions

Ground-based lightning detection systems remain one of the most sought-after detection techniques due to their high detection efficiencies and user customized alert dissemination capabilities (Rudlosky and Fuelberg 2013). These systems continue to improve and are very useful for community/local level lightning detection and alerts. Numerous countries across the world possess national lightning networks developed from ground-based lightning detection systems. However, the dissemination of warnings in a way that can be understood and be responded to appropriately for public safety at a local level is challenging in some countries. This has major adverse impacts particularly on those individuals that reside in rural areas and are vulnerable to the threat of lightning. In South Africa, this situation remains a significant challenge.

The community-based NRT-LWS provided timeous and easy to comprehend lightning warnings for the rural community of Swayimane. The seasonal diurnal variation analysis indicated lightning activity to be greatly influenced by an increased thermodynamic instability, which are found to typically occur in the later stages of the day. The results from the SALDN and the NRT-LWS assessment showed there to be a close temporal correlation between both systems in detecting lightning flashes. Despite an observed underestimation with the NRT-LWS, the community-based system was able to detect flashes at the same time as the SALDN within the 8, 16 and 32 km warn categories. Another important aspect reflected by the results included, as the SALDN current peak parameters increased, the DE of the network decreased. This reflects the fact that the primary source of the DE for the SALDN may be the peak current behaviour as noted by Abarca *et al*. (2010) and Herrera *et al*. (2018). The overall flash DE for the NRT-LWS was 100% at close distances (8km) but at 16 and 32 km, the DE seemed to be significantly lower and storm dependent. The DE was independent of the lightning type, polarity or flash current amplitude and differences may be attributed to the fact that both the systems detect different types of discharges as well as the way in which both software's detect the number of flashes per min. It would be beneficial to replicate this study using a number of NRT-LWS measurement sites.

Overall, the NRT-LWS was found capable of detecting and monitoring lightning activity, diurnal seasonal variations and detecting lightning activity at smaller spatial scales with results comparable to the SALDN. The community-based system is therefore found to be suitable for use in rural communities in South Africa from a public safety and lightning detection standpoint. The study also demonstrated that the SALDN would be a very valuable resource to use for the identification and dissemination of lightning warnings to high risk communities across South Africa.

4.7 Acknowledgments

This work forms part of the uMngeni Resilience Project, funded by the Adaptation Fund, which is a partnership between the Department of Environment. Forestry and Fisheries, the South African National Biodiversity Institute, the uMgungundlovu District Municipality and the University of KwaZulu-Natal's Centre for Transformative Agricultural and Food Systems. Financial assistance from the Durban Research Action Partnership (D'RAP) and the National Research Foundation (NRF) is also acknowledged. We are indebted to the South African Weather Service for providing the SALDN dataset used in this paper and for their collaboration in this research.

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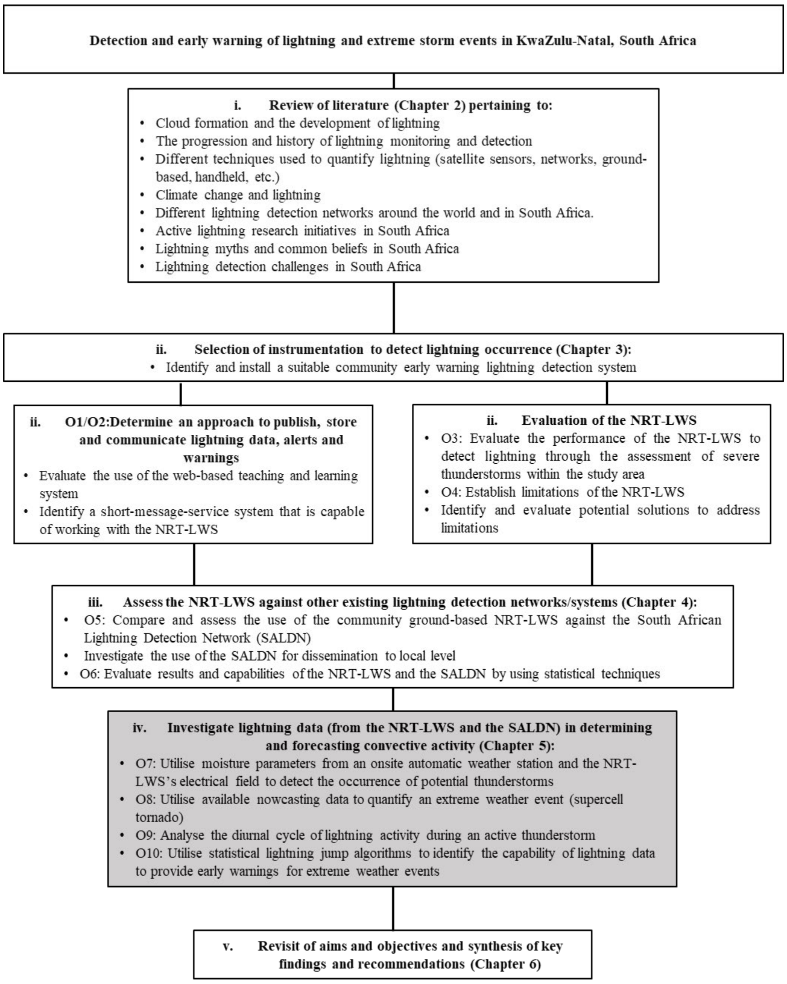
Lead into Chapter 5: The validation of the NRT-LWS against the SALDN showed that it followed the general temporal distribution of the SALDN and for most instances it detected flashes at the same time as the SALDN. The NRT-LWSs data was therefore shown to be a reliable source of information with the potential to identify and disseminate lightning threats at local scales. With the capability of the NRT-LWS to accurately monitor and detect lightning activity (Chapter 4), the objective of Chapter 5 was to assess the use of total (using the NRT-LWSs data) and cloud-to-ground (using the SALDN data) lightning data as a precursor to convective activity and/or severe weather (tornadoes) at a local scale for South Africa.



CHAPTER 5: A SUPERCELL TORNADO EVENT ON 12 NOVEMBER 2019 IN KWAZULU-NATAL, SOUTH AFRICA: RADAR, MESOSCALE PERSPECTIVES AND LIGHTNING CORRELATIONS (PAPER 4)

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5.1 Abstract

With global climate change a reality, there is mounting evidence that changes in the earth's

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climate system will result in more frequent extreme weather events. Amongst these, a tornado is one of the most ferocious weather events, which develops from a thunderstorm. In South Africa (SA), tornadoes and supercells are relatively rare. However, with climate change there is increasingly more evidence that the number of intense thunderstorms are increasing, thereby creating the right conditions for tornadoes to form. A tornado that occurred on the 12^{th} November 2019 was the first of four tornadoes to occur within a two-week period in the province of KwaZulu-Natal (KZN), South Africa. The 12^{th} November event occurred in the New Hanover area (Mpolweni), to the north-east of Pietermaritzburg, KZN. This preliminary study sought to contribute towards the understanding of supercell tornadoes on a local scale for SA, by using the Mpolweni tornado as a case study. The use of total and cloud-to-ground lightning data was evaluated as a precursor to tornadoes and severe weather on a local scale for SA. The meteorological background to this case was the presence of a surface trough and a cut-off low pressure system causing severe convective conditions. The event was analysed by means of observed data, including a METEOR 600S S-band Doppler radar, which showed significant reflectivities (> 55 dBZ) and revealed supercell characteristics. From the satellite perspective, the storms were accompanied by several cloud-top features, which are typical for severe storms. The analysis of lightning data displayed several peaks in flash rate preceding the severe weather at the ground (in this case the tornado). The NRT-LWS (total lightning system) was found to be more beneficial than the SALDN (cloud-to-ground network), providing a lead time of 33 minutes to the event. The synergistic effects of combining radar, satellite and lightning data was beneficial in supporting the early detection of convection.

Keywords: *climate change; cut-off low; satellites; severe weather; surface trough; thunderstorms*

5.2 Introduction

Throughout history, extreme weather has impacted humans, but recently there is concern that these events are getting worse (Farney and Dixon 2015). There is mounting evidence that changes in the earth's climate system will result in more frequent extreme events (Seneviratne *et al.* 2012). Extreme weather events result in large losses to property and/or life, especially when impacting a highly exposed and susceptible population (Farney and Dixon 2015). The continent of Africa is expected to be drastically impacted by climate change during the 21st century, owing to its high levels of vulnerability and low adaptive capacity (Seneviratne *et al.* 2012). According to Farney and Dixon (2015), the increased exposure to weather extremes, led by human behaviour and population growth, coupled with a fear that global climate change may result in more frequent and/or stronger weather extremes, places added value on research that aims to study these extreme events. Of equal significance is the importance of early warning systems to warn the public of these types of extreme weather events. While improved monitoring and detection of extreme weather events will not reduce the number or severity of these events, early warning can significantly reduce the loss of life (Price 2008). Amongst the extreme weather events, the effects of climate change on severe thunderstorms is a particular rapidly growing area of research (Allen 2018).

Tornadoes are global phenomena, having been recorded in every continent except Antarctica (Goliger and Milford 1998; Edwards *et al.* 2013). They are the most violent and destructive of all the severe weather phenomena that localized convective storms produce (Howard 2013). Tornadoes are capable of causing significant property damage, economic disruption as well as human and animal injuries and fatalities (Grobler 2003; Wurman *et al.* 2007; Cheng *et al.* 2013; Elsner *et al.* 2019; Frazier *et al.* 2019). Tornadoes are characterized as a rapid violently rotating column of air that extends from the base of a thunderstorm to the ground (De Coning and Adam 2000; Howard 2013; Kimambo 2018). Tornado occurrence is difficult to predict due to their rapid evolution and complex interactions with environmental features. These events are localized and are known to last anywhere from just a few seconds to an hour or more, with the an average warning lead time of 10-15 minutes for the United States (Wurman *et al.* 2007; Howard 2013; Cintineo *et al.* 2014).

Tornadic formation (termed tornadogenesis) requires several ingredients. The first is a thunderstorm, in which a mass of unstable air promotes the development of strong updrafts and wind shear contributes to an increasing strength of the updrafts, leading to a rotation whereby tornadoes are produced. In the process of thunderstorm development, thunderstorms are grouped into four types, including single cell, multicell cluster, multicell line and supercell storm (Tyson and Preston-Whyte 2000). The most violent is the supercell and of the four types of thunderstorms, tornadoes are found to be associated with supercells (De Coning and Adam 2000; Guillot *et al.* 2008; Kimambo 2018). One of the most common characteristics of a supercell thunderstorm is a rotating updraft (Guillot *et al.* 2008). Apart from the three fundamental ingredients required for thunderstorm formation (moisture, instability and lift), supercell thunderstorms require strong vertical wind shear (directional and/or speed shear) conducive to mesocyclones (De Coning and Adam 2000; Mpanza 2016). These factors contribute towards the promotion of a rotating updraft called a mesocyclone (Grobler 2003). Supercell thunderstorms are not common, but they are the most hazardous, intense and potentially more damaging compared to other types of thunderstorms (Grobler 2003; De Coning 2010; Mpanza 2016). They are usually long-lived (while some are not), which sets them apart from ordinary thunderstorms. The majority of the hazards associated with supercells include hail, damaging winds and tornadoes (Goliger and Retief 2007; Mpanza 2016). The Fujita-Pearson (FPP) scale is the most commonly used measure of intensity for severe storms based on tornado damage inflicted on structures and vegetation. It is based on the work of Fujita in the 1970’s (1971; 1973) and his later collaboration with Allen Pearson in 1973, which in practice ranks tornadoes from F0 (min) to F5 (max) - (Grobler 2003; Edwards *et al.* 2013; Doubell *et al.* 2019). In response to the shortcomings and limitations of the FPP scale, the United States has recently devised an Enhanced F Scale (EF Scale) for operational use in 2007, which included aligning wind speeds to associated damages (Grobler 2003; Edwards *et al*. 2013; Doubell *et al*. 2019).

In southern Africa, tornado-producing supercells are known to be relatively rare (De Coning and Adam 2000), whereas, the occurrence of convective thundershowers is mostly limited to the austral summer months (October-March) for South Africa (SA) (De Coning 2010; Blamey *et al.* 2016), with a seasonal distribution of tornadic events indicating that most tornadoes occur in summer (November to March) (De Coning and Adam 2000). There are however exceptions with the 26th July 2016 tornado in Tembisa, Gauteng as one example of a winter month tornado (Doubell *et al*. 2019). The majority of tornadoes occur in the late afternoon or early evening and often between 16:00 and 19:00 (local - SAST) (De Coning and Adam 2000). Tornadoes occur mainly over eastern SA (particularly over the southern part of the KwaZulu-Natal (KZN) province interior and Gauteng province) as the east coast of the country is vulnerable to potential severe convective environments throughout the summer months (Blamey *et al.* 2016; Kruger *et al.* 2016; Kimambo 2018). Over the past 9 years (between October 2010 to November 2019), 16 tornadoes have been recorded in SA (Doubell et al. 2019). The most fatal tornado to occur in the country, was rated F4 on the Fujita scale with 26 people killed and hundreds injured in the Eastern Cape areas of Mount Ayliff and Thabankulu on January 18^{th}, 1999 (De Coning 2010). The second half of 2019 experienced an unusually active period for tornadic thunderstorms across SA. Four tornadoes occurred within a short space of two weeks in the province of KZN. The majority of these tornadoes occurred in sparsely populated rural areas (Doubell *et al*. 2019) where individuals often lack the knowledge and understanding of weather warnings.

In SA, the South African Weather Service (SAWS) are responsible for providing the public with timeous weather information and warnings as well as operates a sophisticated observation network. The organisation's observation network includes weather radars, upper-air soundings, a lightning detection network and weather satellite observations, amongst others. SAWS also has access to several Numerical Weather Prediction (NWP) models, with the Unified Model (UM) being the main operational model run locally on the SAWS high performance computer four times daily (Gijben *et al.* 2017; Stein *et al*. 2019). Radar, satellite and observational data are powerful tools which are utilized when operational forecasters have to warn the public of hazardous, high-impact weather such as thunderstorms, tornadoes, lightning strikes and destructive winds as well as to analyse and forecast smaller scale weather features (De Coning *et al.* 2015).

While SAWS is capable of predicting areas where thunderstorms as well as supercells (which may produce hail, damaging winds, lightning, heavy rainfall/flash flooding and even tornadoes) are likely to occur well in advance, they can also nowcast (short-term forecasting, 0-2hours) these storms for the next hour or so, but they do not provide specific warnings for tornadoes. In addition, while tornado formation signatures are detectable on a weather radar, it normally happens within 20 minutes of the tornado developing, which is insufficient time for any warning to effectively reach the possibly affected community and the precise location can only be confirmed once it has started to form (Doubell *et al.* 2019). The observation of classic tornado signatures on radar also do not always guarantee the occurrence of a tornado. Signatures in one storm can strongly indicate a high possibility of the storm producing a tornado without any outcome, while another storm with less than obvious signatures might produce a tornado.

Deriving potentially valuable predictive relationships between meteorological factors and tornado occurrences could therefore be a useful tool for assessing tornado climatology (Cheng *et al.* 2013). Several studies have investigated possible interconnections between meteorological covariates with tornado observations, for example, lightning flash polarity and lightning flash rates (Cheng *et al.* 2013). Since lightning in thunderstorms is strongly linked to the microphysics and dynamics of thunderstorms, changes in the lightning activity may indicate changes in the internal processes within the thunderstorms (Deierling and Petersen 2008; Price 2013). Lightning activity itself follows a specific pattern within thunderstorms, with the intracloud (IC) lightning normally appearing first (during the thunderstorms developing stage), followed by the cloud-to-ground (CG) lightning starting during the mature stage (Price 2013). Both types of lightning can occur during the decaying stage. In addition to the lightning changes, the mature stage may be associated with heavy rainfall, hail, and tornadoes, while the dissipating stage is known to be associated with downdrafts, microbursts and wind shear (Price 2013). Past studies have had reasonable success in showing that lightning discharges and characteristics in thunderstorms are an indication of the intensity of atmospheric convection (Goodman *et al.* 2005; Price 2008; Price 2013). This allows forecasters to gain improved situational awareness of storms as the amount of total lightning (CG + IC) is related to the updraft strength of the thunderstorm (Stano 2012).

Seimon (1993) and Perez *et al.* (1997) studied a variety of lightning variables including peak current, flash rates, and polarity reversals, of which lightning flash rate was found to be a simple, accessible variable that indicated a strong potential for predicting severe weather (Eck 2017). The distinguishing feature in severe storms was the abrupt increase in flash rate in advance of severe weather on the ground, which is termed “lightning jumps” (Williams *et al.* 1999; Schultz *et al.* 2009). Because of the availability of CG lightning detection network data over a relatively long period of time, many international studies were carried out to investigate relationships between CG lightning activity and severe weather (Schultz *et al.* 2011). However, early studies discovered using total lightning information seemed to have more useful applications (Price 2013), because total lightning provides a more complete picture of the electrical activity (Finke and Kreyer 2002; Schultz *et al.* 2011). Total flash rate was observed to rapidly increase prior to the onset of severe weather (Cummins *et al.* 2000; Schultz *et al.* 2011; Price 2013), followed by a dramatic decline, indicating the development of strong storms. This pattern of lightning activity precedes the occurrence of CG lightning strikes by several minutes and is information that forecasters could use to issue earlier warnings to communities in a storm's path (Goodman *et al.* 2005).

The rapid development of weather systems (Cummins *et al.* 2000), the limited lead-time, complexities in analysing radar scans as well as the type of warning that is disseminated to the public are some of the challenges for researchers and forecasters. Therefore, automated lightning data can be a valuable addition to cloud observation tools such as radar and satellite observation since they are useful proxies for many storm related hazards. Lightning can be used in monitoring storm hazards around the globe, whilst also providing the possibility of supplying short term forecasts of convective storms motion, called nowcasting (Finke and Kreyer 2002). Lightning data can therefore complement other observations in indicating the need for an imminent warning. While the formation of tornadoes and supercells are difficult to predict, identifying such potential precursors may provide headway.

Consequently, the main aim of this preliminary study is to contribute towards the understanding of supercell tornadoes on a local scale for SA, by using the Mpolweni tornado as a case study. Two main objectives form the basis of the study. The first objective, focuses on analysing the development and structure of the tornado event at a more localized level using a suite of nowcasting data from remote sensing tools such as radar and satellite data. The second objective of study assesses the benefit of using lightning jumps to predict severe storm reports as a precursor for tornado events.

5.3 Study area

The study is for the uMshwathi local municipality which includes an area covering -28.915°S to -30.145°S and 29.293°E to 30.919°E, with rural settlements, Mpolweni and Swayimane (Fig. 5.1). The uMshwathi Municipality is under the Umgungundlovu District Municipality, which lies north-east of Pietermaritzburg, SA and has the second largest population in the uMgungundlovu District, after Msunduzi (StatsSA 2012). The tornado event on the 12th November 2019 was reported to have occurred within the Mpolweni rural settlement in the town of New Hanover. The second rural settlement, Swayimane, is also of importance to the study, as a community-based near real-time total lightning warning system (NRT-LWS) was installed in this community measuring total lightning. Mpolweni lies well within the NRT-LWS detection radius of 32 km. Lightning data were also supplied by the South African Lightning Detection Network (SALDN) measuring CG lightning providing the opportunity to determine whether the inclusion of total or CG lightning data could provide improved warnings and nowcasts of severe convection (Section 5.4).

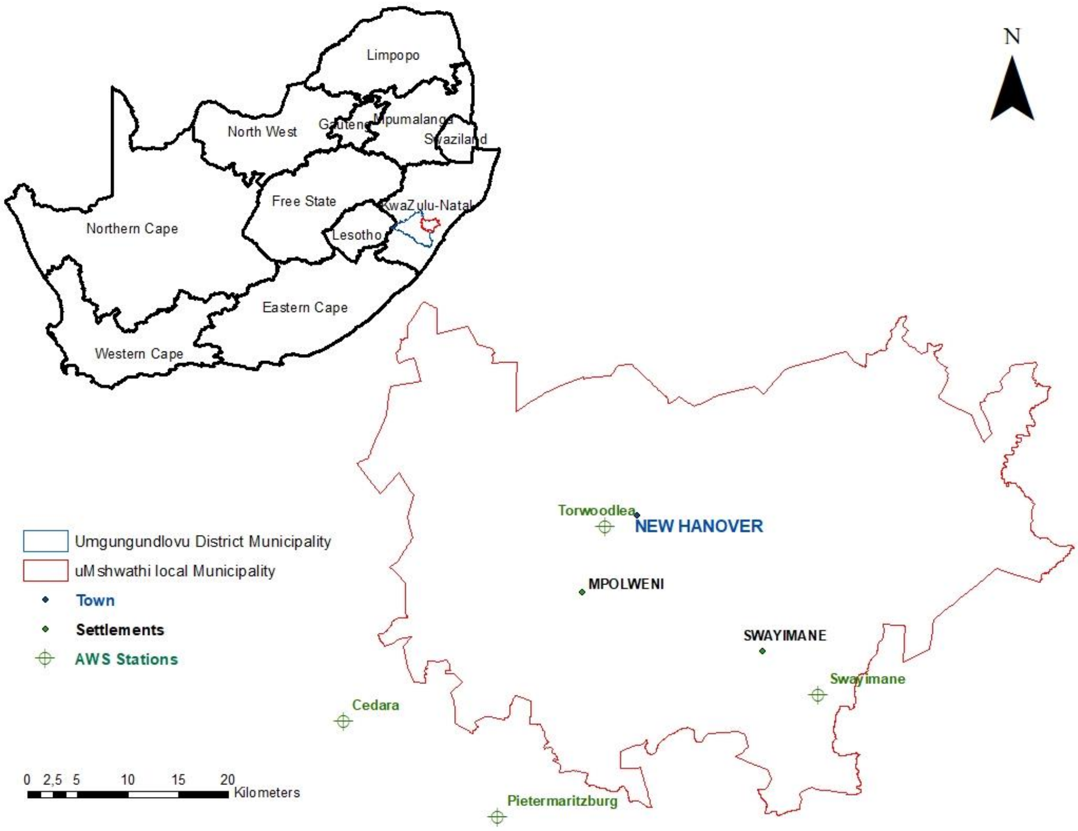


Figure 5.1 The study area showing the tornado site near the town of New Hanover (Mpolweni settlement). The NRT-LWS and an automatic weather station (AWS) were both located at the Swayimane station site.

5.4 Data sources and methodology

The tornado event was analysed using a suite of nowcasting datasets and products, which include: (1) synopsis of weather systems (synoptic chart-courtesy of the SAWS), (2) automatic weather station (AWS) data, (3) S-band Doppler radar scans (visually), (4) data from the SALDN and the community-based NRT-LWS (quantitatively and visually), as well as 5) Meteosat-11 satellite data such as, the RDT (rapidly developing thunderstorm) and CRR (convective rainfall rate) products and RGB (red-green-blue) composite images, which are useful in depicting deep convective features of thunderstorms. All times in this Chapter are reported in Coordinated Universal Time (UTC).

5.4.1 Data sources

5.4.1.1 South African Lightning Detection Network (SALDN)

The SALDN is operated by the SAWS and is a Vaisala lightning detection network operating and comprising of 24 sensors across SA and with one sensor located in Swaziland (LS 7000 and LS 7001, Helsinki, Finland). The distribution of the sensors throughout the country makes it possible to detect lightning flashes with a greater than 90% predicted detection efficiency and lightning strokes with a median location accuracy of less than 0.5 km over most of the country (Gijben 2012; Gijben 2016). The SALDN sensors detect very low frequency (VLF) and low frequency (LF) electromagnetic signals emitted by lightning discharges by means of a combination of magnetic direction-finding and time of arrival methods (Gijben 2012). The sensors are designed to detect CG lightning in the VLF and LF spectrum but is also capable of detecting up to 50% of IC lightning in the LF range depending on the location of the sensors and the distances between, as well as the number of sensors participating in the detection of the IC lightning. The data are stored on a database and can be retrieved using the Fault Analysis and Lightning Location System software package (Vaisala Inc., Helsinki, Finland). In this study, the SALDN's CG flashes dataset extracted at a 32 km radius (from the Swayimane High School) was utilized for the period, November 2019 to February 2020. Studies by Gill (2008, 2009) and Gijben (2012) and Gijben (2016) provide further details on the SALDN.

The nowcasting lightning product used in the study was based on the lightning data from the SALDN. The Thunderstorm Identification, Tracking and Nowcasting algorithm (TITAN) that was applied to radar data was also applied to lightning observations that occurred in the past 6 minutes (to be consistent with radar), and provided information on current storms as well as nowcasts for the next 30 min and 60 min. As with radar tracking and nowcasting, this product updates every 6-minutes.

5.4.1.2 Community-based Near Real Time-Lightning Warning System (NRT-LWS)

A community-based near real-time total lightning warning system was used in this study for comparison with the CG-based SALDN. The NRT-LWS was installed in February 2018 in the rural community of Swayimane (Ward 8), situated approximately 65 km east of Pietermaritzburg and 23 km away from the Mpolweni settlement, within the province of KZN. The NRT-LWS consists of two sensors to detect the threat of lightning. The atmospheric ($V\ m^{-1}$) electric field magnitudes (accuracy within +-5%) was measured by an Electric Field Meter (CS110, Campbell Scientific Inc., Logan, Utah, USA), detecting the presence of nearby electrified clouds that are capable of producing lightning discharges, within a maximum 40 km radius. A lightning flash sensor (SG000, Strike Guard, Wxline, Tucson, Arizona, USA) was also installed together with the electric field meter. According to the manufacturer, the SG000 receives and processes the optical and radio emissions of lightning discharges within 0-32 km of the sensor. The detected discharges include IC and cloud-to-cloud/inter-cloud (CC) flashes as well as CG strikes. The SG000 sensor does not differentiate between flashes and strikes, hence, the term ‘flashes’ with respect to the NRT-LWS will also include strikes in this paper. For the study, the NRT-LWSs total lightning data for November 2019 to February 2020 within the 32 km warn radius of the equipment’s site was utilised. The 32 km warn radius provides coverage over the Mpolweni and New Hanover areas where the tornado had occurred.

An AWS was also installed at a distance of approximately 200 m from the NRT-LWS. Measured 2-min climatic data which included, rainfall (TR252I, Texas Electronics Inc., Dallas, Texas, USA), air temperature and relative humidity (HC2S3 L, Vaisala Inc., Helsinki, Finland) as well as wind speed and direction (Model 05103, R.M. Young, Transverse city, Michigan, USA) for the 12th November 2019 were also used in this study. In addition, data from Pietermaritzburg, Cedara and Torwoodlea AWS stations were also utilised in the study (Figure 5.1).

5.4.1.3 Radar

A METEOR 600S S-band Doppler radar (Leonardo Company, Rome, Italy) was used in this study. The S-band radar signals undergo far less attenuation than that of C-band signals and is also not affected significantly by Radio LAN interference that is often found in the C-band range over South Africa. All the SAWS S-band radars are set to have a maximum unambiguous range of 200 km (Keat *et al.* 2019). The radars are calibrated between once or twice each year to ensure that they operate at optimal performance. The SAWS radar data are available every 6-min and are supplied in polar co-ordinates. The radar data are interpolated onto a regular 3D Cartesian grid using the University Corporation for Atmospheric Research (UCAR) TITAN software (Dixon and Wiener 1993) (Terblanche *et al.* 2001; Keat *et al.* 2019). In this study, visual comparisons between ground-based radar observations from the SAWS and satellite imagery (MSG) was undertaken. The 6-min radar data as well as cross sectional analyses was used to display and analyse the tornado event on the 12th November 2019 within the storm hour (14:00-15:00).

5.4.1.4 Satellite data and products

Data from the Meteosat-11 satellite positioned at 0 degree was utilised in the study to identify the tornado. The satellite provides a choice of twelve channels to use either individually or in combination for various purposes, including nowcasting of convection (De Coning 2010). The image pixels for eleven of the twelve channels are sampled every 15 min at intervals of 3 km over the entire area (De Coning 2010). The High Resolution Visible (HRV) channel has a sampling distance of just 1 km, with the east-west scan limited to half of the full-earth disc (De Coning and Poolman 2011). The RGB combinations that were used in this study include: (1) airmass RGB, (2) tropical airmass RGB, (3) day natural colour RGB, (4) the high-resolution visible (HRV) channel and (5) convection RGB. Full details on the satellite channels can be found in De Coning (2010). The MSG RGB composite imageries used in this study were ordered from Eumetsat, Germany, and processed using Software for the Utilization of Meteosat Outlook (SUMO) activities at the SAWS. For the purpose of the study, the period from 14:00 to 15:00 on the 12th November 2019 was considered, as this period coincides with the storm period during which the tornado event occurred.

Along with the purely visual interpretation of the MSG channels, the ultimate usefulness comes from digital products extracted from the data for different purposes and especially in areas that lack radar data coverage or where no radar systems are available. De Coning (2010) discusses these products in more detail. The Rapidly Developing Thunderstorms (RDT) and the

Convective Rainfall Rate (CRR) products from the NWCSAF software with 15-min intervals for 12th November 2019 were used in the study.

The RDT product makes use of 11 of the 12 channels from the MSG satellite as well as input from several NWP fields, which are further discussed in De Coning *et al.* (2015). Similarly to the satellite data, the RDT product updates every 15 min and is available during day and night-time (Gijben and De Coning 2017). The RDT Interactive Display consists of motion arrows which indicate the direction of movement of the storm, while the length of the arrows indicate the speed of the storm (South African Weather Service 2017). An object-orientated methodology is used in the products algorithm to identify and track thunderstorms through the use of polygons to represent the different phases of the convective storms (triggering, growing, and mature) (Gijben and De Coning 2017). The RDT algorithm's methodology is described in detail in the Nowcasting Satellite Application Facility in support to Nowcasting and Very short-range forecasting (NWCSAF) documentation. De Coning *et al*. (2015) and Gijben and De Coning (2017), provide full details on the RDT product.

The convective Rainfall Rate (CRR) are also amongst the products developed in the NWCSAF context. Convection that is retrieved from the MSG Spinning Enhanced Visible and Infrared Imager (SEVIRI) channels are used to provide information on convective and stratiform rainfall. According to De Coning (2014), the CRR product makes use of either 2 or 3 of the MSG SEVIRI channels, which include IR108 and (IR108 - WV062) (24 h), and IR108, (IR108 - WV062) and VIS006 (day time only). To assess the rainfall during the tornado event, the CRR product from the NWCSAF was utilised in the study, using MSG-11 satellite data as well as the local version of the United Kingdom Meteorological Office (UKMO) UM as input.

5.4.2 Jump algorithm

A study by Schultz *et al.* (2009) tested six lightning jump algorithms (Gatlin 30 algorithm, Gatlin 45 algorithm, threshold 8 algorithm, threshold 10 algorithm, 2σ algorithm, 3σ algorithm) using two very high frequency lightning mapping arrays on both non-severe and severe thunderstorms. It was determined statistically and from parameter sensitivity testing that the ‘‘2σ’’ configuration (σ = standard deviation) held the most promise for an operational algorithm. Therefore, based on the performance of the 2σ algorithm for an operational algorithm, the same algorithm configuration of Schultz *et al*. (2009) was implemented in this study to assess the value of using lightning jumps to predict severe storms. According to Schultz *et al*. (2009), three main steps form the basis for analysing the value of lightning to predict the occurrence of severe weather. These three steps were also followed in this study and are outlined as follows: (1) severe and non-severe thunderstorms had to be identified, (2) the lightning flash rates/behaviour for non-severe thunderstorms was quantified to account for the trends that occur in day-to-day non-severe thunderstorms and to differentiate between severe thunderstorms, and (3) the algorithm was developed and tested for the identified thunderstorm (Schultz *et al.* 2009). A detailed step-by-step method to calculating the algorithm is presented by Schultz *et al.* (2009; 2011).

The datasets utilized in this study were confined to the same spatial and temporal domains. Spatially, the focus was on the 32 km warn range from the NRT-LWS in Swayimane. The SALDN’s data were also extracted at this range, which covered the Mpolweni settlement. Temporally, subsets of data from the 2019-2020 convective season (November-February) was chosen to be studied, with a focus primarily on the 12th November 2019 tornado event. Severe thunderstorm days were chosen based on the SAWS criteria, which uses international best practices (WMO and international Weather Services as a benchmark). The severe weather watches/warnings relate to a list of six specific weather hazards: snow, heavy rainfall, flooding, severe thunderstorms, high seas, and strong winds. According to the SAWS, a severe thunderstorm is a storm which can, or is producing, one or more of the following: Rainfall ≥ 50 mm within 24 hours, hail > 19 mm diameter, large amounts of small hail, tornadoes (any), wind gusts > 50 knots (> 100 km h^{-1}) in association with a thunderstorm and localised urban flooding or flash flooding.

All the SAWS weather watches and warnings having any of the above conditions were studied and chosen as a severe thunderstorm case, while those days having no report of severe weather were classified as non-severe thunderstorms. The Swayimane AWS data was also used in conjunction with the SAWS reports to classify the severe and non-severe thunderstorm days, using the SAWS criteria for a severe thunderstorm. A collection of 46 thunderstorm days were analysed for the NRT-LWS dataset and a total of 51 thunderstorm days for the SALDN dataset. Of the 46 thunderstorms, 24 thunderstorms were in the category of severe and 22 into the category of non-severe. From the SALDN dataset of 51 thunderstorms, 29 were severe and 22 were non-severe. Once the lightning jumps were calculated, data from nearby AWSs (see Fig. 5.1) were used to validate the jumps but analysing the records for any indication of severe weather.

5.5 Description of the tornado impact and damage

On Tuesday afternoon, 12th November 2019 between 14:00 and 15:00, a thunderstorm spurred a tornado near the New Hanover area (Mpolweni), KZN (South African Weather Service 2019b). The tornado-producing thunderstorm developed in the south regions of KZN but tracked a considerable distance to the north east of Pietermaritzburg. Although this event was short-lived, the severity was responsible for significant infrastructural damage, with people being displaced from their homes, power disruption and damage to crop fields (South African Weather Service 2019b). The event claimed two lives (South African Weather Service 2019b) and injured 20 people. Property and trees in the swath of the tornado experienced major destruction. A media statement released by Eskom (South Africa's electricity public utility), reported damage to Eskom's infrastructure by the storm (Eskom 2019). The storm was in the vicinity of Mersey Substation, which resulted in a 33 kV Mpolweni feeder to trip. Hence residents in the Mpolweni and surrounding areas were affected with power interruptions (Eskom 2019). Substantial damage to homes was also reported by the media, including damage and/or removal of roofs, top-floor exterior walls collapsing and other outdoor structural damages. Signs of extreme wind speeds were observed, including uprooted trees, collapsed power lines and folded pieces of roof sheeting, amongst others. Eye-witnesses reported seeing a tornado with a funnel cloud.

5.6 Synoptic discussion and early history of the storm

5.6.1 Early history of the storm

The SAWS issued a watch for severe thunderstorms covering a large part of the country and in particular KZN at 03:53 on the morning of the 12th November 2019 (South African Weather Service 2019b). This weather alert was upgraded to a warning at 12:32 for selected municipalities in KZN (South African Weather Service 2019b). Special weather advisories and watches were also issued prior to the event, from the 10th November 2019 onwards and were upgraded to warnings closer to the time of the tornado event (South African Weather Service 2019a).

5.6.2 Weather patterns

The synoptic observation for the 12th November 2019 at 12:00 indicated a surface trough extending over the central interior, with a high pressure system south of the country (Fig. 5.2). An upper-air cut-off low-pressure system (COL) was also present southeast of the country (South African Weather Service 2019b). A COL is a cold-cored, closed upper tropospheric cyclonic circulation that frequently occurs annually in South Africa and are major contributors to the country's heavy rainfall and flooding events (Barnes *et al*. 2020; Ndarana *et al*. 2021). As a result of these systems, partly cloudy to cloudy and cool to warm conditions with showers and thundershowers as well as light rain occurred over the entire country from 10th to 15th November 2019.

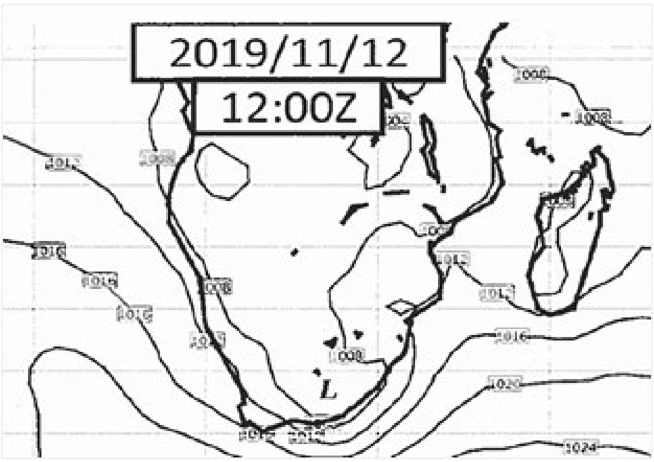


Figure 5.2 The surface synoptic chart on the 12th November 2019 (12:00UTC/Z) (courtesy of the South African Weather Service).

5.7 Results

In this section, two kinds of results are presented for displaying and assessing the tornadic storm event. First, radar scans (including the velocity fields) and processed satellite images are evaluated to visually quantify the tornado event. Secondly, the use of lightning data to forecast severe weather is investigated by demonstrating the use of lightning data as a precursor for the tornado-producing storm event. This is a preliminary study as the focus is only on one severe weather event.

5.7.1 Radar

Six-minute radar scans within the storm's hour (14:00-15:00) are of significant interest to this study and are assessed (Fig. 5.3). The radar scans clearly depict the swath of severe weather in the south-eastern interior of the KZN province with > 55 dBZ reflectivities being evident on the 2D images (composed of max reflectivity). During its lifetime, the storm moved from the south-east in a north-easterly direction showing a deviation to the left when compared to the general motion of other storm cells in the vicinity that moved in a south-easterly direction (Fig. 5.3).

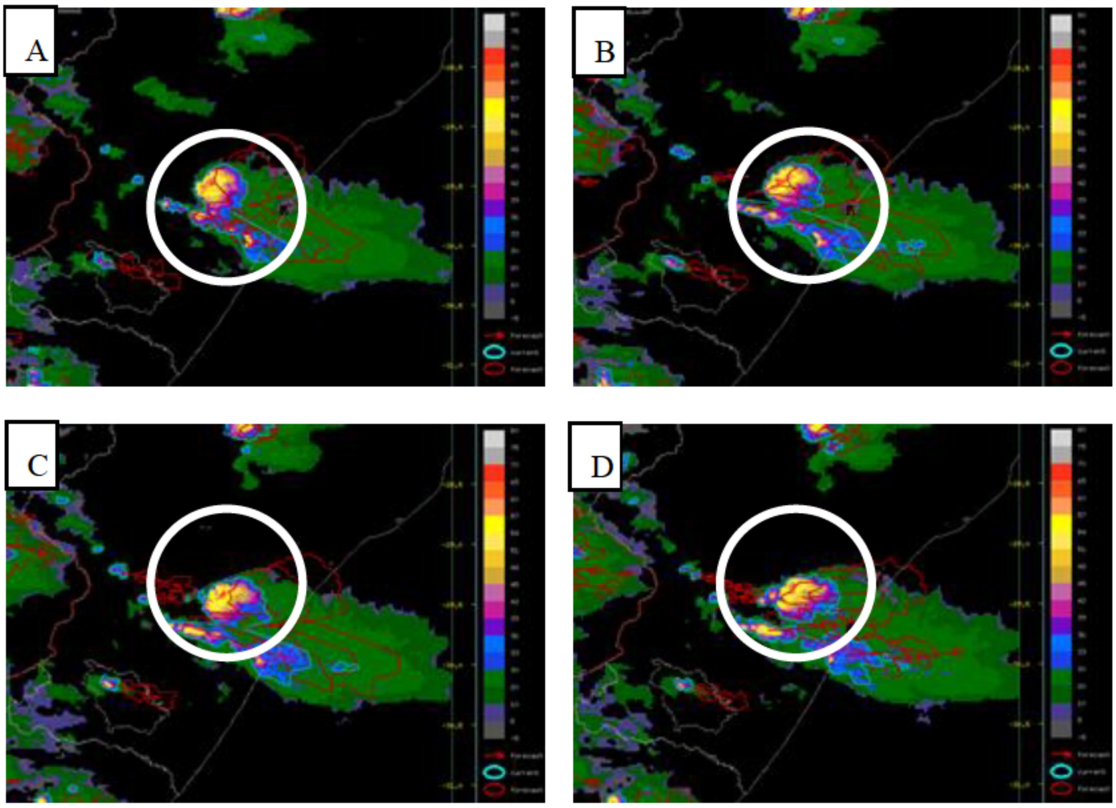


Figure 5.3 Radar reflectivities displayed at (A) 14:30 UTC, (B) 14:36 UTC, (C) 14:42 UTC and (D) 14:48 UTC for the 12th November 2019 over the KwaZulu-Natal province of South Africa. The red arrows indicate the forecasted storm direction, while the red rings indicate the forecasted storm movement, and the blue rings indicate the current position of the storm. The radar reflectivities are ranged bottom-up from -5 (lowest) to 80 (highest).

To further examine structures in the storm and to fully appreciate the intensity of this storm, the vertical structure and velocity field of the storm was analysed (Fig. 5.4). The vertical cut (VCUT) across at 14:33 shows a bounded weak echo region (BWER) and a hook echo, which are meteorological features associated with supercells. This overhang is the consequence of a strong, persistent updraft and correspondingly strong divergence in the upper layers. An area of low reflectivity is also visible surrounding the hook echo. Between 14:33 and 14:39 very high reflectivity extending into the updraft with an intense overshooting top was also visible (Fig.5.4 A,B). The radar velocity profile also shows a mesocyclone (seen as a radar signature that is rotating) in the region of the hook echo (Fig. 5.4 C,D). It is found within the echo region of the thunderstorm and is associated with a supercell tornado. The tornado signature weakened by 14:42 (not shown).

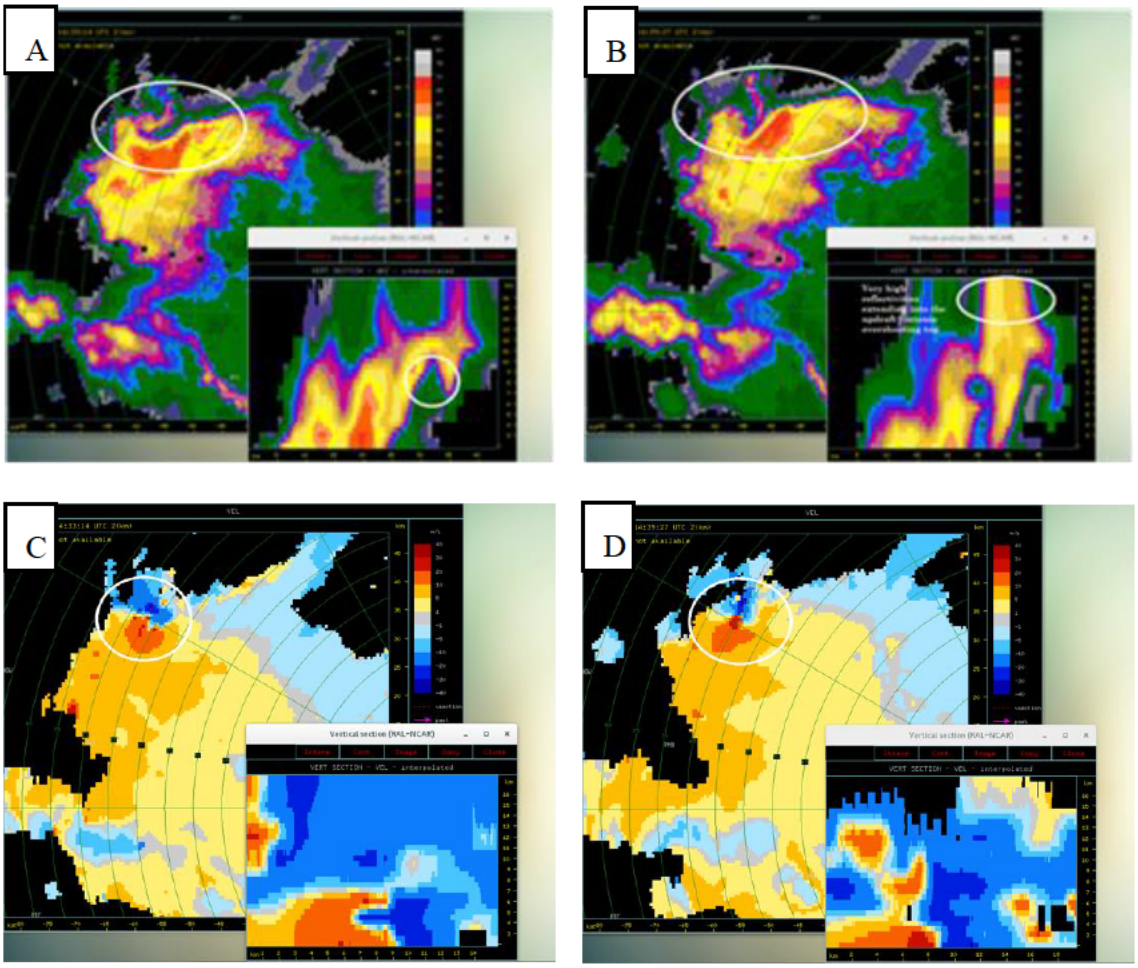


Figure 5.4 The reflectivity field together with the vertical cross-section of the tornadic storm event at (A) 14:33 UTC and (B) 14:39 UTC revealing reflectivities between 57 dBZ to 70 dBZ, a bounded weak echo region (BWER) and a hook echo, whereas the

velocity field of the storm is displayed at (C) 14:33 UTC and (D) 14:39 UTC displaying a mesocyclone.

5.7.2 Satellite perspective

Along with the tornado event in the KZN province, extensive convection occurred over the country, providing a perfect opportunity to visually quantify the tornado event using satellite data. Consequently, MSG-based 15-min observations of clouds at 14:30 was used to identify the severe parts of the convective cloud system.

The RDT product at 14:30 (Fig. 5.5A) indicated a few mature (purple polygons) and growing storms (red polygons) in the province of KZN, with a mature storm detected over the New Hanover area (Mpolweni). At the same time, convective signatures captured by the radar (Fig. 5.5B) identified the supercell tornado event appropriately, displaying reflectivities of 55 dBZ and more. Hence, the mature storm identified by the RDT product for the event was observed to coincide very well with the most intense convective cells within the radar imagery, while other growing storms corresponded with the lower radar reflectivity values. The direction of the storm as detected by the RDT polygons agreed with the radar’s projected movement of the storm (indicated by the arrows).

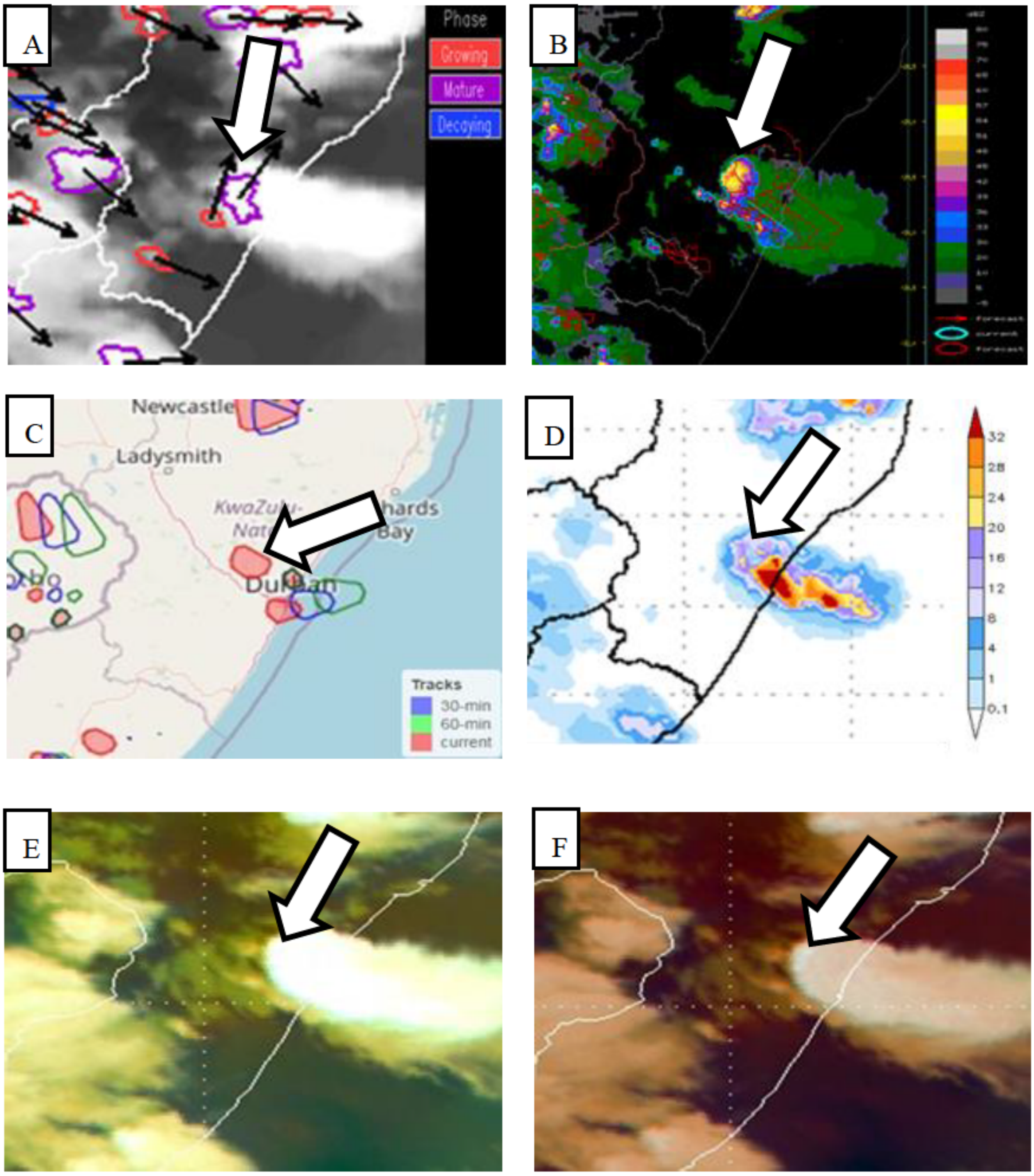
The supercell storm was also found to correspond well to the lightning tracking product, detecting and indicating lightning was currently present during the storm at 14:30 (Fig. 5.5C). Smaller amounts of lightning are also noted within the growing storms as detected by the RDT and radar. According to the CRR imagery, from 14:00, an increase in rainfall was detected, which was between 5-20 mm compared to the previous hour (13:00) of 0.1-10 mm. Rainfall was observed to have further intensified between the hour 14:00 -15:00 with the storm enlarging and moving left. Within the storm hour (14:00-15:00), the highest rainfall amounts were within the convective cloud captured at 14:30 (Fig. 5.5D). Some of the heaviest rainfall amounts were detected over the New Hanover areas as shown by the CRR image (Fig. 5.5D), corresponding to the same location where the RDT classified a mature storm. The highest rainfall totals for the day recorded by the SAWS were for the eastern parts of KZN and this agreed with the CRR product as the eastern parts of the province predicted rainfall totals of up to 32 mm h^{-1}.

The MSG RGB composite images show the presence of a deep convective system over the New Hanover (Mpolweni) area, in the eastern part of KZN (Figures 5.5E-I). There was an extensive cloud shield associated with the cut-off low system over the New Hanover area of KZN, with many high-level cirrus clouds (Fig. 5.5E-I). In the Airmass RGB (E); Tropical Airmass RGB (F); MSG Day Natural RGB (G); MSG HRV (H) and Convective storms RBG (I), the supercell tornadic storm was significant in size, thickness and intensity. The Airmass RBG imagery through the use of the IR channels, allows for monitoring cloud development at low, mid and high levels. The bright white colours visible on the Aimass RBG imagery (Fig. 5.5E) indicate thick high-level clouds, whereas the Tropical version of the Airmass RBG (Fig. 5.5F) distinguishes very high-level ice clouds with overshooting tops easily (indicated by the bright white). The Tropical Airmass combination WV6.2-IR10.8 is useful for discerning cloud depth and overshooting tops. This RGB shows an overshooting top as a bright white localised 'lump' over a pink area, which signifies high level ice clouds (Fig. 5.5F). An overshooting top is an indication of a very strong updraft penetrating the tropopause and relating to severe weather occurring at the surface and was clearly visible on Figures 5.5F-5.5I.

The visible MSG channels (VIS0.8 and VIS0.6) were combined with the Near Infrared band (NIR1.6) to generate an almost “true colour” image known as the Day Natural RGB (Fig. 5.5G) (Kerkmann 2002). The cyan colour in the image depicts the high level, convective clouds with ice content, while low-level water clouds are pink. Vegetation is green and the ocean black. The bright cyan feature in Figure 5.5G, with a lumpy texture is indicative of convective cloud and ice crystals. Convective development is thus visible and evident over the interior of KZN and over the New Hanover area at 14:30 (Fig. 5.5G).

In the HRV image (Fig. 5.5H), the thick deep convective cells (seen as bright white in the imagery) are clearly discernible as overshooting tops, signalling strong updrafts over the KZN interior. These clouds are significantly colder than their surroundings and are thus classified as mature. While, white transparent shades are cirrus clouds, the bright white shade with an extra bright white lump over the New Hanover area is an overshooting top within a cumulonimbus clouds (indicated by the arrow). Therefore, the storm displayed very high-level ice clouds (overshooting tops). The RDT (Fig. 5.5A) identified the intense area and the optically thick areas of the storm as mature cells which are represented as thick convective cells on the HRV imagery.

In the ConvRGB (Fig. 5.5I), the storm cells are even easier to identify, as they are predominantly yellow (deep precipitating clouds with strong updrafts). The ConvRGB image at 14:30 (Fig. 5.5I) displays convective activity occurring over the eastern part of the province. The severe parts of the supercell tornado storm are shown by the red to bright yellow colours on the ConvRGB image indicating deep, precipitation clouds with strong updrafts and small ice particles (Kerkmann, 2005).


A
Phase
Growing
Mature
Decaying
B
C
Newcastle
Ladysmith
KwaZulu-
Natal
hards
Bay
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1
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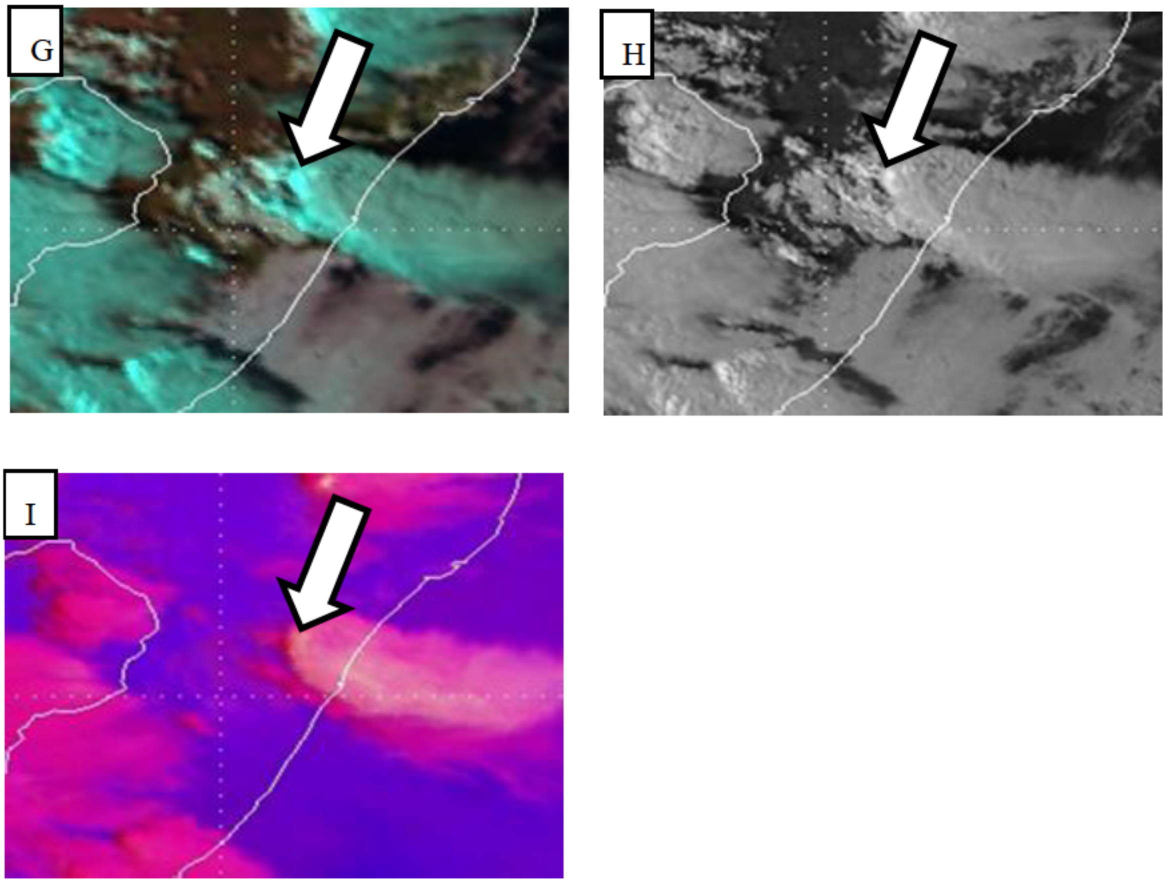

Figure 5.5 (A) RDT; (B) Radar scan indicating echo region (ER); (C) lightning cell tracking; (D) CRR (mm/h); (E) Airmass RGB; (F) Tropical Airmass RGB; (G) MSG Day Natural RGB; (H) MSG high-resolution visible (HRV) channel and (I) Convective storms RBG products at 14:30 UTC for 12th November 2019 over KwaZulu-Natal, South Africa (satellite data courtesy of EUMETSAT). The area in which the tornado event occurred is indicated by a white arrow.

5.7.3 Lightning characteristics of the supercell tornado event and an evaluation of lightning jumps as a predictor for the detection of severe weather

In order to begin the algorithm calculations, the peak 1-min total flash rate was determined. The peak flash rate threshold is used to turn the algorithm on and the peak 1-min flash rate threshold was based on a survey of 22 non-severe thunderstorm cases as observed by both the SALDN and the NRT-LWS during the period November 2019-February 2020. From these cases, the study diagnosed the mean peak flash rate to be 5 flashes min^{-1} for the SALDN and 2 flashes min^{-1} for the NRT-LWS (Fig. 5.6). As indicated by the cumulative frequency line, nearly 72.7% of the SALDN non-severe thunderstorms had a peak flash rate less than 5 flashes min^{-1}, while nearly 77% of the NRT-LWSs non-severe thunderstorms had a peak flash rate of less than 2 flashes min^{-1}. Low flash rates in most thunderstorms are typical worldwide, which pose a challenge with warnings when there are few flashes spread over several minutes. The SALDN's dataset had 90% of the storms display a peak flash rate of less than 15 flashes min^{-1}, whereas the NRT-LWS had a peak flash rate of less than 3 flashes min^{-1} 95% of the time.

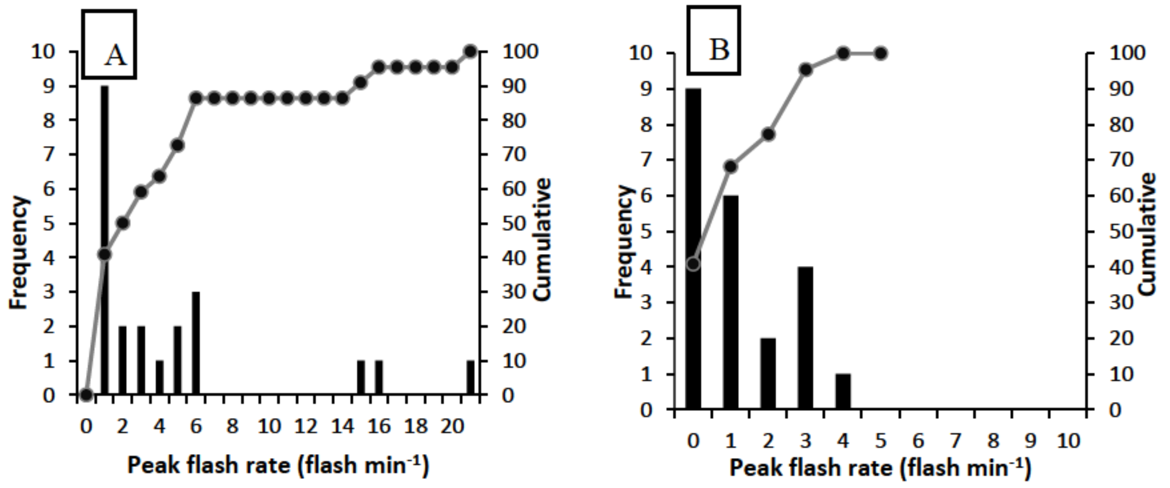

Figure 5.6 Histogram of 22 non-severe thunderstorm peak flash rates (flashes min^{-1}) for the SALDN (Figure A, left) and the NRT-LWS (Figure B, right). The average peak flash rate for the SALDN dataset of non-severe thunderstorms was 5 flashes min^{-1}, whereas the NRT-LWS was 2 flashes min^{-1}.

The next step of the algorithm is based on the time rate of change of the total flash rate within a thunderstorm, also known as “DFRDT”. This DFRDT value determines if the lightning activity is associated with a severe or non-severe thunderstorm. Following this calculation, a standard deviation and 2σ variation is carried out. As indicated by Schultz *et al*. (2009), a ‘‘jump’’ normally occurs once the value of the DFRDT is greater than the 2σ threshold, respectively, whereas a jump ends once the DFRDT value is less than or equal to 0, except if two jumps are separated by 6 min or less. If two jumps are separated by 6 min or less (i.e., jump, no jump, and jump in consecutive periods), this is considered one jump. Once a lightning jump occurs, a severe warning is placed on the thunderstorm for 45 min. This 45-min period was based on the average warning time for severe thunderstorms as provided by the National Weather Service (Schultz *et al.* 2009).

An illustration of how the 2σ algorithm functioned/performed for the tornado storm event using the SALDN data and the NRT-LWSs data is presented in Figure 5.7. On the afternoon of the 12th November 2019, the NRT-LWS began detecting lightning flashes at 13:33 whereas the SALDN, began detecting lightning flashes much earlier, from 11:25 onwards (Fig. 5.7A). The analyses of the NRT-LWSs total lightning for the event displayed a variable fluctuation of lightning throughout the afternoon going into the evening. Higher than average peak flashes were observed occurring rapidly between 14:04 and 14:47, with the maximum number of 6 flashes min^{-1} detected at 14:47 (Fig. 5.7B).

By contrast, the SALDN displayed a gradual increase in flashes which began from 11:25 onwards and thereafter began to decrease at 14:00. Large numbers of flashes were detected during the period 12:28-13:58. A maximum of 36 flashes min^{-1} was detected at 13:28 while the second highest of 35 flashes min^{-1} was detected at 13:52.

Consequently, the peak total flash rate for this thunderstorm was 4.5 flashes min^{-1} while the CG flash rate was 36 flashes min^{-1}. Numerous case studies have been published where lightning activity has been observed to change dramatically before the start of a severe damaging weather and the SALDNs dataset for this event followed the same pattern. The SALDN detected a general pattern of peak in CG flash rate prior to the tornado touch down (Fig. 5.7A).

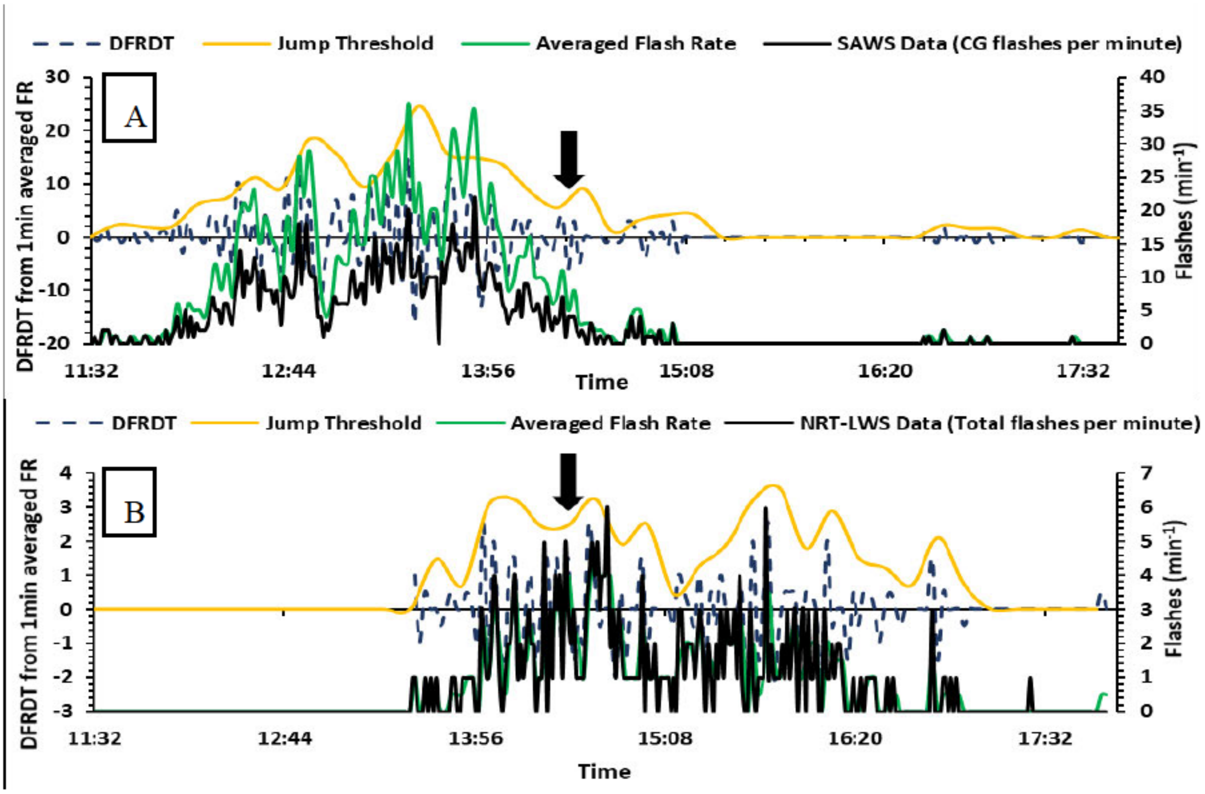

Figure 5.7 The 2 Sigma Algorithm demonstrated for the tornadic supercell storm event that occurred on the 12 November 2019 using the SALDN data (Figure, top) and the

NRT-LWS data (Figure, bottom). The black arrow on both graphs are indicative of when the tornado occurred.

5.7.4.1 The diurnal cycle of lightning during the storm event

After midday (11:32 onwards) the SALDN detected lightning flashes ranging between 0 and 10 flashes min^{-1}. From 12:46, the lightning activity increased rapidly to reach its peak (flashes over 10 min^{-1} were rapidly detected) until 14:00, after which lightning flashes dropped below 10 min^{-1} (Fig. 5.8A). The drop in flashes coincided with the increase in radar reflectivities observed over the New Hanover area. The flash rate for the storm jumped from 6 flashes min^{-1} at 13:00 to its absolute maximum of 36 flashes min^{-1} at 13:28 (Fig. 5.8B). During this period, the algorithm signalled a lightning jump.

The forecast period is the time period starting at the occurrence of a jump and lasting for 45 minutes (default). In order to evaluate the lightning jumps, severe storm reports from the radar scans and nearby AWS datasets were used as ground truth validation. Wind gusts of 34.6 m s^{-1} were detected at 13:55 by the Cedara station (Figure 5.1) with speeds of 17.8 m s^{-1} and at 13:28 a jump was detected. In this case, the 2σ algorithm provided nearly 27 min of lead time to the severe wind and change in wind direction. However, the warning threshold for the jump is valid for a 45 min threshold (13:28-14:13) and the 2σ algorithm missed the tornado ((14:33-14:39 (as per radar signatures)) associated with the demise of the storm.

On the other hand, another jump was analysed several minutes after the tornado had already touched down, for around 11 minutes (14:39-14:50). Four additional CG lightning jumps in the SALDN data were also detected by the 2σ algorithm at 12:04, 12:26, 12:44, and 13:14 during which time nearby weather stations reported changes in wind speeds, wind direction, decreases in air temperature and increases in relative humidity (Fig. 5.8B). However, the several qualifying lightning jumps that were observed with the algorithm did not indicate future storm strength, and are therefore reported as false alarms.

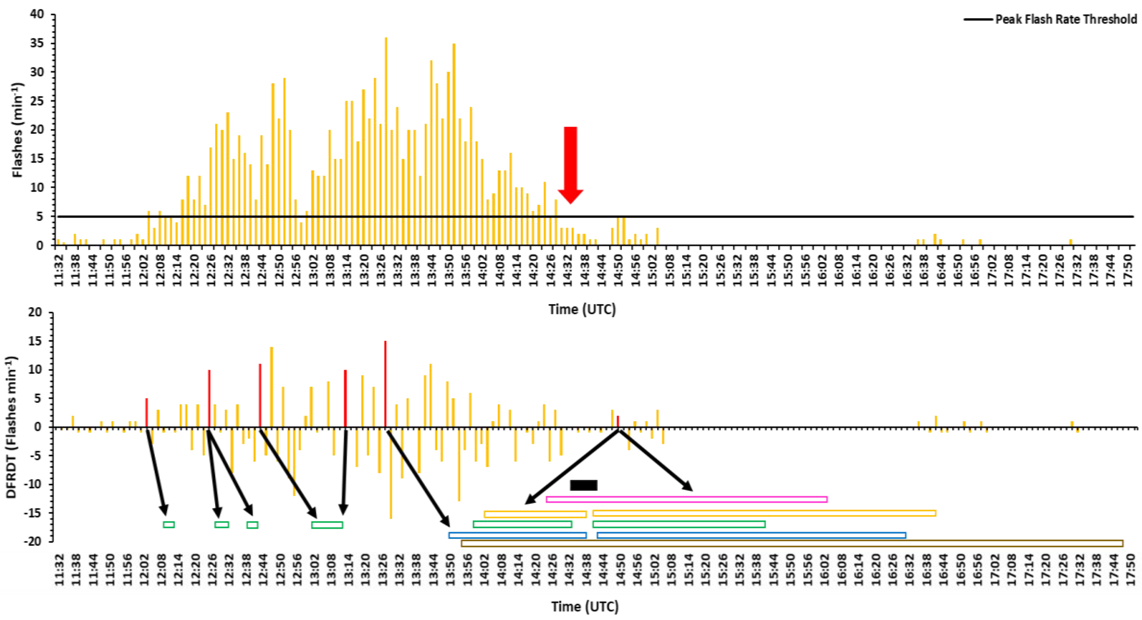

Figure 5.8 Time series of SALDN (top) lightning flash rates (flashes min^{-1}) and (bottom) CG DFRDT (flashes min^{-2}) in the tornado supercell thunderstorm that occurred on the 12th November 2019 in the KZN province. The top plot represents the time–height plots of lightning rates (flashes min^{-1}) from the tornado event. The peak flash rate threshold is denoted by the black line. The red arrow indicates the tornado touchdown time (radar derived). In the bottom Figure, red bars represent DFRDT values that qualified as lightning jumps, orange bars represent DFRDT values that did not reach the jump threshold. Decreases in temperature is indicated by the brown rectangles, recorded rainfall by the blue rectangles, increases in wind speeds and gusts by the green

rectangles, increase in relative humidity by the orange rectangles and detected radar reflectivities > 50 dBZ is highlighted by the pink rectangles. The black rectangle indicates the approximate time the tornado had touched down. Black arrows show lightning jumps corresponding to observed AWS reports on changes in meteorological variables [adapted from Schultz *et al.* (2011)].

The community based NRT-LWS located 23 km from the tornado site started detecting lightning flashes much later at 13:32 compared to the SALDN at 11:32. The NRT-LWSs total flash rates for this storm were generally low. From 13:32 till 13:58, total lightning flashes ranged from 0 to 1 flashes min^{-1}, whereas, from 13:59, flashes increased to 3 flashes min^{-1} and continued to increase (Fig. 5.9A). At 14:00, the 2σ algorithm indicated a lightning jump with a slight increase in the 1-min averaged flash activity, demonstrating that the 2σ algorithm is sensitive to small changes in flash rate. The lightning flashes at this point increased from 0 to 3 flashes min^{-1}.

Again, to evaluate the lightning jumps, severe storm reports from radar scans and nearby AWS datasets were used as ground truth validation. For example, the flash rate for the storm also displayed a dramatic increase in flashes from 0 flashes min^{-1} at 13:58 to a maximum of 4.5 flashes min^{-1} at 14:42 (Fig. 5.9A). During this period, from 14:24 onwards the storm underwent rapid vertical development as indicated by radar signatures (i.e., increases in the height of the 55-dBZ reflectivity contour) and overshooting tops between 14:33 and 14:39 (Figures 5.3 and 5.4), signalling the presence of the severe thunderstorm that produced the tornado. Hence, the total flash rate may have dramatically jumped in response to the vertical growth.

Using the 2σ lightning jump algorithm, the jump that was initiated at 14:00, ended at 14:44. On average the 2σ lightning jump triggered for this case nearly 33 min in advance of the tornado touchdown. The lightning jump data in this case may have reinforced a severe warning decision if there were an operational lightning jump algorithm in place. Four additional lightning jumps using the NRT-LWS lightning data were also indicated by the 2σ algorithm at 14:40, 14:16, 15:42, and 16:10, during which, nearby weather stations reported changes in wind speeds, wind direction and recorded rainfall (Fig. 5.9B). Once again, since these qualifying lightning jumps that were observed with the algorithm did not indicate any future storm strength, they are reported as false alarms.

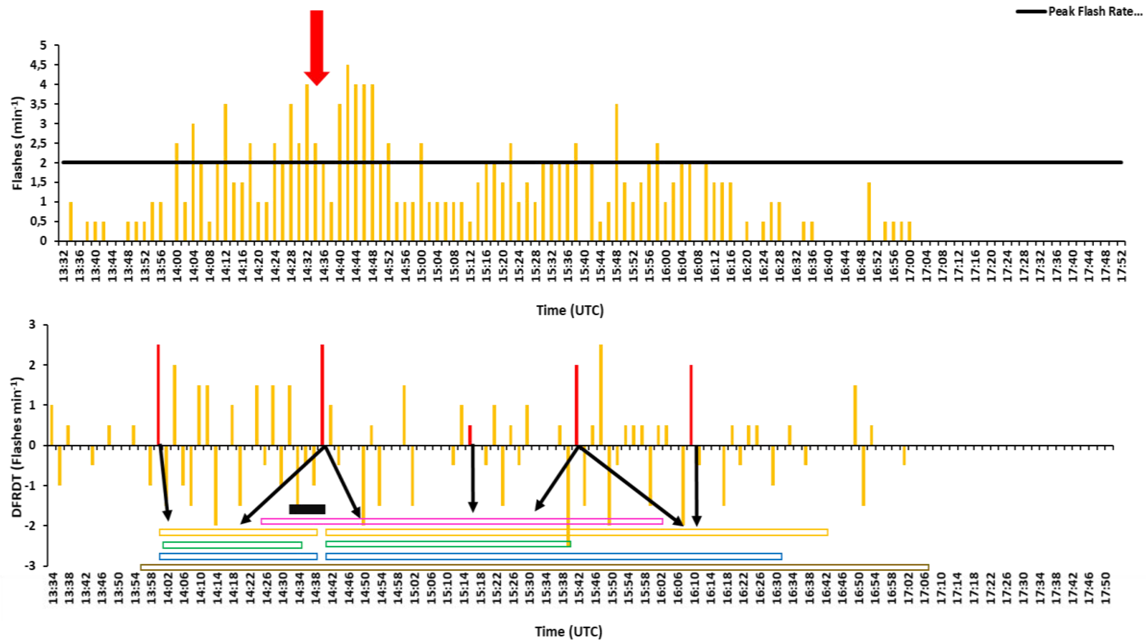

Figure 5.9 Time series of NRT-LWS (top) lightning flash rates (flashes min^{-1}) and (bottom) total lightning DFRDT (flashes min^{-2}) in the tornado supercell thunderstorm that occurred on the 12th November 2019 in the KZN province. The top plot represents the time–height plots of lightning rates (flashes min-1) from the tornado event. The peak

flash rate threshold is denoted by the black line. The red arrow indicates the tornado touchdown time (radar derived). In the bottom Figure, red bars represent DFRDT values that qualified as lightning jumps, orange bars represent DFRDT values that did not reach the jump threshold. Decreases in temperature is indicated by the brown rectangles, recorded rainfall by the blue rectangles, increases in wind speeds and gusts by the green rectangles, increase in relative humidity by the orange rectangles and detected radar reflectivities > 50 dBZ is highlighted by the pink rectangles. The black rectangle indicates the approximate time the tornado had touched down. Black arrows show lightning jumps corresponding to observed AWS reports on changes in meteorological variables [adapted from Schultz et al. (2011)].

5.7.4.2 Schematic cell history

The SALDN dataset displayed a general peak in lightning activity prior to the tornado touchdown, which compared well to the schematic cell history of total flash rate for a storm as discussed by Williams *et al.* (1999) and Liu and Heckman (2011). The total lightning rate has a sudden jump at t_0 and the severe weather followed at t_s after the rate peaked at t_p (Fig. 5.10A) The systematic evolution for the supercell tornado event on the 12th November 2019 is schematically demonstrated in Fig. 5.10B where the SALDN lightning rate graph clearly follows the pattern as described Williams *et al.* (1999) and Liu and Heckman (2011)(Fig. 5.10A). Before the storm approached and intensified, the lightning flash rate jumps began increasing, reaching a peak and then decreasing. This pattern is known to be repeated several times in the lifetime of a supercell thunderstorm and was seen to be repeated for the SALDN. Shortly after the abrupt decrease in flash rate, a tornado was observed (between 14:33 and 14:39), associated with the most strongly descending reflectivity contours and declining reflectivity within the respective mesocyclonic core and increase in reflectivities surrounding the hook echo. Hence, the highest peak flash rate (36 flashes min^{-1}) preceded the tornado activity at the ground by close to an hour, while the second highest flash rate (35 flashes min^{-1}) preceded by 35 min. The purpose of these comparisons is further clarification of the physical basis of the precursor signals in lightning activity.

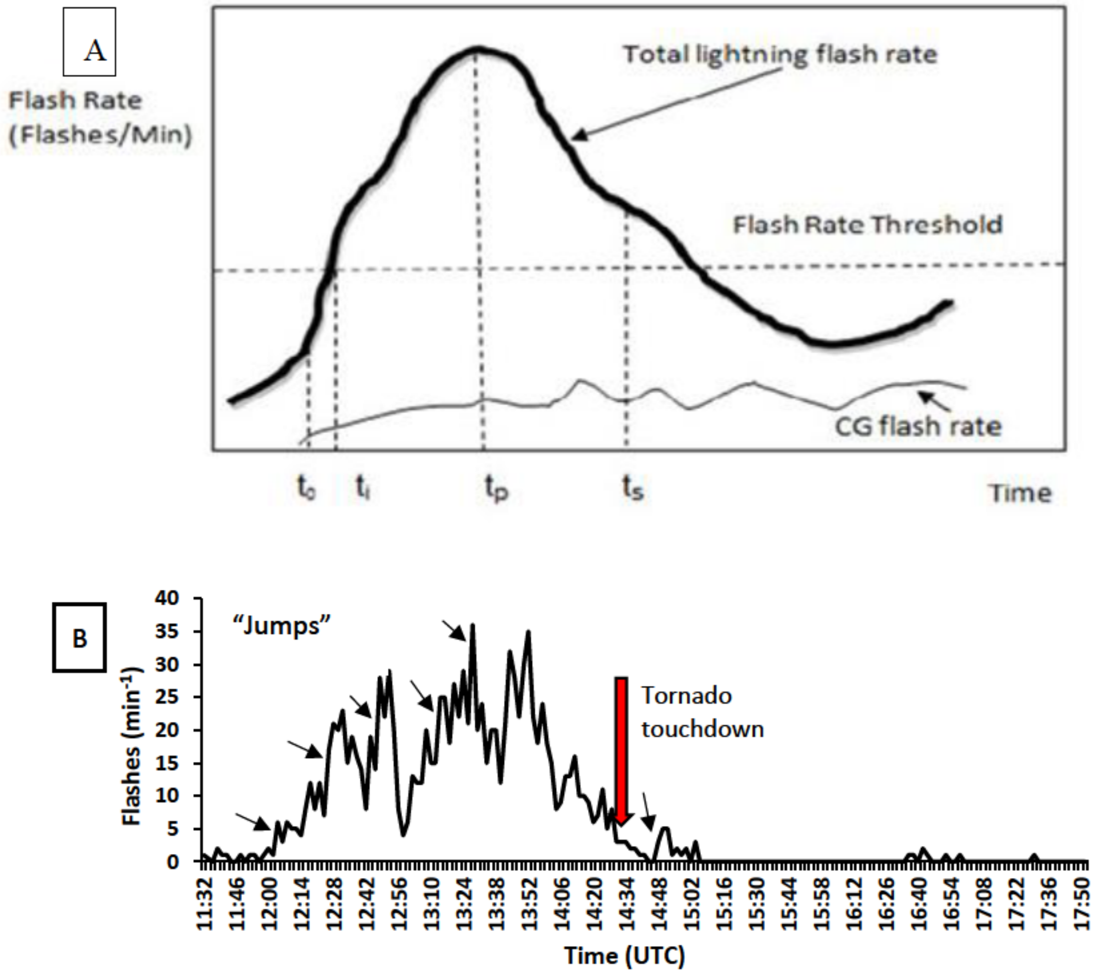

Figure 5.10 Schematic depicting how a lightning jump can be used to predict severe weather by Williams *et al.* (1999) and Liu and Heckman (2011) (Figure A). The top graph shows total lightning graph with t_0 = lightning jump, t_p = peak lightning rate time, t_s = time of severe weather, t_i = issuing of alert and t_s - t_i represents the lead time of the

alert. The bottom graph shows the SALDN lightning flash rates (flashes min^{-1}) for the New Hanover supercell which occurred on 12th November 2019.

5.8 Discussion

For the New Hanover (Mpolweni) tornado event, several indicators of severe weather and tornadic activity were present. Prior and leading up to the tornado event (from 10th November 2019), a 5-day period of adverse weather conditions included heavy rainfall, thunderstorms, localized flooding and damaging winds, which prevailed across most parts of the country. At the time of tornado event there were two weather systems dominating over the region including a surface trough and an upper-air cut-off low-pressure system. This is therefore potentially an important macroscale observation indicating suitable conditions for tornados.

The initiation of convection for the tornado was identified from observations typically using the ground-based weather radar observations and the geostationary satellite measurements. For this event, radar imagery analyses revealed maximum reflectivities (> 55 dBz) (Visser 2001), and the vertical cross sections revealed textbook signatures indicative of a supercell tornado between 14:33 and 14:39. According to radar observations of storm cell development, tornadoes are more likely to form if the cells track in a ‘deviant motion’ from the south-west to the northeast (Bluestein *et al.* 2019). In this tornado event, a similar observation was seen, where the storm moved from the south-east in a north-easterly direction as opposed to the general motion of other storms in the area that moved in a south-easterly direction. This deviation to the left is a classical signature of supercell storms in the southern hemisphere (David-Jones 2014). The tornado formed over the KZN highland areas, which provided ideal topographical and atmospheric conditions for the development of the tornado producing storm (Doubell *et al.* 2019).

The supercell storm that developed a tornado provided a very useful opportunity to study this phenomenon, understand the development and access the tools available to provide early warnings. Lemon and Doswell (1979) stated that during the first stage of supercell formation, the left rear flank of the storm (in the southern hemisphere) develops a mid-level overhang and weak echo region (WER). The overhang forms as a consequence of a strong, persistent updraft and correspondingly strong divergence in the upper layers. The second stage of a supercell life cycle is when a BWER is detected. This is an indication of increasing water and ice content around the core of the updraft and also of continued updraft intensification. A vault, associated with a strong updraft region, and a BWER were both visible at 14:33 (Fig. 5.4) for the New Hanover (Mpolweni) tornado. Furthermore, the VCUT displayed a hook echo and the radar velocity profile displayed the mesocyclone in the region of the WER. A hook is often associated with a mesocyclone (form within the BWER), indicating conditions favourable for tornado formation. The mesocyclone was found within the BWER of this thunderstorm and was seen as a radar signature that is rotating. However, due to the low resolution of the radar data, the tornado itself could not be detected, but there was evidence in terms of extremely high reflectivities, overshooting tops, the persistent updraft, a BWER and a mesocyclone within the storm.

Moller *et al.* (1994) also summarised supercell characteristics as: ‘steady state’ convective storms, a single, continuous cell, to have a deviate motion (not an absolute prerequisite) and to have a deep, persistent mesocyclone and a BWER. Moller *et al.* (1994) also discussed that the lift needed to initiate deep, moist convection in supercell environments is provided by mesoscale or storm-scale processes. For the Mpolweni event, the surface trough (Fig. 5.2) was located over the central interior, with a high, south of the country providing the moisture at the surface. The upper-air COL present southeast of the country also contributed to triggering strong convergence and instability (Barnes *et al*. 2020; Ndarana *et al*. 2021). These characteristics of surface convergence and upper air divergence are necessary dynamics for thunderstorms, including supercell thunderstorms (Barnes *et al*. 2020; Ndarana *et al*. 2021). Overall, the radar analysis was useful in identifying and providing precise information on the location, intensity, direction and characteristics of the severe convective cells during the event.

The MSG data was also found to be useful in studying the thunderstorm activity and providing insight into tornado development (Reason 2017). The MSG RGB imagery complemented the storm size distribution and the identification of the supercell tornado by the radar (Fig. 5.5). The core of this storm was well identified as a mature storm by the RDT product (Fig. 5.5) and there was a good correlation observed with the locations of the most intense areas of radar reflectivity. Furthermore, the demarcation of activities in Figure 5.5 were supported by the updraft as depicted from the echo region in the radar imagery (Section 5.7.1). The bright white in the Airmass (Fig. 5.5E), the Tropical Airmass (Fig. 5.5F) and in the HRV RGB (Fig. 5.5H), as well as the yellow, red areas of the Convection RGB (Fig. 5.5I), the cyan colour and lumpy texture in the Day Natural colour (Fig. 5.5G) indicated strong convection with the possibility of severe weather that coincided to a large extent with the area where the radar had the maximum reflectivity values and where the supercell event occurred. Lightning and high rainfall were also observed to have accompanied the storm as analysed by the CRR product and the lightning storm tracking product at 14:30 (Fig. 5.5C,D). From the radar analysis, the supercell storm had an overshooting top feature which was also clearly visible by the Tropical Airmass RGB. Damaging winds, large hail and a tornado were associated with this feature. In the HRV image, the bright white colour symbolised the thickness of the storm at 14:30 and indicated the cold tops and severe convection with cumulonimbus clouds corresponding to the area of high radar reflectivity. Several other smaller convective storms were also evident in the MSG RGB imagery and products.

To supplement the existing radar and satellite observations, the study explored using lightning to nowcast severe convection/weather, using the supercell tornado event as an example. The SALDN data detected lightning flashes much earlier and produced higher flash rates compared to the NRT-LWS. This may be attributed to the network of sensors used in the SALDN. The 25 sensors are distributed around the country and accurately detect lightning strokes using magnetic direction and time-of-arrival principles. Each lightning stroke is detected by at least two sensors but typically by 5-9 sensors for the study area (or even more), whereas the NRT-LWS is a point measurement. In addition, there is a reduction in DE of the NRT-LWS with distance together with algorithms designed to minimise the chance of false alarms, which may work together resulting in a reduced flash count.

The SALDN was sensitive to the increases in the lightning activity and rapid increases in lightning flashes were measured in advance of the observed tornado signatures on the radar at 14:33 and 14:39. A jump was detected prior to the tornado event and provided a lead time of 27 min to the severe wind and change in direction measured at nearby weather stations. However, based on the 45-min warning threshold of the jump algorithm, the tornado event was not detected. On the other hand, another jump was analysed 11 minutes after the tornado had already touched down (14:39-14:50). These findings were consistent with MacGorman *et al.* (1989) that documented a peak in CG rate occurring 15 min after an increase in IC lightning and several minutes after a tornado had already touched down. Findings were also in agreement with Perez *et al.* (1997) who found a general pattern of a peak in CG flash rate prior to the tornado, a relative minimum in CG rate at about the time of the tornado, and a second peak in rate following the tornado. Perez *et al.* (1997) concluded that it is not practical to exclusively use CG lightning flash patterns to detect tornado formation, as it offers little predictive value for tornadogenesis. However, as stated by Eck (2017), CG flash rate may provide useful additional information when used in conjunction with other operational tools. Since, the qualifying lightning jumps observed by the algorithm for the SALDN dataset did not indicate future storm strength, they were marked as false alarms.

Interestingly, the schematic cell history for the storm using the SALDN was found comparable to those by Williams *et al.* (1999) and Liu and Heckman (2011), showing an increase in lightning activity prior to the tornado touchdown. According to Williams *et al.* (1999), in a microburst, the increase in lightning pattern may show up once, while in a super cell thunderstorm the pattern can repeat many times during the lifetime of the cell. This finding was also observed for the supercell tornado storm in the study. A maximum total flash rate followed an abrupt drop in flash rate (Fig. 5.10B). This may suggest a reduction in updraft strength with an attendant reduction in the rotational velocity (Williams *et al.* 1999).

The NRT-LWS indicated a gradual increase in lightning flashes leading up to the tornado touchdown. The 2σ algorithm for this dataset also demonstrated its sensitivity to small changes in flash rates using the NRT-LWS dataset. The first jump was detected at 14:00 and the algorithm was successful in providing a lead time of 33 min in advance of the tornado touchdown. This agrees with multiple studies, which have shown total flash rate to increase prior to the onset of severe weather. However, just as in the case for the SALDN, the remaining lightning jumps observed by the algorithm for the NRT-LWS dataset also did not indicate any future storm strength, and therefore were false alarms. Hence, the lightning jump algorithm should be cautioned for use for a single storm.

Apart from this study, relatively few studies have examined concurrent trends in both total and CG lightning within the same severe thunderstorm, using an objective lightning jump algorithm. Overall, the SALDN and NRT-LWS results indicate that while both lightning datasets demonstrated the presence of increased lightning activity prior to the onset of severe weather, the use of total lightning trends (NRT-LWS) was more effective than the CG trends (SALDN) for tornado warnings using the 2σ algorithm. Conversely, the use of CG lightning trends to diagnose the potential for severe weather on this tornadic thunderstorm, while not poor, was not as effective as the use of total lightning trend information. By monitoring the flash rates and the rate changes, the severe storm cells or the ones to potentially become severe, could be identified by the SALDN. Therefore, a very rapid increase in lightning activity in a short period of time can serve as a precursor to a thunderstorm developing into a severe thunderstorm and this was also illustrated by the SALDN for the supercell storm, despite it missing the 2σ algorithm's 45-min warning threshold.

Overall, the 2σ algorithm showed promise for the detection of severe weather using lightning trend data on a local scale for SA, however, it is cautioned for use within single storms. The algorithm demonstrated its ability to provide a warning of a supercell tornado storm type on a local scale. An increased sample dataset to allow for a more robust understanding of different thunderstorm types and their associated lightning characteristics would be a beneficial study. This preliminary study may also be extended to demonstrate how this case study lightning event differs from other lightning events detected by the NRT-LWS. In addition, further work to determine the appropriate lightning threshold for various storm characteristics would be useful. In this study an algorithm developed internationally was applied and could potentially be adjusted for SA conditions to better reflect the local storm characteristics.

The incorporation of a total lightning jump algorithm could be valuable for SA's warning decisions for severe and non-severe thunderstorms at local scales. The results in this study elucidate a need to work on an operational total-lightning jump algorithm for nowcast operations for SA at a local scale and to correlate the lightning jump alerts to the SAWS severe thunderstorm warnings to evaluate lead time and accuracy. The results presented herein have implications for the use of CG data as the dataset missed the 2σ algorithm's 45-min warning threshold and hence was unable to provide a lead time prior to the tornado touch down. A jump was however observed ~65 min before the suggested tornado touchdown time, and further analysis of the validity of the 45-min warning threshold could also be investigated. The study could also be expanded to consider large hail (associated with severe thunderstorms), and the lightning jumps could have predicted hail preceding the tornado touchdown. Of all the lightning detected by the SALDN, 30-50% of the lightning detected is cloud lightning, which was not included in this study. Further analysis of the usefulness of using the cloud lightning together with the CG lightning to calculate jumps could also be an interesting study.

5.9 Conclusions

There is ongoing evidence of global climate change and more frequent extreme events. The climate of southern Africa has undergone significant warming and this creates suitable conditions for severe thunderstorms and tornadoes. Tornadoes are amongst the most destructive natural hazards to human life and property (Frazier *et al.* 2019). Although only a few tornadoes occur every year in SA, these events result in significant damage and loss of lives.

This study focussed on the first of a series of four tornadoes that were experienced in the province of KZN, in New Hanover (Mpolweni) area on the 12th November 2019. The tornado event was identified and evaluated using a suite of data from the SAWS observational network which included: synoptic, satellite, radar and LDN data. Following the tornado event and further evaluation, radar analyses in the study showed this event to be a supercell tornado. In SA, tornado producing supercells are relatively rare, however, based on the analysis of available data, several supercell criteria were met.

The use of MSG data used in the study demonstrated their potential to study thunderstorm activity and provide insight on tornado development. The MSG imagery showed the presence of a deep convective system predominantly oriented over the study area, with the updrafts and overshooting tops being easily visible.

In addition, the study examined concurrent trends in both total (NRT-LWS) and CG (SALDN) lightning within the same supercell event, using the 2σ lightning jump algorithm. The most obvious and distinguishing feature of the tornado producing supercell event in this study was the rapid increases in flash rate followed by a dramatic decline, signalling the tornado at the ground. The use of the total lightning dataset was found to be more beneficial over the

CG lightning dataset and provided a lead time of 33 min. This indicates that a total lightning jump tracker could augment radar, computer model data and observations at the SAWS to issue reliable severe weather warnings at local scales in SA. Developing automated visualizations of the lightning jump may aid forecasters when to be alerted. Lightning jumps are particularly useful in helping forecasters predict severe weather before it is observed on radar and particularly so where radar coverage is unavailable in SA. Finally, there are synergistic effects of combining lightning, radar and satellite data to support the early detection of convection in this area.

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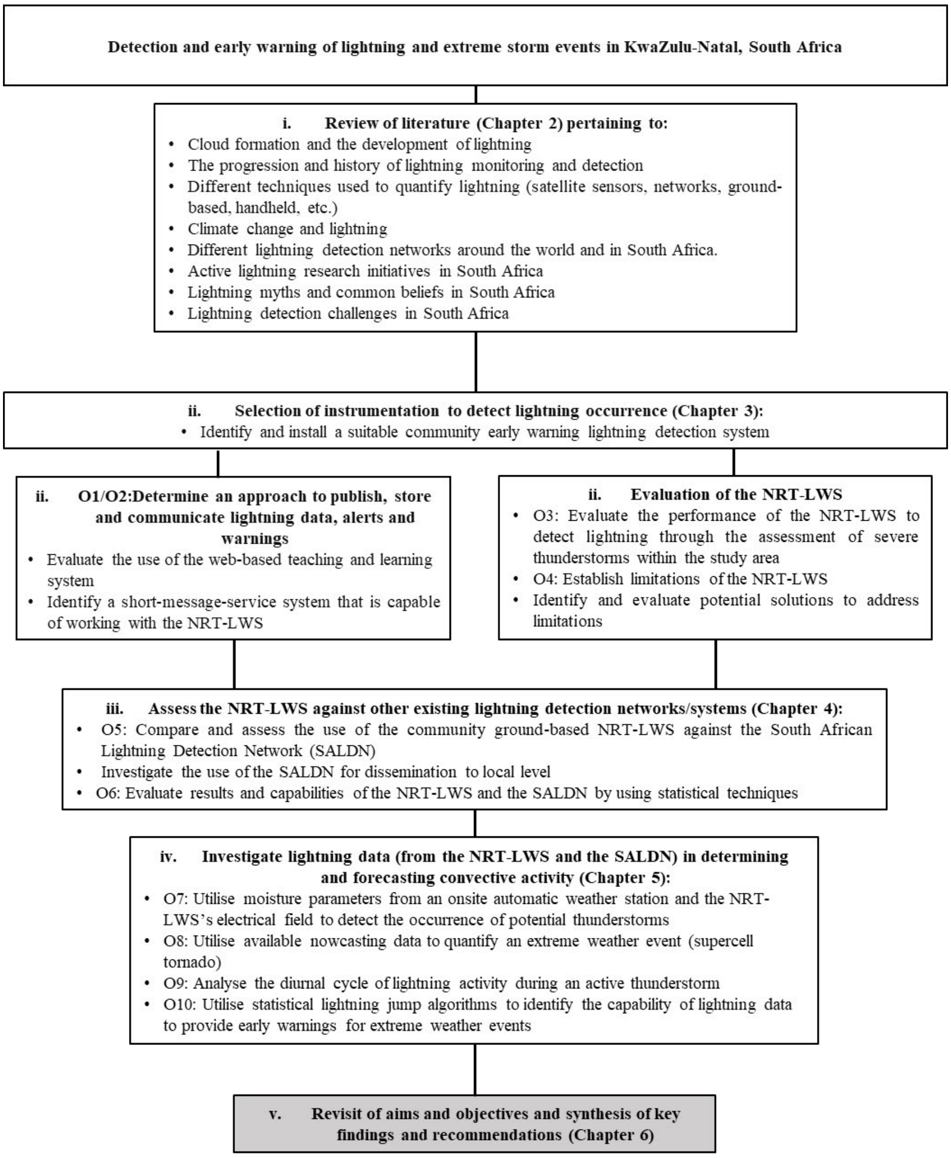
Lead into Chapter 6: With the main aim of the study to reduce the vulnerability of rural communities within South Africa to lightning and to better understand the use of lightning for severe weather prediction in South Africa, being addressed in Chapters 3 to 5, Chapter 6 highlights the key findings of the research and proposes recommendations for future investigations.



CHAPTER 6: SYNTHESIS – REVISIT OF AIMS AND OBJECTIVES, KEY FINDINGS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 Introduction

Lightning is one of the most frequently occurring geophysical phenomenon (Dwyer and Uman, 2014). Despite lightning being necessary and beneficial for maintaining an electrical balance on earth (Changnon, 1985), for the production of nitrogen fixation (by nitrogen oxides) (Leigh, 2002, Price 2013) and as a major source of ozone (Jasaitis *et al*., 2016), it is a significantly underestimated hazard (Dlamini 2009, Cooper *et al*. 2016, Gomes 2017, Cooper and Holle 2019b). Globally, it leads to significant economic losses, many fatalities and injuries, as well as causing damage to infrastructure annually (Holle *et al*., 1999, Holle, 2008, Gomes, 2017, Cooper and Holle, 2019c). Lightning also represents a major natural disaster and risk to the public, power companies, aviation and to forestry sectors (Price 2013). The damaging characteristics are a result of the immense naturally occurring electrostatic currents (Bhavika 2007, Blumenthal *et al*., 2012). South America, Africa, Asia, North America and Oceania are amongst the lightning hotspots in the world, whilst South Africa has one of the highest incidences of lightning-related injuries and deaths in comparison to the rest of the world. Technological advances have contributed towards improving lightning detection and monitoring activities in many countries around the world. South Africa has made considerably more progress in the field of lightning research than most African countries and possesses one of the three ground-based lightning detection networks in the southern hemisphere. However, despite these developments, rural communities in South Africa, and indeed the African continent, are still vulnerable to lightning, the occurrence of which is predicted to increase with climate change. The large proportion of the population of these African countries reside in rural areas, where citizens participate in subsistence farming. They often travel in the open to reach their destinations. Also, myths and belief systems exist and there is a lack of awareness regarding the dangers and necessary precautions of lightning. Particularly in rural areas there is a lack of fully enclosed metal-topped vehicles and lightning safe built infrastructure (Cooper *et al*., 2016, Gomes, 2017, Cooper and Holle, 2019b). This results in rural communities being vulnerable to the threat of lightning.

In an attempt to improve detection and warning of lightning threats at a local/community scale, a system with monitoring and predictive capacity to detect lightning occurrences and assist rural communities in preparing for lightning through risk knowledge and near real-time/early warning systems is ultimately needed. For this purpose, the research presented in this thesis progressively documents the development and assessment of a community ground-based lightning early warning system to detect and disseminate lightning threats and alerts in a timeous and comprehensible manner within the rural community of Swayimane, KwaZulu-Natal, South Africa. The system is comprised 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 SMSs and email alerts. To our knowledge, this research contributes to the first ever community-based lightning early warning system providing insights into lightning detection and monitoring at a local/community-level for South Africa.

The research was centred around developing and evaluating the potential of the new system developed to detect lightning threats and disseminate warnings timeously as well as, the use of the system's lightning data to monitor and warn of severe weather within a rural community in South Africa. To achieve this, the community-based, near real-time lightning warning system (NRT-LWS) was evaluated against the South African Lightning Detection Network (SALDN), which operated concurrently at a national scale. This provided a first insight into the use of the SALDN for local scales, encouraging the South African Weather Service (SAWS) to expand their lightning warnings to rural communities across the country. The NRT-LWS's dataset was also used to examine lightning events in detail, highlighting the system's beneficial use for characterising lightning activity in the Swayimane research area. Furthermore, research into the use of lightning data to monitor and nowcast severe weather such as supercell tornadoes on a local scale was conducted. The research demonstrated that total lightning data from early warning systems can be beneficial and add to other lightning warning indicators, providing a greater lead-time over radars on its own, for example. Extending warning lead times may be especially useful when adverse weather occurs over populated areas. Thus, the research in this thesis also provides invaluable insights to weather forecasters on the use of lightning data for nowcasting at local scales for South Africa.

The thesis throughout clearly documents and highlights the invaluable contribution gained from this first-ever community early warning system (EWS). Prior to this, there was a dearth of information focussing on lightning detection and monitoring within a rural community, which is now provided in this thesis. This research has provided avenues to expand existing knowledge and understanding of lightning occurrence at a local scale, as well as for improved monitoring and provision of early warnings for severe weather phenomena using lightning data, at local scales in South Africa.

6.2 Revisiting the aims and objectives

The overall aim of this study was to investigate the possibility of reducing the vulnerability of lightning threat of rural communities within South Africa (as epitomised by the Swayimane community), and to better understand the use of lightning for severe weather prediction in South Africa.

Considering the overall aim of the study, the thesis was divided into four parts, which progressively documented existing, and innovative approaches, which were intended to fulfil the following specific objectives;

i. review of relevant literature on the history and development of lightning as well as on the different techniques that exist to detect and monitor lightning occurrence (Chapter 2)
ii. develop and implement a NRT-LWS to reduce the vulnerability of lightning threat and the impacts of climate-driven risks and the associated projected increase in lightning activity for rural communities (Chapter 3)
iii. employ a multi-disciplinary approach, using existing lightning system data and automatic weather station (AWS) data in conjunction with the developed NRT-LWS to quantify lightning and thunderstorm activity within the study area (Chapters 3, 4 and 5)
iv. assess the use of lightning to predict severe weather by investigating if there was evidence of a lightning jump as a precursor to a tornado event within the vicinity of the study area (Chapter 5)

A detailed literature review was conducted in Chapter 2, which addressed research objective 1 and reviewed the current state and the advances in lightning monitoring and detection over the years, along with the major lightning detection challenges facing South Africa, including the impact on rural communities. The main findings that were brought to light in the review included the fact that climate change projections predict increases in lightning incidence. This potentially poses significant challenges to rural community resilience to lightning threats since rural communities currently continue to live without any warnings or access to proper EWSs. The literature review showed the SALDN to be operational at a national level and capable of disseminating the lightning data to a local level, but not currently being used. However, with advances in communication technology, improved dissemination of lightning threats and alerts within rural communities in South Africa should be considered. The limitation of no recommended design guidelines for informal dwellings and no safety protocols for rural communities was also highlighted in Chapter 2. As such, the knowledge gained from this review along with the key findings assisted in informing the aim of this research study.

The development and assessment of 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 addressed the second research objective (Chapter 3). The study investigated the operational implementation of a community-based NRT-LWS towards 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. The NRT-LWS comprised 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 SMSs and email alerts. Diurnal variations in lightning activity indicated the influence of solar heating, causing convective conditions with peaks in lightning activity occurring during the late afternoon and early evening (between 14h00 and 21h00), coinciding with learners exiting the school grounds on foot and many people returning home from work on foot, and therefore being out in the open in most cases. In addition to detecting the threat of lightning, the NRT-LWS was beneficial in characterising lightning activity in the area with two sample lightning events examined in detail, which addressed part of objective 3. Overall, the NRT-LWS was found to be reliable and disseminate warnings timeously. The results from this study provided the research area's community with a system that offers reliable warnings to lightning danger to mitigate the risk of losses. The insights acquired from this chapter could provide a framework for other rural communities in considering similar warning systems (such as the system described in this thesis) for installation at schools in similar high-risk areas with a focus on densely populated communities.

South Africa's existing national lightning network, known as the SALDN is operated by the SAWS only at a national scale. This study (Chapter 4), addressed the third objective, which investigated the performance of the newly developed community ground-based system and evaluated the performance of the system using the existing national network, SALDN. The study also provided insights on the use of the SALDN at a local level for South Africa. While, the two systems do not target exactly the same discharges, the lightning activity was well captured by the NRT-LWS. Results indicated that the community-based system when compared against the SALDN followed the same general temporal distribution and produced a correlation coefficient of 0.95. Furthermore, despite an observed minor underestimation with the NRT-LWS, the community-based system was able to detect flashes at the same time as the SALDN within the 8 to 32 km warn categories. These results reaffirmed the use of the NRT-LWSs data as a reliable source of information with the potential to identify and disseminate lightning threats at local scales, especially from a public safety and lightning detection standpoint. The study also demonstrated that the SALDN is capable of disseminating lightning data to the local communities. It was also shown in the study that the average peak current parameter was found to constitute an indicator for the Detection Efficiency (DE) of the study area. It was further suggested that the existing SALDN's polarity and peak current abilities be incorporated with data from the ground-based system to provide combined warnings.

Despite lightning being a severe life-threatening weather phenomenon, it may also be a valuable tool for monitoring severe weather changes and keep track of changes in the earth's climate system, with lightning being regarded as an indicator for convective activity in climatology, particularly in tornado climatology. While the NRT-LWS was in operation, a tornado event occurred within the vicinity of the study site, providing an ideal opportunity to assess the benefit of using lightning jumps (the internationally developed 2σ algorithm) to nowcast severe storms and as a precursor for tornado events in South Africa (Objective 3). The development and structure of the tornado event at a more localized level using a suite of nowcasting data from remote sensing tools such as radar and satellite, as well as available observational data became the focus of Chapter 5. The study considered a combination of cloud-to-ground (CG) and the fraction of cloud lightning that the SAWS lightning network provided along with the NRT-LWS (total lightning warning system). The analysis of the lightning datasets showed there to be several peaks in flash rates preceding the severe weather at the ground (in this case the tornado). The total lightning system was found to be more beneficial than the CG network, providing a lead time of 33 mins to the event. The study further demonstrated that the total lightning count was an additional observation that provided a greater lead-time for the tornado case study warning. The 2σ algorithm was only used in this case study, however, many other lightning jump algorithms exist. This preliminary study should serve as a foundation for future lightning jump studies and studies focussing on the correlation between lightning and severe weather, which is lacking in South Africa, both at a local and national scale.

6.3 Contributions of this research to new knowledge

Overall, the study addressed the risk of lightning that rural communities across the world face and more specifically the focus of this research was based on the South African context. South Africa possesses a high mortality rate as well as being found to be vulnerable to climate change, due to socio-economic factors, prevailing high levels of poverty and low adaptive capacity. Despite the existence of a national lightning network, lightning alerts and warnings are not disseminated well to such rural communities. Consequently, a community-based NRT-LWS was developed and assessed to detect and disseminate low cost lightning threats and alerts in a timeous and comprehensible manner for rural communities in South Africa. It is envisaged that this could serve as a framework from which a network of similar warning systems (such as the system described in this thesis) in similar high-risk areas with a focus on densely populated communities could be developed in future, thereby providing rural communities with a system that offers to mitigate losses and save lives.

The specific contributions of this research to new knowledge within each chapter (Chapters 2 to 5) are summarized as follows:

Chapter 2:

- contributed to the progress and challenges in lightning detection in South Africa over the recent years. This research found the number of lightning fatalities in many rural communities within South Africa to be high and on-going, despite lightning detection systems making great strides in detecting the occurrence of lightning throughout the world;

- highlighted forums that are currently active and displaying a strong academic lightning infrastructure within South Africa as well as future endeavours in improving South Africa's lightning detection at a local-level;
- identified the lack of literature pertaining to lightning detection within rural communities across the world. No literature exists on determining effective approaches to communicate lightning data, threats and improving warnings in a manner appropriate for rural communities.

Chapter 3:

- developed an innovative ground-based NRT-LWS towards increasing the climate resilience and adaptive capacity for rural communities in South Africa. The system was aimed at providing low cost, easily accessible, timeous and comprehensive lightning alerts and warnings for rural communities in South Africa. Furthermore, the system provided warnings based on measurable thresholds upon which people will able to respond;
- contributed towards the first insights on early detection and monitoring of lightning and electrical activity at a community-level for South Africa.

Chapter 4:

- identified the current focus on analysing spatio-temporal characteristics of lightning incidences around the world and a lack of assessment using operational ground-based early warning systems. Consequently, the assessment and evaluation of the developed NRT-LWS for lightning warnings showed some advantages;
- illustrated the SALDN's capability to disseminate lightning data to a local level and provided insights on the detection capability of this existing national network and the potential benefit in providing for warning dissemination at a local level. This research highlighted the desperate need and potential benefit of bridging the gap between the SALDN and rural communities in South Africa;
- provided the first ground-based insights for describing the characteristics of lightning in the rural community of Swayimane.

Chapter 5:

- enhanced the understanding of lightning as a short-term predictor to severe storms and as a precursor to severe weather (including tornadoes and supercell events) on a local scale for South Africa. The research conducted in this chapter provided insights on the use of lightning data to forecast tornadoes, supercells and severe weather on a local scale for South Africa. This could assist future South African operational forecasters identify what to focus on in lightning datasets in order to forecast severe weather with improved confidence. The study highlighted that an increased lead-time in advance of a warning provided by lightning jumps may be especially useful when adverse weather occurs over populated areas;

- provided an analysis of concurrent trends in both total and CG lightning within the same severe thunderstorm, using the same objective lightning jump algorithm, illustrating the usefulness of using a total lightning dataset over a GC-based lightning dataset for issuing warnings and for providing a greater lead-time over radars for supercells;
- highlighted the need for an operational total-lightning jump tracker, as an automated severe storm prediction tool, which can be used to augment radar, computer model data and observations at the SAWS to issue reliable severe weather warnings with a greater lead time than radar for local scales in South Africa;
- showed the suitability of applying the internationally developed 2σ algorithm for the detection of severe weather using lightning trend data on a local scale in South Africa;
- showed the synergistic benefit of combining radar, satellite and lightning data to support the early detection of convection or using lightning data where radar coverage is unavailable.

6.4 Challenges experienced during the course of this research

The greatest challenge that surfaced during the development and testing operations of the NRT-LWS was the variable network signal coverage within the research area. Consequently, the systems communication was affected, resulting in some data not being downloaded. A total of 67 days of missing data was reported during the frequent communication failure period. However, continuous datasets were thereafter successfully collected through the use of GSM modems that are able to switch between multiple network providers.

The study evaluated the NRT-LWS performance based on the SALDN. The missing data in the NRT-LWS dataset were gap-filled using the SALDN as this was the only available lightning dataset covering this region in South Africa. Comparison of the NRT-LWS and SALDN was conducted and worked well despite the potential complexity of this comparison. The two systems were quite different in architecture and in what they detect and it was surprising to find how well they agreed for lightning within 8 km of the site. The correlation was not as good with distance from the site, which is likely due to a decreasing detection efficiency of the SG000 sensor (particularly approaching its outer detection limit of 32 km). With no available lightning datasets for South Africa except for the SALDN, no evaluation with worldwide systems/networks could be carried out. In previous years, a World-Wide Lightning Location Network sensor was operational in South Africa. However, due to the absence of skilled and trained professionals to monitor and maintain the system, its operation was terminated prior to the present study.

While there was no damage to any of the system's hardware during the study, critical consideration was given to battery capacity since in remote areas such as the research site, electricity is unreliable. In this study a 24 A h battery was installed to provide sufficient power for the system to run on the battery backup for 24 h. Apart from battery capacity, regular inspection was required including cleaning and basic maintenance of the LWS. Spider webs, dust and replacement of the CS110 desiccant (when relative humidity was greater than 60%) were some of the maintenance tasks required.

A large screen (56-inch monitor) was installed within the corridors of the school displaying the NRT-LWS and climatic data for teaching and learning purposes at the school. However, the challenge of ensuring that the screen had connectivity and remained powered on during school hours proved to be difficult.

In addition to the belief systems and lack of education around lightning, a lack of literature on lightning detection within rural communities across the world emanated from the literature review. This proved to be a challenge in trying to develop a system to cater for the needs of rural communities as no background knowledge for lightning monitoring in communities was available.

In order to assess the skill of using lightning jumps to predict severe storms and as a precursor for tornado events amongst other severe weather in South Africa, the study utilised a 2σ algorithm based on the algorithms performance in Washington D.C. by Schultz *et al.* (2009) and from past studies. This was the first time a lightning jump algorithm was calculated on a local scale for South Africa. As such, the algorithm's warning and lead time results could not be evaluated further for South African conditions. Uncertainties in the 2σ algorithm for use in South Africa could not be verified, due to the lack of research on lightning jump algorithms in South Africa. Consequently, an assessment of additional extreme weather events would be beneficial. Due to the nature of the investigations applied herein, geostationary satellite measurements were also required to identify the convection for the tornado event analysed in the study. These images were difficult to obtain as the EUMETSAT requires archived data to be downloaded in formats such as BUFR and HRIT formats, amongst others. These data formats require appropriate skills and software in order to extract information. The necessary training and software required to access and process these images was not available within the time frame of this project. Fortunately, the SAWS provided the processed images through its SUMO software.

This study was undertaken during the global Covid-19 pandemic, which resulted in the closure and gradual opening of many institutions that caused delays in obtaining datasets and satellite images. Furthermore, the study was isolated from international exposure as a number of conferences were cancelled due to the pandemic. For example, the study was accepted for presentation at the International Lightning Detection Conference (ILDC), however, the conference was cancelled. Lastly, capacity constraints, such as computing power to support the NRT-LWSs large datasets were also some challenges experienced throughout the investigation period.

6.5 Future research opportunities

Throughout this research study, an in-depth analysis of all available literature was undertaken to guide the various approaches which were implemented and tested in the study. However, given the additional knowledge that was acquired of the research area the following is proposed for future consideration:

- whilst lightning is a familiar and well-researched phenomenon worldwide (Dwyer and Uman, 2014), and recognisable as an important research topic on the African continent, research at a local level remains void. In light of the anticipated projected increases in extreme weather and occurrence of lightning due to climate change (Price, 2009; Ziervogel *et al.,* 2014), developing countries in Africa that are already prone to lightning will now face elevated risk. Myths and beliefs regarding lightning in rural areas also continue to remain a challenge and often hinder necessary precautionary measures (Dlamini, 2009; Blumenthal *et al.,* 2012; Trengove and Jandrell, 2015; Cooper *et al.,* 2016). Further investigations into education around lightning safety, the development of lightning safety protocols/guidelines, conducting mock events and the involvement of multiple stakeholders, from community members, government extension officers and NGO's is required;

- the community-based NRT-LWS provided a foundation for early warning at a community level and offers opportunity for future research. While the NRT-LWS was found capable of disseminating reliable lightning warnings to the rural community of Swayimane, the use of this system beyond this community requires further investigation. Further research on the packaging of early warning information, including translation of the alerts/warnings into local languages, adding an action/precautionary measure that needs to be taken with the safety advisory and its impact on the community also requires further investigation. The community's perception and uptake of the warnings also requires investigation. The use of the NRT-LWS for practical teaching purposes within the classroom in alignment with the school syllabus would make a useful contribution. Furthermore, continued monitoring at the research site may contribute to an improved understanding of the system under a changing climate and allow for invaluable time-series comparisons of seasonal and spatial variations. The newly developed NRT-LWS was neither site- nor system- specific and therefore has the potential to be applied in other environmental settings. However, local studies should be prioritised over regional studies;
- there is an emphasis given to analysing the spatio-temporal characteristics of lightning incidences around the world. Future research on local measurement systems varying in terms of their spatial-temporal characteristics and warning dissemination capabilities should be undertaken together with evaluation of detection efficiency. Such investigations can also be used to compare with the NRT-LWS to determine if the newly

developed system offers any significant improvement over other ground-based systems, focussed towards the early detection and warning of lightning for rural communities;

- whilst lightning detection systems may provide reliable warnings, the community response to warnings is still complex as the only shelter available to them is often rural housing which is not necessarily structurally lightning-safe. Without lightning-safe shelters, individuals remain vulnerable to the threat of lightning after receiving a warning alert. Therefore, future studies need to address the economic feasibility and implication of constructing lightning-safe shelters around rural communities and/or identifying high-risk lightning areas and installing lightning conductors in these areas across South Africa;
- investigation into determining the most effective way to utilise existing monitoring networks such as the SALDN, but with warning dissemination to rural communities, should be the focus of research in the future;
- evaluating the error ellipse of the SALDN and other existing networks within the research study area is further recommended,
- the use of the 2σ algorithm was selected for application in this study based on the algorithms performance by Schultz *et al.* (2009) to investigate lightning as a precursor to severe weather on a local scale for South Africa. However, there are alternate lightning jump algorithms such as Gatlin 30 algorithm, Gatlin 45 algorithm, threshold 8 algorithm, threshold 10 algorithm and 3σ algorithm, which could offer new and exciting research opportunities into determining their applicability, use and comparison against the 2σ algorithm to enable more accurate lead times and warnings for South Africa. Additionally, future studies, based on longer data periods, to determine the

appropriate lightning threshold for various storm characteristics in South Africa is required;

- a need to work on an operational total-lightning jump algorithm for forecast operations in South Africa and to correlate the lightning jump alerts to the SAWS severe thunderstorm warnings to evaluate lead time and accuracy is required. A total-lightning jump algorithm may be useful in helping forecasters to determine when severe weather is coming before it is detected by radar. Improving adverse weather lead-times can be especially useful when adverse weather occurs over populated areas.

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