

**INITIAL STEPS IN THE DEVELOPMENT OF A COMPREHENSIVE
LIGHTNING CLIMATOLOGY OF SOUTH AFRICA**

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Thesis submitted in fulfillment of the requirements for the Master of Science degree at the University of the Witwatersrand, School of Geography, Archaeology and Environmental Studies: Climatology Research Group, South Africa.

2008

Declaration

I, Tracey Gill, do hereby declare that the research presented in this dissertation is my own.

Signed this Tenth day of March 2009

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Abstract

The summer rainfall region of South Africa is dominated by convective thunderstorm development from October to March. The result is that lightning is a common event over most of the country during this time. The South African Weather Service (SAWS) installed a state-of-the-art Lightning Detection Network (LDN) in late 2005 in order to accurately monitor lightning across South Africa. Data from this network for 2006 was utilised in order to develop an initial climatology of lightning in South Africa. Analyses were performed of lightning ground flash density, flash median peak current and flash multiplicity on a 0.2° grid across South Africa. The highest ground flash density values were found along the eastern escarpment of the country, extending onto the high interior plateau. There is a general decrease in flash density from east to west, with almost no lightning recorded on the west coast of the country. The regions of highest flash density recorded the highest percentages of negative polarity lightning. The percentage of positive lightning was higher in the winter months, as was the median peak current of lightning of both polarities. The median peak current distribution displayed distinct bands of current values oriented in northwest to southeast bands across the country. The bands of higher median peak current correspond to the regions to the rear of the interior trough axis in areas dominated by stratiform cloud development and were more dominant in the mid summer months. The highest flash multiplicity was recorded in the regions of highest flash density. Along the southern escarpment, on the eastern side of South Africa, flash multiplicity values exceeded 3 flashes per square kilometer. The highest flash multiplicity of negative polarity lightning was recorded in the spring and early summer. Throughout the year, the percentage of single stroke flashes for positive lightning is high. Topography and the position of the surface trough have a very strong influence on the ground flash density and median peak current distributions, but not on the flash multiplicity distribution. The results from the analyses of the three lightning variables were then combined to determine risk indexes of high intensity lightning and of positive polarity lightning. The eastern part of South Africa is at extreme risk from both large amounts of lightning and from positive polarity lightning, whereas the regions in the northwest of the country that are dominated by mining are at extreme risk from mainly positive polarity lightning.

Preface

Lightning poses a significant risk to people and property in South Africa. Most of the central and eastern parts of the country experience in excess of 50 thunderstorm days a year. In the past, the number of thunderstorm days has been used as a proxy for the lightning distribution across South Africa. A network of lightning flash counters was in operation across the country for the 11 year period from 1975 to 1986. The data from these flash counters was utilized to construct a climatology of lightning flash density for South Africa. To this day, the information from the flash counter network is utilized as input into the setting of lightning safety and protection standards.

Advances in satellite technology have enabled the mapping of global lightning distributions. Information from the Lightning Imaging Sensor indicates that a larger expanse of South Africa may be at risk from lightning than first indicated by the flash counter network. Most of this higher risk area is found in regions of high urban populations that also have an industrial and manufacturing economic focus. Recent research into precipitation trends in South Africa indicates that in some parts of the country, rainfall events are becoming more intense and are producing larger extreme rainfall values. Most of these high rainfall events are associated with convective activity and so also with lightning.

In South Africa, the average number of lightning-related deaths is 6.3 per million of the population, which is more than 15 times the global average. Insurance claims resulting from the loss of electronic equipment or from fires initiated by lightning strikes amount to more than R500 million per year. In the most active summer lightning months, 70% of the power utility faults reported in South Africa are as a result of lightning. Lightning-ignited fires in commercial plantations can smoulder for days before flaring up and destroying millions of Rands worth of commercial trees. Other industrial sectors would benefit from an accurate lightning location and advanced warning system in order to evacuate high-risk personnel and to cease dangerous activities. If South Africans are to be in a position to protect themselves and their property from lightning damage, then a more detailed and up to date climatology will have to be determined from accurate lightning data.

In order to ensure that life and property are better safe-guarded against lightning risk, the South African Weather Service (SAWS) installed a state-of-the art lightning detection network in late 2005. The network of 19 sensors is able to detect 90% of cloud-to-ground

lightning over the whole of South Africa with an accuracy of 500m or less. The data from this network for 2006 has been analysed in this research in order to develop a comprehensive climatology of lightning for South Africa. The network is able to detect a number of parameters for cloud-to-ground lightning. The proposed climatology is not merely an analysis of ground flash density by also of the amount of energy discharged to ground by the first stroke of a multiple stroke flash. This expanded analysis is based on the premise that, not only is it important to know the spatial concentration of cloud-to-ground lightning, but it is also vital to know the exact magnitude of the risk. Knowing the amount of electrical current reaching the ground allows decision-makers to install the correct lightning protection for buildings and structures. It is also important for physical and meteorological studies of cloud-to-ground lightning.

The amount of electrical current reaching the ground in very short periods of time is also a function of the multiplicity of the lightning flash. Flash multiplicity refers to the number of individual lightning strokes that are discharging energy in a limited spatial area in a short time interval. Knowing whether a lightning flash consists of one or more strokes and the intensity of these strokes has important implications for lightning protection and lightning test standards.

A literature study of storm electrification and lightning discharge has been undertaken in order to gain a better understanding of the technology required to develop lightning detection systems. In particular, the detection technology of the SAWS lightning detection network has been explored in detail. The analysis of the actual lightning data has been done for the lightning ground-flash density, the median peak current and the flash multiplicity. All analyses have been performed for the full data set and then also for the individual seasons. Each lightning parameter has been discussed in a separate chapter.

The ultimate aim of this research is to develop a climatology of lightning that can be used for risk assessment. The final chapter in this research addresses the development of lightning risk indexes. Despite the fact that positive polarity lightning comprises about 10% of all cloud-to-ground lightning, it can be very dangerous. As such, separate risk indexes have been developed for high intensity lightning and for positive polarity lightning. A third risk index, which assesses the combined risk of high intensity and positive polarity lightning, has been determined. The methodology used in calculating these indexes is flexible so as to enable clients who are at risk from lightning to customize them for their specific purposes.

The intention in this research is to provide the building blocks for the development of a comprehensive climatology of lightning in South Africa. As each successive year of lightning data becomes available from the SAWS lightning detection network, the methodology that has been developed in this research can be applied in order to refine the climatology.

Acknowledgements

I would like to extend my gratitude to Dr Stuart Piketh as supervisor of this dissertation and to the staff of the South African Weather Service for their assistance. A special word of thanks goes to Karin Marais and Anastasia Demertzis, the South African Weather Service librarians, for whom no request was ever too much trouble, no matter how demanding the request may have been. I would like to thank the South Africa Weather Service for providing the lightning data and computer facilities for this research. I would especially like to thank my husband Peter and our sons, Duncan and Connor, for their patience and support throughout this research.

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List of Abbreviations

Abbreviation	Description
CSIR	Council for Scientific and Industrial Research
ELWC	Effective Liquid Water Content
GIS	Geographic Information System
LDN	Lightning Detection Network
LF	Low Frequency
LIRI	Lightning Intensity Risk Index
LIS	Lightning Imaging Sensor
LPATS	Lightning Positioning and Tracking System
MCC	Mesoscale Convective Complex
MCS	Mesoscale Convective System
MDF	Magnetic Direction Finder
NLDN	National Lightning Detection Network
PLRI	Positive Lightning Risk Index
RNSS	Range Normalised Signal Strength
SAWS	South African Weather Service
TLRI	Total Lightning Risk Index
TOA	Time of Arrival
TRMM	Tropical Rainfall Measuring Mission
USA	United States of America
VLF	Very Low Frequency

CHAPTER 1

Introduction and Objectives

1.1 Introduction

South Africa is a lightning prone country. Large parts of the summer rainfall region of South Africa experience more than 60 thunderstorm days a year (Figure 1.1). A thunderstorm day is defined as “a local calendar day during which thunder is heard at least once at a given location” (Rakov and Uman, 2003). Thunder is the audible sound wave produced by a lightning discharge. Such a lightning discharge is a movement of electrical energy between two adjacent regions in a cloud that are oppositely charged. Lightning discharges can take place between a thundercloud and the adjacent air (cloud-to-air), within the thundercloud itself (intra-cloud), from one thundercloud to another (inter-cloud) or between the thundercloud and the ground (cloud-to-ground) (Rakov and Uman, 2003). The number of thunderstorm days can thus be used as a proxy for the lightning distribution across the country.

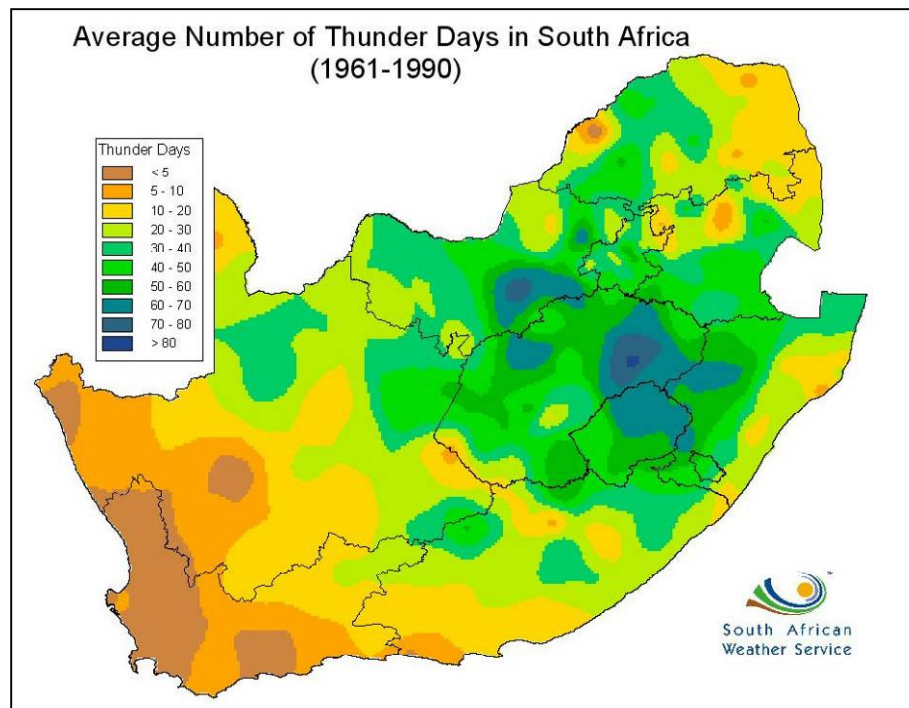


Figure 1.1: Average number of thunder days in South Africa for the period from 1961 to 1990 (SAWS)

Another source of information on lightning distribution is satellite imagery. The Lightning Imaging Sensor (LIS) is currently in a low orbit of about 350 km above the earth and is part of the Tropical Rainfall Measuring Mission (TRMM). The detection efficiency from the LIS

is estimated to be in the order of 70 to 98% (Koshak *et al.*, 2000). The satellite is able to detect cloud-to-ground as well as cloud-to-cloud and intra-cloud lightning. Images from LIS indicate that South Africa has lightning flash densities in excess of 10 flashes per square kilometer over much of the country (Figure 1.2). The greatest concentration of lightning flashes in the world occurs in the tropics, with the highest values recorded over the Democratic Republic of the Congo. There are also comparable flash densities to those in South Africa along the windward sides of most of the large mountain ranges of South America and Asia. Most of the countries that experience higher flash densities have lower population densities and more rural population distributions than does South Africa. South Africa, like the Tampa area in the USA for example, experiences high lightning flash densities over areas of urban populations that also have an industrial and manufacturing economic focus.

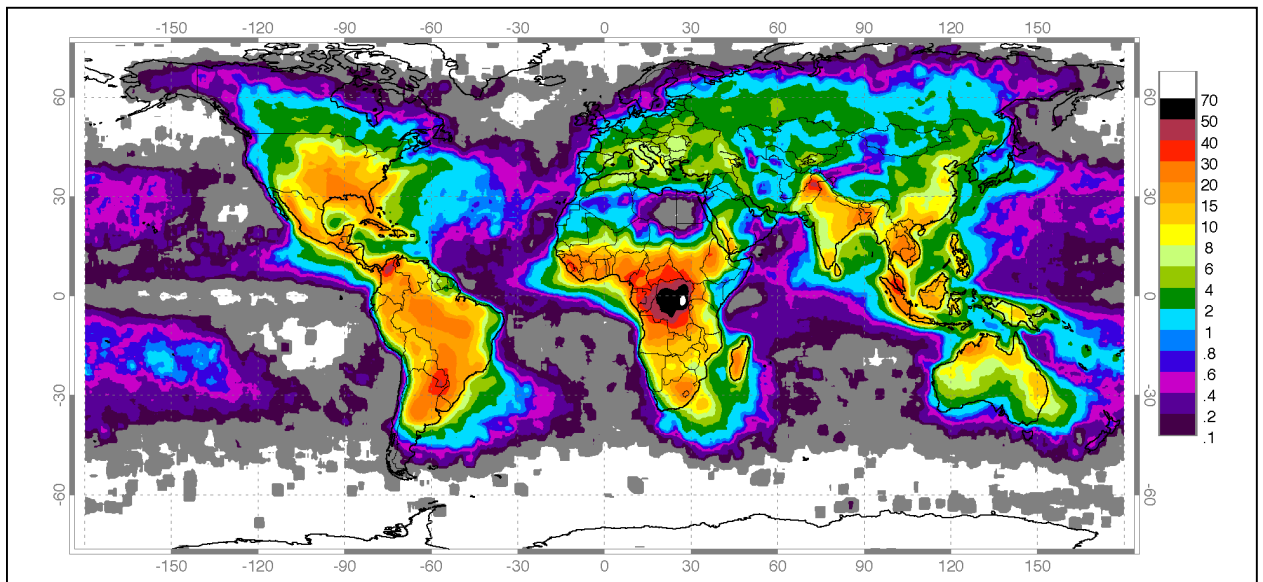


Figure 1.2: Global annual lightning flash density based on a 2.5° grid from the Lightning Imaging Sensor (LIS) (<http://thunder.msfc.nasa.gov/data/>)

For many years attempts have been made to assess the distribution of lightning over South Africa (Malan, 1963; Anderson *et al.*, 1984; Proctor, 1993). In the early 1990s, ESKOM, South Africa's major power utility, operated a network of Lightning Position and Tracking System (LPATS) lightning detection sensors, but the network soon became redundant as sensors failed and were not repaired (Evert and Schulze, 2005). Prior to this, the Council for Scientific and Industrial Research (CSIR) operated a country-wide network of lightning flash counters (Proctor, 1993). The data from this network was used to generate the first map of lightning ground flash density in South Africa (Figure 1.3). Up to the end of December 2005

this was the only map of lightning ground flash density available in South Africa. The detection efficiency and location accuracy of the flash counter network was never calculated. In the absence of more accurate data, the flash counter data has been used extensively in the setting of lightning protection standards in South Africa. A validation of these standards is required from accurate lightning data in order to ensure the adequate protection of life and property in this country.

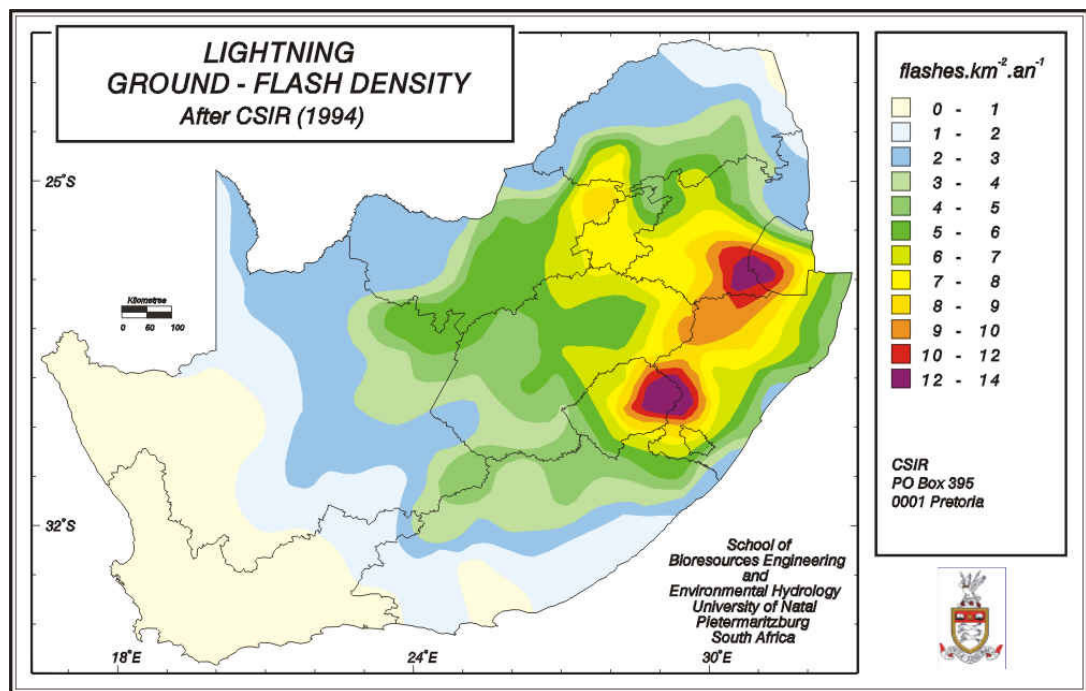


Figure 1.3: Lightning ground flash density map of South Africa after CSIR (Schulze, 1997)

Recent research into precipitation trends in South Africa (Kruger, 2006) indicates that in some parts of the country, rainfall events are becoming more intense and are producing larger extreme rainfall values. Most of these high rainfall events are associated with convective activity and so also with lightning. The latter specifically highlights the need for the South African Weather Service (SAWS) to issue lightning warnings, forecasts and services for the protection of life and property, in fulfillment of its legal mandate. As such the SAWS made a very large capital investment by purchasing and installing a VAISALA Lightning Detection Network (LDN) in 2005. The SAWS LDN is only one of three ground-based lightning detection networks in the Southern Hemisphere, the others being in Brazil and Australia (VAISALA, 2004b)

On average, about 2000 deaths occur around the world each year as a direct result of lightning (Geerts and Linacre, 1999). This is a global annual average of approximately 0.4 deaths per million of the population. In South Africa, the average number of lightning-related deaths is 6.3 per million of the population, which is more than 15 times the global average (Blumenthal, 2005). According to Blumenthal (2005), this is probably an under-report of the number of lightning death victims since the pathology of lightning damage to the human body is still poorly understood in most areas of the country.

In the United States of America, there has been a significant reduction in the number of lightning-related deaths over the last century. This has been attributed to the fact that more of the population has become urbanized with time (Lopez and Holle, 1998). In South Africa, despite fairly rapid urbanization in the last few decades, many people still reside in the rural areas or in poorly constructed dwellings in the urban areas. These, coupled with poor education around lightning safety, are the principal reasons for the high lightning-related mortality rate.

Not only are the people of South Africa at enormous risk from lightning, so too are a host of economic sectors. Substantial financial loss each year is attributed directly to lightning damage. Insurance claims resulting from the loss of electronic equipment or from fires initiated by lightning strikes amount to more than R500 million per year (Evert and Schulze, 2005). Across the world, lightning is responsible for most of the unplanned power outages and systems faults experienced by power utilities. In the United States, lightning is estimated to cause \$100 billion in damages to power utilities and their customers each year (Smidt, 2003; Chisholm and Cummins, 2006). In South Africa, in the most active summer lightning months, the ESKOM Transmission Division report that almost 70% of the utility faults reported were as the result of lightning (Evert and Schulze, 2005). These faults have an impact on the ability of the power utility to provide an uninterrupted supply of electricity to its clients and cost the organisation large amounts of money in lost revenue and reduced credibility.

Lightning-ignited fires in commercial plantations can smoulder for days before flaring up and destroying millions of Rands worth of commercial trees (Ballantyne, 2006, personal communication). In the Kruger National Park in South Africa, lightning-induced fires affected 21.6% of the total area (2.5 million hectares) in the period from 1957 to 1996 (Van Wilgen *et al.*, 2000). Other industrial sectors, such as the petrochemical, explosives, construction and

mining industries would benefit from an accurate lightning location and advanced warning system in order to evacuate high-risk personnel and to cease dangerous activities. It is only with the recent installation of the LDN, however, that such warning mechanisms have become possible. The SAWS LDN has been fully operational since December 2005 and represents a major leap forward in being able to determine an accurate climatology of lightning in South Africa. The level of accuracy of detection of cloud-to-ground lightning by the LDN has, for the first time, made it possible to study lightning strike risks accurately in this country.

1.2 Objectives

The primary goal of this study is to analyse the 2006 lightning data, which is the first complete year of accurate lightning data from the LDN, to lay the groundwork for the continuous updating of a lightning climatology for South Africa. The outcome of the research will be an analysis of the distribution of lightning in South Africa in order to determine the degree of risk to which people and property are exposed in different parts of the country.

The four main objectives of the study are:

- 1.2.1 To analyse the differences in the seasonal cloud-to-ground lightning flash density distributions in order to determine the risk from high concentrations of lightning of both positive and negative polarity;
- 1.2.2 To investigate the median peak current distribution of both positive and negative polarity lightning to determine the differences in intensity of cloud-to-ground lightning for the different seasons;
- 1.2.3 To determine the average cloud-to-ground lightning flash multiplicity distribution of positive and negative polarity lightning as a secondary indicator of seasonal lightning intensity; and
- 1.2.4 To devise and calculate simple indexes that will quantify the risk from high concentrations of intense lightning as well as from predominantly positive polarity lightning for different seasons and the year.

CHAPTER 2:

Literature Review

As a background to understanding lightning and how it is formed, it is important to first explore thunderstorm distribution in South Africa. Once it is clear as to what types of synoptic situations give rise to thunderstorm development over the country, then further investigations will be carried out into the manner in which these thunderclouds become electrified and discharge their energy. Detail will be provided on the mechanisms utilized to detect lightning ground stroke positions so that the results from the SAWS LDN may be utilized with confidence in subsequent chapters and analyses.

2.1 Lightning Distribution over South Africa

Lightning is a product of convective storm cell development. In South Africa, the northern, central and eastern parts of the country experience a lot of convective activity, whilst the Western and south-western regions are almost devoid of thunderstorms (Figures 1.1 and 1.2). There are two distinct rainfall seasons in South Africa that are dominated by different rain-producing systems (Taljaard, 1996). Summer rainfall is usually the result of either single cell or multiple cell thunderstorm development. Single isolated storm cells tend to be localized, are typically 5-10 km in diameter and generally last less than an hour. Multi-cell storms consist of individual cells that all follow the same growth cycle, but at different times. Multi-cell storms may be organized in groups or in lines, depending on the meso-scale influences on storm development. They may be 30-50 km in diameter and have life cycles that can last a few hours (Taljaard, 1996).

Watson *et al.* (1994) emphasized the importance of three mechanisms in the development of thunderstorms: moisture, instability and a triggering mechanism. During the summer, moisture is fed in over South Africa from the eastern oceans, around the South Indian Anticyclone (Figure 2.1) and into the central and northern parts of the country (Harangozo and Harrison, 1983).

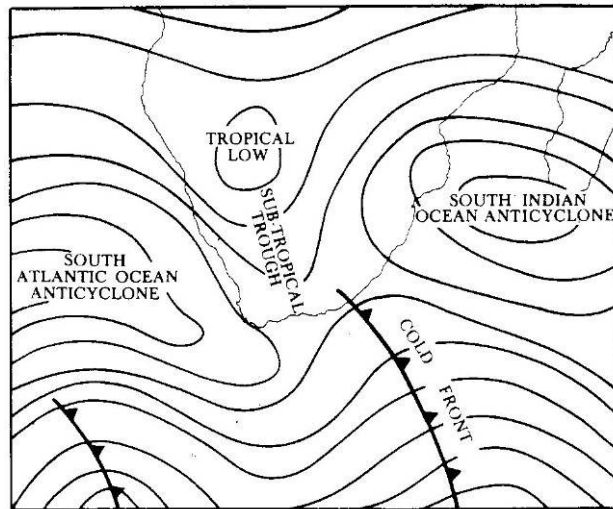


Figure 2.1: Schematic representation of the surface synoptic circulations influencing weather conditions over Southern Africa (Harangozo and Harrison, 1983)

The atmosphere is fairly unstable in the summer due to the presence of the dominant easterly lows which extend into the country to the south of the Inter-tropical Convergence (Taljaard, 1990). In the late afternoon in the summer months, when surface temperatures reach their maximum, the heat often acts as a trigger to convective storm development (Preston-Whyte and Tyson, 1988). In such instances the thunderstorms tend to be single-cell in nature and fairly short-lived.

Multi-cell or line thunderstorms are usually triggered by larger scale synoptic forcing (Preston-Whyte and Tyson, 1988). The main source of moist air is from the Indian Ocean, around the northern extent of the sub-tropical high pressure (Figure 2.2), from whence it flows westwards towards Botswana and Namibia (Taljaard, 1990). As this air moves westwards it encounters a strong sub-tropical trough from the Atlantic Ocean and convergence is triggered. The deep sub-tropical trough is preceded by a zone of upper level divergence, which acts to enhance the surface convection on the eastward boundary of the trough (Taljaard, 1990). In the event that there is a coastal low pressure developing ahead of a mid-latitude disturbance or that there is a cold-front lying off the coast of South Africa, and if coupling of the tropical low takes place with this southern low pressure system, a cloud band will form across the country with a Northwest to Southeast Orientation (Figure 2.2) (Harangozo and Harrison, 1983; Harrison, 1984; Taljaard, 1990). Multi-cell thunderstorms form within the zone of maximum convergence along this band and are responsible for a large portion of the summer rainfall over the interior of the country (Harrison, 1984).

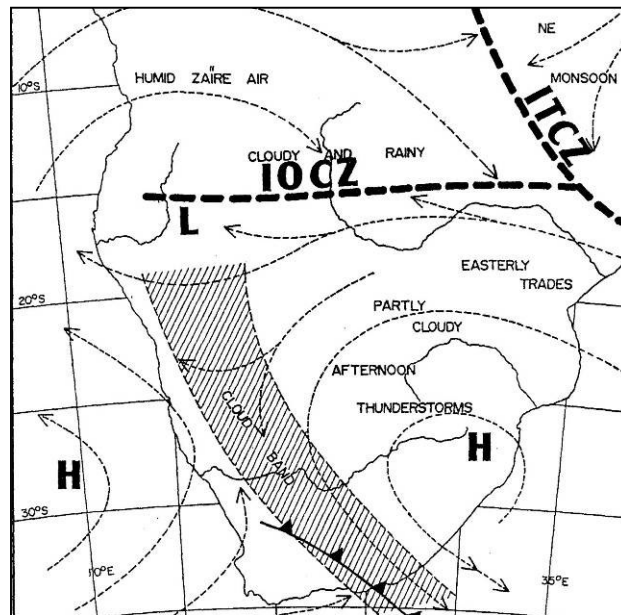


Figure 2.2: Schematic representation of near-surface circulation patterns responsible for cloud-band formation (Taljaard, 1990)

On the eastern side of the country, east of the Escarpment, the source of moisture is once again the warm Indian Ocean, with orographic triggering of thunderstorm development as this warm, moist air is forced to rise up against the windward slopes of the Drakensberg Mountains (Taljaard, 1996). Thunderstorm development is thus integral to the summer rainfall over South Africa and the distribution of lightning in summer is extensive, covering most of the central and northern interior regions as well as the eastern regions on the windward sides of the Drakensberg Mountains.

In the winter rainfall region, however, most of the rainfall is derived from the passage of cold fronts (Preston-Whyte and Tyson, 1988; Taljaard, 1996). It is possible for shallow cumulus development to take place along the front itself and for some lightning to occur. The Western Cape is thus not completely devoid of lightning, but ground flash densities are very low (Figure 1.2).

Meteorologists have for a long time understood the mechanisms responsible for thunderstorm development over South Africa, but there is not a lot of literature available on the ground flash density distribution of lightning across the country. Much of the research that has taken place in South Africa has been targeted at understanding the processes involved in the formation of lightning (Malan, 1963; Proctor, 1991; Proctor, 1993; Anderson *et al.*, 1984). In 1962, D J Malan built the first lightning flash counter in South Africa (Anderson *et al.*, 1984).

Based on the initial results from this flash counter, it appeared likely that the electromagnetic wave propagation from most cloud-to-ground flashes occurred in the range from 5 to 10 kHz (Anderson *et al.*, 1984). To further validate this finding, three flash counters were erected in the Pretoria Area, two were 500 Hz counters and the third was a 10 kHz counter. These flash counters only operated at night since each was fitted with a camera for lightning flash verification purposes and these cameras were not able to operate during the day. Data was collected for a period of about 12 years. From the analysis of this data, it was concluded that the counter that fared best in the detection of cloud-to-ground flashes was in fact the 10 kHz counter.

The first complete network of flash counters was installed by a collaborative partnership led by the CSIR in 1975 (Anderson *et al.*, 1984). This network was operational for 11 years, and monthly readings from 380 flash counters were sent to the CSIR for processing (Schulze *et al.*, 1997). These flash counters had an effective range of about 20 km (Anderson *et al.*, 1984; Manry and Knight, 1986) and were placed more densely in areas of higher expected thunderstorm activity. The only map of lightning ground flash density to have been generated in South Africa was done using the 11 years of data from this flash counter network (Figure 1.2). The resulting analysis of this ground flash density data indicated that about 53% of the total variance of average annual lightning density could be accounted for as a function of both longitude (36% of the variance) and altitude (Manry and Knight, 1986).

Following the demise of the flash counter network, ESKOM installed a network of Lightning Positioning and Tracking System (LPATS) sensors to monitor lightning in areas of high risk to the power utility. The intention was not to get coverage over the entire country, but to provide the power utility with vital information for operational purposes (Evert and Schulze, 2005). As such no maps of lightning flash distribution are freely available from this network. The analysis from the SAWS LDN will thus enable the first accurate assessment of lightning cloud-to-ground flash density distribution in South Africa.

In order to provide a meaningful analysis of lightning in South Africa, it is essential to clarify how thunderstorms develop and become electrified as well as to explore the mechanisms governing electrical discharge.

2.2 Thunderstorm Development

The discussion of thunderstorm development in this section will refer primarily to the formation of heat-generated thunderstorms, though any trigger mechanism will ultimately have the same result. In an unstable atmosphere, a number of pockets of warm, moist air initiate close to ground level and rise through the lower atmosphere, cooling and expanding as this happens. Successive pockets interact with each other until organized thermals develop. These thermals are able to push up to great heights. As the air within these thermals cools to the dew-point temperature, the water vapour in the air condenses to form small water droplets and latent heat is released. This latent heat release provides additional energy to fuel the system and causes the cumulus clouds that have formed as a result of the condensation process to grow vertically (Preston-Whyte and Tyson, 1988; Rakov and Uman, 2003).

As thermals rise in the cumulus clouds, with continuous moist air being brought into the cloud from below, the water droplets grow in size. When these droplets become too heavy to be supported in the top of the cloud, they begin to fall, setting up a downward directed flow of air called a downdraft. As the storm cell grows, distinct regions of updrafts and downdrafts develop in the cloud (Figure 2.3).

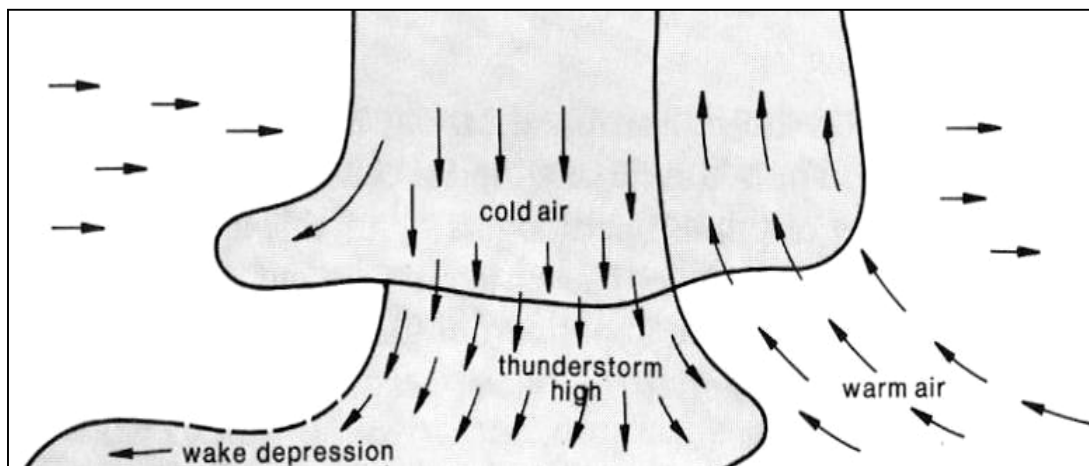


Figure 2.3: The development of updrafts and downdrafts in a thunderstorm cell (Preston-Whyte and Tyson, 1988)

As the cloud grows to greater heights it moves through the freezing level and so a particle phase separation is set up within the cloud. The lower sections of the cloud consist mainly of water droplets. In the middle section of the cloud, in the temperature range from -40° to 0° , there is a mixture of super-cooled water and ice particles. This section is known as the mixed

phase layer. The top part of the cloud is predominantly ice crystals and small hailstones. It is widely accepted that it is this interaction between solid and liquid particles within the mixed phase layer that is responsible for the electrification of the cloud (Malan, 1963; Kufa and Snow, 2006; Rakov and Uman, 2003; Takahashi, 1978; Saunders *et al.*, 1991 and Avila and Pereyra, 2000).

The characteristics of single cell thunderstorms have been the main focus of much of the research into storm electrification. Every cloud electrification mechanism involves a process that electrifies individual hydrometeors (water and ice particles in the cloud) and one that separates the charged hydrometeors by polarity (Rakov and Uman, 2003).

2.3 Electrification and Charge Separation in Thunderclouds

2.3.1 The Dipole Electrification Structure

Experimental observations making use of camera images of lightning carried out by Malan (1963) indicated that discharges inside a convective cloud tended to give negative field changes when the cloud was relatively far away from the observer and positive field changes when it was nearby. From this, he deduced that the charge distribution within a convective cloud must be bipolar in nature with positive charge higher up in the cloud (P) and negative charge lower down (N). This is referred to as a dipole electrification structure. These oppositely charged regions may not lie vertically above each other and there may also be a small region of positive charge at the base of the cloud (p) (Figure 2.4).

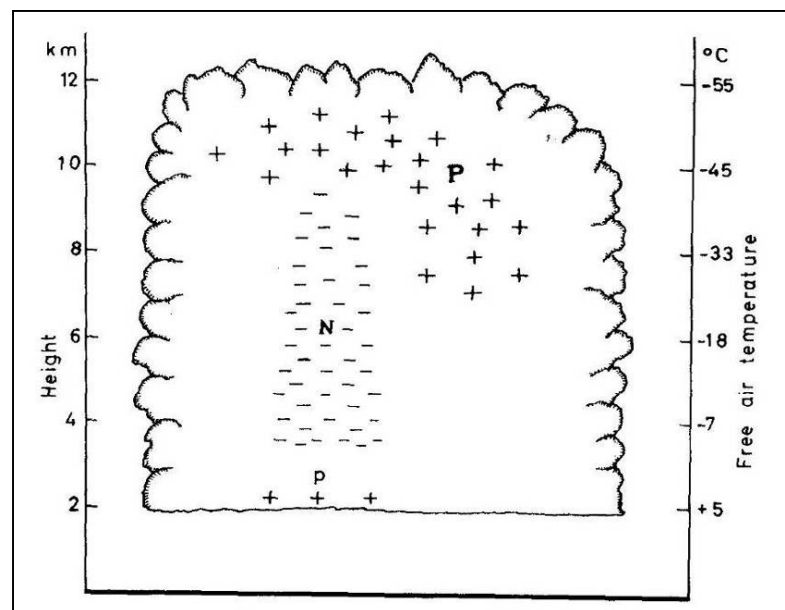


Figure 2.4: Probable distribution of the main thundercloud charges P, N and p (Malan, 1963)

In support of this theory, Proctor (1991) found that in the early phase of thundercloud development, the lightning flashes tended to originate lower down in the cloud than during the latter phase of the development. He was only able to determine the polarity of 165 of 214 flashes and all except one of these were negative. It was not possible to deduce whether the different regions of origin of lightning flashes were also different regions of polarity.

Cooray (1997) expanded on the dipole structure of a single cell thundercloud, indicating that the top positive charge in the cloud is usually found at an altitude of about 12 km above the ground (at a temperature of about -25°C), the middle negative charge layer is at approximately 7 km above the ground (at a temperature of about -10°C) and the lower positive charge layer, if it is present in the cloud, is at about 2 km altitude above the ground. In contrast, many thunderclouds display more numerous charge layers and may consist of anything from four to ten charge regions (Marshall and Rust, 1991).

Proctor (1991) found that lightning flashes originate either above or below a mean altitude of about 7.43 km and that flashes that originate below this level were far more numerous than those originating above it. If one then extrapolates these results to the findings of Malan (1963) and Cooray (1997), taking into account that individual storm cells may have charge centers at slightly different altitudes, it would make sense to assume that there are fewer flashes originating in the positively charged part of the storm than in the negative region. This is borne out by research done on the polarity of lightning flashes measured from the National Lightning Detection Network (NLDN) in the USA (Kufa and Snow, 2006; Orville and Huffines, 2001; Zajac and Rutledge, 2001; Orville *et al.*, 2002 and Orville and Silver, 1997).

In most individual thunderclouds with a typical dipole electrification structure, negative charge is usually found in the temperature range from -25°C to -10°C , in the lower portion of the mixed phase layer (Rakov and Uman, 2003; Saunders *et al.*, 2006). This temperature range depends on the storm type and on the speed of the updrafts. The higher the updraft speed the greater the temperature range of the negative charge layer (Stolzenburg *et al.*, 1998). Once established, the negative charge layer tends to remain within this temperature range for the entire duration of the active part of the thunderstorm. The upper positive charge layer is carried aloft throughout the duration of the storm updrafts (Saunders *et al.*, 2006).

2.3.2 The Ice-Graupel Mechanism

Extensive laboratory experiments have been carried out in order to try to explain the mechanisms of cloud electrification (Takahashi, 1978; Jayaratne *et al.*, 1983; Jayaratne and Saunders, 1985; Saunders *et al.*, 1991; Avila and Pereyra, 2000; Takahashi and Miyawaki, 2002; Saunders *et al.*, 2006). The consensus, following these recent studies, is that the charging mechanism first proposed by Reynolds *et al.* (1957) is in fact the most likely mechanism of charge generation in a thundercloud. They outlined a non-inductive charging mechanism whereby the vertical charge layers were generated by the physical separation of graupel (precipitation particles) and ice crystals in a thundercloud.

The ice-graupel mechanism involves the production of electrical charges through collisions between graupels, which can be soft ice particles or water droplets, and cloud particles, which generally take the form of ice crystals (Rakov and Uman, 2003). The electrification of the particles takes place through the collisions between the graupels and the ice crystals in the presence of supercooled water droplets (Takahashi, 1978; Latham, 1981; Dye *et al.*, 1986, 1988).

The precipitation particles are distinguished from the cloud particles by their fall speed. Any particle falling through a cloud at more than 0.3 m/s is considered a precipitation particle, while those with lower fall speeds are classified as the cloud particles. As a consequence, precipitation particles tend to be bigger than their cloud counterparts. The precipitation particles are thus in the process of falling out of the clouds, while the cloud particles either remain suspended in the cloud or move upwards on updrafts (Rakov and Uman, 2003). The size distribution of the cloud droplets is very important to the polarity of charge transferred in ice-graupel collisions (Avila and Pereyra, 2000). In clouds with larger concentrations of precipitation particles, ice-graupel collisions resulted in the negative charging region becoming bigger.

Jayaratne *et al.* (1983) found in laboratory experiments, that when the temperature in the cloud is below a critical value, which they referred to as the reversal temperature, the falling precipitation particles acquire a negative charge when colliding with ice crystals. At cloud temperatures above the reversal temperature they acquire a positive charge. They found that the reversal temperature lay between -20 °C and -10 °C, which is within the temperature range of the main negatively charged region in the cloud. These results were supported by

laboratory experiments conducted by Baker *et al.* (1987) (Figure 2.5). Any graupels that pick up positive charge in ice collisions below this reversal temperature could explain the presence of the lower positive charge layer in the cloud (Jayaratne *et al.*, 1983).

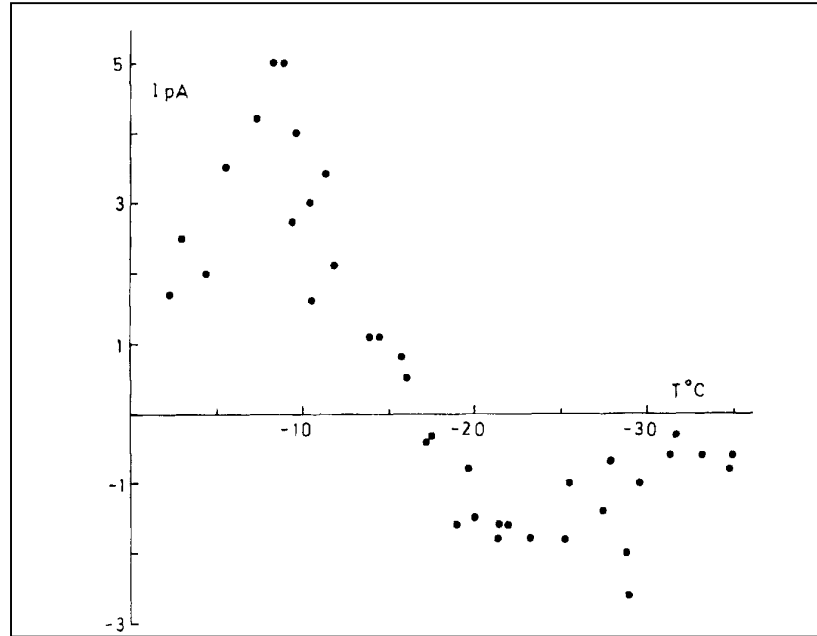


Figure 2.5: The general pattern of positive charging at higher temperatures and negative charging at lower temperatures around the reversal temperature between -20 °C and -10 °C (Baker *et al.*, 1987)

The size of the precipitation and cloud particles play a role in determining the reversal temperature (Jayaratne, 1998). He showed that for droplets smaller than 10 μm , there may be more than one charge sign reversal temperature and could be as many as 4 of these reversal temperatures for droplets smaller than 4 μm . This explains why some clouds have multiple cloud charge layers and not just the typical dipole structure.

The sign of the charge transferred in ice-graupel collisions also depends on the effective liquid water content in the cloud (ELWC) (Takahashi, 1978; Jayaratne *et al.*, 1983; Saunders *et al.*, 1991; Avila and Pereyra, 2000; Rakov and Uman, 2003). Smaller cloud droplets (less than 30 microns in diameter) at temperatures below -18°C tend to acquire positive charge for high and low values of ELWC and negative charge at intermediate values (Avila and Pererya, 2000). Negative charging of large water droplets was independent of ELWC. This was supported by experiments carried out by Saunders *et al.* (1991). They also found that as the ELWC increases, the reversal temperature decreases.

In addition, the rate at which the ice and graupel particles are growing in a thundercloud plays an important role in the transfer of charge in ice-graupel collisions. Most ice crystals gather water and vapour to their surfaces in a process known as riming. The consensus is that the faster growing riming particle will acquire a positive charge (Baker *et al.*, 1987; Rakov and Uman, 2003). Super-saturation in a cloud thus influences the moisture available to promote cloud particle growth rate and so has an important influence on the charging in a cloud (Saunders *et al.*, 2006).

Finally, it has been found that the speed of the updrafts in a cloud also impacts on the electrification of that cloud (Zipser and Lutz, 1994; Avila and Pereyra, 2000; Sherwood *et al.*, 2006). Continental thunderclouds tend to discharge more lightning than maritime thunderclouds (Zipser and Lutz, 1994). The reason for this is that, in general, updraft speeds tend to be higher over continental landmasses than over the oceans. Sherwood *et al.* (2006) determined that lightning counts tend to be related to the amount of small ice in the top of the thundercloud. The higher updraft speeds in continental clouds are able to sustain larger quantities of small ice at the top of the thundercloud, thus enhancing the number of lightning discharges from these clouds.

Strong updrafts influence the size of the particles developing in a cloud. They tend to cause precipitation droplets to break up and they then carry the smaller particles to great heights in a cloud, where they freeze. Strong updrafts have also been known to enhance the supercooled water content in a cloud, thus encouraging positive charging of cloud particles. (Sherwood *et al.*, 2006). Avila and Pereyra (2000) postulated a theory that severe storms tend to be dominated by high effective water content and strong winds that inhibit the growth of precipitation droplets, resulting in a positive build-up of charge throughout the storm.

The ice-graupel charging mechanism in a cloud is a complex inter-relationship between the size of the particles, the temperatures within the cloud, the ELWC of the cloud, the super-saturation in the cloud, the updraft speeds, as well as the growth rate of the hydrometeors in the cloud. The mechanism is still not totally understood by scientists, but there is general agreement that this mechanism is the primary mechanism for storm electrification, especially in the mixed phase layer of the thundercloud. This theory, does not, however, negate the fact that other electrification mechanisms may also be active in the thundercloud at different stages of its development.

2.3.3 Other Charging Mechanisms

Once strong electrification has taken place in the developing stages of the thundercloud formation, it is likely that other electrification processes can begin to operate. The appearance of screening charge layers, similar to the one depicted in Figure 2.4, cannot be explained fully by the ice-graupel collision charging mechanism. It is likely that charge can be accumulated from the boundaries of the cloud through conduction and convection processes (Malan, 1963; Rakov and Uman, 2003).

The main upper positive layer attracts negative ions into the cloud from the negatively conducting air around the cloud, which is a product of the fair weather current. This current is always present, even in the absence of clouds, and results from the ions released by cosmic rays, other high energy electromagnetic radiation and from outer space (Rakov and Uman, 2003). These negative ions attach to positively charged ions at the cloud boundaries and generate a screening layer around the main positive charge region that is a few hundred meters thick. Downdrafts in the cloud then carry some of these negative screening particles down in the cloud to the lower levels. At low levels, the positive corona from the surface of the earth are attracted to the base of the main negative region in the cloud and may also be responsible for the development of the lower positive screening charge layer evident in some thunderclouds (Vonnegut, 1953; Rakov and Uman, 2003).

This lower positive layer may also be a function of inductive electrification within the cloud (Chiu and Klett, 1976). In the mixed phase region of the cloud, above the freezing level, large positively charged droplets are able to collide with the negatively charged, smaller graupels. This imparts positive charge to the riming ice particles, which fall through the cloud to the base, creating a new, or enhancing an existing positive screening layer at the base of the cloud (Chiu and Klett, 1976).

Hallett and Mossop (1974) proposed a mechanism of ice shattering associated with the riming process. When an ice crystal is growing by riming, small rime fragments break off. These fragments are charged oppositely from the main ice crystal. If the original riming crystal is positively (negatively) charged, the splinter particles will carry a negative (positive) charge. The larger remaining particles will fall in the cloud relative to the smaller splinter particles. The smaller particles will be carried upwards into the clouds on updrafts.

Inductive charging mechanisms may also play a role in enhancing cloud electrification. Once the separation of charged precipitation and cloud particles has taken place and the classic dipole structure has been established, polarization of droplets can take place. At this time, negative charges on the upper part of the polarized droplets would be transferred to ice crystals to neutralize the positive charge and leaving these ice crystals negatively charged. The particles of different charge are then separated by updrafts and downdrafts (Rakov and Uman, 2003).

Cloud electrification is thus complex and not restricted to a single process. The ice-graupel collision mechanism is most likely the dominant process during the initiation of electrification in thunderclouds and of the electrification of developing thunderclouds. Once the main charge regions have been established, conduction, convection and inductive electrification have a role to play in continuing this electrification process.

All of the theories and experiments cited above infer a charge structure within a single convective cloud. Not all systems that produce lightning, however, are single convective thunderclouds. When a cloud forms as a result of condensation of water vapour around condensation nuclei to form cloud hydrometeors, there is an accumulation of charge at the boundaries of the cloud, which results from the fair weather conduction current. Thus, all clouds are electrified to some degree (Rakov and Uman, 2003). Research has found that the charge density within some nimbostratus and altostratus clouds can be comparable to that found in cumulonimbus clouds. Lower charge densities have been found in stratus and stratocumulus clouds (Rakov and Uman, 2003).

2.3.4 Electrification in Mesoscale Convective Systems

Extensive studies into the electrification characteristics of the stratiform regions in Mesoscale Convective Systems (MCSs) have been undertaken in the last three decades (Chauzy *et al.*, 1985; Schuur *et al.*, 1991; Marshall and Rust, 1993). Marshall and Rust (1993) studied a number of MCSs and classified them into two main types: the first type is associated with a convective squall line structure trailing a stratiform region and the second takes the form of a “bow” of convective activity trailing a stratiform region. The charge structures identified in these two types of MCSs were very similar.

The MCSs with leading convective lines and trailing stratiform regions had four main charge regions in the stratiform layers. The bottom charge layer was negative and the top layer positive, with the spacing between the vertically charged layers almost the same (Marshall and Rust, 1993). They also found a fifth, smaller charge layer at the top of the cloud. Their findings corroborated earlier research undertaken by Chauzy *et al.* (1985) and Schuur *et al.* (1991).

The MCSs with “bowed” convective leading edges and trailing layers at mid levels also displayed 4 main vertical charge layers with the lowest layer being negative and the upper layer positive. There was, however, an absence of the smaller charge layer at the top of the stratiform region. The spacing between the main charge centers is approximately the same, but the second and third charge layers were found to be at specific altitudes (Marshall and Rust, 1993).

The main differences between the charge structures in the trailing regions of the two types of MCSs studied were that the “bow” edged systems had fewer vertical charge layers than the line systems and the charge polarity around 0°C was different. The line MCSs displayed negative polarity around 0°C and the “bow” structured systems, positive polarity around this temperature (Marshall and Rust, 1993). Schuur *et al.* (1991) found that the charge advection from the core convective storms at the leading edges of MCSs was important in the transition zone and part of the stratiform region. Screening layers may also be present in these zones.

Despite the observed differences in charge structures between these two types of MCSs, the cloud-to-ground lightning patterns were very similar. This implies that the upper charge structure in MCSs may be less important than the lower charge structures (Marshall and Rust, 1993). None of these studies could determine precisely where the cloud-to-ground lightning originated in the stratiform layers, but the cloud-to-ground strike polarities do indicate more elevated levels of positive lightning than is often found in isolated convective storms (Rakov and Uman, 2003).

Once there is a well established charge structure in the thundercloud, it is possible for electrical discharge processes to be initiated both within the cloud and between the cloud and other clouds or objects on the ground.

2.4 Electrical Discharge in Thunderstorms

Electrical discharges take place between the positively and negatively charged parts of the cloud (intra-cloud lightning) as well as between positive and negative charge areas of adjacent clouds (inter-cloud lightning). These discharges are most common in the developing stage of the thunderstorm, though they can take place throughout the life-cycle of the thunderstorm, and are usually the pre-cursor to the cloud-to-ground lightning.

There are also discharges that occur above convective clouds following strong cloud-to-ground discharges. These “sprites” and “elves” have been documented in a number of research studies (Kufa and Snow, 2006; Lyons *et al.*, 1998), but these are beyond the scope of this study.

Most research into the manner in which electrical discharges originate, move and die within clouds and between the cloud and the ground has been done using camera photo detection of flashes, observations of rocket triggered lightning, video observations as well as recordings of radio wave signatures of flashes (Malan, 1963; Proctor, 1991; Proctor, 1993; Rakov *et al.*, 1994; Jerauld *et al.*, 2005). There is general consensus among all of these authors as to the propagation of a stepped leader from the base of a cloud and the return stroke that ultimately results when the leader finally touches the ground. By far the most comprehensive explanation is provided by Malan (1963). The following is a summary of the theory he postulated.

Large parts of convective thunderstorm cells are negatively charged. This produces a strong electric field in the cloud that in turn affects objects on the ground by causing them to give off positive ions. All objects that stick up above the surface of the earth give off positive ions known as point discharges (also called corona). The higher the object, the greater the point discharge that it is able to generate. These point discharges move upward mainly as a results of the movement of air blowing them towards the base of the cloud. The electric field itself does play a small part in this movement, but it is not a significant cause of the movement. Not all of the objects generating point discharges have the same height or are evenly distributed across the earth. This, coupled with the fact that when thunderstorms develop the winds tend to be gusty, means that unevenly distributed pockets of air become positively charged in the space between the cloud and the ground. This uneven space charge influences the path taken by the lightning from the cloud to the ground.

In the presence of a strong negative electric field in a cloud, an initial discharge is lowered from the cloud called a leader stroke. As it moves downwards the leader leaves an ionized channel between its tip and the charge center in the cloud. This channel starts to lower negative charge towards the ground. The path taken by the leader is determined by the strength of the lines of electrical force at the tip. The irregularly-distributed pockets of positive charge, which result from the point discharges, act to divert the leader, giving the first stroke in a lightning flash its erratic appearance. When the downward-oriented leader tip reaches a point where there are two equally distributed pockets of positive charge below it, the leader will split and each branch will follow separate paths to the individual pockets.

Once a lightning channel has branched, the distribution of pockets of positive charge will determine which of the branches continue to propagate and which will cease to grow. Often the leader channel is sloped in the horizontal. Whichever branch of the channel reaches the ground first is considered to be the main channel. When the leader gets close to the ground, a strong electrical field is set up between the leader tip and positive charge on the ground. At this point the ground starts to send up a positive streamer discharge (called an upward leader) from the ground. When the downward leader and the upward leader join, an ionized channel is created that links the cloud to the ground.

It is common that a negative discharge from the cloud to the ground appears to hesitate along its passage to the ground – to travel in an almost step-like motion. It is for this reason that the leader from the cloud is often called a stepped leader. The length of each step is a function of the strength of the electrical field in front of the leader. Malan found that most intervals along a stepped leader are about 20m in length with a 50 μ sec break in between. Both Loeb (1967) and Proctor (1993) found results which indicate slightly different average lengths of stepped leaders, but both were in full support of the theory that a leader progresses from a cloud base with interruptions in its path.

Most stepped leaders advance at a speed of about one thousandths of the speed of light and carry average currents of about 300 Amps (Proctor, 1993). The width of a stepped leader can vary from 1 to 10 m (Malan, 1963). In the leader stage the negative charge is removed from the cloud and distributed along the entire leader channel to the ground. As soon as the channel reaches the ground, a very bright return stroke travels up the channel. The return stroke carries positive charge up the channel in order to neutralize the negative charge in the channel. The

return stroke has an average diameter of about 16 cm and the charge travels up the channel at close to the speed of light. The stepped leader and the resulting return stroke constitute a single lightning stroke (Figure 2.6a).

Once an ionized lightning channel is neutralized by the return stroke, it continues to conduct and very often remains luminous during the period between the termination of the first stroke and the initiation of any subsequent strokes. The time separation between successive strokes that utilize the same channel is usually about 40 to 50 milliseconds. In the event that an already conducting channel is established by a first stroke which is both stepped in nature and jagged in appearance, and that a second leader initiates from the cloud base, this leader will follow the already ionized main channel to the ground and so will not have the jagged appearance of the first stroke. Such a discharge is called a dart leader and tends to be a continuous discharge that travels at about ten times the velocity of the stepped leader (Proctor, 1993).

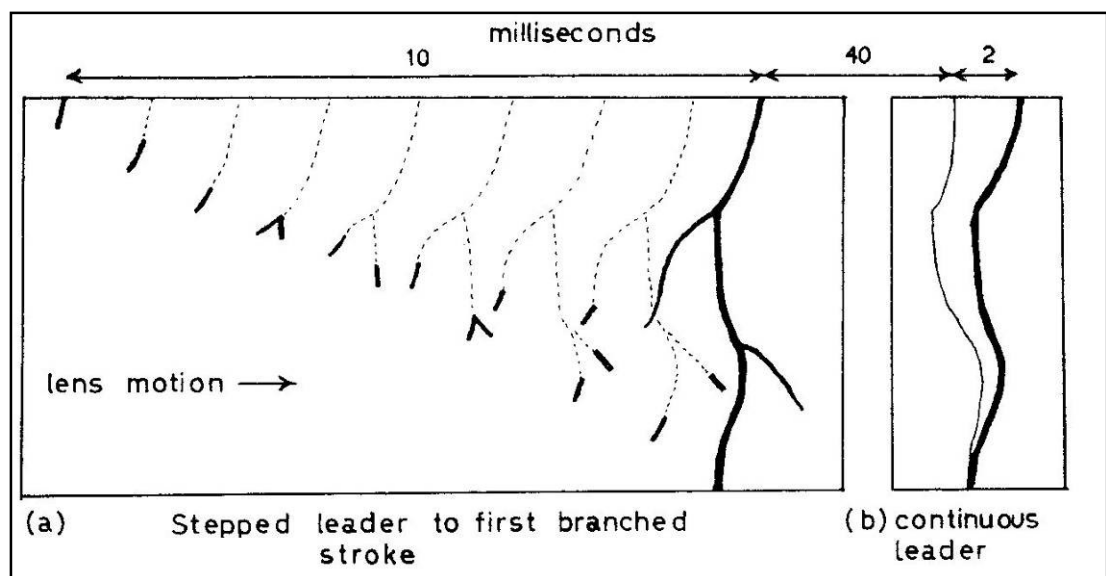


Figure 2.6: The formation of an ionized lightning channel showing the stepped leader and branching (a) and continuous propagation (b) (Malan, 1963)

Dart leaders are also followed by return strokes. In general, the longer the time interval between strokes, the lower the velocity of the discharge and the amount of energy dissipated to ground (Malan, 1963). Should 100 milliseconds pass after the termination of a previous stroke, then the channel will not have enough conductivity to guide a dart leader and the flash

will end. Any subsequent stroke will more than likely forge a new channel and will be considered as the initiator of a new flash.

The first leader in a flash does not remove all the negative charge from the cloud. Once the first return stroke flows up the ionized channel, the top of the channel at the base of the cloud becomes positively charged. A localized electrical field is set up between the channel top and the rest of the negative charge zone in the cloud. Positive streamers are set up that radiate upwards and spider outwards within the lower reaches of the cloud (Figure 2.7). These streamers, called J-streamers, ionize the air between the negatively charged cloud particles and so dissipate positive energy into the cloud. These streamers are often seen as continuing luminosity in the cloud between successive cloud-to-ground strokes (Malan, 1963).

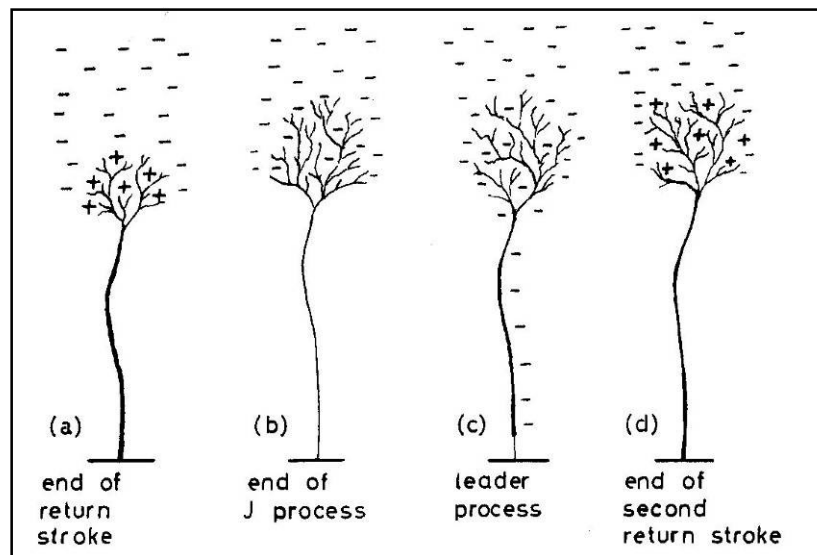


Figure 2.7: The formation of J-streamers in a cloud in order to dissipate positive energy within the cloud (Malan, 1963)

Once all the positive energy has dissipated into the cloud, a region of negative energy re-establishes itself at the base of the cloud and, depending on the time lapse since the termination of the first stroke, either a dart leader is generated or a new stepped leader is initiated. Following the termination of the second return stroke at the base of the cloud, a positive region is once again established and the process repeats itself until all the negative charge in the cloud has been removed or neutralized.

Should a very strong negative charge zone re-establish itself at the base of the cloud following positive energy dissipation after a first return stroke, then a continuous discharge of energy can take place down the established channel. This long-continuing stroke lasts for 40 milliseconds or more (Figure 2.6b). Long continuing strokes seldom occur as single strokes in flashes or as the first stroke in multiple flashes – flashes consisting of more than one stroke (Kitagawa *et al.*, 1962).

Cooray (1997) found that all of the charge that was brought down to ground by a stepped leader was stored on the channel as it was progressively extended by successive steps in the leader, but that this was not the case with a continuing stroke. Very little charge was stored on the channel in a continuing stroke with most of the charge moving directly down the channel to the ground. The multiplicity of flashes with long continuing strokes tends to be low since these continuing currents result in large, but slow discharges of energy to ground (Figure 2.8).

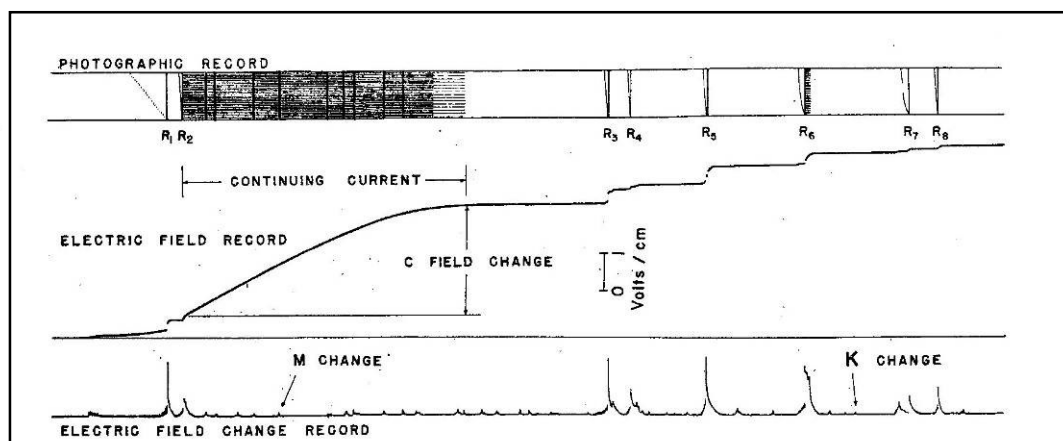


Figure 2.8: The detection of a long continuing stroke from photographic evidence and from electric field change records for a cloud-to-ground lightning flash with multiplicity of 8 where the third stroke was a long continuing stroke (Kitagawa *et al.*, 1962).

Lightning strokes that lower positive energy to ground are not as common as their negative counterparts, but tend to be more intense than negative strokes. Some of the positive regions in the cloud may be located to the side of the negative regions (Figure 2.4). Photographic studies done by Malan (1963) identified numerous horizontal discharge streamers inside the cloud, which would only be possible if the positively charged region was lying adjacent to the negatively charged center. He also found that positive charge in the upper parts of the cloud often lagged behind the negative charge, resulting in the rear of the clouds often carrying a positive charge.

Zajac and Rutledge (2001) studied positive lightning stroke distribution in the United States and found that in most cases where positive energy was discharged to the ground, the storms were either in their dissipating stage (most of the negative energy had already been brought to ground during the preceding negative cloud-to-ground events); or they were in their mature stage and accompanied by high wind shear within the storm; or were part of the stratiform regions in Mesoscale Convective Complexes (MCC); or were cold season storms. In all of these instances there is a positive charge center close to the base of the cloud. Once a positive leader is initiated at the cloud base, it does not follow the stepped progress down the channel that is demonstrated by negative stepped leaders. Instead the positive energy tends to discharge to the ground in very direct channels that persist for a fair length of time, thus allowing large amounts of energy to be dissipated to ground.

Differentiating between negative polarity stepped leaders, more direct positive strokes, continuing currents and subsequent strokes of varying magnitudes is a complex process. The most modern technologies make use of the fact that a lightning discharge has both electrical and magnetic properties and utilizes these properties in order to pinpoint an accurate position of the stroke on the ground.

2.5 Ground Flash Detection Technology

An atmospheric sferic is a form of electromagnetic wave radiation. When an atmospheric sferic is generated by the return stroke of a cloud-to-ground lightning stroke, it is referred to as a sferic (Malan, 1963). On average, return strokes from cloud-to-ground lightning generate sferics in the very low frequency (VLF) spectral range from 5 to 10 kHz (Grandt and Volland, 1988, Grandt, 1992). The variation in time of a recorded sferic pulse is called the waveform of the sferic. The waveform gives scientists a fairly good picture of the point of origin of the pulse as well as the speed of propagation and can be recorded at great distances from the observer (Malan, 1963).

Electromagnetic waves generated by the return stroke of a cloud-to-ground lightning stroke can reach an observer in many forms (Figure 2.9). Low frequency (LF) electromagnetic waves propagate along the surface of the earth as well as by reflection through the atmosphere. The first wave to reach the observer is typically the ground wave (“g” in Figure 2.9). The first sky wave (S1) to reach the observer is a shallow wave that reflects once off the ionosphere before reaching the observer (Malan, 1963). Each successive sky wave follows a

longer reflective path to reach the observer – the second sky wave reflects twice off the ionosphere and once off the ground in the interval between the cloud-to-ground stroke and the observer and so on (Malan, 1963). Successive sky waves have smaller and smaller amplitudes and are separated by longer time intervals. The time of the day, the number of sky waves and the time intervals between successive sky waves reaching the observer give an indication of the distance of the stroke from the observer as well as the strength of the stroke (Malan, 1963).

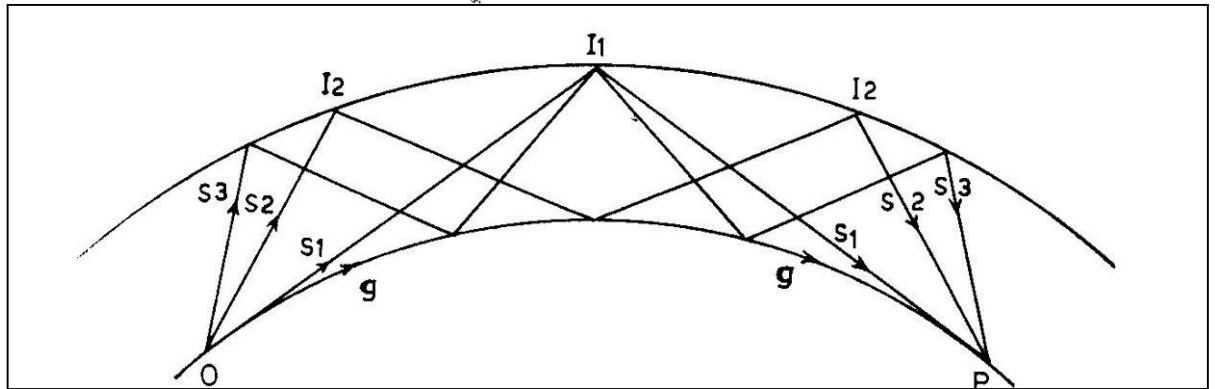


Figure 2.9: Propagation of low frequency electromagnetic waves (Malan, 1963)

Lightning discharges generate radiation field pulse signatures in different frequency ranges (Figure 2.10). Lightning detection sensors that are designed to detect cloud-to-ground lightning utilize two frequency ranges, the VLF and the LF ranges. This is to ensure that the ground propagation wave is recorded and not any of the reflected sky waves. The VLF detectors (1 to 10 kHz) record the strengths of the return strokes by detecting the components of the signal that propagate along the ground (VAISALA, 2004a). In order to identify whether return strokes are associated with the initial stepped ionization of a negative cloud-to-ground stroke or are successive strokes in a flash or even positive cloud-to-ground strokes, the LF (10 to 100 kHz) wave signals are analysed. Most sky waves detected in the LF range are usually rejected by the positioning algorithms due to the fact that their waveforms differ from those of the detected ground waves.

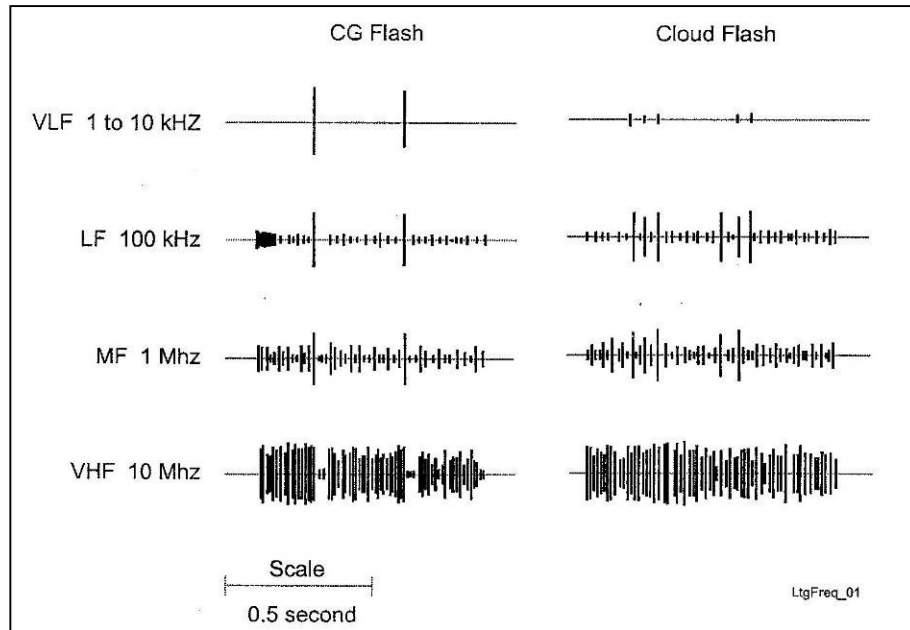


Figure 2.10: Cloud-to-ground and cloud flashes at various frequency ranges (VAISALA, 2004a as adapted from Malan, 1963).

The first return stroke of a cloud-to-ground flash is usually preceded by a stepped process that consists of a number of consecutive pulses of current. The waveform of an atmospheric originating as a stepped leader followed by a return stroke is depicted in the LF range as a strong radiation pulse that is preceded by a number of small pulse disturbances (Krider *et al.*, 1980; Malan, 1963). Following the first return stroke, there is a lull before the second stroke propagates down the already established channel. Any smaller disturbances between successive return strokes do not reflect the stepping process, but rather the dissipation of J-streamers in the cloud.

2.5.1 Basic Direction Finding Principals

All magnetic direction finders (MDF) utilize two or more sensors to determine the azimuth (the angle from true north) between the sensor and the lightning stroke (VAISALA, 2004a). Most magnetic direction finders in use around the world, use some form of magnetic antennae setup. These can either take the form of two loops set up at right angles to each other or may be four separate antennae erected at the corners of a cubic structure within the lightning detector. These magnetic antennae are usually erected on a flat plate electric antenna to detect polarity and electromagnetic field strength (Krider *et al.*, 1980). The bandwidths of the antennae are set quite wide (1 kHz to 1 MHz) in order to preserve the shape and polarity of

the lightning field waveform (Figure 2.11). Each MDF is configured to distinguish the unique cloud-to-ground electric and magnetic field waveforms so as to exclude the detection of most cloud lightning or background noise (Peckham *et al.*, 1984; Wacker and Orville, 1999).

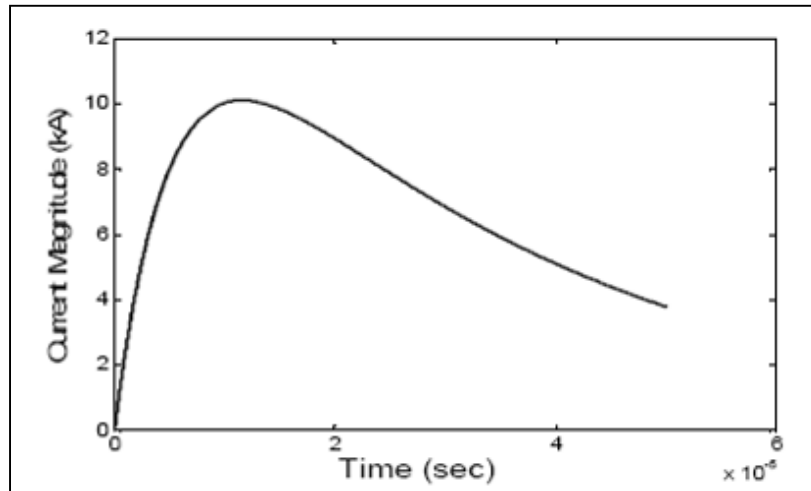


Figure 2.11: Typical return stroke impulse current waveform (Razzak *et al.*, 2004)

Krider *et al.* (1980) explain in detail the waveform configuration of a MDF. The field in the first return stroke of a flash must rise to peak within about 20 μ s. No successive peak can exceed that of the first peak by more than 15%. The electric field generated by the return stroke must have a positive polarity and must remain positive for at least 15 μ s after the first peak. When the ground wave from a return stroke is detected, the magnetic direction is determined at the precise time that the stroke field reaches its first peak.

The incoming magnetic field from any lightning return stroke sets up a current in each one of the magnetic antennae in the lightning detector. This field strength or voltage is proportional to the lightning magnetic field multiplied by the cosine of the angle between the plane of the antenna and the direction from which the magnetic wave was initiated (Krider *et al.*, 1980; Reap, 1986). From the ratio of the signals in the different magnetic antennae, the direction of the lightning stroke can be determined (Krider *et al.*, 1980). If only MDFs are used, then 3 or more sensors are required to determine this optimal location (Figure 2.12). Most modern sensors, however, utilize both MDF and Time of Arrival (TOA) techniques to pinpoint a stroke position.

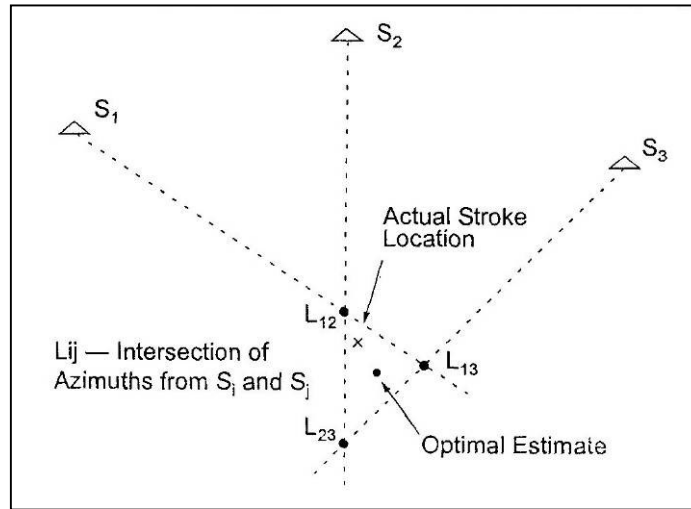


Figure 2.12: Optimal Location Algorithm for Magnetic Direction Finding (VAISALA, 2004a)

2.5.2 Time of Arrival (TOA) Algorithms

In addition to using MDF technology, the latest technology lightning detection sensors utilize two TOA algorithms: the hyperbolic method and the circular method. The first algorithm requires at least three sensors in order to provide a possible stroke location. Each pair of sensors provides a set of possible longitude / latitude co-ordinates based on the difference in arrival time between the two sensors. These co-ordinates generate a hyperbolic curve. If three sensors detect a stroke, two hyperbolic curves are generated that may have a unique intersection point or two intersection points (VAISALA, 2004a).

In order to either refine the calculated location or to resolve the ambiguity of a double solution to the hyperbolic location calculation, a second method, the circular intersection method, is used. The estimated time of the lightning discharge as determined from the hyperbolic calculation is used to place a distance range circle around each sensor. The point of intersection of all of the circles as well as of the hyperbolae provides the optimal position of the lightning stroke (Figure 2.13) (VAISALA, 2004a).

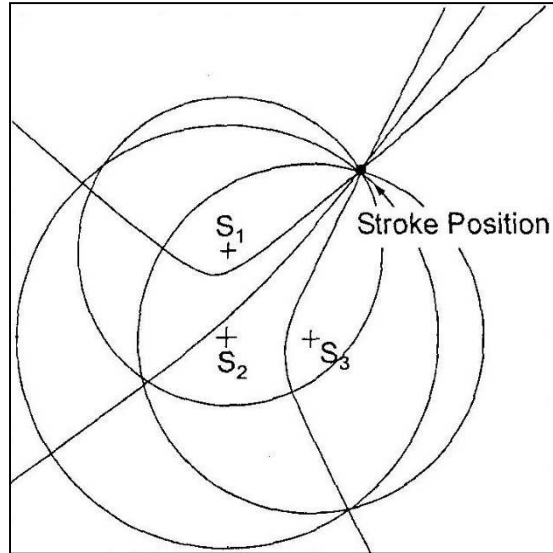


Figure 2.13: Optimal location of a lightning stroke using TOA algorithms (VAISALA, 2004a)

2.5.3 Combined Technology

Using a combination of MDF and TOA technologies, it is now possible to obtain an accurate lightning location from only 2 sensors, even if the lightning occurs on the baseline between the two sensors (Figure 2.14) (VAISLA, 2004a). Most MDF networks reported the accurate position, polarity and magnitude of the first stroke of a lightning flash (Idone *et al.*, 1993). The more sophisticated MDF sensors were able to determine flash multiplicity by counting all strokes that occurred within network-specified time frames and distances of the initial stroke (Cummins *et al.*, 1998).

It is not possible, even with combined MDF and TOA technologies to obtain a lightning ground stroke position, which is 100% accurate. It is, however, possible to determine the degree of accuracy of the calculated lightning solution.

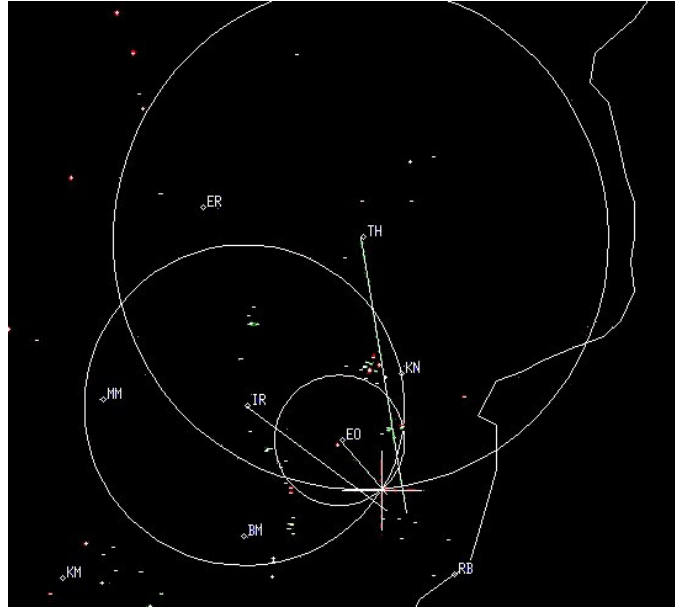


Figure 2.14: Demonstration of the combined MDF and TOA lightning location technique from the SAWS LDN. Magnetic directions are shown as straight-line vectors and range information is represented by TOA circles.

2.5.4 Location Accuracy

The Location Accuracy Model has been developed to calculate the error ellipse for stroke location accuracy. The model is a two-dimensional Gaussian distribution model for determining location errors (Figure 2.15). An assumption is made that the two-dimensional errors in latitude and longitude are Gaussian in nature and that the optimal stroke location is the point at the peak of the distribution (Cummins *et al.*, 1998).

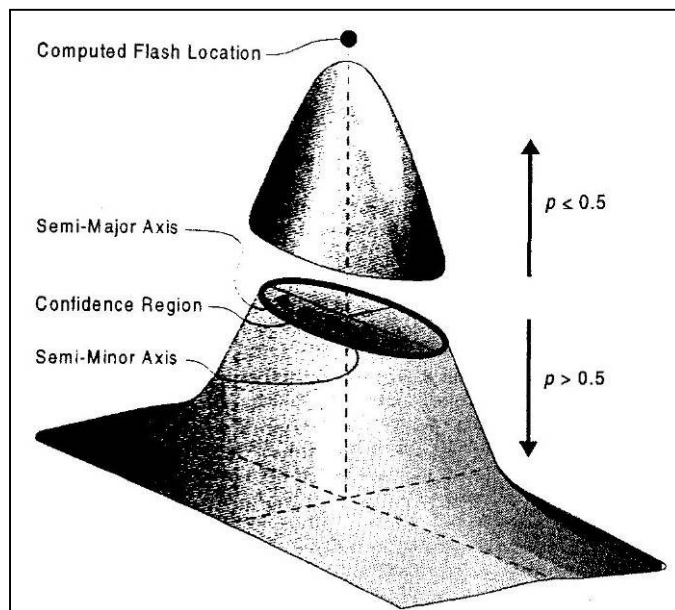


Figure 2.15: Two-dimensional Gaussian distribution of location errors (Cummins *et al.*, 1998)

In the SAWS LDN, the reference probability level is always 0.5, so that the error ellipse describes the median location accuracy. The 50% error ellipse is thus defined as the confidence region for which there is a 50% probability that the actual stroke lies within the area circumscribed by the ellipse, with the center of the ellipse being the most probable stroke location (Jerauld *et al.*, 2005). The shape of the error ellipse for any stroke depends on the location of the stroke relative to the sensors (Cummins *et al.*, 1998). The confidence ellipse for each stroke is described in terms of the length of its semi-major axis, the length of the semi-minor axis, its eccentricity (the ratio of the semi-major axis to the semi-minor axis) and the orientation of the semi-major axis in degrees from true north (VAISALA, 2004a).

2.5.5 Calculation of Peak Current

The peak currents of the return strokes are estimated from the peak magnetic field strengths measured by the sensors. The problem with this is that the magnetic signal often becomes attenuated with distance (Jerauld *et al.*, 2005). In order to combat this problem, the Range Normalised Signal Strength (RNSS) algorithm was developed that normalizes the signal strength to 100 km from the individual sensors reporting the stroke (VAISALA, 2004a; Cummins *et al.*, 1998; Cummins *et al.*, 2006).

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The thunderstorm distribution across South Africa is controlled by the influx of warm moist air from the Indian Ocean. Local forcing in the form of excessive heat at the surface or topography results in the formation of single cell thunderstorms. Larger synoptic scale forcing results in the formation of line thunderstorms or Mesoscale Convective Complexes. Once electrification has taken place within these developing thunderclouds, lightning is discharged within the cloud or between clouds or between the cloud and the ground. The ground-terminating discharges are detected by the SAWS LDN and accurate locations of these discharges are calculated by making use of both MDF and TOA techniques.

## CHAPTER 3

### Data and Methodology

*The methodology applied in this research is to use the lightning cloud-to-ground flash data for 2006 from the SAWS LDN and to calculate statistics for different components of the data against a grid across South Africa and the surrounding oceans. GIS software has been used to map these statistics in order to facilitate the analysis and interpretation of the results. The methodology utilized in the interpretation of the data from the NLDN will be adopted in this study for comparative purposes.*

#### 3.1 Data

In 2005 the SAWS purchased and installed 19 LS7000 combined technology lightning detection sensors across South Africa (Figure 3.1). The network installation was completed in late December 2005. The calendar year from January to December 2006 is thus the first complete year of data from the LDN that can be analysed and exploited both from a research and a commercial perspective.

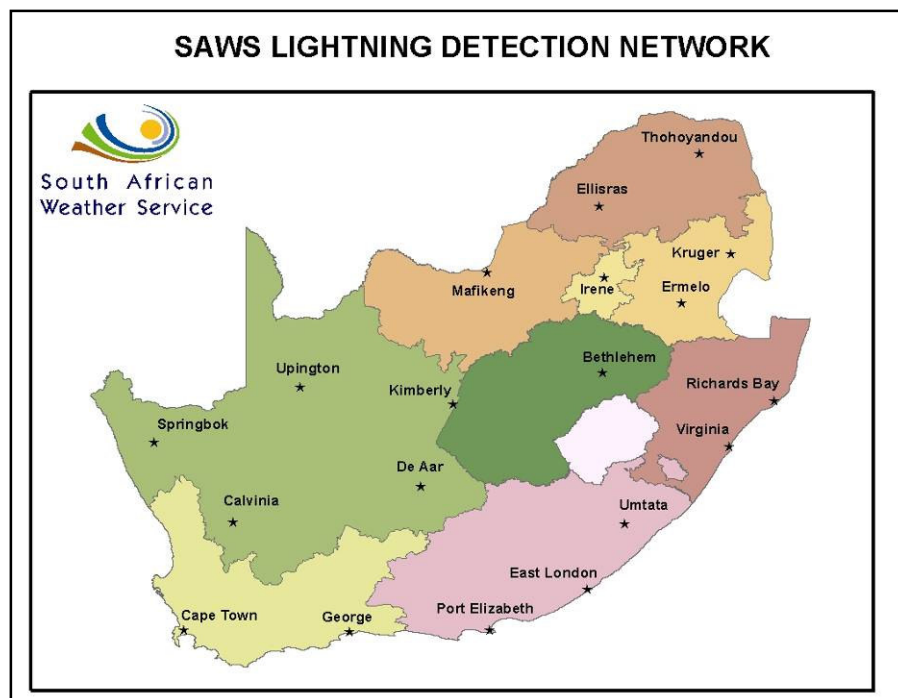


Figure 3.1: The SAWS LDN sensor sites (SAWS)

The SAWS LDN is one of a few lightning detection networks in the world to consist exclusively of combined technology sensors. Most other detection networks are older than that of the SAWS and thus consist of a mix of sensors that utilize only MDF technology as well as more modern sensors that utilize combined MDF and TOA technologies (Krider *et al.*, 1980; Orville, 1991; Wacker and Orville, 1999; Cummins *et al.*, 2006; Kuleshov *et al.*, 2006; Morales, 2005; Silveira, 2005). The advantage of having combined technology sensors reporting lightning discharge information from the inception date of the LDN is that both lightning stroke data and flash data are derived for the entire history of the network. The countries operating sensors utilizing mixed technologies are only able to analyse the lightning flash information since most MDF sensors only record flash data (Krider *et al.*, 1980; Murphy, 2007).

In order to generate an initial climatology of lightning in South Africa, only the flash data from the LDN will be utilized. The primary reason for this is to be able to do comparisons with research that has been undertaken in other countries. The second reason is that the initial projections of the detection efficiency and location accuracy of the SAWS LDN were generated by the suppliers of the network for flash data only. A theoretical placement of sensors was performed in the planning phase of the SAWS LDN in order to generate maps of projected detection efficiency (Figure 3.2) and location accuracy (Figure 3.3). This theoretical exercise was performed using the NPEP model that was developed in the United States and which originally utilised lightning information from the National Lightning Detection Network (NLDN). The NLDN consists of an amalgamated network of detection sensors from Canada and the United States (Orville *et al.*, 2002).

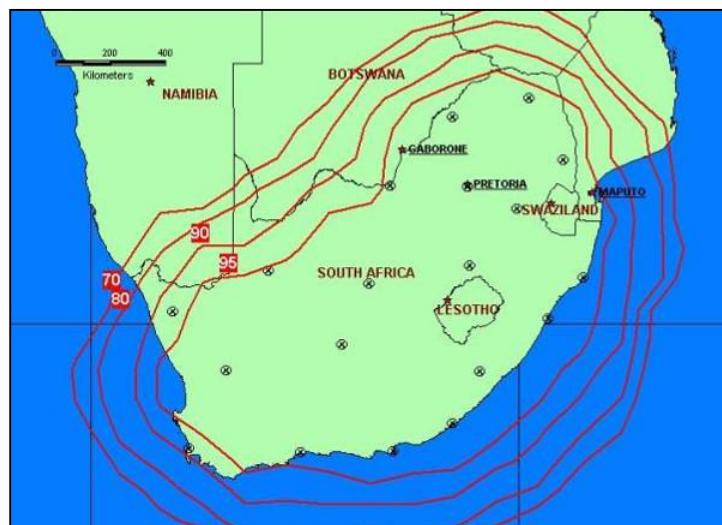


Figure 3.2: Projected detection efficiency (%) of cloud-to-ground lightning flash data for the SAWS LDN from the VAISALA NPEP model (VAISALA)



Figure 3.3: Projected location accuracy (km) of cloud-to-ground lightning flash data for the SAWS LDN from the VAISALA NPEP model (VAISALA)

The projected detection efficiency for the SAWS LDN for flash data is 90% over most of the country and the location accuracy is 0.5 to 1km. The SAWS LDN maintains the use of the 50% probability ellipse in the calculation of the location accuracy of the network. This is so that the median location accuracy can be used to evaluate the performance of the network against the theoretical contour maps of median location accuracy of 500 m generated by the technical experts who installed the network (Figure 3.3).

Testing the accuracy of these projections is very difficult and can only be achieved through some form of physical verification. Such physical tests involve either the use of video recording of flashes (Idone *et al.*, 1998a, b) or rocket-triggered lightning verification (Jerauld *et al.*, 2005; Rakov and Uman, 2003). No such verification has yet taken place in South Africa and so these figures have been accepted for the purposes of this research. The range of each of the SAWS sensors has been restricted to 625 km in order to try to fulfill the projected detection efficiency and location accuracy. In all of the calculations performed in this study, no corrections are made for the detection efficiency and all data has been utilised as it was recorded by the network.

Due to the sensitivity of the combined technology sensors, there is an increase in the detection of cloud lightning that is often erroneously interpreted by the system as cloud-to-ground lightning. Cummins *et al.* (1998) found that most positive strokes with peak current strength less than 10 kA were more than likely cloud discharges. The data that has been used in this study therefore excludes all strokes with recorded amplitudes of less than 10 kA.

Strokes are clustered into flash data by making use of a spatial and temporal clustering algorithm that is also in use in the NLDN. All strokes are considered to be part of a single flash if they occur within 1 second of the initial return stroke, within 10 km of the first stroke and with a time interval of less than 500 milliseconds from the previous stroke. If a stroke is calculated to be part of two flashes, it is placed in the flash with the closest first stroke. If the stroke meets the time criteria, but it is outside the 10 km radius requirement while still being within 50 km of the first stroke with its location accuracy ellipse overlapping that of the first stroke, then it is included as part of the flash. Finally, if a flash consists of more than fifteen strokes, the sixteenth stroke is considered to be the first stroke of a new flash (Cummins *et al.*, 1998). Knowing the average number of strokes in a cloud-to-ground lightning flash, or the multiplicity of the flash, is important when analyzing the intensity of the lightning.

### **3.2 Methodology**

All of the 2006 lightning flash data for South Africa and within a 100 km radius of the outer sensor positions in South Africa was downloaded and mapped onto a  $0.2^\circ \times 0.2^\circ$  grid across the country using ESRI ArcGIS software. A grid of this size was selected because  $0.2^\circ$  covers a distance of roughly 20 km and falls within the range of audible thunder. This is also the resolution used in most analyses of the NLDN and so will provide an interesting comparison base to other pieces of research of a similar nature. The following statistics were calculated for each grid box: lightning ground flash density, the median peak current and the average flash multiplicity. These statistics were calculated for lightning of both negative and positive polarity and a further statistic, the percentage of positive flashes, was also calculated. In order for any calculated statistics to be valid, they need to be based on a reasonable sample of data. Flash densities and percentage of positive lightning were calculated for all the grid boxes, irrespective of the number of flashes recorded in the specific grid box. All other statistics were only calculated for the grid boxes that contained 100 or more flashes (VAISALA, 2004a). Maps of the spatial distributions of these calculated lightning statistics were then generated using the ArcGIS software.

All maps were generated for the entire year and then for each of the months of the year. For discussion purposes, graphs of comparative monthly statistics were generated in order to analyse the seasonal distribution of the lightning. The analyses will focus on the interior of South Africa, but will at times include some discussion of the lightning over the surrounding oceans. No discussion of the lightning characteristics beyond the northern borders of the

country will be undertaken. The discussion of lightning over the oceans will be restricted to a distance of 100 km from the coast of South Africa. The reason for this is that the detection efficiency of the LDN deteriorates towards the periphery of the network. Any lightning detected at a distance of more than about 100 km from the outer ring of lightning sensors is very often a false recording since it may be the reflection of more distant lightning off the ionosphere (Zajac and Rutledge, 2001; Murphy, 2007). The patterns of lightning distribution will be analysed as a function of topography, latitude, longitude and the influence of mesoscale and synoptic weather systems.

In order to fulfill the four main objectives of the research, information pertaining to each objective will be analysed in a separate chapter.

### *3.2.1 Objective 1: Lightning Ground Flash Density*

Lightning ground flash densities are a function of the influence of topography, land-sea interactions, latitude and longitude (Reap, 1986; Mackerras and Darveniza, 1994; Orville and Huffines, 2001; Zajac and Rutledge, 2001; Orville *et al.*, 2002). The influence of each of these variables is discussed with respect to the ground flash density distribution of the SAWS LDN. Initially the general flash distribution for the year is discussed. Thereafter, a discussion of the flash distributions of positive and negative polarity lightning takes place, with an emphasis on the distribution of the percentage of positive lightning.

Originally the maps of positive ground flash density were plotted at the same scale as those of negative ground flash density. The results were maps of a single colour in the lowest category for positive polarity lightning, since positive flash densities seldom exceed 1 flash per square kilometer for the year. Of the 8,892,022 lightning flashes recorded by the LDN in 2006 across the grid area, only 10.7% of these lowered positive energy to ground. The flash density of positive cloud-to-ground lightning thus varies considerably from that of the dominant negative cloud-to-ground lightning. In order to analyse the spatial characteristics of positive polarity lightning, the ground flash density maps for positive lightning were redrawn at a scale one-tenth that of the negative lightning. An analysis of the spatial distribution of positive polarity lightning is undertaken using the smaller scale maps.

In order to group the months with lightning of similar flash distributions for the seasonal analyses, graphs of monthly lightning amount and percentage of positive lightning were determined. As a result, the monthly flash distribution maps are grouped by season and are

discussed in order to highlight the differences in the seasonal cloud-to-ground lightning flash density distributions. For purposes of the seasonal analysis, summer is represented by the months from January to March, autumn and winter by the months from April to September and spring and early summer from October to December.

The analysis concentrates on flash density distributions of both polarities and on the percentage of positive lightning. The flash density maps and the negative flash density maps for each month very closely resemble each other. The spatial analysis was thus performed on total flash density, the density of positively charged lightning and on the percentage of positive lightning. The analysis of negative polarity flash density can be inferred from that of the overall density.

### 3.2.2 *Objective 2: Median Peak Current*

Not only is it important to know the spatial concentration of cloud-to-ground lightning, but it is also vital to know the exact magnitude of the risk. The signal strength of a lightning return stroke is proportional to the current flowing to the ground. Knowing the amount of current reaching the ground allows decision-makers to install the correct lightning protection for buildings and structures as well as being important for physical and meteorological studies of cloud-to-ground lightning (Tyahla and Lopez, 1994).

The distribution of median peak current (kA) will be evaluated over South Africa in order to determine the degree of agreement between the flash strength distribution and the ground flash density. This analysis will also be separated into analyses of negative polarity and positive polarity lightning and will be done for each month of the year to determine the differences in intensity of cloud-to-ground lightning for the different seasons. A number of studies in the United States have identified that the peak current for both positive and negative discharges is considerably higher in the winter months than in the summer (Orville *et al.*, 1987; Orville and Huffines, 1999, 2001). The monthly median peak currents of positive and negative lightning will be graphed and analysed in order to determine if this is indeed the case in South Africa.

It must be noted that the LDN records the peak currents of all strokes detected by the network. When running an analysis of flash data, such as in this study, only the peak current of the initial stroke is displayed. The peak current of the flash is thus taken as being represented by the peak current of the initial stroke. The assumption in this analysis is that this initial stroke

will discharge the greatest energy in the flash, with all subsequent strokes having lower peak currents.

### 3.2.3 *Objective 3: Mean Flash Multiplicity*

The amount of current reaching the ground in short periods of time is a function of the multiplicity of lightning strokes within a single flash. Knowing whether a lightning flash consists of one or more strokes has important implications for lightning protection and lightning test standards (Rakov *et al.*, 1994). Since the LDN records the peak current of the initial stroke in a flash, an analysis of the multiplicity is critical in determining how much energy is potentially being discharged in a single flash.

The SAWS LDN is one of two lightning detection networks in the world that records flash multiplicity data, the other being the NLDN in the USA. This is due to the fact that both of these lightning detection networks consist entirely of MDF and TOA technology sensors. Comparative analysis with international research is thus limited to the results reported for the USA (Orville and Huffines, 2001; Orville *et al.*, 2002). The only other research into flash multiplicity has been conducted on individual thunderclouds by making use of video records and electric field measurements. In these studies it was found that the average negative stroke multiplicity is 4.6, 6.4, 3.4 and 4.5 for Florida, New Mexico, Sweden and Sri-Lanka respectively (Rakov and Huffines, 2003). Similar results were not obtained for positive stroke multiplicity since a large majority of positive flashes consist of a single stroke (Orville and Huffines, 2001; Wantuch and Szonda, 2005). The detection of subsequent strokes in a flash is not always an efficient process. In general, the first stroke in a flash is usually more intense than any of the subsequent strokes (Rakov *et al.*, 1994). It is often the case that the subsequent strokes are considerably weaker than the first stroke and so will not be detected by a lightning detection system (Rakov *et al.*, 1994; Cummins *et al.*, 1998; Rakov and Huffines, 2003). It is for this reason that calculations of multiplicity are often under-estimates of reality (Orville and Huffines, 1999) and over-estimates of the percentage of flashes consisting of single strokes (Orville *et al.*, 2002; Rakov and Huffines, 2003).

In the course of 2006, problems were identified with the earthing of some of the SAWS Lightning sensors. Copper earthing radials were installed at all sensor sites in November and December of 2006 to address the earthing problem. The poor earthing of the SAWS LDN sensors will most likely have the greatest impact on the recording of stroke multiplicity than on any of the other lightning characteristics discussed thus far. The purpose of installing a

copper earthing radial around a sensor with a poor performance is to improve the ground conductivity around that sensor. Electromagnetic waves cannot propagate efficiently through the ground if there is high impedance. Sensors surrounded by poorly-conducting ground will not always be able to accurately detect lightning signals and so may not detect subsequent strokes in flashes. The fact that many of the SAWS LDN sensors did not have earthing radials installed in 2006 can lead to an over-estimation of the percentage of single strokes as well as the under-detection of subsequent strokes in a flash. Since the impact of the earthing problem on some of the sensors cannot be determined, the analysis will proceed without making any compensation for poor earthing. As successive years of data are added to the data for 2006, any bias presented by the 2006 data should gradually diminish.

Rakov *et al.* (1994) undertook a detailed study of stroke multiplicity in flashes of different polarity by making use of electric field measurements and simultaneous video records. They found that in many instances the first subsequent stroke in a flash was often more intense than the initial stroke. The algorithm to aggregate stroke data into flash data in use at the SAWS does not distinguish which stroke in the flash carried the largest charge. The peak current of the flash is accepted as being the peak current of the initial stroke. As such, the assumption throughout the analysis of stroke multiplicity in this chapter will be that the initial stroke is in fact the strongest. As a point of clarity, a flash has a stroke multiplicity value. This value has been referred to interchangeably in the literature as “flash” multiplicity or as “stroke” multiplicity. Where either term is used in this analysis it infers the number of strokes in an individual flash.

The analysis of the monthly mean flash multiplicity distributions for both polarities has been used as a third indicator of seasonal lightning intensity.

#### *3.2.4 Objective 4: The Development of Risk Indexes*

The purpose of the annual and seasonal analyses in the previous three objectives is to devise a methodology of quantifying lightning risk in South Africa. Not much literature exists on the development of risk models for lightning. Most of the models that have been developed are to service very specific needs, such as fire in the forestry or explosives industries (Caprio *et al.*, 1997; Eisenhower *et al.*, 2005; Rorig *et al.*, 2007). No references could be found to models of lightning risk that can be applied for general usage or as a precursor to more in-depth risk analysis. It is for this reason that the development of such a general model of lightning risk for South Africa is undertaken in this study.

The flash multiplicity distribution, the median peak current distribution and the ground flash density will all be compared in order to determine the areas in South Africa that have a large lightning risk. The main objective is to create three risk indexes. A very simple methodology was utilised in drafting the three risk models. All lightning information derived from the ground-flash density, the median peak current and the multiplicity was reduced to indexes ranging from 0 to 1 by dividing all values for the relevant parameter by the maximum value of that parameter. These index values were then added together and the result was once again reduced to an index in the range from 0 to 1. The original ten risk categories will be reduced to 5 equal interval categories which indicate potential degrees of risk ranging from “Extreme Risk” to “Almost Risk Free”.

The first index will be representative of the areas in South Africa most at risk from high volumes of lightning. This index takes into account the lightning ground flash density, the peak current discharge and the multiplicity of lightning of all polarity. All three of these parameters have been assigned equal importance in this linear index calculation.

The second index will be designed to specifically look at the parts of the country at risk from positive lightning damage. The emphasis on positive lightning is due to the fact that positive lightning tends to discharge greater energy to ground along channels that remain open for longer than in negative strokes (Rakov and Uman, 2003). The heating potential, and thus the fire risk, associated with positive lightning discharges is much greater than for negative polarity lightning. This index will take into account the positive flash density, the percentage of positive lightning, the median peak current and multiplicity of positive lightning flashes. All four of these parameters have been assigned equal weighting in the linear calculation of this index.

The final index is a representation of total risk from both high volumes of lightning and from lightning which is positive in nature. It is an index which aims to identify the parts of South Africa that not only experience a large amount of lightning, but also potentially experience very damaging lightning from positive discharges and high peak current negative polarity discharges. The lightning intensity and positive polarity indexes will be added together and the result normalized to unity.

Risk indexes will be developed for the annual data only, but a similar methodology can be applied to the calculation of seasonal risk indices.

### 3.3 Orientation Maps

All analyses in the ensuing chapters make reference to topographic or physical features in South Africa (Figure 3.4) as well as to climate regions of South Africa (Figure 3.5).

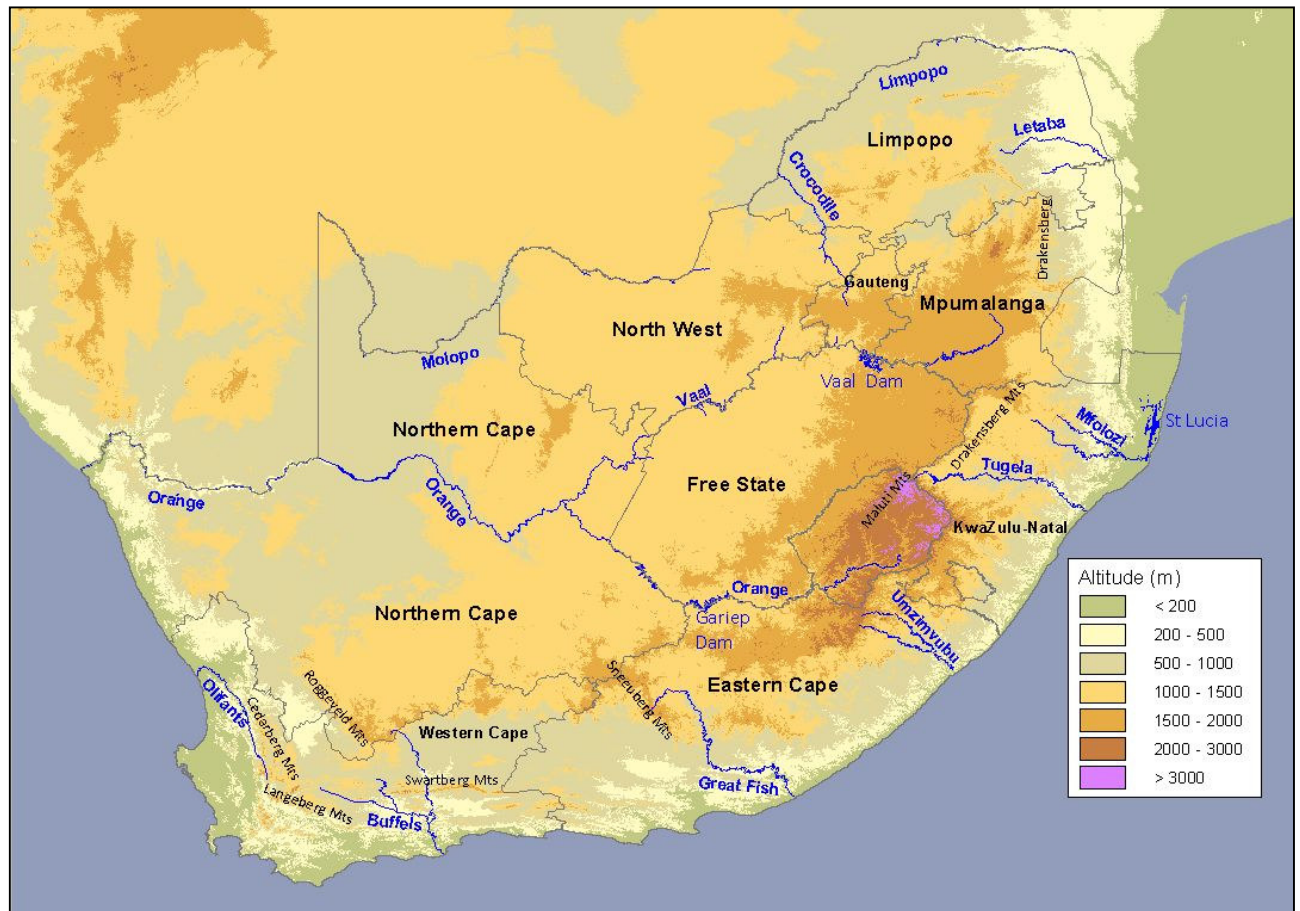


Figure 3.4: Physical map of South Africa (SAWS)

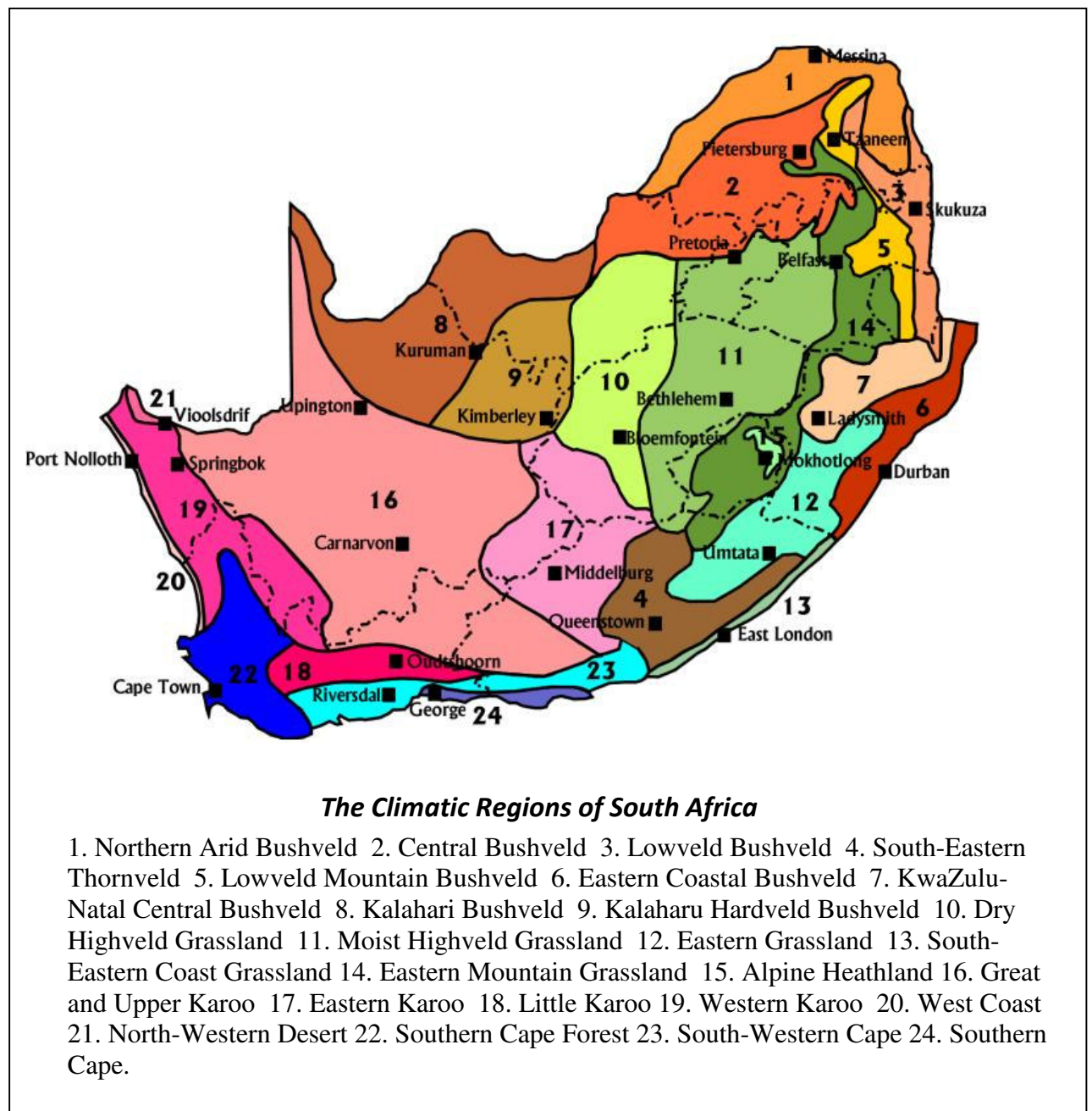


Figure 3.5: Climate regions of South Africa (Kruger, 2004)

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The proposed methodology will allow for the spatial representation of ground flash density, median peak current and mean multiplicity distributions across South Africa and parts of the ocean immediately adjacent to the coast. This spatial analysis will result in the development of indexes which will highlight the areas in the country at greatest risk from high intensity lightning as well as from damaging positive polarity lightning.

CHAPTER 4

Lightning Ground Flash Density

The mechanisms controlling the ground flash density distribution of both positive and negative polarity lightning will be discussed in general. An analysis of the seasonal lightning flash distribution will give some insight into the types of synoptic and mesoscale systems that control lightning ground flash density at different times of the year.

4.1 Ground Flash Density

It is possible when studying the distribution of lightning over a single year that the statistics can be influenced by the fact that one or two significant storms may be responsible for most of the lightning (Orville, 1991). This may be the case in South Africa for 2006 in the winter months, but so much cloud-to-ground lightning was recorded in the summer months over the country (a total of 6,220,000 flashes in January, February, November and December - 70% of all lightning for the year), that this is unlikely to be the case over the northern and central regions.

The lightning ground flash distribution for 2006 (Figure 4.1) very closely follows the topography of the country (Figure 3.4). The highest flash densities are experienced along the windward slopes of the Northern Drakensberg Mountains in Kwazulu Natal, through the Mpumalanga Lowveld region and the northern-most reaches of the Drakensberg Range in Northeastern Mpumalanga. In the summer months, the eastern parts of South Africa have all three of the critical elements necessary for convection: moisture, instability and a triggering mechanism (Watson *et al.*, 1994). Moist maritime air is fed in over the eastern parts of the country from the warm Agulhas current, which flows southwards down the east coast of South Africa. This moisture-laden air is forced to rise up the Drakensberg Mountains and the Escarpment, resulting in orographically enhanced, deep convection.

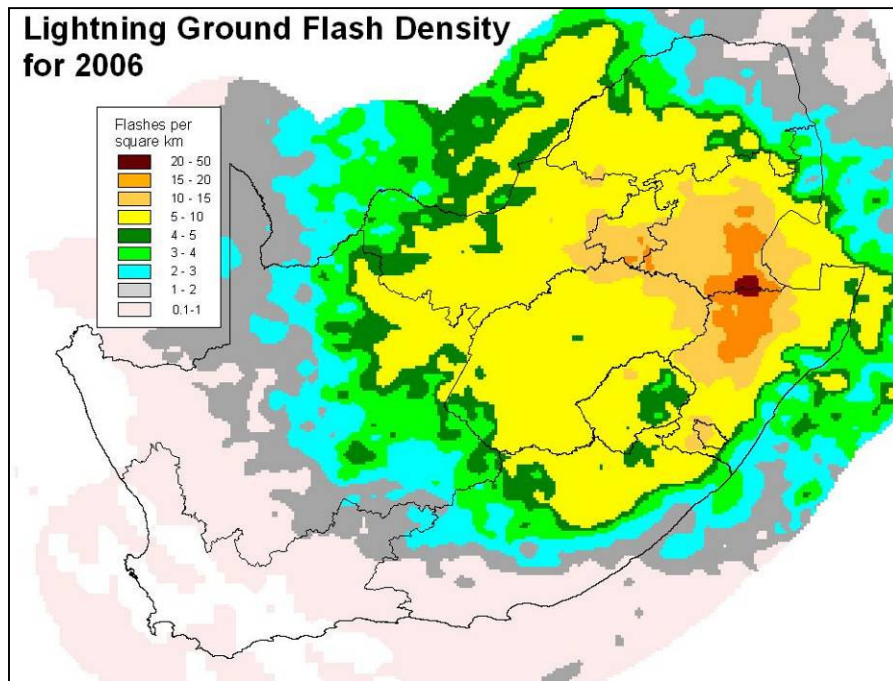


Figure 4.1: Lightning ground flash density map for 2006 as derived from LDN data.

Similar topographic enhancement of lightning intensity has been observed in Russia (Rakov and Uman, 2003), along the eastern edge of the Canadian Rockies (Orville *et al.*, 2002) and in the USA in Central Florida, the White Mountains in New Hampshire, the Mogollon Rim in Arizona, the south-eastern Mountain Ranges in Arizona, the eastern side of the Colorado Rockies and the Sierra Madre Mountains in Mexico (Lopez and Holle, 1986; Lopez *et al.*, 1997; Zajac and Rutledge, 2001).

The interior plateau of South Africa has a relatively high altitude (Figure 3.4). Altitudes on this plateau range from around 2,000 m in the east to just below 1, 000 m in the west. The entire interior plateau experiences summer rainfall. Most of this rainfall takes the form of thunderstorm activity (Preston-Whyte and Tyson, 1988). The moisture supply for this convective activity in the interior is derived from the northern tropical regions. Frequently in summer, a surface trough associated with the deep intrusion into the country of a well-defined easterly wave will result in the development of a line of convection extending from the northwest toward the southeast over the country. Such line thunderstorms are well organized and move from west to east, bringing rain and accompanying lightning to most of the Free State, North West Province, Gauteng and the higher lying areas of Mpumalanga (Preston-Whyte and Tyson, 1988).

Heat-generated, isolated or scattered thunderstorm activity is also common over the interior plateau, especially in the late afternoon. The lightning flash densities are thus high across the

entire plateau. Flash densities in excess of 10 flashes per square kilometer are observed over most of central and southern Gauteng, along the course of the Vaal River, where it forms the border between the Free State, Mpumalanga and Gauteng, over Mpumalanga and in northeastern KwaZulu Natal.

Flash densities in excess of 10 flashes per square kilometer per year are also found in the southeastern parts of Gauteng, close to the border between this province and the Free State and Mpumalanga. At the convergence point of these three provinces, the Vaal Dam, one of the largest dams in South Africa, is the most noticeable feature on the landscape. There is no evidence, however, in international studies of lightning flash densities, that large inland water bodies enhance lightning activity (Orville *et al.*, 2002). The other possible explanation for this is that that area falls into a region of both industrial pollution and of domestic biomass burning. There is some evidence for enhanced lightning activity in areas of large-size cloud condensation nuclei production, such as those associated with fires and with large industrial processes (Westcott, 1995; Orville and Huffines, 2001; Van den Heever and Cotton, 2007). A more detailed analysis of the lightning in this area would have to take place before enhanced flash densities are conclusively attributable to increased pollution.

A very small region of high flash densities in excess of 10 flashes per square kilometer is found on the border between the Northwest and Limpopo Provinces. This is in the vicinity of the Crocodile River, very close to the town of Thabazimbi. No immediate cause for this elevated flash density could be determined.

The southern and central Drakensberg Mountain regions have a lower ground flash density distribution than the northern parts of the range. The very high peaks of the Maluti Mountains in Lesotho have flash densities in the order of 4 to 5 flashes per square kilometer per year. This is in contrast to the densities of 5 to 10 flashes per square kilometer per year in the surrounding areas. Similar observations were made in the United States, where increases in flash density have been observed along the sides of terrain features up to about 3,000 m, but then this decreased towards the top of high features (Reap, 1986). Orville (1994) noted a similar pattern in the Appalachian Mountains where the flash densities over the mountains were lower than in the surrounding plains. This is most likely due to the fact that many of the convective storms will form below the level of these very high peaks or that the thunderstorms developing on the windward side of these mountains will already have lost most of their precipitation on the lower slopes.

The influence of topography can even be seen in the low flash density regions of the southwestern Cape. Along the windward sides of the Cedarberg Mountains and the Roggeveld Mountains, which are orientated from northwest to southeast, there are distinct lines of lightning activity, with little lightning in the valley between these two mountain ranges. This lightning is associated with the eastward passage of frontal systems in the winter. The lightning activity reflects a similar pattern to the rainfall in this area in winter (Bruitjies, 1988). The reason for the enhancement of both precipitation and lightning by the mountains in this region is related, in the most part, to the presence of a low-level jet stream that usually precedes the winter frontal systems (Browning and Pardoe, 1973). Moisture carried along in the jet stream is forced to rise up the orographic barrier, resulting in rapid convection associated with enhanced rainfall and lightning.

The eastern parts of the Northern Bushveld region of Limpopo Province have flash densities of less than 2 flashes per square kilometer. This is also one of the few regions in the northern parts of the country that receives less than 400 mm of rainfall on average per year. Most of the moisture required for the generation of thunderstorm activity over the summer rainfall region of South Africa is derived from troughs that develop in the easterly waves. These troughs feed moisture in over the country in a region west of the continental high pressure, which is dominant over the northern and northeastern parts of Limpopo Province (Preston-Whyte and Tyson, 1988). Thunderstorm activity over these parts of the province is thus inhibited by this high pressure system.

The flash densities decrease towards the west of the country. As one moves westwards towards the West Coast of South Africa the altitude decreases and arid conditions prevail, largely as a result of the reduction in the convective rainfall. The West Coast of South Africa is dominated by colder, drier and more stable air. This is largely as a result of the influence of the cold, north-flowing Benguela Current and the presence of the strong South Atlantic Anticyclone (Preston-Whyte and Tyson, 1988). There is very little lightning activity along the West Coast. Similar decreases in lightning flash density have been observed in Canada (Orville *et al.*, 2002) and in the United States along the California coast (Orville and Huffines, 2001; Zajac and Rutledge, 2001). These parts of North America are also influenced by colder ocean currents.

On the Southern Cape coastal belt of South Africa, the lightning ground flash densities are also low, seldom exceeding 2 flashes per square kilometer. The same is not true for the

Eastern Kwazulu Natal coastal region. Flash densities in excess of 2 flashes per square kilometer occur in a narrow band directly adjacent to the sea. In northern Kwazulu Natal, in the estuarine environment around the Cape St Lucia wetland area, the flash densities range between 5 and 10 flashes per square kilometer. Similar densities also extend out to sea at this point. Researchers in the USA have noted a similar high lightning flash density over the warm waters of the Gulf of Mexico (Zajac and Rutledge, 2001; Orville and Huffines, 2001; Orville *et al.*, 2002). This demonstrates the importance of moisture and instability in thunderstorm formation over these regions. Research has discounted the theory that enhanced lightning activity over warm oceans relates to the greater conductivity of the sea water than that of the land surface (Tyahla and Lopez, 1994; Orville and Huffines, 2001). Tyahla and Lopez (1994) indicated that individual storm characteristics may play a more important role in cloud-to-ground lightning density than the conductivity of the surface itself.

The ground flash density maps of the USA for the period from 1989 to 1998, also show a distinct zone of increased flash density where the Mississippi River flows into the Gulf of Mexico (Orville and Huffines, 2001). A similar zone of high ground flash density is visible off the Kwazulu Natal coast, just north of where the Tugela River flows into the sea. As yet, no explanation has been found for this phenomenon. Once again there may be an influence from elevated pollution levels. A paper mill and other associated industries are situated almost at the mouth of the Tugela River and large particulate production could have an influence on the flash densities in this region. The industrial town of Richards Bay is situated on the Mhlathuze River just north of the mouth of the Tugela and the pollution generated in this region may also have an impact on the lightning densities. North of Richard's Bay, there are elevated flash densities over the ocean adjacent to a part of northern Kwazulu Natal with few major pollution sources. The role of pollution in increasing lightning flash densities will thus have to be explored further in the future.

Plotting maps of flash density by polarity (Figure 4.2) highlights the fact that the phenomenon identified above is only evident in the ground flash density map of lightning of negative polarity. The map of positive ground flash density shows the northern region of higher flash density lying off the coast, but the region of higher flash density associated with the Tugela and Mhlathuze River outflows is not clearly defined.

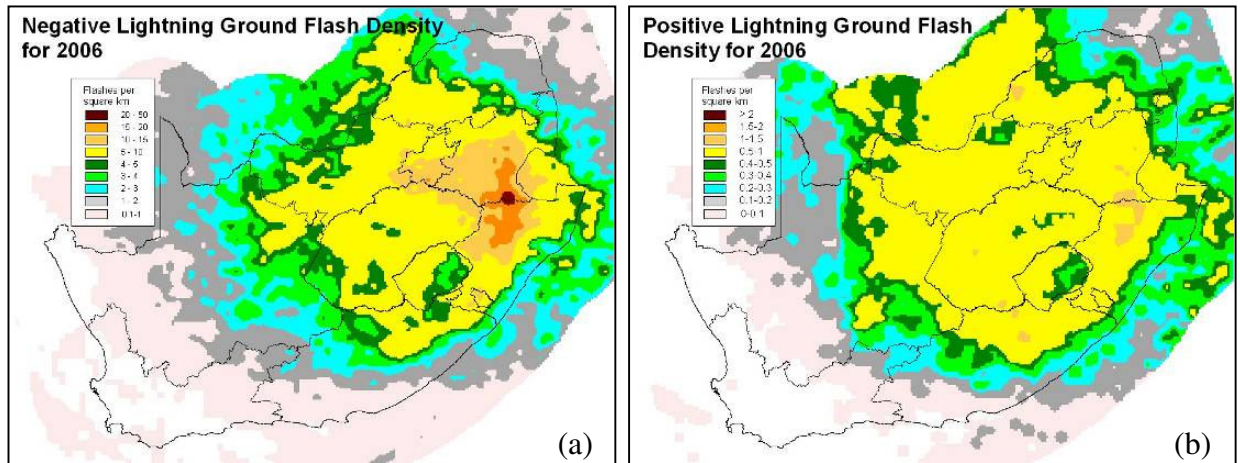


Figure 4.2: The cloud-to-ground lightning flash density of negative polarity lightning (left) and positive polarity lightning (right).

The negative flash density closely mirrors that of the general density distribution, which is reasonable since negative lightning comprises almost 90% of all lightning recorded by the LDN in 2006. The regions of higher positive lightning flash density extend further beyond the borders of South Africa and further westwards across the country than the negative flash density regions. The positive lightning densities on the outskirts of the network are often inaccurate readings resulting from the lack of triangulation capacity on the edge of the network where LDN sensors lie in a straight line, making it difficult to determine an accurate lightning solution (Zajac and Rutledge, 2001). However, the higher positive lightning flash densities in the Great Karoo region of the Northern Cape are acceptable since they lie within the interior of the LDN coverage area.

The highest positive flash densities are also found along the northern Drakensberg in a similar location to the high negative densities. An enormous amount of lightning was recorded in this area by the LDN and so it is not unrealistic for large positive densities to occur here as well. There is a broken line of high positive flash densities extending from the southern Free State, in a southeasterly direction into the northern parts of the Eastern Cape. The seasonal analysis of lightning characteristics will better identify when the more positive dominated lightning occurs in this region.

4.2 Percentage of Positive Lightning

Positive lightning is considered to be much more damaging than negative lightning since it tends to discharge large amounts of energy to a concentrated ground contact point for longer periods of time (Rakov and Uman, 2003). In a study of lightning risk, a good understanding of the climatology of positive lightning is thus critical. This in no way undermines the importance of understanding the distribution of negative polarity lightning, but is critical in understanding risk factors such as fire hazards. One of the simplest ways of interpreting the amount of positive polarity lightning is to investigate the distribution of the percentage of the total lightning that discharges positive energy to ground.

Over the regions with the highest overall flash densities, less than 10% of the lightning is positive in polarity (Figure 4.3). Over most of the northern and eastern parts of Limpopo and in a band across South Africa extending from western Northwest Province southeastwards to the Eastern Cape, approximately 10 to 20% of the lightning is positive in nature. Along a narrow band off the Eastern Cape coast in the vicinity of East London, extending into the adjacent ocean, the percentage of positive strokes reaches values of 30 and 40%.

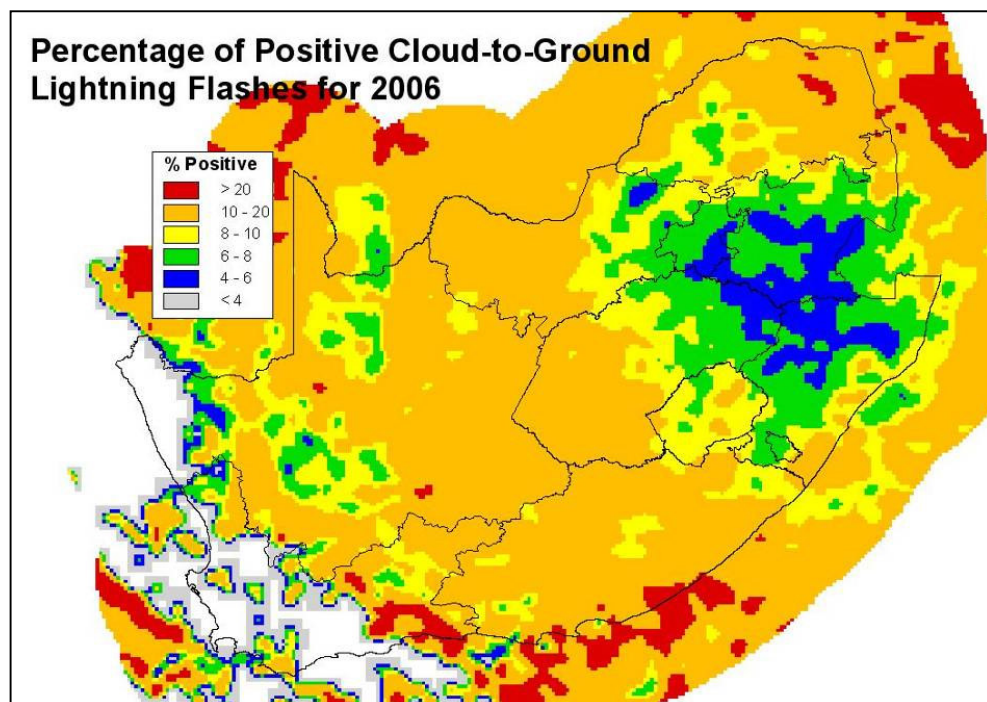


Figure 4.3: Percentage of positive lightning across South Africa for 2006.

The small percentage of positive lightning over much of the interior plateau indicates that most of the lightning in the high flash density regions tends to be negative in nature. As one

moves off the plateau towards the western and central parts of the country, the number of flashes per square kilometer starts to decrease, but the percentage of these flashes that lower positive energy remains above 10% for the most part.

There is a band of northwest to southeast oriented lightning over the ocean just off the southwestern Cape coast. This band shows a low flash density, but a high percentage of positive flashes. Up to 30% of lightning in this area is positive. Since most of the rainfall in the Western Cape is frontal in nature and occurs in the winter months, the lightning in this band is most likely associated with frontal activity and winter storms. A number of scientists have studied winter storms in Japan and have found that cold season storms, whether they be frontal in nature or not, tend to discharge a large percentage of positive strokes (Takeuti *et al.*, 1978; Brooke *et al.*, 1982; Brook, 1992).

The results found over South Africa in 2006 are supported for the most part by findings from other countries. Studies carried out in the Carpathian Basin, in Russia and in the United States have all highlighted the importance of storm type in determining the percentage of positive lightning discharged to ground (Rutledge and MacGorman, 1988; Rakov and Uman, 2003; Zajac and Rutledge, 2001; Wantuch and Szenda, 2005). In all of these international studies the same lightning characteristics were noted for particular storm types. In convective parts of Mesoscale Convective Systems, as well as in isolated, heat-generated thunderstorms, the lightning tended to be dominated by negative discharges. In the stratiform regions of Mesoscale Convective Systems and in the shallower cloud layers of frontal storms and of some summer storms, a large percentage of positive lightning was discharged to ground.

In South Africa, the regions along the escarpment and on the Highveld that have the highest ground flash densities are also those regions which tend to be dominated by strong convective processes. Many of the summer thunderstorms that develop over this region are heat generated or result from some kind of other forcing (such as orography). A large percentage of these storms are either single cell storms or well-organized multi-cell storms. Preston-Whyte and Tyson (1988) indicate that scattered thunderstorms occur on about 54% of storm days over the Highveld and that isolated thunderstorms occur on a further 39% of storm days. More than 90% of all thunderstorm activity over the Highveld is thus of the type that is dominated by negative cloud-to-ground discharges. Any positive discharges are either related to the dissipating stages of this scattered and isolated storm activity (Rakov and Uman, 2003) or to other storm types such as squall line activity.

The percentage of positive lightning increases to the west of the Highveld region. The central part of the country is very often influenced by the presence of a surface trough that is oriented from northwest to southeast over the country. Convergence occurs ahead of this trough, often resulting in well-organized line thunderstorms (Preston-Whyte and Tyson, 1988). One of the earliest models explaining the development of line thunderstorms across South Africa was postulated by Taljaard (1959) and verified by Harrison (1984). They found that vertical wind shear was an important pre-requisite for the development of such line storms. Brooke *et al.* (1982) found that vertical wind shear was a pre-requisite for the development of winter storms in Japan that were dominated by large percentages of positive lightning. It would thus appear that the development of line storms, as well as the development of thunderstorms within stratiform cloud layers over the central parts of the country may be responsible for the higher percentage of positive lightning over these parts of South Africa.

A region of high positive lightning activity occurs in the Western Cape extending inland in a northwest arc from the Plettenberg Bay area. This pattern of high percentage positive lightning extends along the Eastern Cape Coastal area and slightly offshore as far north as East London. This coastline of South Africa experiences rainfall all year round and so it is difficult to make conclusions about the cause of this high percentage of positively charged lightning without doing a thorough analysis of the lightning at different times of the year.

The monthly distribution of the lightning flash count for 2006 highlights the large differences in lightning activity from summer to winter. Most of the lightning occurred in the months of January, February and December. By comparison, the months from May to September were almost devoid of lightning activity. March, October and November also show reasonably high lightning flash counts (Figure 4.4). The fall-off in flash counts from summer to winter is very steep and the rise to spring and early summer lightning activity is equally steep. The monthly distribution of the positive polarity lightning flashes shows a similar pattern as that of the total lightning (Figure 4.4). The summer months have a larger number of positive polarity strokes than do the winter ones.

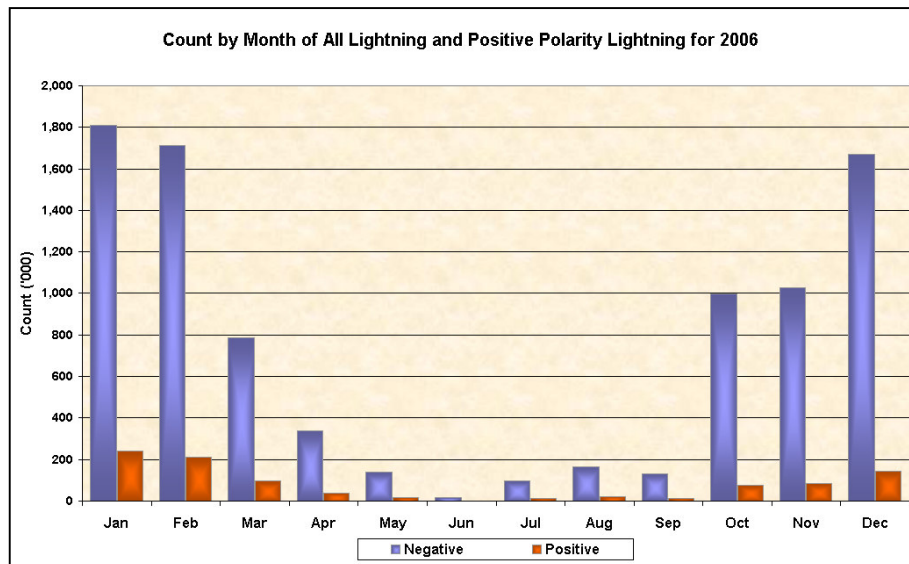


Figure 4.4: Lightning flash count of all lightning and of positive polarity lightning by month for 2006

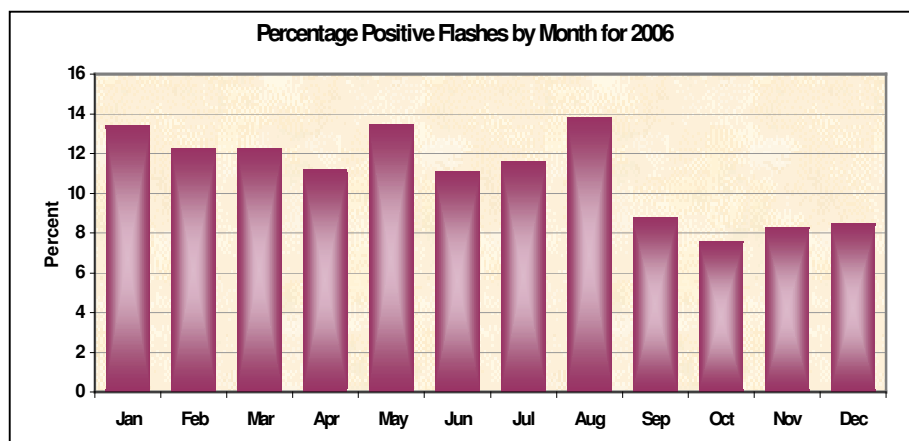


Figure 4.5: Percentage of positive lightning by month for 2006

The monthly analysis of the percentage of positive lightning for 2006 (Figure 4.5) indicates that the percentage of positive lightning was fairly constant throughout the year. The data thus does not show the distinct winter increase in the percentage of positive lightning that has been reported elsewhere. Orville and Huffines (2001) reported a distinct winter maximum in percentage of positive lightning in the USA (16 to 18% in December and January), falling off symmetrically on either side of the winter period leading to a minimum of 4-5% in July and August. They also found that this pattern was consistent from year to year. In Japan, the percentage of positive lightning discharges ranges from around 33% in winter to approximately 10% in summer (Rakov and Uman, 2003).

In South Africa in 2006, the percentage of positive lightning was above 10% from January to August, from whence it fell off by about 2%. Winter and summer months alike recorded similar percentages of positive lightning, with January, May and August all reporting percentages above 12%. The reasons for this apparent lack of high percentage of positive lightning in the winter could be twofold. In South Africa in 2006, the winter was anomalously warm and dry. Very few mid-latitude cyclones passed over the country. Of those that did reach the country, most were not strong enough to intrude very far into the interior. This situation may be different in successive years and will have to be closely monitored in years to come as more data is archived from the LDN. The second possibility is that the percentages depicted in Figure 4.5 for the entire country may be masking differences in the spatial distribution of the percentage of positive lightning in the different months.

An analysis of the seasonal spatial distributions of lightning flash density and the percentage of positive lightning follows in order to try to better understand the lightning distribution across South Africa.

4.3 Seasonal Analysis of Ground Flash Density and Percentage of Positive Lightning

The analysis that follows concentrates on flash density distributions of both polarities and on the percentage of positive lightning (Figure 4.6 and Figure 4.7).

4.3.1 Summer

From January to March, most of the lightning occurred over the escarpment and interior plateau regions (Figure 4.6 A to Ci). Of the three months, January experienced the most lightning and this was spread fairly evenly over southern Mpumalanga, Gauteng, most of Northwest Province, the Free State and most of the eastern parts of Kwazulu Natal (Figure 4.6 Ai). The highest flash densities occurred in southern Kwazulu Natal, southern Mpumalanga, southeast Gauteng and along the border between the latter two provinces and the Free State. The positive flash densities do not follow a similar distribution to the overall density pattern. The highest flash densities of positive polarity lightning are found along the Limpopo and Northwest Province borders and in the Northwest to Southeast directed band across the centre of the country.

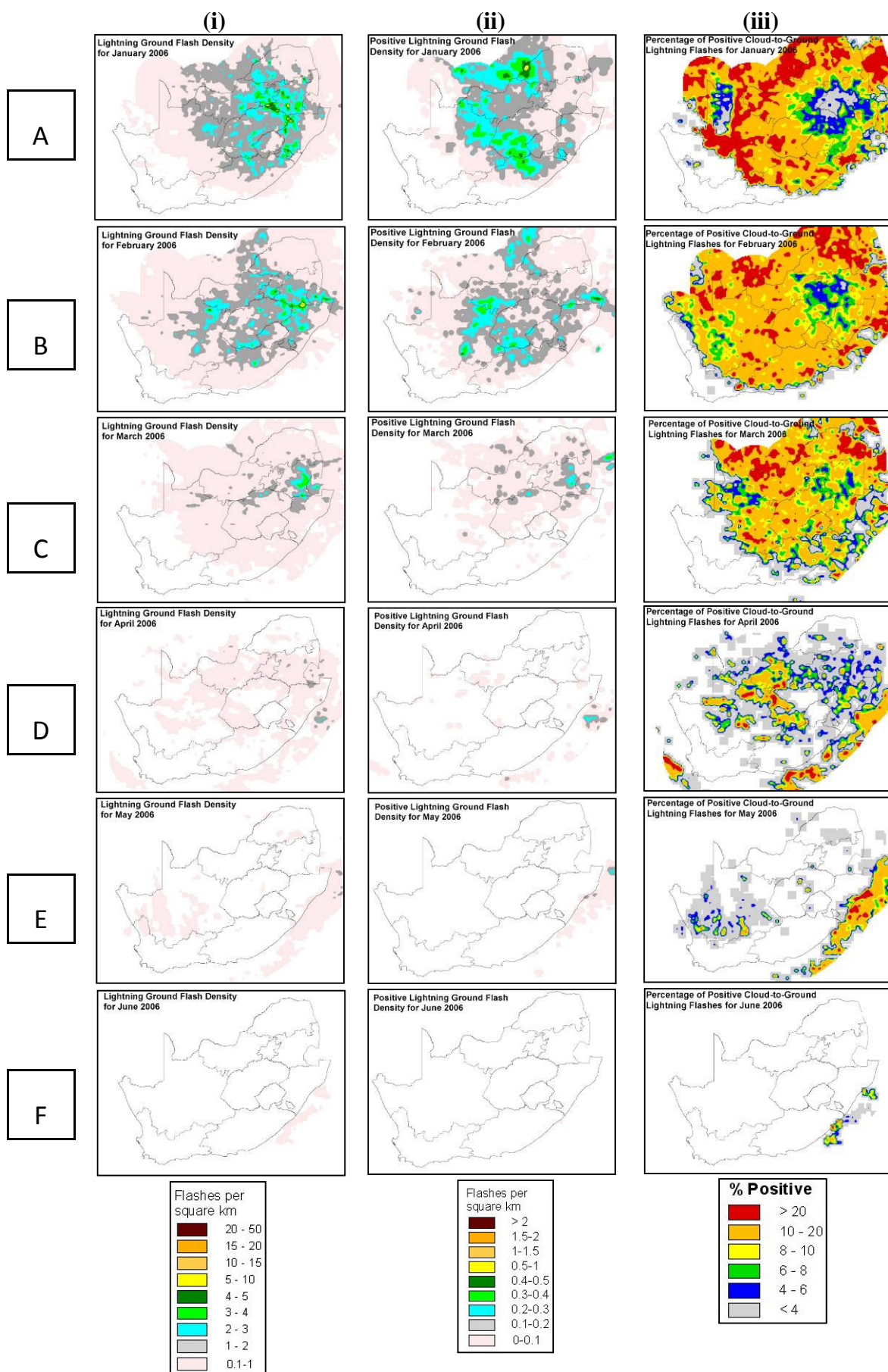


Figure 4.6: Lightning ground flash density (i), positive ground flash density (ii) and percentage positive lightning (iii) from January to June 2006 (A to F respectively).

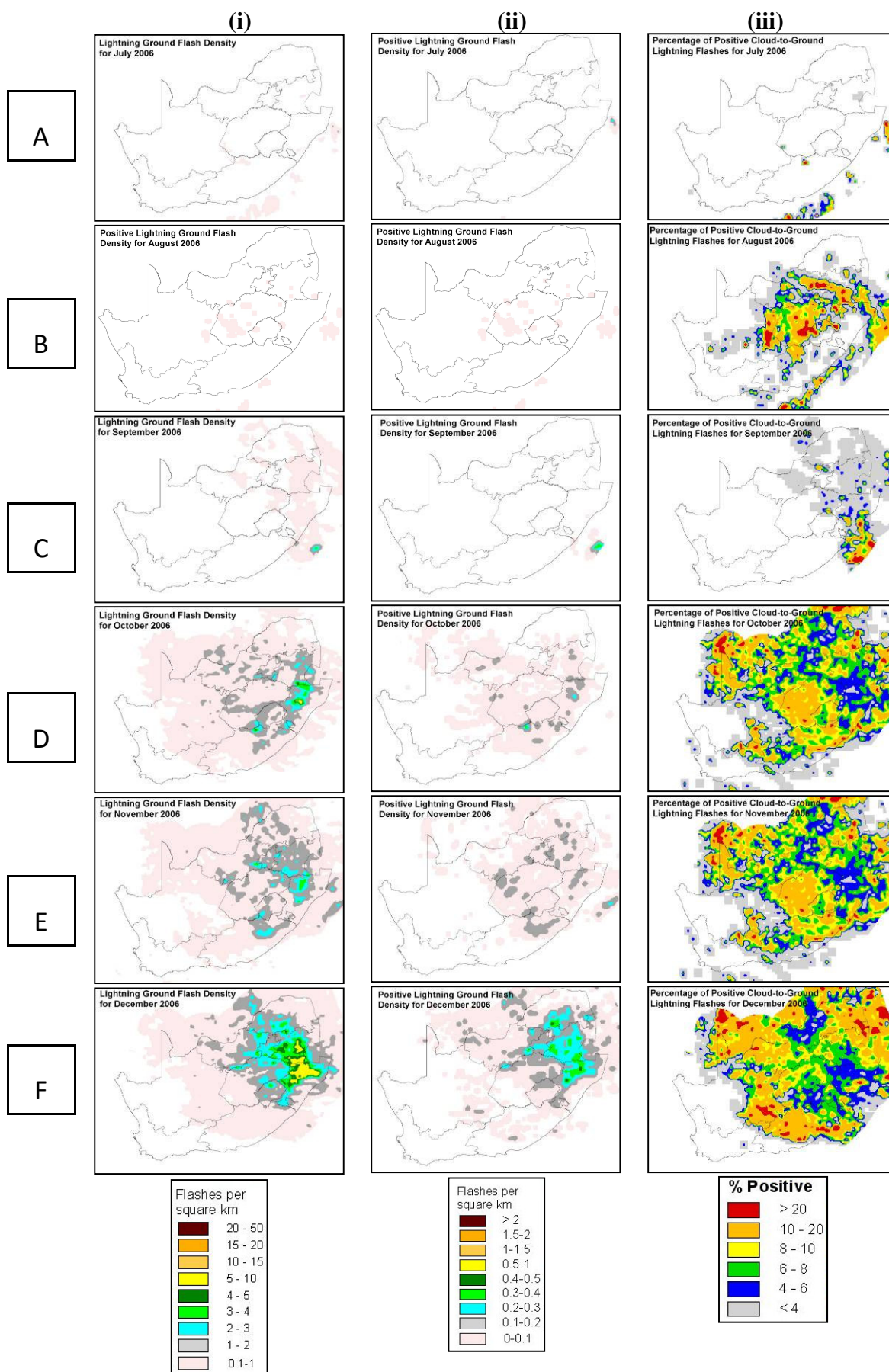


Figure 4.7: Lightning ground flash density (i), positive ground flash density (ii) and percentage positive lightning (iii) from July to December 2006 (A to F respectively).

In February, more of the country was influenced by lightning than in any other month of the year (Figure 4.6 Bi). The distribution of lightning extends to within 60 km of the West Coast of South Africa. The regions of high flash density are more patchy than in January, but still dominate the eastern and central parts of the country. The highest flash densities occur in southern Mpumalanga and northern Kwazulu Natal and extend westwards along the Vaal River. A small zone of high flash density is found on the border between the eastern Free State and the Eastern Cape along the Orange River. Another is found in the northern Eastern Cape Province and a final high-density area is visible on the border between the Northern Cape and the Northwest Province.

In March, the flash densities were considerably lower than in either of the first two months of the year (Figure 4.6 Ci). The highest flash densities were recorded in a concentrated zone in the Lowveld and Drakensberg regions of eastern Mpumalanga.

In all three months, the regions of high overall flash density are dominated by mainly negatively charged lightning. In January, the highest positive flash densities occur in a band lying across the country from the northwest towards the southeast (Figure 4.6 Aii). These are the parts of the country most affected by line thunderstorm development and which experience fewer heat-generated cells than the central Highveld region. This lightning pattern is thus indicative of the fact that the surface trough was fairly dominant in January. An analysis of the synoptic charts for this month verifies this conclusion, with the surface trough in evidence on every day of the month.

There are pockets of high positive lightning density scattered all over the summer rainfall regions of the country, but of particular interest is the distinct pocket of positive flash density in excess of 0.5 flashes per square kilometre on the border between Limpopo and Botswana. This region is well within the range of the northern lightning detectors and it is thus highly unlikely that this is a false reading as is usually found on the extreme periphery of a LDN. In January, this region recorded 42% of the cloud-to-ground flashes as having positive polarity. An analysis of the synoptic charts for January does not give much insight into why this may have been the case.

Slightly different synoptic situations occurred on all of the days that experienced a percentage of positive lightning in excess of 60%. The South African Weather Service does not have a weather station in close proximity to this site and so it is not possible to investigate the

dynamics of the storms occurring in this area on the high lightning discharge days. The concept that the phenomenon may be the result of a single large thunderstorm is not borne out by the data since the pattern is persistent throughout the month. There are also no distinguishing land features in the area that could possibly be enhancing lightning in the area. It is a phenomenon which should be a topic of future research.

The map of the percentage of positive lightning for January (Figure 4.6 Aiii) indicates that the highest flash density areas are indeed those with the least positive lightning. The regions of higher positive flash densities are also the regions with a fairly high percentage of positive lightning. The three maps for January show that, despite the fact that not a lot of lightning occurs in the western and far northern and north-western parts of the country, the lightning that does occur tends to be positive in nature.

February was a very wet month. Many parts of the country experienced rainfall well above the normal, especially parts of the Northern Cape, Northwest Province and the Free State and parts of central and northern Eastern Cape. A feature of the maps of percentage positive lightning for all three of these wet summer months is the high percentage positive lightning in the northern parts of Limpopo Province (Figures 4.6 A to C iii). These regions do not experience high flash densities of lightning, nor do they experience very high rainfalls. The small amount of lightning that does occur in these regions is thus mostly positive in nature. High percentages of positive lightning are also starting to materialize along the southern and eastern ocean areas adjacent to the coast in February (Figure 4.6 Biii). These regions follow the warm Agulhas Current, which is a source of moisture, with much of the cloud development being more stratiform in nature.

Despite the fact that there was less lightning across the country in March, a large part of the country experienced percentages of positive lightning in excess of 10% (Figure 4.6 Ciii). In keeping with the patterns of high positive lightning discharge, the regions of lowest percentage positive lightning in March were recorded in the same areas as the highest flash densities. Thus it would appear that the lightning in the Lowveld area of Mpumalanga took the form of isolated or scattered convective storms. The rainfall over the rest of the country, however, was most likely derived from stratiform cloud types. High ratios of positive to negative lightning were once again recorded in Northern Limpopo.

A feature of the January analysis is the region in the western Kalahari that is almost completely devoid of lightning. This is a phenomenon which does not persist into February and which does not occur during any other lightning month in 2006. A possible explanation for this is that the surface trough axis tends to lie diagonally over this area. Most active convergence takes place ahead of the trough axis and so it is unlikely that a lot of lightning will be recorded along the trough axis itself. Despite experiencing cloud on many of the days in January, Upington, which lies in the southern part of this low lightning area, only experienced significant rainfall on one day in the month when there was a large cold front approaching the country from the west.

Despite the fact that the amount of lightning decreased from January to March, the spatial distribution of lightning was very similar. There was a distinct zone of high negative lightning flash density over the Highveld and along the escarpment, with high percentage of positive lightning on the western boundary of the high flash density region and in the northern parts of Limpopo Province

4.3.2 Autumn and Winter

From April to September, there was not much lightning recorded over the grid area (Figures 4.6 D to Fi and 4.7 A to Ci). Most of the lightning activity occurred adjacent to the southern and eastern coastal regions. This was mainly associated with the passage of cold fronts. Large percentages of this lightning were positive in nature, as can be expected from shallow winter systems (Figures 4.6 D to Fiii and 4.7 A to Ciii) (Rakov and Uman, 2003).

In these 6 months not much lightning was recorded over the interior of the country. In April, a small amount of lightning of both polarities was detected over the Northern Cape (Figures 4.6 Di and Dii) and in August, the central parts of the country experienced some lightning (Figures 4.7 Bi and Bii). A feature of the winter of 2006 was the fact that not many frontal systems moved over the sub-continent. In the beginning of the winter, the northward migration of the frontal systems in the Westerly wind belt did not proceed as would normally be expected. The frontal systems that did move towards the country tended to brush the coast or veer off before reaching the coast. As a consequence, the winter rainfall region experienced below normal rainfall, especially at the start of the season.

It is thus not completely unexpected that the lightning patterns tend to hug the coast and do not extend inland. By August the frontal systems started to penetrate deep into the country. The result is that August is the only one of the winter months that recorded any significant lightning flash density figures over the land. A large percentage of this lightning was positive in polarity.

The influence of topography in August is also noticeable. As a result of the fact that most of the convergence happens ahead of the cold fronts as they move from west to east over the country, lightning is recorded to the west of the main Drakensberg Mountain range. There is a lack of lightning against the eastern escarpment and on the eastern coastal plain, with a large percentage of positive lightning offshore.

The September lightning density is much lower than would normally be expected in this month (Figure 4.7 Ci). By mid-September in most years, the rainfall season has begun and this month can sometimes experience some volatile and even severe weather conditions. In 2006, there was a late onset of rainfall – it did not really start until October. As a result there was very little rainfall in September. Almost all of the lightning activity was recorded in 3 days, on the 17th, 25th and 26th. All three of these days experienced the passage of a cold front accompanied by a strong ridging South Atlantic Anticyclone.

In September, there is a cell of high flash density, high positive flash density and high percentage of positive lightning lying approximately 100 to 150 km offshore from Durban on the east coast of South Africa. This lightning was produced from a single storm system on 26 September. A cold front moved up the coast from Port Elizabeth on 25 September and was moving relatively slowly as a result of an impeding high pressure ahead of the front. Almost all of the lightning recorded on 26 September was centred around the central low pressure system associated with this frontal system and along the front itself.

4.3.3 Spring and Early Summer

The rainfall season in 2006 started in the first week of October. The amount of lightning recorded by the LDN rose very rapidly from that which had been recorded in the preceding 6 months. Most of this lightning was from convective storms – the percentage of positive lightning was very low across the entire country (Figure 4.7 Diii). The lowest percentage of positive lightning of all the months in 2006 was recorded in October.

The highest flash densities in October were reported against the eastern Escarpment and Central Drakensberg Mountains (Figure 4.7 Di). There were also regions of moderate flash density on the western side of the Maluti Mountains of Lesotho. This is indicative of the fact that some cold fronts were still passing over the country while at the same time the usual summer inflow of moist air from the Indian Ocean was starting to re-establish itself. This is also reflected in the separation between the low percentage of positive lightning regions in the northeast of the country by comparison to the higher percentage of positive lightning regions to the west and over the central parts. The pocket of flash densities in excess of 5 flashes per square kilometer in Kwazulu Natal was dominated by negative polarity lightning since the same area has a value of less than 4 percent of positive lightning. In contrast the pocket of high flash density close to the border between the Free State, Eastern Cape and Lesotho is of a similar size to the one in Kwazulu Natal, but also has a higher percentage of positive polarity lightning.

November experienced a similar amount of lightning to October, but the distribution of the discharges started to resemble the summer distribution with most of the lightning occurring over the northern Drakensberg Mountains and the Highveld and Central Bushveld Regions (Figure 4.7 Ei). In Kwazulu Natal, where the flash densities are the highest, the percentages of positive lightning are low (Figure 4.7 Eiii). In Mpumalanga, Limpopo and Northwest Provinces, there is a mixture of high and low percentage positive regions. The Free State, Eastern Cape and the eastern parts of the Northern and Western Cape Provinces are dominated by higher percentages of positive lightning. Despite the fact that November marks the end of the transition into summer in South Africa, there were still a large number of cold fronts reaching the country in this month. In total, eight cold fronts reached the South African sub-continent in November 2006 and four of these actually penetrated inland as far as the northern parts of the Western Cape and the northern parts of the Eastern Cape. It is highly likely that the regions of high percentage positive lightning along the southern and eastern coastlines can be attributed to the passage of these frontal systems.

December did not record the most lightning of any month in the year, but it did experience the highest flash densities in parts of Central Kwazulu Natal, the Central Drakensberg Region, the southern Lowveld and the eastern parts of the Highveld of any of the individual months (Figure 4.7 Fi). The lightning in December was concentrated over the northeastern parts of the country, with low flash densities extending towards the west. The regions of high positive flash density closely mirror those of the negative flash densities (Figure 4.7 Fii). Once again,

the areas of highest overall flash density are not the areas with the highest percentage of positive lightning (Figure 4.7 Eiii). The high percentages of positive lightning lie within low flash density areas in the Eastern Cape and parts of the Great Karoo in the Northern Cape Province. The high percentage positive lightning region in Limpopo Province, first seen in the January and February lightning maps, is starting to re-establish itself. This region is displaced slightly southward of the January and February positions.

The western border of the high percentage positive lightning region in eastern Mpumalanga is one of the few regions where high flash densities occur concurrently with high percentages of positive lightning. The primary consequence of this is that the industries, which include commercial plantations, are at risk from a large amount of lightning which is also carrying damaging positive charge.

In summary, the seasonal analysis of lightning has provided a better understanding of the risks of high density cloud-to-ground lightning and the portion of that lightning which carries positive energy to the earth's surface. Not only is January the month with the highest amount of lightning, it is also a month with a large percentage of positive lightning distributed across most of South Africa. Almost no lightning occurred during the winter of 2006, but the summer and spring months of January to March and September to December experienced a large amount of lightning.

The spatial distribution of the lightning in the spring and early summer months closely resembles that of the later summer months, but the percentage of positive lightning is much lower in the spring and early summer than in the previous late summer months. The spring and early summer months appear to have a higher concentration of lightning over the escarpment and interior plateau, with little of this being positive in nature. The months from October to December recorded the lowest percentages of positive lightning for 2006.

Parts of the eastern Northern Cape, the eastern Western Cape and most of the Eastern Cape experience fairly low flash densities, but consistently record percentages of positive lightning in excess of 10%. The eastern ocean regions bordering the Kwazulu Natal coast and parts of the Eastern Cape coast also experience high percentage positive lightning values.

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The analysis of ground flash density of lightning of both polarities indicates that the summer and spring months experience considerably more lightning than do the autumn and winter months. The highest percentage of positive lightning is experienced in the late summer. The distribution of lightning of positive polarity appears to be closely linked to the position of the interior trough in the summer and spring months and to the passage of mid-latitude synoptic systems in winter.

## CHAPTER 5

### Lightning Median Peak Current Distribution

*The distribution of the median peak current has been analysed in order to identify the degree of correlation with high flash density lightning regions in South Africa. Median peak currents of lightning of both negative and positive polarity has been analysed separately in order to identify the parts of South Africa most at risk from high polarity lightning. A discussion of the seasonal median peak current distribution highlights the times of the year in which parts of the country will be at particular risk from large current discharges.*

#### 5.1 Median Peak Current Distribution

The analysis of the median peak current indicates that the majority of the country is dominated by discharges of relatively low current strength (Figure 5.1). The areas of the country with the highest ground flash density experience lightning with median peak currents of less than 15 kA. The most notable regions of the country with median peak currents between 15 and 20 kA are along the southern and eastern coastal regions, in the northern parts of Limpopo Province, in a northwest to southeast directed band across the central parts of the country and off the south-western coast of the Western Cape.

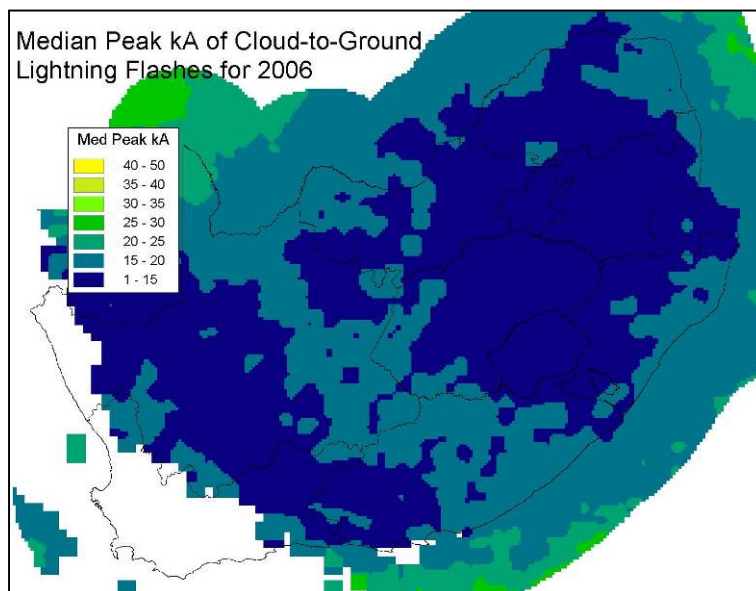


Figure 5.1: Median peak current distribution over South Africa for 2006

The distribution of median peak current for negative polarity lightning (Figure 5.2) almost mirrors that of the overall distribution of median peak current. The most noticeable difference in the two distributions is to be found in the eastern parts of the Northern Cape. The overall peak current distribution (Figure 5.1) displays a definite northwest to southeast band in this region which represents a higher median peak current than is evident in the distribution of peak current of negative amplitude (Figure 5.2). The implication is that the positive peak current values in this region must be reasonably high.

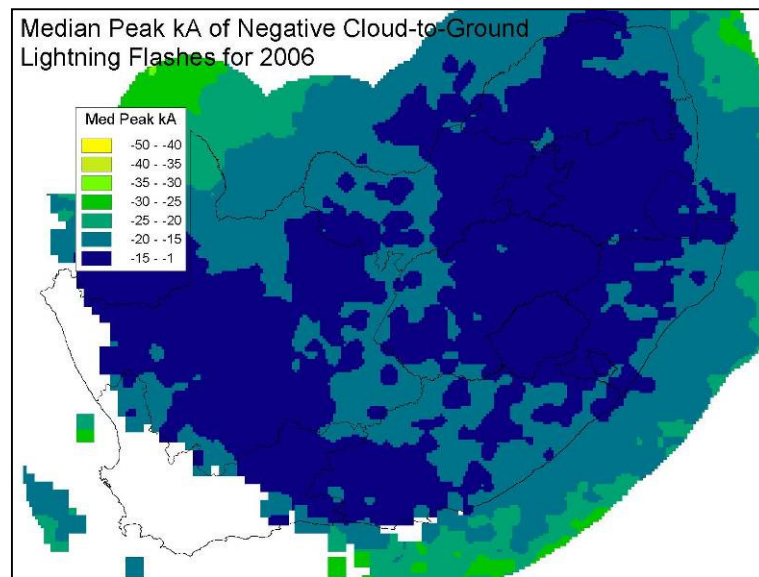


Figure 5.2: Median peak current distribution of negative lightning over South Africa for 2006

Over most of the country, the median peak current for positive polarity flashes is between 15 and 20 kA (Figure 5.3). There are small regions of lower median peak current values in the central Drakensberg regions as well as in the Lowveld and parts of the Highveld in the northeastern Free State. On the eastern side of the country, the regions of low median peak current values for positive flashes are found where the percentage of positive lightning is low. This gives an indication that the small amount of positive polarity lightning that occurs here does not discharge large amounts of energy.

On the eastern border of the Western Karoo in the Northern Cape, there is a band of low peak current lightning that corresponds to regions of between 6 and 10% percent of positive lightning. There is a similar region of low percentage positive lightning and corresponding low positive median peak current in the northern Great Karoo, close to the Namibian border. In contrast, immediately to the east of this latter region is a north to south directed band of median positive peak current values in excess of 20kA. This band accounts for the identified

difference in the distributions of median peak current of negative polarity lightning and the overall pattern (Figures 5.1 and 5.2).

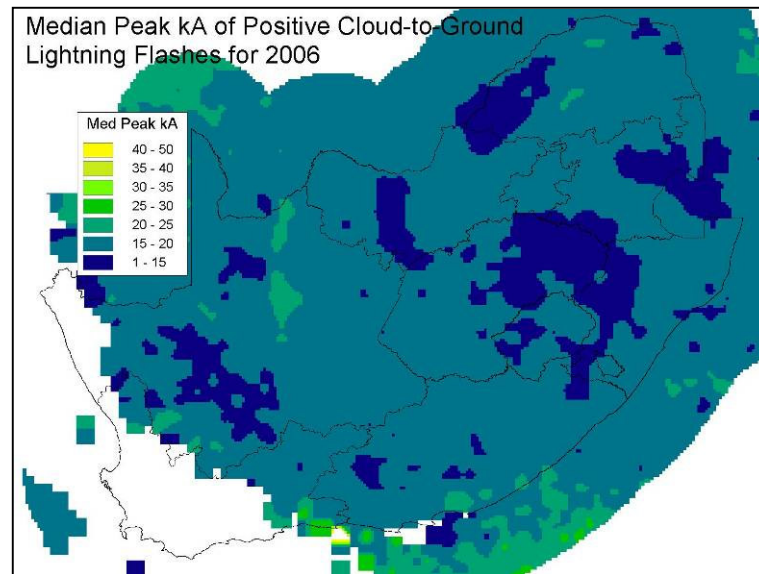


Figure 5.3: Median peak current distribution of positive lightning over South Africa for 2006

Higher median peak current values of positive polarity lightning are recorded along the southern and eastern coastal regions in a similar pattern to that displayed by the negative polarity lightning. There are also small high positive peak current regions in northern and western Limpopo Province. The northern, almost zonal region corresponds to the regions of high percentage of positive lightning, but low flash density of both positive and negative polarity lightning. The small high positive peak current area in western Limpopo falls within an area of higher flash density, but lower percentage of positive lightning.

It is difficult to attempt an explanation of the distribution of median peak currents based purely on spatial characteristics for the entire year. Tyahla and Lopez (1994) indicate that caution should be exercised when comparing peak current values from different regions. It is not always easy to differentiate whether these perceived differences are as a result of individual storm dynamics and microphysics or whether surface conductivity plays an important role. If a surface has a higher conductivity, it is possible that the initial charge on the lightning channel will be transported away from the strike point on that surface more quickly than on a surface of lower conductivity. This leads to a faster charge transfer down the channel and so to a discharge of more energy (Tyahla and Lopez, 1994).

Orville and Huffines (2001) tested a similar theory by investigating the difference in median peak currents over land and over the ocean. This study was prompted by the fact that the median peak current values in the United States showed a very distinct discontinuity where the continental land mass met the ocean. Their theory was that the higher surface conductivity of the ocean led to less attenuation of the electromagnetic signal over the oceans and so to a calculation of higher peak current values from the radiation fields generated by lightning discharges over the oceans. Unfortunately, the discontinuity in peak current was only evident in the spatial distribution of lightning flashes of negative polarity and not in those of positive polarity. If surface conductivity was a major contributor to the differences in median peak current distribution, then the positive and negative polarity lightning distributions should be similar, which they were not. This discontinuity was also not present between land masses and large inland water bodies (Orville *et al.*, 2002). The use of surface conductivity as a means for explaining the difference in median peak current values was thus discarded by the American scientists.

In the analysis of the lightning over South Africa, the spatial distribution of negative polarity lightning does not display a very pronounced discontinuity at the land-sea interface. The distributions of median peak current values for positive and negative polarity lightning discharges are, in fact, very similar over the southern and eastern oceans adjoining the land mass of southern Africa. There are consistently higher peak current values of lightning of both polarities over the oceans than over the land. This is especially so off the Eastern Cape coast and off the northern Kwazulu Natal coast.

Tyahla and Lopez (1994) indicated that one of the possible explanations for the appearance of higher median peak currents over the oceans is that there is a relatively low percentage of low peak current discharges and a high percentage of stronger ones over the oceans than over the land. It is evident from the distribution over South Africa and the surrounding oceans, that this may indeed be the case, especially along the southern Cape and Eastern Cape coastlines.

Little research has taken place into identifying the controlling mechanisms of high peak current discharges. Limited studies in the United States indicate that high peak current positive lightning discharges are found over the Appalachian Mountains, as well as in the Midwest and Great Plains (Orville and Huffines, 1999; Orville *et al.*, 2002).

Since surface conductivity had effectively been eliminated as a controlling mechanism of peak current discharge, and topography was proving an inconclusive determinant, attention was once again directed at the structure of individual storms. Lyons *et al.* (1998) found that the high peak current in positive discharges over the Appalachian Mountains was most likely associated with the Mesoscale Convective Systems (MCSs) that dominated the region. Zajac and Rutledge (2001) investigated lightning ground flash densities in the American Midwest and found that lightning was primarily produced in the summer just after sunset by isolated storms as well as by the convective regions of MCSs. The convective storms that they studied were usually characterised by one or two cells of high positive lightning flash rates and large positive peak currents. They concluded that intense convection was the main cause of high positive peak current values and that this convection need not necessarily be associated with MCSs.

There is thus no agreement by the experts on the definitive mechanisms responsible for high peak current discharges. In the South African analysis, the key to explaining the distribution of the median peak current of both negative and positive discharges most likely lies in an analysis of the seasonality of the distribution. A number of studies in the United States have identified that the peak current for both positive and negative discharges is considerably higher in the winter months than in the summer (Orville *et al.*, 1987; Orville and Huffines, 1999, 2001). This theory will be evaluated in the seasonal analysis of the peak current distribution over South Africa.

## **5.2 Seasonal Analysis of Peak Current Distribution**

The median peak current for the entire year for lightning of negative polarity was -15 kA and for positive polarity lightning was 17 kA. For most of the summer months, the median peak current values for lightning of both polarities closely mirror the annual values (Figure 5.4). In keeping with the results from the United States, the median peak current values increase in autumn and early winter (Orville *et al.*, 1987; Orville and Huffines, 1999, 2001).

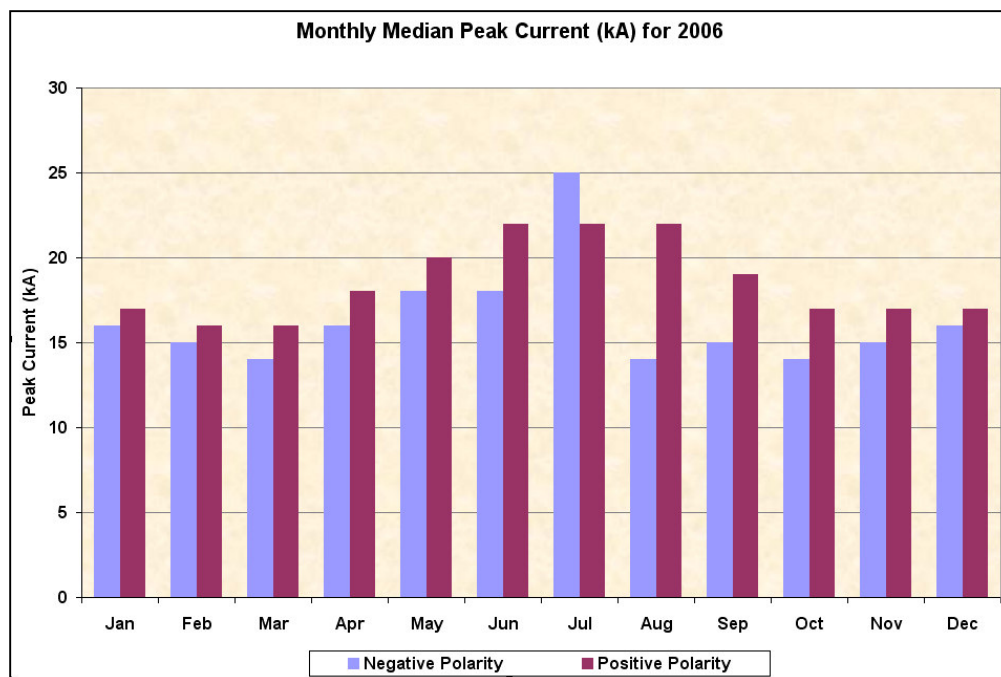


Figure 5.4: Median Peak Currents of both negative and positive polarity lightning by month for 2006

There was very little lightning in June, July and August and so the figures in the graph represent mainly the median peak current distribution of the southern and eastern oceans, rather than being representative of activity over the land itself. Of particular interest in July is the substantial jump in median negative peak current from the June value of -18 kA to -25 kA. This is a feature of the influence of a single synoptic event, namely the passage of a large cold front on 22 and 23 July 2006. The results for September also reflect mainly the characteristics of a single, complex frontal system which extended over South Africa as far as Limpopo Province on 16 and 17 September.

The median peak current of positive polarity lightning remains fairly constant at 22 kA throughout the winter months, but drops off in the spring to re-establish its summer value of 17 kA by October. The median peak current of negative polarity lightning is more variable than that of the positive lightning. Following the rapid rise in July, it drops off substantially in August. It then fluctuates around the 15 kA level for the rest of the summer months. It is not completely unrealistic that the median peak current of the negative polarity lightning will be low in August considering that this is the month with the highest percentage of positive lightning in 2006.

A possible explanation for the increase in the peak current of winter lightning was provided by Brooke (1992). He found that the radiation associated with the stepped-leader process is greater in winter than in summer. In addition, the velocity of the leaders is approximately two to three times greater in winter than in summer. The electric fields initiating lightning in winter thus appear to be larger than in summer. The winter discharges are thus more energetic than their summer counterparts and as a result have higher peak current values.

The seasonal comparisons of median peak current distribution (Figures 5.5 A to F and 5.6 A to F) demonstrate once again, that over the land mass of South Africa, the median peak currents of positive polarity lightning are indeed higher than those of negative polarity lightning.

#### *5.2.1 Summer*

In January, the median peak currents of negative lightning are less than 15 kA over most of the Highveld, the Lowveld, the central and Northern Drakensberg and the central parts of Kwazulu Natal (Figure 5.5 Ai). The negative flash density in these areas is high, while the percentage of positive lightning is low. The low flash densities on the western boundary of the main lightning region, which is also the region of high percentage of positive lightning, shows elevated peak current values for both positive and negative lightning. The peak currents of positive lightning in this area are particularly high, reaching peak current values of up to 30kA (Figure 5.5 Aii). This has important implications from a risk perspective. Despite the fact that lightning discharges in this area are not very numerous, those that do occur in January appear to be quite dangerous from the perspective that many of these discharges are positive and carry large peak current values. This lightning region lies in the eastern part of the Great Karoo which is the more densely populated part of the Northern Cape with a number of fairly large towns situated in this high peak current zone.

There are isolated pockets of high positive peak currents in the northern parts of Limpopo and of high negative peak currents in the Central Eastern Cape. The latter may indeed be a topographical influence since the regions of elevated negative peak current follow closely the orientation of the Waterberg and the Sneeuwberg Mountain ranges. The high positive peak current zones in Limpopo are very similar to those seen in the annual pattern.

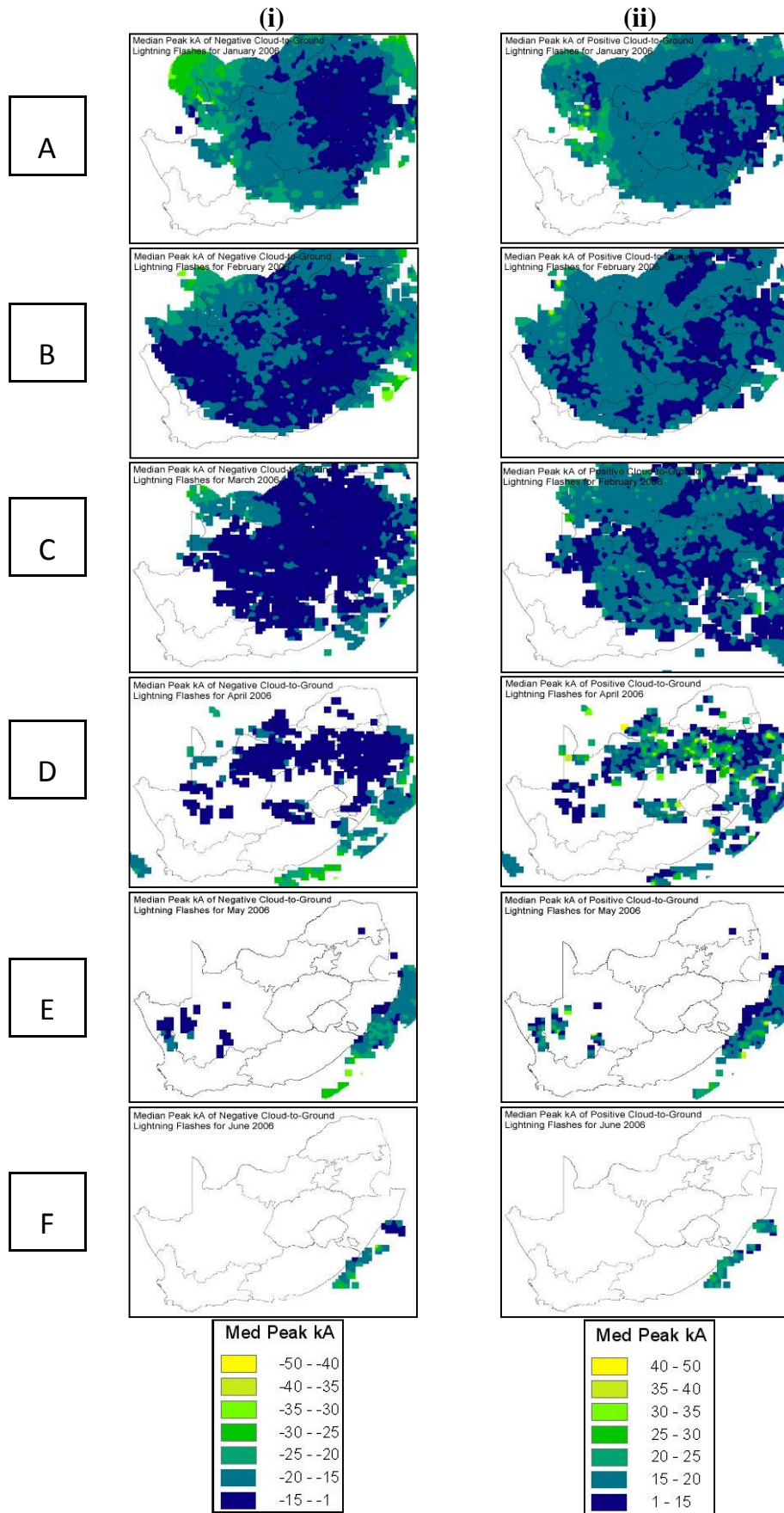


Figure 5.5: Lightning median peak current (kA) for negative polarity (i) and positive polarity (ii) from January to June 2006 (A to F respectively).

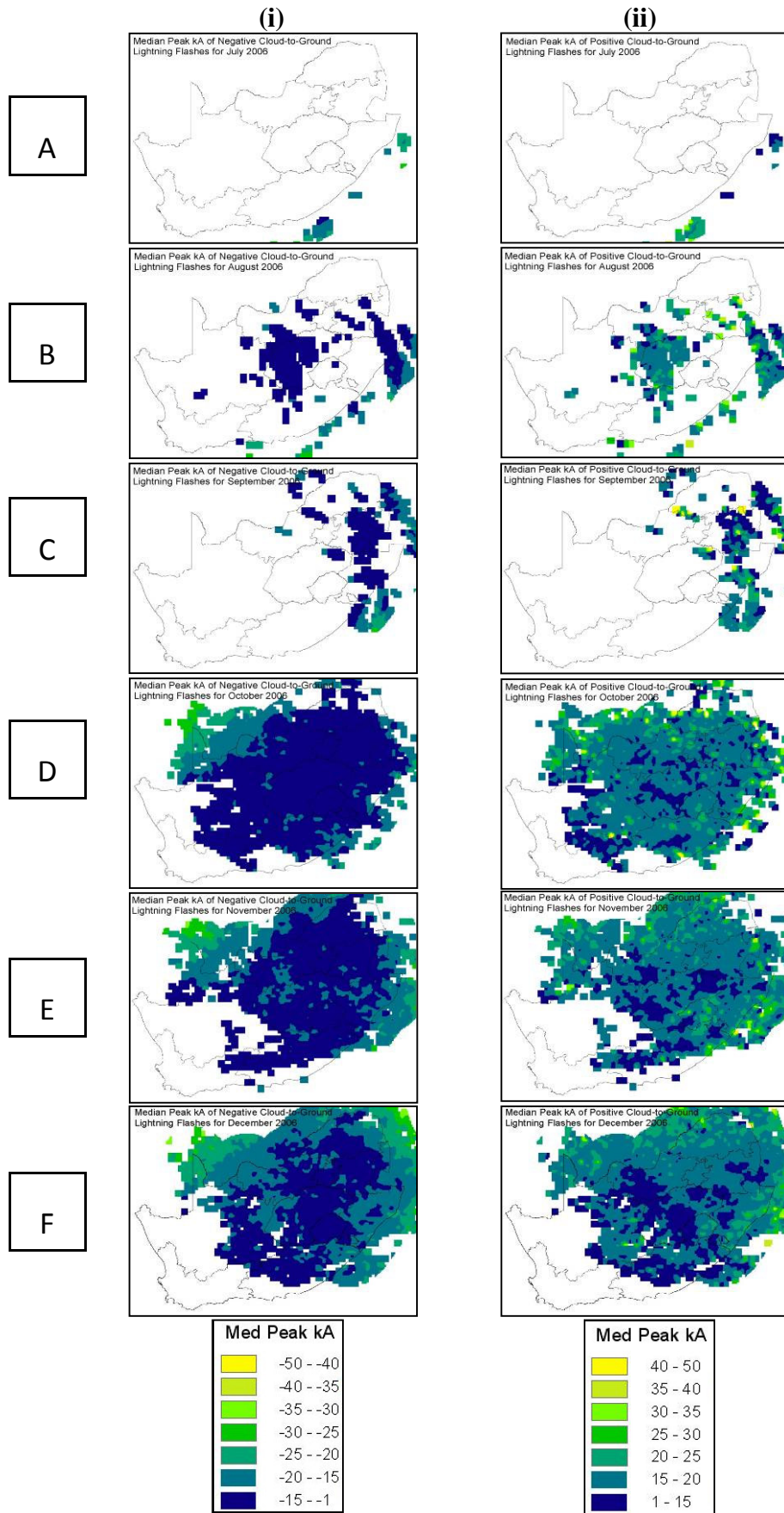


Figure 5.6: Lightning median peak current (kA) for negative polarity (i) and positive polarity (ii) from July to December 2006 (A to F respectively).

The January distribution of median positive peak current very closely resembles that of the year, indicating that the large amount of lightning in January had a definite impact on determining overall distributions of median positive peak currents. The zone of high positive peak currents in the annual distribution that is found in the northern central parts of the Northern Cape is almost exclusively attributable to the lightning that occurred in January.

In February and March, the median peak currents decreased across the country for both polarities (Figure 5.5 Bi and ii and Ci and ii). No distinct patterns of median peak current are distinguishable over the sub-continent, except that the regions of low percentage of positive lightning are also the regions of lowest peak current of both polarities. The zone of high positive peak current in the northern Great Karoo that was evident in January has been replaced by a band of low peak current. To the southeast of this low peak current area, there is a remnant of a high positive peak current band extending southwards in the central Great Karoo (Figure 5.5 Bii).

Another interesting phenomenon appears over the oceans off the Kwazulu Natal coast. There is a distinct lightning “outflow” into the Indian Ocean originating approximately at the mouth of the Tugela River. This is evident for the maps of lightning of both polarity, but the negative peak currents in this region are higher than those of the positive lightning. Once again, it may be an enhancement of activity which is the result of the pollution in the area from the industrial processes.

In March, almost the entire country experiences negative polarity lightning with weak peak currents and positive polarity lightning with peak currents in excess of 15 kA. The positive peak current distribution takes the form of poorly defined alternating bands of high and low peak current extending across the country in a northwest to southeast orientation. The distribution is thus not perfectly meridional, but appears to be determined by the orientation of the surface trough which dominates South African summer rainfall.

The summer months were thus dominated by low median peak currents of negative polarity lightning and slightly higher peak current values of positive polarity lightning. As the summer progresses, the magnitude of the current in strokes of both polarity decreases. The zone of high peak current on the western boundary of the lightning region shows the greatest weakening and has disappeared completely by the end of the summer.

### 5.2.2 *Autumn and Winter*

Early mid-latitude cyclone activity was experienced in April. The interactions between the passing cold fronts, the ridging South Atlantic Anticyclone behind these fronts and the warmer moist air in the easterly circulation over the northern part of the country resulted in an almost zonal lightning pattern centred between 25°S and 27°S. This zone was dominated by pockets of high peak current positive lightning activity. In some grid blocks the median peak current exceeds 40 kA (Figure 5.5 Dii). The percentage of positive lightning was not consistently high across the identified zone, and the positive flash density was very low. The implication is that the small amount of positive lightning that did occur was very intense. The negative lightning in the same region had a much lower peak current value.

The April lightning may be the result of a few isolated severe convective cells either developing as heat-generated storms or as part of MSCs. If the theory of Zajac and Rutledge (2001) were to apply in this instance, then there would be more intense positive lightning from these cells. They, however, postulated an increase in the positive flash density as well, which is not evident in the April data.

The influence of the frontal systems is also obvious along the southern Cape, Eastern Cape and Kwazulu Natal coasts, where most of the lightning is lying a few kilometres offshore. In these coastal areas, the median peak current of the negative lightning is higher than that of the positive lightning. Evident for the first time is the band of lightning activity lying offshore of the Southwestern Cape. This band is associated with the passage of a single frontal system in the late evening of 2 April and the early morning of 3 April.

From May to July, the peak current distribution of lightning of both polarities was concentrated in the narrow band off the eastern coastal regions of the Eastern Cape and Kwazulu Natal (Figure 5.5 Ei and ii to Fi and ii and Figure 5.6 Ai and ii). In general the peak current of the positive polarity lightning is higher than that of the negative lightning. In May, the negative lightning over the oceans was marginally stronger than the positive lightning. The lightning in the winter months of 2006 was associated with convective activity ahead of weak frontal systems that barely brushed the coast of the country. It is thus possible that convection associated with frontal activity in winter leads to the establishment of larger electric fields than in the summer storms and thus to more energetic lightning discharges (Brooke 1992).

In June, the only distinguishing feature between the lightning of different polarities is that the northern-most lightning region off the northern Kwazulu Natal coast has distinctly higher positive peak currents (Figure 5.5 Fi and ii). In July, the median peak current of negative lightning is higher than for positive lightning by 3 kA. Once again it is the small region of ocean lightning off the northern Kwazulu Natal coast that appears to be exerting a large influence. In this instance, the peak current of the negative lightning in this region is higher than that of the positive lightning.

August was the first winter month of the year in which the cold fronts penetrated deep into South Africa. In the preceding months these frontal systems had tended to either affect only the south-western parts of the Western Cape or they merely brushed the coast. The effect of the inland incursion of these frontal systems in August is evident in the bands of lightning activity across the country (Figure 5.6 Bi and ii). Most of the positive lightning recorded peak currents between 20 and 25 kA, with small bands in Mpumalanga of higher peak current.

The negative peak current values in August were the lowest of all the months in 2006. The patterns observed in August are in keeping with the findings of Orville and Huffines (2001) and Rakov and Uman (2003) who reported winter maxima in positive lightning discharges. If this is coupled with the research by Brook (1992), then it would appear that the winter lightning pattern in August is representative of a significant number of very energetic positive discharges, releasing large amounts of energy over South Africa.

Most of the lightning in September was attributable to a single large frontal system. This system discharged a high percentage of positive lightning with strong peak currents. Along the border between the Northwest Province and Limpopo, the line of lightning activity has a greater percentage of positive lightning towards the southeast of the lightning band, but high positive peak currents across the entire band from northwest to southeast (Figure 5.6 Cii). Not many of the discharges were positive on 16 and 17 September, but most of those that did occur were centred very close to the northern Gauteng border. In this band, positive peak currents varied from 11kA to 78 kA, with a median peak current value of 36 kA.

Little lightning occurred in both autumn and winter, but the autumn lightning had higher peak current values of negative polarity lightning than that of positive lightning. The same was not true in winter, where the peak currents of positive polarity lightning were considerably higher

than those of negative lightning. The international findings that lightning of both polarities contain higher peak currents (Orville *et al.*, 1987; Orville and Huffines, 1999, 2001) is thus not fully supported in this analysis. In South Africa, the winter lightning currents show large increases for positive polarity lightning, but little increase for negative polarity lightning.

### 5.2.3 *Spring and Early Summer*

In October, the majority of the negative lightning over the country recorded peak currents in the order of 15 kA (Figure 5.6 Di). The peak currents recorded for positive lightning were 5 to 10 kA higher than those of the negative lightning over most of the country (Figure 5.6 Dii). Large positive peak currents were recorded in some regions in the eastern parts of the Eastern Cape, in central Kwazulu Natal, along the Kwazulu Natal coast, extending eastwards into the Indian Ocean, and in parts of the eastern and northern Northwest Province. Some of these regions are concurrent with regions of high percentage of positive lightning and others are not. The Eastern Cape appears to be experiencing the largest correlation between these two variables, which is a good indicator of the possible risk from lightning in this area.

In November, the peak current values for negative polarity lightning over most of the country are around 15 kA. The exception to this is the central and northern parts of Kwazulu Natal and most of the Lowveld region, where peak negative currents range from 15 to 25 kA (Figure 5.6 Ei). Most of the regions of low peak current for positive lightning are found in the central and western parts of the country (Figure 5.6 Eii).

The peak current of positive lightning is generally high over most of the country, with three distinct regions of high positive peak current discharge. The first is in the eastern part of the Eastern Cape, extending into Lesotho and up onto the Maluti Mountains, the second is off the Kwazulu Natal coast and the third is along the western Limpopo border in the Northern Bushveld region. The latter region is found in an area of low percentage of positive lightning. Despite the fact that the positive flashes in this region carry large currents, they are not very numerous and so not of considerable risk. A small region of very high positive peak current in eastern Mpumalanga corresponds to a region of high percentage of positive lightning. From a risk perspective, this is not a good situation since the majority of the lightning that does occur in this region is positive in polarity and carries very high peak currents. This is a region in the Kruger National Park where fire risk is of particular concern.

In the region off the Kwazulu Natal Coast, the high peak currents of positive lightning over the land are associated with low percentage of positive lightning, but over the sea, large parts of this high peak current zone are found in regions of high percentage of positive lightning. Possibly the region most at risk from the high peak current discharges of positive lightning, is the region in the Eastern Cape. In this region, the pockets of high peak current discharge correlate very well with the regions of high percentage of positive lightning. This is consistent with the observed patterns in October.

In December, the majority of the interior parts of South Africa are dominated by negative lightning with weak peak currents around 15 kA. Encompassing this central low peak current region is a zone of higher peak current. The region of highest flash density in central Kwazulu Natal falls, for the most part, within a region of peak currents ranging from 15 to 20 kA. Higher peak current values of negative lightning are found off the Kwazulu Natal North Coast (Figure 5.6 Fi).

Most of the interior of the country experienced median positive peak currents between 15 and 20 kA, with lower currents in a northwest to southeast oriented band across the central parts of the country and in the western part of the lightning region. The high positive peak current region in the Northern Bushveld region persists from the November distribution, but the Eastern Cape high peak current region has almost disappeared. Throughout the coastal regions of Kwazulu Natal, and up into the foothills of the Drakensberg Mountains, regions of high positive peak current discharge are evident. In the northern parts of the province and in the southern coastal regions of Kwazulu Natal, these high current values are accompanied by high percentages of positive lightning. In the coastal region in and around Durban, the percentage of positive lightning is lower. High positive peak currents were once again recorded off the Coast of Kwazulu Natal. The highest current values were reported in a region of relatively low percentage of positive lightning.

The spring and early summer months show a progressive decrease in the distribution of low median peak current lightning of negative polarity. The peak current of positive lightning shows an increase in the amount of low peak current lightning as the season progresses.

In summary, the months most at risk from high peak currents are the spring and summer months, mainly because the lightning coverage over the country is more extensive at this time of the year. Negative peak currents tend to be weak in the autumn and spring. The largest

distribution of strong positive peak currents was reported from October to December. In some instances these strong positive peak currents are found in regions of low percentage of positive lightning, such as in Limpopo, but in others, such as in the Eastern Cape and small pockets in Mpumalanga, they are often concurrent with regions of high percentage of positive lightning and it is in these areas that the risk from lightning damage is highest.

One feature which is of interest is the high lightning area off the Kwazulu Natal coast that corresponds to the outflow region of the Tugela River. It is difficult to conclude whether pollution from industrial processes is having a major impact in this region. The high lightning occurrence is persistent for most of the year, except in the middle winter months. This may not negate the impact of pollution on lightning enhancement in the area, but may merely be an indication of insufficient moisture and instability for condensation or for cloud electrification to take place.

The positive peak current distributions over South Africa in the spring and early summer were distinctly different from those of the mid to late summer. In the latter half of the year, the median positive peak currents were higher than in the beginning of the year. This distinction in distribution is also evident in the percentage of positive lightning distribution. In the first three months of the year, the percentage of positive lightning over the country was much higher than in the last three months. The implication is that despite the fact that the positive lightning discharges are more intense in the spring and early summer, there are fewer of them and so possibly will not cause as much damage as in the later summer months.

The band of lightning that is evident offshore of the south-western Cape in the annual distribution is solely a function of single frontal system in April. This band is not evident in the data for any of the other months of the year.

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In general, the median peak currents of both negative and positive lightning are low in the high flash density regions of the country. The parts of the country most at risk from high intensity lightning are those that experience high median peak currents of positive lightning where the percentage of positive lightning is high. In general the median peak currents of positive lightning are higher in the spring and early summer months than in the late summer.

CHAPTER 6

Lightning Flash Multiplicity Distribution

The flash multiplicity distribution will be analysed in order to identify areas of agreement between high flash density and high flash multiplicity over South Africa. Flashes that consist of a large number of strokes are capable of discharging vast amounts of energy to concentrated strike points on the ground in very short time intervals. Multiple stroke positive flashes are particularly dangerous from a fire perspective. A discussion of the seasonal flash multiplicity will indicate the precise risks from high intensity multiple stroke flashes.

6.1 Flash Multiplicity Distribution

The stroke multiplicity across the country (Figure 6.1) shows a similar distribution to the ground flash density (Figure 4.1). The regions of highest multiplicity are also the regions of highest flash density. The noticeable difference is that the region of highest multiplicity along the Drakensberg Mountains is displaced further south than the nucleus of highest flash multiplicity. A secondary zone of flash multiplicity in excess of 3 is found in southern Kwazulu Natal, on the border with the Eastern Cape.

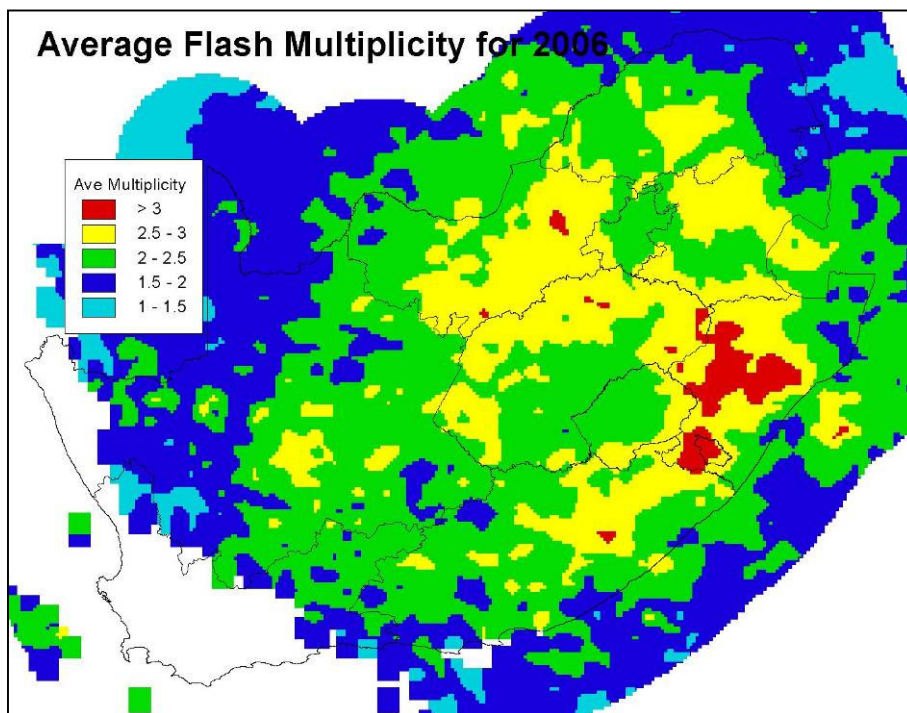


Figure 6.1: Average flash multiplicity for 2006

The greatest multiplicity values which are found along the southern and central Drakensberg Mountains extend into the adjacent interior of Kwazulu Natal. High multiplicity values extend along the course of the Vaal River, but do not extend over the entire Highveld and Lowveld regions as is the case with the ground flash density values. The high multiplicity region extends throughout most of the western Highveld region, covering a large amount of the Northwest Province and the north-western Free State. High multiplicities are evident in the Eastern Karoo and Southeastern Thornveld regions of the Eastern Cape. In patches along the Eastern Cape and Kwazulu Natal coastlines, multiplicity values in excess of 2 are found offshore, with a zone of values in excess of 2.5 off the central coastal area of Kwazulu Natal. The band of lightning activity off the Southwestern Cape coast is dominated by flashes with stroke multiplicity of between 2 and 2.5.

The assessment of stroke multiplicity masks distinct differences in multiplicity distributions for different polarities. If most of the positive flashes consist of single strokes, then identifying the areas of the country where multiple stroke flashes do occur is very important from a risk perspective. Rakov *et al.* (1994) found that if a lightning channel is properly conditioned by the initial stroke, the first subsequent stroke is often a continuing current stroke. Since positive lightning discharge channels tend to lack the stepped structure of negative channels, they tend to be better conditioned at the outset. Where positive flashes consist of more than one stroke, the first subsequent stroke is very often a continuing current stroke (Malan, 1963). This has important implications for fire risk, since it is the energy dispensed in a continuing current which very often leads to excessive heating at the strike contact point (Rakov and Uman, 2003).

The distribution of flash multiplicity of negative flashes closely resembles that of the overall distribution (Figure 6.2a). The high multiplicity regions of negative lightning cover a larger expanse of the interior than in the overall distribution. Multiplicity of negative lightning flashes over most of South Africa is in excess of 2, with the highest values recorded in the areas of highest flash density. The multiplicity of positive lightning lies between 1 and 1.3 over the entire country, with the exception of isolated regions of slightly higher multiplicity in Kwazulu Natal, the Free State and Northwest Province (Figure 6.2b). These high multiplicity regions also coincide with regions of high negative multiplicity.

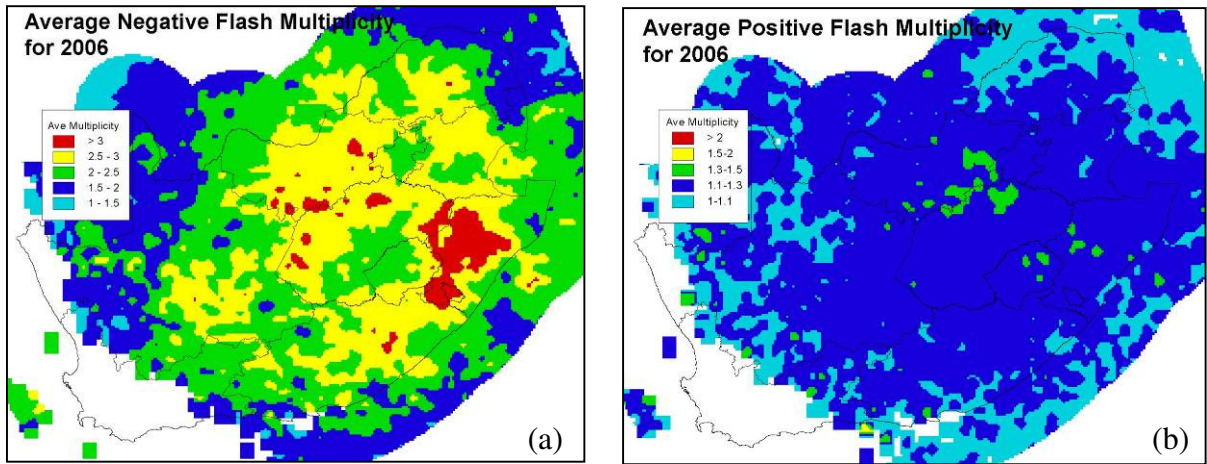


Figure 6.2: Average flash multiplicity for negative (a) and positive (b) lightning in 2006

The results for South Africa are similar to those in the USA for the first ten years of operation of the NLDN (Figure 6.3). Average flash multiplicity of negative lightning exceeds 2 over the majority of both countries and exceeds 2.5 in large parts of the eastern and central parts (Figure 6.2a and Figure 6.3a). Average flash multiplicity of positive lightning is low in both instances, implying that most positive flashes consist of a single stroke. Average multiplicity of positive lightning exceeds 1.3 in small isolated pockets on the eastern parts of both countries and in the northern central parts (Figure 6.2b and Figure 6.3b). Few seasonal analyses are available for the USA, but the seasonal average multiplicity distributions that follow for South Africa will address both the distribution of mean multiplicity as well as the percentage of single strokes.

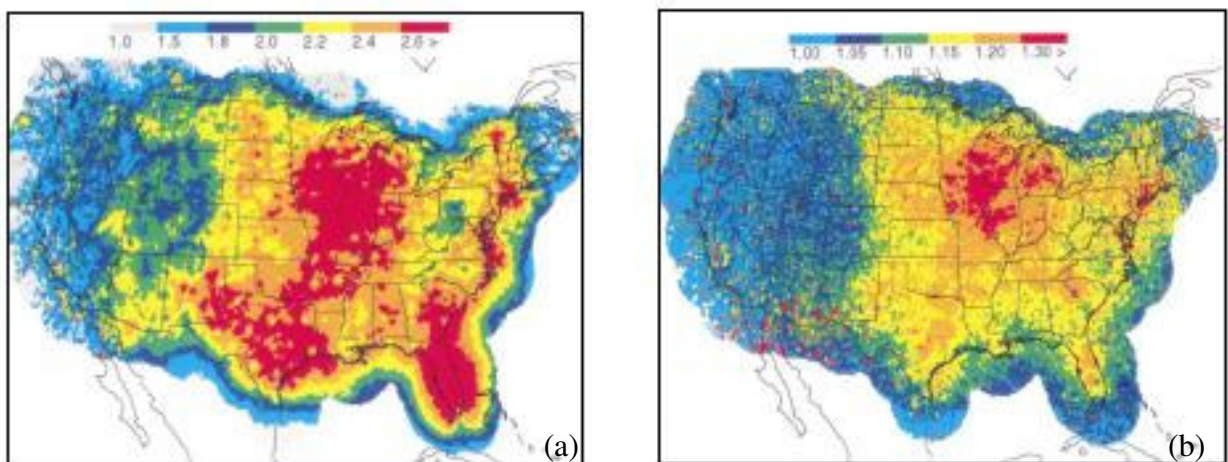


Figure 6.3: Average flash multiplicity for negative (a) and positive (b) lightning in the United States of America from 1989 to 1998 (Orville and Huffines, 2001)

6.2 Stroke Multiplicity Distribution by Month

The percentage of single stroke negative flashes is variable by comparison to that of the single stroke positive flashes (Figure 6.4). The percentage of single stroke positive flashes remains fairly constant throughout the year. A similar result was observed in the United States by Orville and Huffines (2001). Orville *et al.* (1987) observed an increase in the percentage of single stroke negative flashes from approximately 40% in summer to over 80% in winter. This pattern was not evident in the percentage of single stroke negative flashes in South Africa in 2006. In fact, January recorded the highest percentage of single stroke negative flashes. The values in winter were slightly higher than the autumn and spring values, but not markedly so and certainly not of the magnitude observed in the United States.

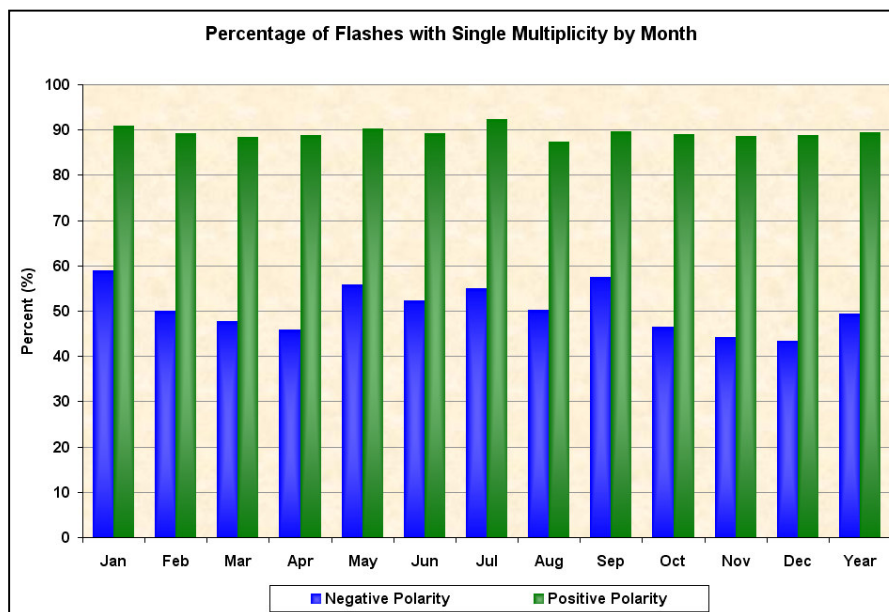


Figure 6.4: Percentage of flashes with single strokes by month

Arising from the fact that most of the positive cloud-to-ground lightning flashes in 2006 were single stroke flashes, it is not unexpected that the average positive stroke multiplicity for the year is only 1.2 (Figure 6.5). The same is not true for the negative polarity flashes. The average multiplicity of negative flashes in 2006 is 2.5, but this value varies substantially throughout the year (Figure 6.5). The highest negative stroke multiplicity values are found in the early summer months, declining rapidly from summer to winter and then rising equally quickly in the spring. In the USA, the monthly distribution of mean negative and positive flash multiplicity for the decade from 1989 to 1998 shows little variation. The average negative flash multiplicity ranges from 2 in the winter to 2.5 for most of the summer, while

the average positive flash multiplicity is between 1.2 and 1.3 throughout the year (Orville and Huffines, 2001).

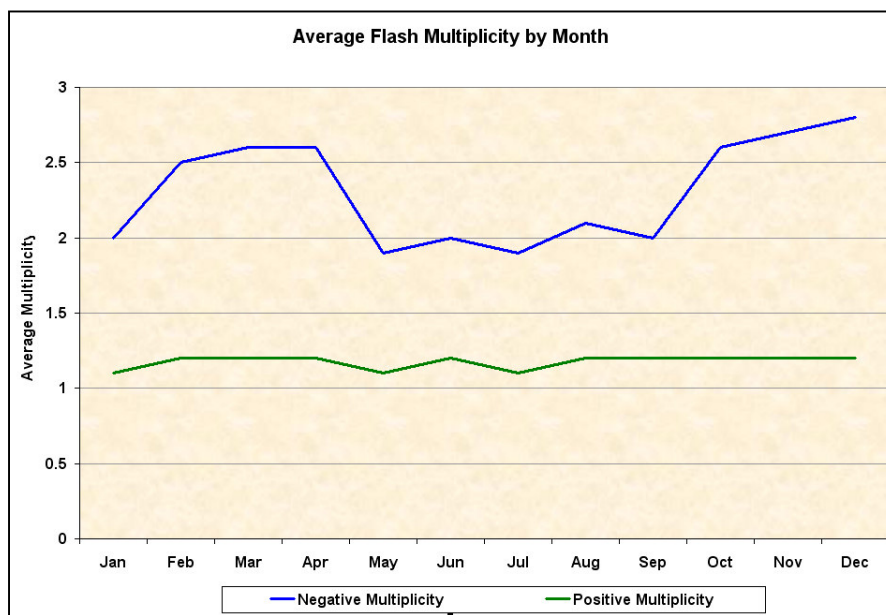


Figure 6.5: Average flash multiplicity by month for 2006

6.3 Seasonal Analysis of Flash Multiplicity

The analysis that follows concentrates on flash multiplicity for both positive and negative polarity lightning (Figure 6.6 and Figure 6.7).

6.3.1 Summer

The high percent of single stroke negative flashes in January can be clearly seen in the multiplicity distribution for this month (Figure 6.6 Ai). Most of the western part of the country is dominated by northwest to southeast oriented bands of flash multiplicity. The lowest negative multiplicity values occur in the far west and beyond the northern border of South Africa. The highest negative multiplicity values are found in central Kwazulu Natal, the Lowveld and the Highveld, where flash densities are also high in this month.

The positive multiplicity distribution is lower over the central parts of the country than over the western regions and the coastal areas of the Eastern Cape and Kwazulu Natal (Figure 6.6 Aii). On the Highveld, there are scattered cells of slightly higher positive flash multiplicity. Most of these occur in the region of low percentage positive lightning, but higher median peak current.

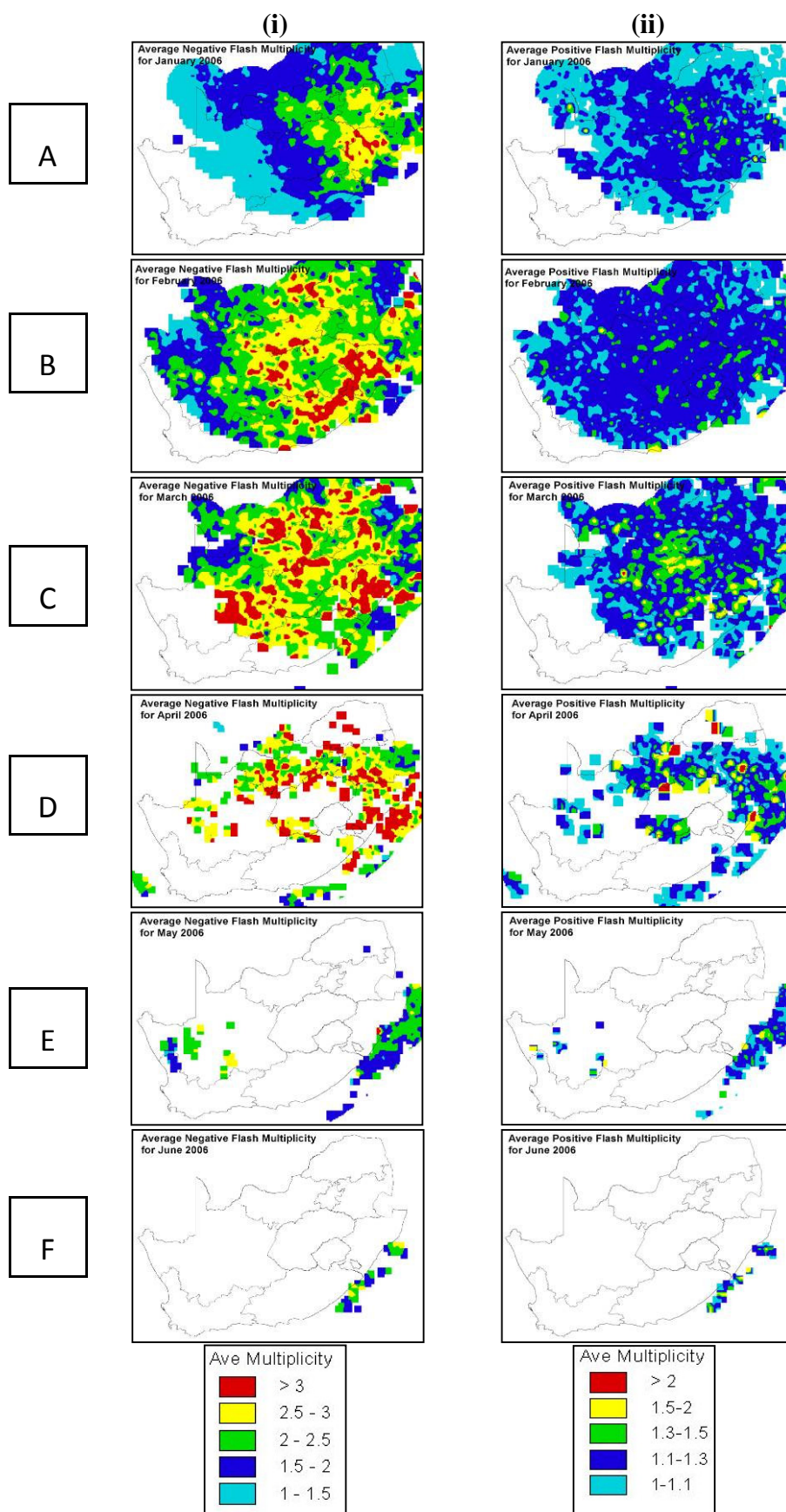


Figure 6.6: Lightning flash multiplicity of (i) negative polarity and (ii) positive polarity from January to June 2006 (A to F respectively).

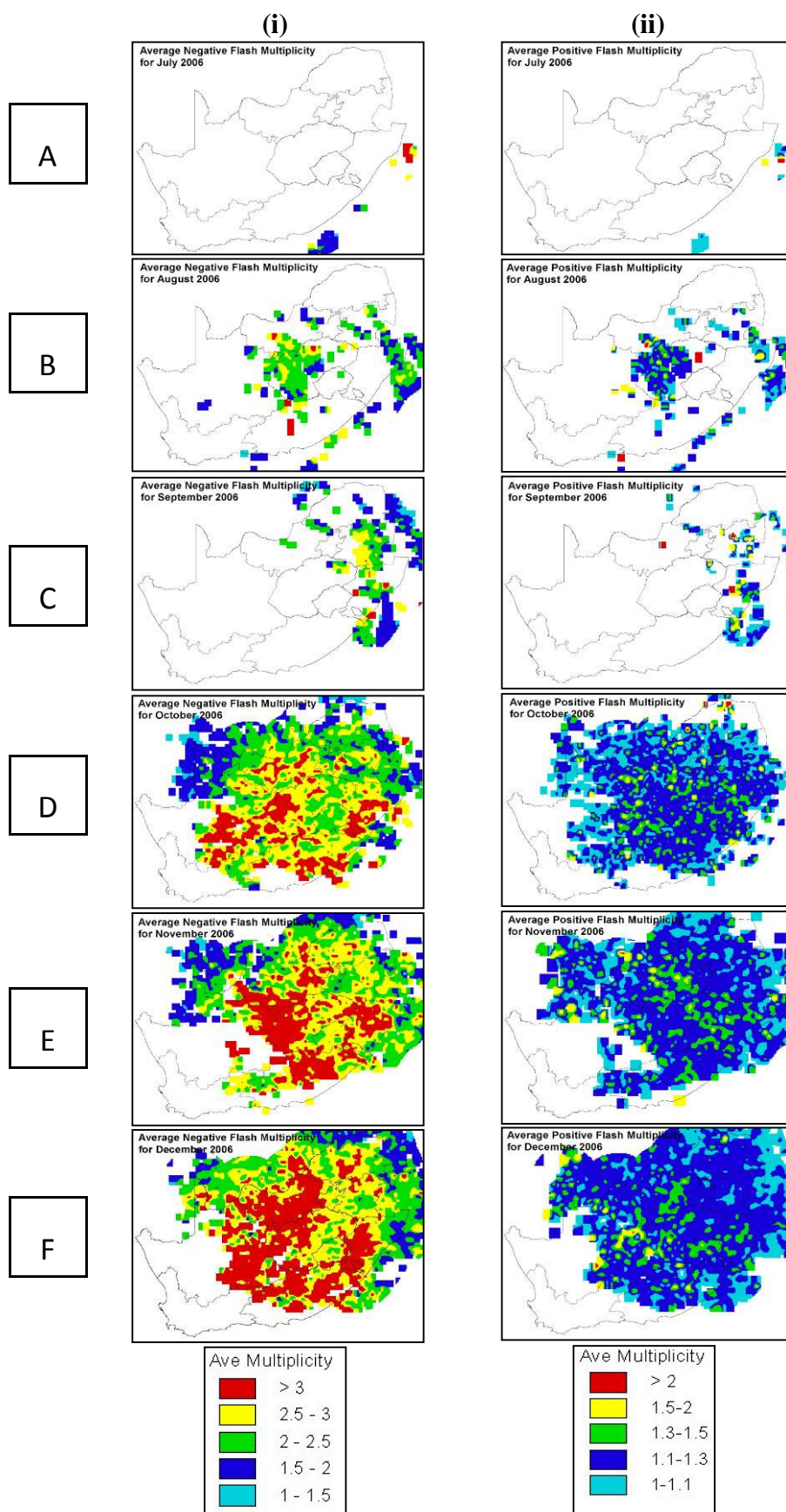


Figure 6.7: Lightning flash multiplicity of (i) negative polarity and (ii) positive polarity from July to December 2006 (A to F respectively).

By implication, not a lot of positive lightning is being discharged in this area, but recorded positive flashes that do occur carry higher current and consist of more than one stroke. As such a large amount of energy could be streaming to the earth's surface, especially if any of the subsequent strokes in a multiple stroke positive flash are continuing strokes.

In February, the percentage of single stroke negative flashes decreases from that observed in January. This is obvious in the increase in the distribution of negative flashes of multiplicity in excess of 3 strokes per flash (Figure 6.6 Bi). It is only in the far western parts of the country and in the Kalahari that negative multiplicity values fall below 2. The most notable region of high negative flash multiplicity is along the Drakensberg Mountains from central Kwazulu Natal and intruding southwards into the Eastern Cape.

The higher multiplicity region then extends in a north westerly band into the eastern parts of the Northern Cape and curves to follow the border of the country through Northwest Province and into western Limpopo (Figure 6.6 Bi). Most of these regions coincide with regions of percentage positive lightning above 10%. In the lower percentage of positive lightning areas, which also correspond to the higher flash density regions, lower negative multiplicity values are recorded. Negative flash multiplicity values remain between 2 and 2.5 for most of the eastern Highveld and the Lowveld. The negative flash multiplicity in the Tugela "outflow" region is of the order of 2.5 close to the coast and decreases with distance into the ocean.

Most of the country is covered by positive multiplicity values between 1 and 1.5 (Figure 6.6 Bii). This is evident in that the percentage of single stroke positive flashes decreased slightly in February. There are more small regions of positive multiplicity between 1.3 and 1.5 scattered throughout the country in February than in the previous month, but these show no distinct pattern or correlate to any of the other lightning characteristics.

In March, the percentage of single stroke negative flashes decreases further. The region of high negative flash multiplicity in the Eastern Cape is no longer in evidence, but the high average negative multiplicity regions with multiplicity in excess of 2.5 have grown to encompass almost all of the Lowveld, the Highveld, central Kwazulu Natal, the central Bushveld regions and the eastern part of the Great Karoo (Figure 6.6 Ci). An interesting phenomenon is the almost complete absence of any regions in the interior with negative multiplicity between 1.5 and 2.

Notable about the positive flash multiplicity in March are the regions of high multiplicity over central Kwazulu Natal, the northern and north-western parts of the Free State and almost the entire Northwest Province (Figure 6.6 Cii). March is the first month of the year in which the small spots of higher positive flash multiplicity are started to form cohesive regions. The region of particularly high positive multiplicity (> 2) in the Northern Cape, very close to the Northwest border is also a region of high positive peak current discharge.

6.3.2 *Autumn and Winter*

In April, a region of very high negative multiplicity is lying off the coast of northern Kwazulu Natal (Figure 6.6 Di). In this region the median peak currents of the negative discharges are quite high. Over the land, high values of negative flash multiplicity are found along the zonally-orientated band of lightning activity. This band is characterised by low negative flash multiplicity values (Figure 5.5 Di). In this band, the flash density of negative polarity is low (Figure 4.6 Di). The small amount of negative polarity that is discharged in this band contains weak currents, but numerous strokes in each flash.

This region also corresponds to the region of high percentage of positive lightning. Median peak positive currents are between 15 and 25 kA in this region, but the positive flash multiplicity is variable across this band (Figure 6.6 Dii). There are pockets of both high multiplicity and high median peak current discharge of positive lightning in parts of the northern Free State and central Northwest Province. From a risk perspective, this is extremely dangerous.

The single storm system responsible for the band of lightning off the coast of the southwestern Cape consisted of negative lightning flashes with multiplicity of 2 to 5 on average (Figure 6.6 Di). At the leading edge of the storm, the percentage of positive lightning was high, with slightly elevated positive multiplicity values and median positive currents in the range of 20 kA (Figure 4.6 Dii, Figure 5.5 Dii and Figure 5.6 Dii).

In the Lowveld, a distinct cell of high positive multiplicity lightning is visible that corresponds to median peak positive lightning values in excess of 30 kA. This is a highly dangerous situation, especially for the forestry industry in the area.

In May, most of the lightning along the Kwazulu Natal coast and extending into the ocean had negative multiplicity values below 2.5 and positive multiplicity values less than 1.3 (Figure 6.6 Ei and ii). The lightning in June is dominated by both positive and negative multiplicity values in the middle ranges (Figure 6.6 Fi and ii), with embedded cells of higher multiplicity. In July almost all of the positive flashes consisted of single strokes, with the exception of two small pockets of higher multiplicity off the coast (Figure 6.7 Aii). The negative multiplicity was low for the southern lightning cell off the Eastern Cape coast, but high for the cell off the northern Kwazulu Natal coast (Figure 6.7 Ai). In this northern cell, the median peak current of the negative discharges is of the order of 20 to 25 kA (Figure 5.6 Ai).

The lightning in August displayed high negative multiplicity values over the central regions of the country where flash densities and median negative peak currents were low (Figure 6.7 Bi). Over the Lowveld and northern Kwazulu Natal region, the highest negative multiplicity values are found over the ocean with most of the land areas experiencing one or two stroke flashes. The positive flash multiplicity in both of these regions is lower than that of the negative lightning (Figure 6.7 Bii). Small pockets of high positive flash multiplicity are found in northern Kwazulu Natal, eastern Free State and in the Northern Cape along the southern Free State border. The high positive flash multiplicity in northern Kwazulu Natal is associated with high median peak currents, but low flash densities and low percentage of positive lightning. The region in the eastern Free State has low median peak currents, but high percentage of positive lightning, whereas the region in the Northern Cape is associated with high percentage of positive lightning and moderate media peak currents. Positive lightning in the latter two regions is thus not that frequent in August, but very dangerous when it does occur.

The September storm system that was responsible for the lightning in this month consisted of mainly negative lightning flashes of multiplicities between 2 and 5 over the land and 1 to 2 over the sea (Figure 6.7 Ci). The positive lightning flashes were mainly single stroke flashes over the sea and over the far eastern land mass, with a few flashes on the westward side of the lightning region discharging numerous strokes in a single flash (Figure 6.7 Cii).

Negative flash multiplicity during the winter months appears to be fairly high over the land and quite low over the sea. The lightning distributions of both positive and negative lightning in winter display no marked patterns of distribution and are probably the function of individual storm characteristics, rather than of some large synoptic or topographic influence.

6.3.3 *Spring and Early Summer*

The negative flash multiplicity for October increased rapidly over most of the country from that experienced in winter (Figure 6.7 Di). In this month the negative polarity lightning had weak peak currents (Figure 5.6 Di). The large numbers of flashes with multiple strokes were thus discharging fairly small amounts of energy. The distribution of positive multiplicity indicates that many of the flashes were in fact single stroke flashes over the most of the country, especially around the periphery of the lightning area (Figure 6.7 Dii). Positive flashes with multiplicity between 1.1 and 1.5 occupied most of the interior plateau area. Cells of higher positive multiplicity dotted the interior region with no distinct pattern of distribution.

The distribution of the multiplicity of lightning flashes in November and December is quite similar (Figure 6.7 Ei and Fi). In November, the multiplicity of negative lightning flashes increases considerably over the eastern Northern Cape and over most of Kwazulu Natal and the Southern Thornveld region of the Eastern Cape. In December the percentage of single stroke negative flashes achieves its lowest values for the year. The regions of high negative flash multiplicity correspond in both months to weak negative peak currents, the exception being in central Kwazulu Natal and the Kalahari in December. Here the peak negative currents range from 15 to 20 kA corresponding with high multiplicity values (Figure 5.6 Fi).

The distributions of positive flashes with multiplicities between 1 and 1.3 remain almost constant in November and December (Figure 6.7 Eii and Fii). The main difference between the positive multiplicity distributions for these two months is that the more ordered northwest to southeast band of higher values established in November decreases slightly and migrates marginally to the west in December. In December, a region of high positive flash multiplicity establishes itself in the western Free State and extends in an arc into the southern part of the Northern Cape. This is a region of high positive flash density and moderate peak current values.

In summary, currently there is no consensus among lightning experts as to why negative flashes are usually composed of 3 to 5 flashes while positive flashes usually have a single stroke or a single stroke followed by a continuing current (Rakov and Huffines, 2003). What is evident from the analysis of seasonal flash multiplicity of both polarities is that lightning over South Africa in 2006 conforms to the international findings of lower multiplicity positive

strokes. It also conforms to a degree, to the findings that the percentage of single strokes of negative polarity lightning increases in winter. There is, however, no perceptible increase in the winter percentage of single stroke flashes, as is evident in the American Studies.

In general in the summer months in South Africa, a large portion of the negative flashes had multiplicity values in excess of 3 strokes per flash. The highest distribution of negative flashes with multiplicity exceeding 3 was in December, which was also the month of the lowest percentage of single stroke flashes as well as the month of the highest overall flash density.

One feature of the seasonal distribution of negative flash multiplicity is the almost complete absence of lightning with average multiplicity in the 1.5 to 2 range from March to December over the land. The only deduction that can be made is that the lightning over the land in these months consists of numerous single stroke flashes as well as many flashes with multiplicities in excess of 3 in order to arrive at these average results.

The distribution of the multiplicity of positive flashes is a bit chaotic. In most months the lightning area is dominated by multiplicity values lower than 1.3. It is the scattering of higher multiplicity cells within these larger lower multiplicity regions that results in the chaotic appearance of the distribution. In March, the higher positive multiplicity areas tend to be congregated in the central parts of the country and in November and December there is a merging of smaller cells into a detectable band across the country, but for the rest, trying to identify a pattern of distribution is almost impossible.

What does emerge from the analysis is that there is no controlling topographic influence on the distribution of the multiplicity of lightning flashes of either polarity. Nor does there appear to be a longitudinal or latitudinal control. The only discernible pattern that emerges fairly regularly in the multiplicity distribution is the northwest to southeast orientated band structure to the distribution, reaffirming that the surface trough has a key role to play in the monthly and seasonal distribution of flash multiplicity. The almost complete lack of lightning in winter makes it difficult to make any significant deductions about the flash multiplicity distribution in this season.

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The flash multiplicity of negative polarity lightning is higher than that of positive lightning. The spring and early summer months recorded the highest negative flash multiplicities, with the multiplicity dropping as summer progressed. The positive flash multiplicity values were chaotic in most seasons with the only discernable pattern being the northwest to southeast oriented band of higher positive multiplicity appearing in the early summer.

## **CHAPTER 7: Development of Risk Indexes**

*Undertaking an analysis of the various aspects of lightning flash distribution over South Africa serves little purpose unless it can be utilized to identify regions in the country at greatest risk from lightning. For most people in South Africa, the greatest risk is from high volumes of lightning over short periods of time, whereas for a large number of economic activities, this is not sufficient to quantify risk. In order to satisfy the requirements of the technology and manufacturing industries, quantifying risk from dangerous, positive polarity lightning is essential. In the chapter that follows this lightning risk will be quantified in the development of three lightning risk models.*

### **7.1 Lightning Risk Indexes**

Three indexes of lightning risk are proposed. The first identifies areas at risk from high intensity lightning, the second identifies areas at most risk from mainly positive polarity lightning and the third index is a combination of the first two and identifies areas at risk from high intensity lightning that may be positive in nature. Different sectors of the population may require information from only one of the first two indexes or may choose to evaluate their general risk by making use of the third index.

#### *7.1.1 Lightning Intensity Risk Index (LIRI)*

The Lightning Intensity Risk Index (LIRI) makes use of the following parameters: overall ground-flash density, overall median peak current and overall flash multiplicity. The aim of the index is to identify areas where a lot of lightning occurs and where most of the flashes consist of a large number of strokes, which may potentially be discharging large amounts of energy to ground. Indexes were calculated for these three parameters based on the annual lightning data. Each parameter was assumed to have made an equal contribution to overall risk and so a simple sum of the three indexes was performed. The result was then reduced to an index ranging from 0 to 1 and divided into 5 categories, namely, Almost Risk Free (0-0.2),

Minimal Risk (0.2-0.4), Moderate Risk (0.4-0.6), Severe Risk (0.6-0.8) and Extreme Risk (0.8-1).

The Central Kwazulu Natal region, extending northwards to just over the Mpumalanga border is a well-defined zone of extreme lightning risk (Figure 7.1). There are smaller cells of extreme risk along the Vaal River in the vicinity of the Vaal Dam, as well as isolated cells along the Central Drakensberg Mountains, southern Kwazulu Natal and in central Mpumalanga.

Most of the western Lowveld region bordering the escarpment, the Highveld, the Southeastern Thornveld of the Eastern Cape, the Central Bushveld, the Eastern Karoo and parts of the southeastern Kalahari Bushveld are all regions of severe lightning risk. The coastal plains of Kwazulu Natal and the Eastern Cape, as well as the Upper and Great Karoo, the northern Kalahari Bushveld and the Northern Bushveld region in Limpopo all experience moderate risk from high intensity lightning. The West Coast, Western Karoo, Southwestern Cape, Little Karoo and Southern Cape are almost free of any high intensity lightning risk.

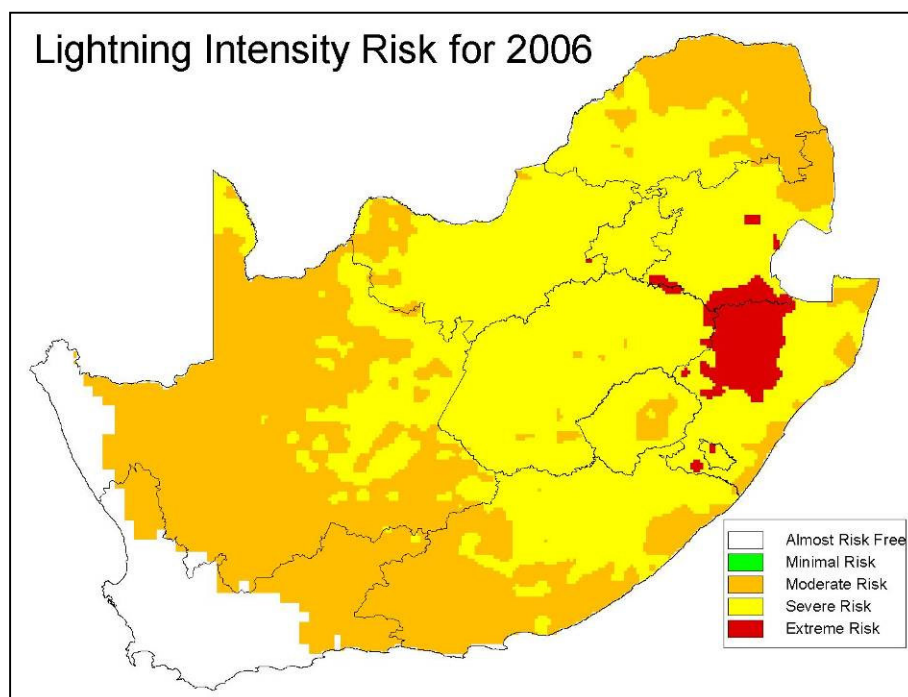


Figure 7.1: Lightning Intensity Risk for South Africa for 2006

### *7.1.2 Positive Lightning Risk Index (PLRI)*

The Positive Lightning Risk Index (PLRI) makes use of the following parameters: flash density of positive polarity lightning, the percentage of positive lightning and the median peak current and the average multiplicity of positive polarity lightning. The aim of the model is to identify areas where lightning is predominantly of a positive nature and where this lightning carries large peak currents in multiple strokes. Indexes were calculated for these four parameters based on the annual lightning data. Each parameter was assumed to have made an equal contribution to overall risk and so a simple sum of the four indexes was performed. The result was then reduced to an index ranging from 0 to 1 and divided into 5 categories, namely, Almost Risk Free (0-0.2), Minimal Risk (0.2-0.4), Moderate Risk (0.4-0.6), Severe Risk (0.6-0.8) and Extreme Risk (0.8-1).

It is important to look at the risk from positive polarity lightning as a separate index since the highest fire risk is derived from positive lightning. If there are regions with flash multiplicity in excess of 1, then the chances are strong that these are areas where subsequent strokes in flashes are continuing currents. If the peak current of the initial stroke in a multiple stroke flash is high and the first subsequent stroke is a continuing current in that same flash, then the fire risk is extremely high.

There are a number of regions in South Africa that recorded very high risk from positive polarity lightning in 2006 (Figure 7.2). The first region is in Central Kwazulu Natal, extending over the northern border into Mpumalanga. The main determinant of this high risk classification in this area is the high positive flash density coupled with high peak current values. The percentage of positive lightning is quite low, but a huge amount of lightning was discharged in this area in 2006, which means that there were still large numbers of positive lightning flashes recorded by the network. The multiplicity in the area was low, implying that most positive flashes took the form of single stroke flashes. Large commercial plantations are found in the southern Lowveld and the risk from lightning-initiated fires is always a concern. This risk index indicates that the concern is well founded.

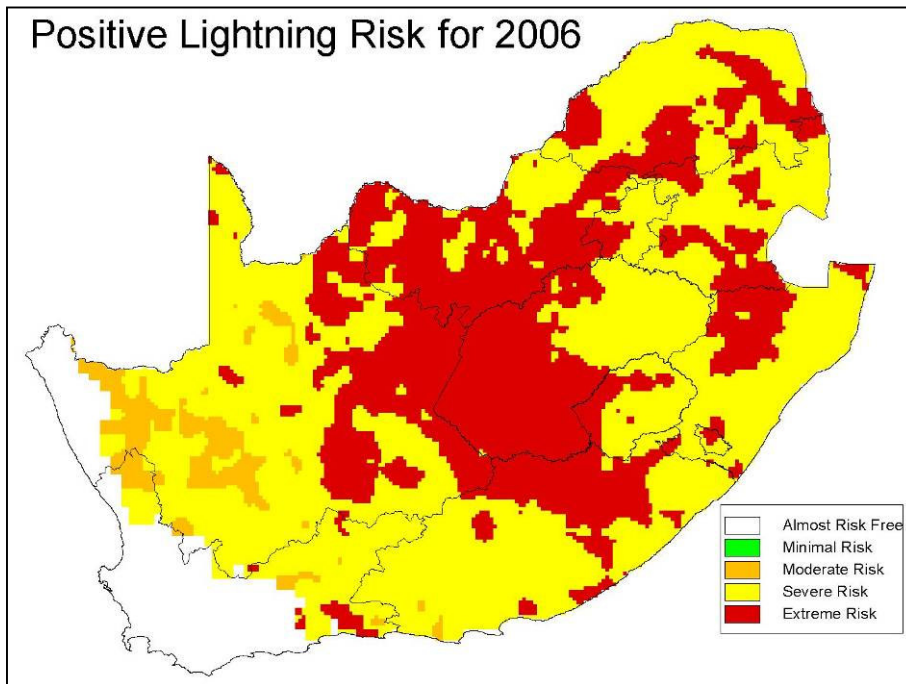


Figure 7.2: Positive Lightning Risk for South Africa for 2006

The cells of extreme positive polarity lightning risk that are found in the Limpopo Province, the rest of Mpumalanga and on the border between Limpopo and Northwest Provinces are all attributed to higher flash densities and higher median peak currents. Flash multiplicities and percentage of positive lightning are both quite low in these cells.

The main region of extreme risk from positive lightning extends in a northwest to southeast band from southern Northwest Province, through most of the Free State and into the northern parts of the Eastern Cape. In this region, three of the four index parameters are high, with the multiplicity parameter displaying elevated values only in the south eastern parts of the Northwest Province. Many mining operations are active in this latter zone of high positive multiplicity. Not only is it important to evacuate the miners during times of extreme lightning activity, but the potential continuing currents in subsequent strokes of positive polarity flashes with high multiplicity, are extremely dangerous for industries such as the mining industry, that use explosives.

The rest of the country is at severe risk from positive polarity lightning, with the exception of the far western and south western parts of the country. Any industry that utilises power or that is at risk from fire is therefore at risk from positive lightning. The regions of severe and

extreme positive lightning risk cover the parts of the country with the highest population densities as well as the highest industrial development.

### 7.1.3 Total Lightning Risk Index (TLRI)

The Total Lightning Risk Index (TLRI) utilises the indexes from the LIRI and the PLRI and gives each index an equal importance weighting. An index from 0 to 1 is then derived from the sum of the LIRI and the PLRI to gain an index of total lightning risk (Figure 7.3).

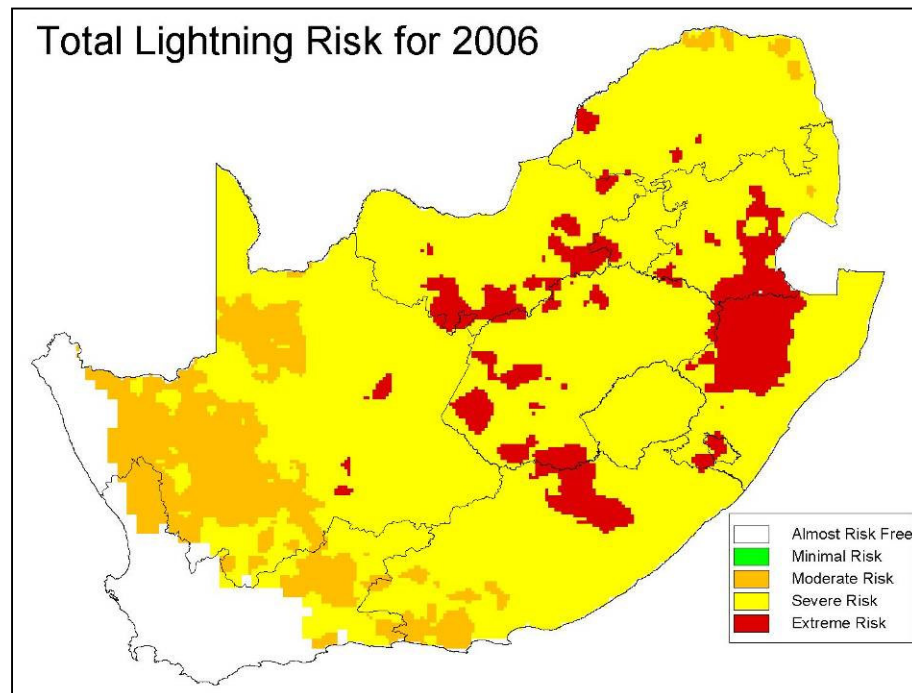


Figure 7.3: Total Lightning Risk for South Africa for 2006

The parts of the country with the highest total risk from lightning are divided into two distinct groups: those that have high risk from both positive lightning and high intensity lightning and those that are mainly at risk from positive lightning. The central Kwazulu Natal region, extending north into Mpumalanga is a region that is evident on both the LIRI and PLRI, thus indicating that this area probably has the highest lightning risk in South Africa. It is an area of high fire risk to the commercial plantations and also to some of the coal mining enterprises in Kwazulu Natal.

The remaining cells of high total lightning risk are mainly found in regions of high positive polarity lightning. The northern areas of high lightning risk that follow the border between the

Northwest Province and the Free State are also regions where there are a lot of mining activities.

The band of high risk lightning that stretches across the western Free State and into the Eastern Cape falls within a mainly agricultural region of South Africa. What is interesting to note, though, is that most of the tornados reported in South Africa annually occur in the north eastern parts of the Eastern Cape. The relationship between tornado activity, severe weather and this particular cell of high positive lightning risk requires further research and investigation.

With the exception of the Northern Bushveld region in northern Limpopo and the Western parts of the Northern Cape and Eastern Cape and a small portion of the eastern Western Cape, the rest of the country experienced severe total lightning risk in 2006. The far western parts of the country remain almost risk free from lightning.

In summary, most of the land area of South Africa is at moderate to severe risk from lightning, whether it be lightning of high intensity or positive lightning or both. The most consistent region of extreme lightning risk lies in the central Kwazulu Natal Province and extends northwards into southern Mpumalanga. In 2006 there was very little winter lightning and as such the Western Cape and West Coast regions of South Africa experienced almost no risk from lightning. As future years of data are added to the 2006 dataset, this risk classification may change.

The risk indexes proposed in this study are currently fairly straight-forward linear calculations of derived indexes. They are flexible enough to be adapted to meet the needs of any specific industry sector in order to identify areas of potential high risk from lightning. Once identified, further, more detailed and industry-specific analyses can be undertaken. It is important that each industry sector be able to identify the lightning parameters that affect them the most and to determine aggregation methods for adapting these risk models to suite their purposes.

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Quantifying lightning risk is difficult since "risk" means different things to different people and to different industry sectors. The risk indexes developed in this chapter are flexible enough to enable them to be modified to accommodate the needs of any person or industry at risk from lightning. The initial analysis has given an indication of those parts of the country which experience considerable lightning damage annually.

CHAPTER 8: Conclusion

The development of a lightning climatology is critical before any risk assessments can be attempted. For many years the only lightning ground flash density study available for South Africa was the one undertaken by the CSIR with a limited flash counter network (Proctor, 1993). The installation of the SAWS LDN has finally provided scientists with an accurate ground strike data set derived from some of the most advanced ground-based detection sensors in operation in the world. In the past the climatology of lightning in South Africa was in fact a climatology of ground flash density. The LDN provides data on numerous other characteristics of lightning and thus this is the first study undertaken in South Africa that evaluates lightning parameters other than ground flash density.

For the purposes of this research, the data has been analysed in detail for a single year, but as the data from each successive year is added to this initial climatology, patterns of lightning characteristics will start to better define themselves. There are many features in the analysis of the seasonal data that are attributable to single storm systems, especially in the low lightning months. These features will either be absorbed once a larger data set is available or will be reinforced.

8.1 Ground Flash Density

The analysis of the ground-flash density distribution of lightning over South Africa indicates that most of the lightning occurs in spring and summer. The regions of the country experiencing the highest ground flash density values are along the eastern Escarpment and onto the Highveld region of the interior plateau. The primary mechanisms responsible for the high lightning flash densities differ for these two regions. The high lightning flash densities in the eastern parts of KwaZulu Natal and the Mpumalanga Lowveld are a function of the orographic enhancement of convection in warm, moist air which is fed in over the country from the warm Agulhas current system. The high flash densities on the plateau result from a multitude of isolated thunderstorms which develop mainly in the summer when the land mass is very hot and where moisture laden air is fed in over the northern parts of the country from the circulation around the continental high pressure.

In South Africa in 2006, the areas of highest flash density in the summer months were also the areas of the country with lower percentage of positive lightning. The lightning in this area is mainly of negative polarity. The percentage of positive lightning increases westwards across the country and tends to follow a northwest to southeast oriented pattern, especially in the later summer months. The indication is that the formation of line thunderstorms ahead of the surface trough in summer may be responsible for this pattern of distribution. In the United States, longitude has a strong influence on the lightning distribution (Orville and Huffines, 2001), but neither longitude nor latitude appear to play an important role in the distribution of lightning ground flash density over South Africa.

8.2 Median Peak Current

The regions of lowest median peak current in South Africa correspond in the eastern part of the country to the areas of highest flash density. Most of the lightning in this part of the country is also negative in polarity. The large amounts of lightning in this high flash density part of the country tend to carry smaller amounts of energy to ground than elsewhere in the western parts of the land mass. A feature of the annual and seasonal median peak current distribution is the northwest to southeast orientation of bands of distribution across the country. This is attributable to the position of the surface trough.

In general the median peak currents of positive lightning are 2 to 5 kA higher than those of negative lightning. The median peak current for the entire year for lightning of negative polarity was -15 kA and for positive polarity lightning was 17 kA. In keeping with the results from the United States (Orville, *et al.*, 1987; Orville and Huffines, 1999, 2001), the median peak current values of lightning of both polarities increase in autumn and early winter in South Africa. The difference between the peak currents of positive and negative flashes is larger in the winter and early spring than in the summer. Very little lightning occurred in the winter of 2006, but that which did occur was found off the coast of the Eastern Cape and Kwazulu Natal and was attributed to the passage of mid-latitude cyclones. In general this lightning displayed higher median peak currents of positive polarity lightning.

The positive peak current distributions over South Africa in the spring and early summer are different from those of the mid to late summer. In the latter half of the year, the median positive peak currents were higher than in the beginning of the year. This distinction in distribution is also evident in the percentage of positive lightning distribution. In the first

three months of the year, the percentage of positive lightning over the country was much higher than in the last three months. The implication is that despite the fact that the positive lightning discharges are more intense in the spring and early summer, there are fewer of them and so possibly will not cause as much damage as in the later summer months.

8.3 Flash Multiplicity

The regions of highest flash multiplicity in South Africa correspond to the regions with highest flash density, but lowest median peak current. Despite the fact that the individual lightning strokes may be weaker in these areas, the amount of lightning discharging to ground is considerable. In general, most lightning of negative polarity in South Africa consists of more than one stroke per flash, whereas positive lightning tends to be dominated by single-stroke flashes. In the summer months, a large portion of the negative flashes have multiplicity values in excess of 3 strokes per flash. The highest distribution of negative flashes with multiplicity exceeding 3 was found in early summer, when the overall flash density was also very high.

The distinct northwest to southeast bands of lightning evident in the flash density and in the median peak current distributions is not always evident in the distribution of flash multiplicity. There is some evidence of these bands of distribution in the mid summer months for flash multiplicities of negative lightning, but the pattern is not consistent throughout the year and seems to really only be clearly defined along the western boundary of the lightning region. The distribution of the multiplicity of positive flashes is a bit chaotic for all months of the year with a scattering of higher multiplicity cells within large regions of lower multiplicity.

There is no controlling topographic influence on the distribution of the multiplicity of lightning flashes of either polarity. No strong longitudinal or latitudinal control is evident either. The only discernible pattern that emerges in the multiplicity distribution of negative lightning is a poorly defined northwest to southeast orientated band structure. The almost complete lack of lightning in winter makes it difficult to make any significant deductions about the flash multiplicity distribution in this season.

8.4 Lightning Risk

Knowledge of the amount of lightning that is recorded, the strength of the peak current and the number of strokes in each flash is important in determining lightning risk. Following the study of each of these lightning parameters, it was possible to put these results into simple linear indexes to determine the areas in South Africa at highest risk from lightning. Three risk indexes were devised: one evaluating risk from large amounts of lightning, one for the assessment of risk from positive polarity lightning and finally one which evaluates overall risk from high intensity lightning of either parameter.

Most of the land area of South Africa is at moderate to severe risk from lightning, whether it be lightning of high intensity or positive lightning or both. The most consistent region of extreme lightning risk lies in the central Kwazulu Natal Province and extends northwards into southern Mpumalanga. In 2006 there was very little winter lightning and as such the Western Cape and West Coast regions of South Africa experienced almost no risk from lightning.

The main region of extreme risk from positive lightning extends in a northwest to southeast band from southern Northwest Province, through most of the Free State and into the northern parts of the Eastern Cape. In the south-eastern parts of the Northwest Province, the positive ground flash density, the percentage of positive lightning, the median peak current of positive lightning and the positive flash multiplicity values are all high. The result is that this region has one of the highest calculated risks from positive polarity lightning in the country. It also happens to be the region in the country in which a lot of mining takes place. Not only is it important to evacuate the miners during times of extreme lightning activity, but the potential continuing currents in subsequent strokes of positive polarity flashes with high multiplicity, are extremely dangerous for the mining industry since they make extensive use of explosives.

CHAPTER 9

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