Cut-off lows over South Africa and their contribution to the total rainfall of the Eastern Cape Province

by

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DECLARATION

I, Samuel Molekwa, declare that the dissertation / thesis, which I hereby submit for the degree Master Science at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE　　　　DATE

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Summary

Cut-Off Lows (COLs) are certainly amongst the most important synoptic-scale rain producing weather systems in South Africa. Rainfall associated with COLs is usually widespread, while about 20% of COLs are associated with heavy rainfall. Both these attributes of rainfall associated with COLs are important to agriculture. Widespread rainfall secures good grazing potential, while heavy rainfall not only contributes largely to maintaining dam levels that are needed for irrigation, but also to flooding and erosion. Agriculture in the Eastern Cape Province of South Africa is predominantly rain-fed, while agricultural activities that depend on irrigation are mostly located along the western coastal belt of the province. Despite of the fact that all COLs do not pass directly over the Eastern Cape Province, most of them appear to have a direct or indirect influence on the rainfall of the province, and in turn, impact on agricultural production and even the economy.

In this study, the contribution of COLs to rainfall over the Eastern Cape Province is investigated. In order to achieve this, a climatology of COLs for the period 1979 to 2009 (31 years) was constructed by utilizing the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data to create 6-hourly contour images of geopotential heights and air-temperatures at the 500 hPa pressure level. All COLs that occurred over South Africa bounded by 20^0S to 40^0S and 0^0E to 50^0E from the day they started (at the formation of a closed low pressure system) until the day they ended (at the disappearance of the closed low pressure system), and that were cold cored, were considered as potential COLs in this study. In addition, low level circulation maps obtained from the South African Weather Service's (SAWS's) daily weather bulletins were used to ensure that the defined COLs were indeed extending from the 500 hPa pressure level to the land surface. Daily rainfall totals from 22 well-distributed weather stations over the Eastern Cape Province were used to determine the contribution of COLs to the rainfall over the province.

It was found that 64% of COLs that lasted for more than 24-hours over the study domain had an influence on the total rainfall over the Eastern Cape Province. Monthly frequency distribution of COLs reveal that April and May had the highest occurrences, while December and January have the least occurrence. Long-term seasonal frequencies distributions of COLs show the highest occurrence during March-April-May (MAM) with the least occurrences during December-January-February (DJF). Most COLs lasted for 2-4 days over South Africa and the Eastern Cape Province for the study period of 31-years. The contribution of rainfall associated with the occurrence of COLs is found to be approximate 37-38% annually along the coastal areas, while it is less than 10% annually over the interior of the Eastern Cape Province.

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LIST OF ABBREVIATIONS

AA	Annual Average
AO	Atlantic Ocean
ABFZ	Angola Benguela Frontal Zone
AC	Annual Average Contribution of Cut-off lows
AGIS	Agricultural Geo-Referenced Information System
ARC-ISCW	Agricultural Research Council-Institute for Soil Water and Climate
amsl	above mean sea level
COLs	Cut-Off Lows
DBSA	Development Bank of Southern Africa
DJF	December-January-February
ECDC	Eastern Cape Development Corporation
FAO	Food and Agriculture Organization
GrADS	Grid Analysis and Display System
GDP	Gross Domestic Product
GIS	Geographic Information System
GFI	Gross Farming Income
GMT	Greenwich Mean Time
hPa	hectopascal
IO	Indian Ocean
ITCZ	Inter-Tropical Convergence Zone
JFM	January-February-March
JJA	June-July-August
MAM	March-April-May
NCEP-NCAR	National Centers for Environmental Prediction-National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
PO	Pacific Ocean
PSA	Pacific South America
SAST	South African Standard Time
SAWS	South African Weather Service
SH	Southern Hemisphere
SON	September-October-November
SST	Sea Surface Temperature

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Cut-Off Lows (COLs) are defined as baroclinic temperate disturbances that occur in the westerlies as deep troughs, and that are associated with a cold-cored depression (Preston-White and Tyson, 1988). It is known that COLs are globally responsible for extreme precipitation events (Sabo, 1992; Muller et al., 2007; Porcù et al., 2007; Zhao and Sun, 2007).

These systems often cause significant weather over the Mediterranean and the European continent, especially south of the Alps. COLs are also associated with long-lasting heavy precipitation in large parts of Austria (Sabo, 1992). According to Hu et al. (2010), anomalous regional climate and many convective events over northeast China are closely associated with the occurrence of COLs. For example, during June to August 1998, COLs were associated with a record flood that resulted in serious damage to the local economy and social societies of northeast China (Zhao and Sun, 2007). Over West Africa, a COL caused extreme precipitation during the cool season of 09 to 11 January 2002. During this event, up to 116 mm of rain per day fell in the northern part of West Africa (Mali, Mauritania and Senegal). In another African COL event that lasted from 30 March to 01 April 2002, rainfall of half the average annual total was recorded over the arid southern part of northwestern Africa (Knippertz and Martin, 2007). Muller et al. (2007) also documented a COL event that caused heavy rainfall during the austral summer of 2006 in southwestern Africa. During this event, 102 mm of rain was recorded which was six times the Annual Average (AA) rainfall.

In South Africa COLs are regarded as important synoptic-scale weather systems that occur over the sub-tropics, and which are normally associated with widespread rainfall, with about one out of five systems resulting in flood events, especially along the southern and eastern coastal belts and adjacent interior of the country (Taljaard, 1985; Roux and van der Vyver, 1988; Singleton and Reason, 2007a; Singleton and Reason, 2007b; Browne et al., 2009). The most extensive flood events caused by COLs over

South Africa typically occur along the south to south-eastern coastal regions of the country (Taljaard, 1986). According to Jury and Levey (1993b) the highest rainfall associated with the occurrence of COLs occurs in March in the Eastern Cape Province. Both Taljaard (1985) and Singleton and Reason (2007b), who had constructed a climatology of COLs for the period of 1973 to 1982 and 1973 to 2002, respectively, found that an average of 11 COLs occur per year with a maximum number observed during the austral autumn season (March-April-May: MAM).

The following are documented examples of COLs associated with heavy rainfall over South Africa:

- In September 1968 the city of Port Elizabeth experienced more than 500 mm of rainfall in 24 hours because of the occurrence of a COL over the southwestern part of South Africa (Tyson and Preston-White, 2000).
- In August 1970 East London received 500 mm of rain because of a COL that was situated over the central part of South Africa (Tyson and Preston-White, 2000).
- In January 1981 a COL situated along the west coast of South Africa led to flooding in the semi-desert town of Laingsburg, some 150 km inland of the south coast (Tyson and Preston-White, 2000).
- In September 1987, a COL caused severe flooding over the coastal areas of the Kwa-Zulu Natal Province. This system tracked east over the Northern Cape and North-West Provinces with more than 900 mm of rainfall recorded over three days (Tyson and Preston-White, 2000).
- In August 2002, East London received more than 300 mm of rain in 24 hours because of a COL that was situated over the western interior of South Africa (Singleton and Reason, 2006).
- In March 2003, the town of Montagu received close to 200 mm of rain in 24 hours because of a COL that tracked east along the south coast of South Africa (Singleton and Reason, 2007a).

Earlier studies of COLs are found to be more of a descriptive nature, whereas more recent studies aim at addressing the processes responsible for the associated extreme rainfall. The influences of topography and Sea Surface Temperatures (SST) have been shown to be important in the formation of heavy rainfall associated with COLs (Singleton and Reason, 2006).

In this study a climatology of COLs relevant to rainfall over the Eastern Cape Province for the period 1979 to 2009 (31 years) is constructed. The main purpose for this study is to quantify the importance and contribution of COLs to the total rainfall over the Eastern Cape Province.

1.2 SOUTH AFRICA

1.2.1 Geographical location

South Africa is located in the southern part of Africa. Its northern boundary is located at approximately 22^0S and its southern boundary of approximately 35^0S. Neighboring countries include Mozambique, Zimbabwe, Botswana, Namibia, while Swaziland and Lesotho are enclosed within South Africa. It also has borders with the Atlantic Ocean (AO) in the west and southwest, Indian Ocean (IO) to the south and southeast (Figure 1.1). South Africa has nine provinces, which are the Limpopo, North-West, Mpumalanga, Gauteng, Northern Cape, Western Cape, KwaZulu-Natal, Free State, and the Eastern Cape Province.

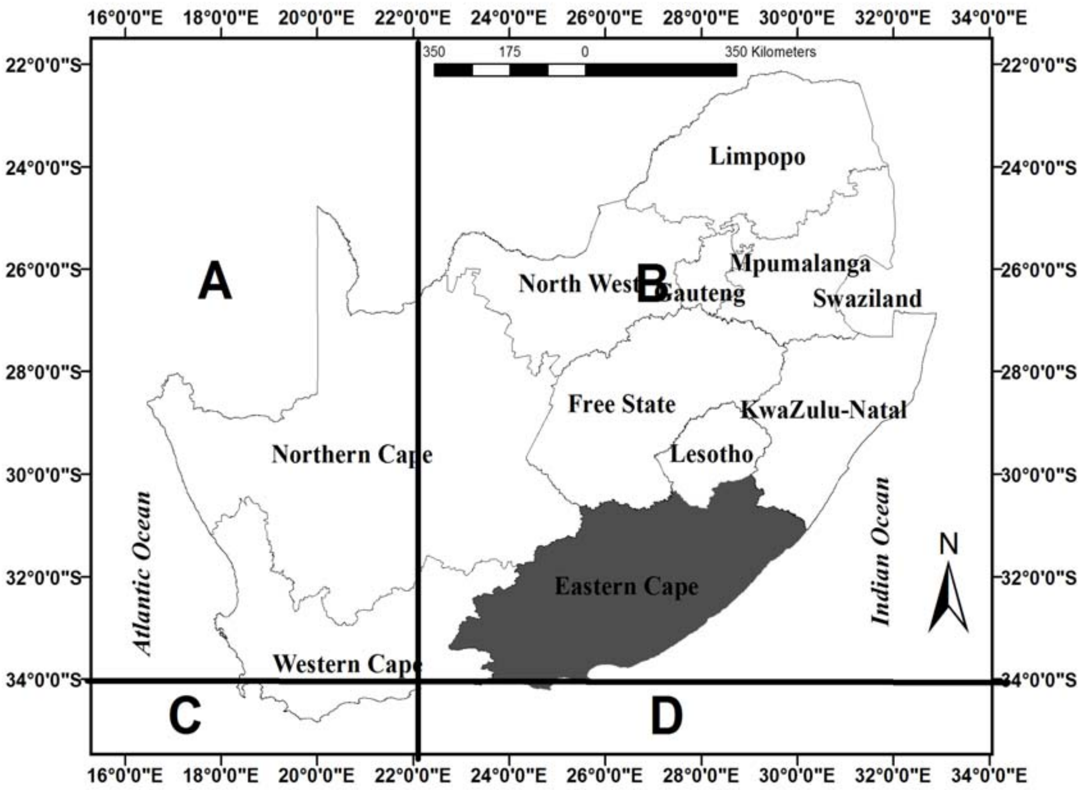


Figure 1.1: A map of South Africa with its nine provinces. The study area is indicated by a dark color which is the Eastern Cape Province. For the purpose of classification of Cut-Off Lows (COLs), South Africa is divided into square Regions A, B, C, and D.

1.2.2 Topography and drainage

According to Taljaard (1994), South Africa is characterized by a temperately elevated plateau with the greater part rises to over 1 km above mean sea level (amsl) and to more than 1.5 km amsl over widespread areas in the east (Figure 1.2). From the north, a steep plateau runs southward from the Soutpansberg, becoming the Drakensberg of Kwazulu-Natal, and the northeastern interior of the Eastern Cape Province. In the east, the main escarpment rises steeply from the coast in most areas over the first 200 to 300 km from the coast. The Maluti Mountains in Lesotho rises to over 3 km amsl, as shown in Figure 1.2.

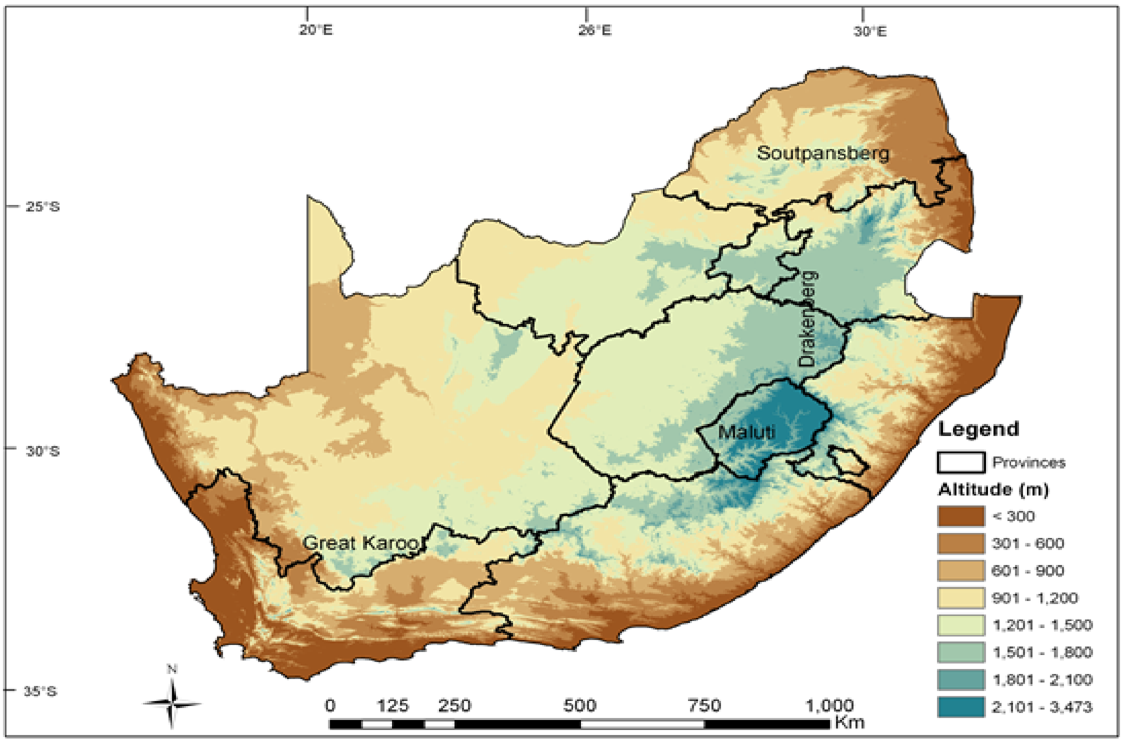


Figure 1.2: Topographical map of South Africa with altitudes ranging from 300 m to 3473 m above mean sea level (amsl).

Runoff over South Africa takes place through a large number of rivers from higher altitudinal locations towards the IO and AO. The major rivers of South Africa are the Limpopo, Vaal and Orange rivers. Parts of the Eastern and Western Cape Provinces, as well as the KwaZulu-Natal Province, have seasonal rivers with coastal lagoons.

1.2.3 Climate and climatic variability

South Africa is regarded as a semi-arid region, with high interannual rainfall variability (Tyson, 1986). Most of the country receives less than 500 mm per year (Jury and Levey, 1993; Jury and Majodina, 1997). According to Mason et al. (1999), over large areas of the country the intensity of the 10-year high rainfall events has increased by 10%, except for the south-west winter rainfall region and part of the north-east and north-west. The most obvious feature in the country's spatial rainfall distribution is the east-west gradient, with more rain to the east and less rain to the west. Most of South Africa receives rainfall during austral summer months (December-January-February: DJF), while the southwestern part receives austral winter (June-July-August: JJA) rain. The southern coastal belt receives rainfall throughout the year (Taljaard, 1996). According to Preston-Whyte and Tyson (1988), the weather and climate of South Africa, which is situated in the subtropics of the Southern Hemispheres (SH), are influenced by tropical as well as extra-tropical disturbances from the mean circulation of the atmosphere.

The mean circulation of the atmosphere over South Africa is predominantly anticyclonic, except for lower atmospheric pressure levels during summer when heat troughs develop over the subcontinent (Taljaard, 1996). It is in the vicinity of these surface troughs with their cyclonic circulation that moisture (often in the form of cloud bands) from the tropics is transported to South Africa during summer months. Rainfall variability over the summer rainfall region of South Africa is therefore linked to the variability in near-surface troughs, where tropical cloud bands typically occur further eastwards over the Mozambique Channel during the dry season (Washington and Todd, 1999). During winter months, the moisture source from the tropics is reduced by the northward migration of the Inter-tropical Convergence Zone (ITCZ) and the intensification of the mean anticyclonic circulation over South Africa (Tyson and Preston-Whyte, 2000). During winter, frontal troughs approach South Africa on a regular basis from the south-west, with cold fronts advancing as far as to the northern parts of the country.

Interannual rainfall variability over South Africa is often linked to global and regional SST anomalies (e.g. Nicholson, 2003), as atmospheric circulation responds to changes in SSTs. The IO is regarded as the major source of moisture for South Africa rainfall during summer. It was found that cold SST anomalies in the Mascarene region, with warm SST anomalies to its south, are normally associated with wet conditions over southern Africa as this SST anomaly pattern induces a stronger surface high pressure system that aids in moisture advection towards the subcontinent from the southern IO (Washington and Todd, 1999). Warm SSTs in the western tropical IO are also sometimes associated with wet conditions over southern Africa (Landman and Mason, 1999).

SST variability in the AO also seems to be important for the climate of southern Africa (Reason et al., 2006). For example, SST anomalies over the south-east AO often influence moisture fluxes and rainfall over north-eastern South Africa and southern Mozambique (Reason et al., 2006). In the study of Hermes and Reason (2009) it was indicated that the tropical south-east AO is regarded as important for seasonal rainfall and for regional fisheries in austral summer months along the west coast of Africa. This link is associated with the variability in winds in the Angola Benguela Frontal Zone (ABFZ) and the influence of SSTs anomalies on moisture advection and rainfall.

Interannual rainfall variability over South Africa has also been related to the interaction of far-field SST anomalies in the equatorial Pacific Ocean (PO) with South Africa atmospheric circulation (Mason, 1997; Mason et al., 1994; Viguad et al., 2009). Atmospheric circulation and SST changes over the equatorial PO are often referred to as the El Niño Southern Oscillation (ENSO). The ENSO have shown to be a primary cause for rainfall variability over the summer rainfall region of South Africa (Lindesay, 1988). During warm / El Niño (cold / La Niña) ENSO episodes, South Africa usually experiences below (above) normal rainfall during summer (van Heerden et al., 1988).

1.2.4 Weather systems

As mentioned before, South Africa is located in the subtropics of the SH, which is also known as a region dominated by subtropical high-pressure systems (Tyson, 1986). Apart from near-surface (and sometimes deeper) low-pressure systems during summer, the mean circulation over South Africa is characterized by anticyclonic circulation (Harrison, 1984). Over South Africa most of the year atmospheric circulation is dominated by extra tropical weather systems such as the ridging AO High, cold fronts and COLs especially southern and central regions (Dyson and van Heerden, 2002). This explains the clear skies that mostly occur over the country. The anticyclonic circulation, however, is often interrupted by circulation patterns that favour cloud development and rainfall. The following shed some light on the conditions favorable, or not favorable, for rainfall over South Africa (Preston-White and Tyson, 1988):

1. *Weather systems not favorable for rainfall*

   Fine weather is usually associated with higher pressure (anticyclonic circulation) that is either dominant throughout the troposphere, or strong in the upper atmosphere (~500 hPa pressure level). Such systems are associated with subsidence and limited cloud development.

2. *Summer rainfall producing weather systems*

Tropically influenced weather systems are known to be rain producing and are dominant over South Africa during the austral summer season. Easterly waves and subtropical lows are mostly responsible for moisture advection from the IO and tropics towards the eastern parts of South Africa. Easterly waves are disturbances that are associated with tropical easterly flow around the northern sector of the IO anticyclone, and are associated with warm humid easterly winds in the ITCZ which bring moisture to the African continent. Subtropical lows develop over southern Africa in the form of surface anticyclonic circulation that is centred over the eastern subcontinent, with a trough over the west which often extends from the tropics.

3. *Moderate disturbances in the westerlies*

Westerly waves, west coast troughs, ridging anticyclones, southerly meridional flow, cold fonts, COLs are weather systems that are associated with higher latitudes. Well-developed westerly waves are normally slanted westward with height and are associated with baroclinic instabilities and mid-latitude cyclones to the south of the country. Westerly waves can produce light rainfall at coastal regions during summer as they move over the southern coast-line of South Africa. West coast troughs have a maximum frequency of occurrence during the early summer and late autumn seasons and frequently produce rain between October and April. During early summer and autumn, it might happen that widespread rainfall occurs over the central and western parts of South Africa when a surface trough is located at the west coast with the support of an upper-tropospheric westerly wave situated to the west of the continent this type of circulation pattern is referred to as a west coast trough. Ridging anticyclones at the surface that extends from the southern AO towards the southern IO and adjacent inland areas provide favorable surface circulation for the development of rainfall as moisture is advected toward the country from the south and eastern oceans as these systems progresses eastwards / north-eastward. The cooler air from the south often undercuts the more humid and potentially unstable warm air from the north, which could produce rain over the eastern interior of South Africa (Taljaard, 1996). It frequently happens that ridging anticyclones are also associated with deeper westerly waves at 500 hPa. The combination of ridging anticyclones and upper air westerly waves often produces widespread rainfall over the eastern parts of the South Africa. A special case of ridging anticyclones is referred to as southerly meridional flow, which occurs when air is advected from the south of the subcontinent towards the country. This type of circulation is characterized by a relatively strong high pressure system ridging eastward from the west with a low pressure system situated south-east of the country, resulting in a strong zonal pressure gradients and winds. Over the southern regions of the country, the southerly meridional circulation produces light rainfall in spring and temperatures could drop severely, particularly in the southern parts of South Africa. Another system associated with disturbances in the westerlies is cold fronts. Cold fronts are associated with cold air masses flowing from the south and south-west to produce rainfall and low surface temperatures. Warmer tropical air often rises against the slope of the cold frontal air to produce rainfall.

An intense form of an upper tropospheric westerly wave is known as a COL. COLs start to develop in the upper westerlies as a trough, extending downward to the surface and deepens into a closed circulation which becomes displaced out of the basic westerly current. In South Africa many flood-producing rains are caused by COLs, which most frequently occur during the seasons March to May and September to November. A more comprehensive discussion on COLs is given in Section 1.4.

1.3 CUT-OFF LOWS

According to Palmer (1949), if an upper air system separates from the principal westerly flow of the mid-latitudes it could become “cut-off” from the westerly flow to form a COL. However, the definitions of COLs vary to some extent in the literature. In Qi et al (2000), COLs are defined as synoptic scale low-pressure systems, which have a deep trough at the 500 hPa level and a closed circulation at the surface. Preston-White and Tyson (1988) defined a COL as a feature that is defined by a cold-cored depression formed by a westerly trough, and which starts in the upper westerlies as a trough and deepens into a closed circulation that extends downward to the surface (see Figure 1.3). Taljaard (1985) defined COLs as a deep low-pressure system which is the strongest in the upper troposphere where it forms at 500 hPa. There are certain areas where COLs occur more frequently, such as for example over the south-western parts of South Africa (Jetton, 1966).

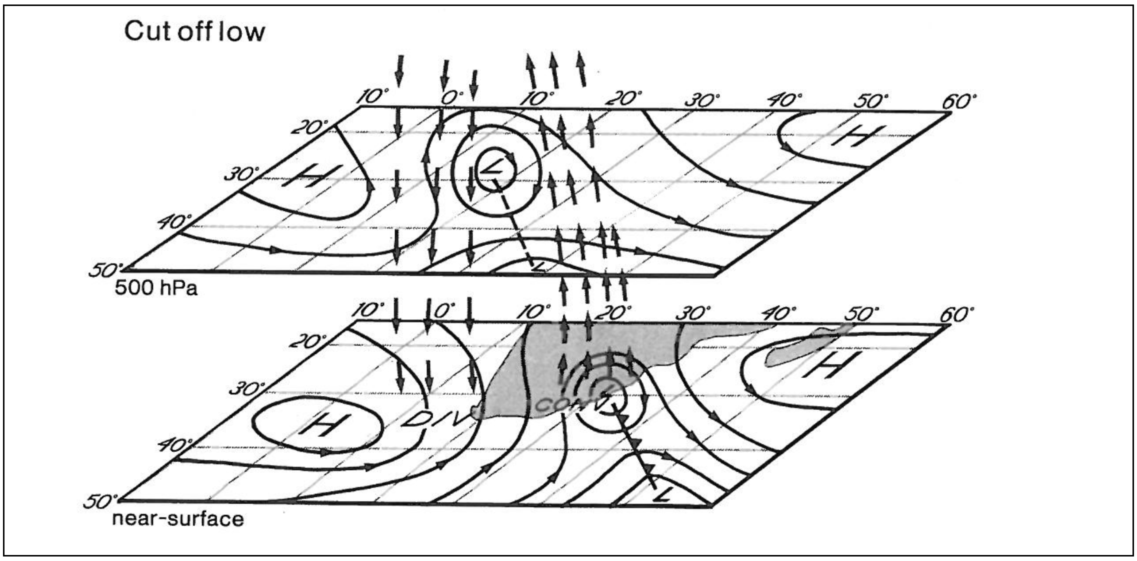


Figure 1.3: An illustration representing the 500 hPa and the near-surface circulation as well as vertical flow associated with a typical Cut-Off Low (COL) system. (Acknowledgement to Preston-White and Tyson, 1988).

COLs could be categorized into three groups, depending on the nature of the jet streak that leads to their formation (Singleton and Reason, 2007a):

- Polar-type COLs develop as results of the equatorward extension of a polar jet. Such a COL tends to become situated pole-wards of this jet.
- Subtropical COLs develop through a split in a zonal polar or subtropical jet that extends equatorward.
- Polar vortex-type COLs develop from an extension of the polar vortex itself, and tends not to be advected away from the main polar vortex.

Singleton and Reason (2007b) have identified COLs over southern Africa from 1973 to 2002 on the 300 hPa pressure level, where they defined a COL as being present when a closed geopotential height contour lasting for more than 24 hours of existence within the region bounded by 10^0E to 40^0E and 20^0S to 40^0S. The potential vorticity for closed lows were examined and available satellite images were used to verify that an identified system was indeed correct. Upper-air and surface charts for the 10-year period from

1973 to 1982 were used to identify all COLs that occurred over South Africa (Taljaard, 1985). Taljaard (1985) defined the characteristics of COLs as systems that develop in the zone 40^0S to 50^0S when relatively cold air from the middle-latitudinal south AO is trapped by a marked south-eastward flow of subtropical warm air. COLs on average move in an eastward direction at the 500 hPa pressure level, unlike at the surface where they move generally more in a southeasterly direction (Keable et al., 2002).

The locations and tracks of COLs were described in Taljaard (1985) as follows:

- COLs might develop off the west coast of South Africa and move to the IO past the south-west coast, or they might proceed in a south-easterly direction across the Cape Province (old province forming the southern section of South Africa).
- COLs might remain close to the coast or enter the South Africa continent after they developed off the south and east coasts, causing cold rainy conditions along their western flanks.
- In some cases COLs might move away from the South Africa continent (southwards) and then retrograde westwards.

The climatology of COLs over subtropical southern Africa was investigated by Taljaard (1985) and Singleton and Reason (2007b). The frequency of COLs shows a semi-annual variation with peaks in March to May and September to November, while December to February is associated with the lowest frequency of COLs (Tyson and Preston-White, 2000). In a technical paper by Taljaard (1985), only seven systems lasted for more than two days in 1976, four systems occurred during September 1975, three systems during April 1978, three systems during July 1980 and four systems during April 1982. In both articles of Taljaard (1985) and Singleton and Reason (2007b) it was shown that COLs occurred most often during spring and autumn. The annual average frequency of COLs was approximated to be 11 per year with a maximum in spring and autumn and a minimum in summer (Singleton and Reason, 2007b). During warmer seasons COLs occur during April to September and during colder seasons they occur during October to March (Delgado et al. (2007).

1.4 AGRICULTURE AND RAINFALL

In general there are two types of agricultural activities in South Africa, namely irrigated and rain-fed agriculture. Rain-fed agriculture is defined as the type of farming that depends on rain, which will particularly be addressed in this study. As a matter of fact the largest portion of the world's rural poor population depends on rain-fed agriculture and in developing countries droughts often reduces crop yields production (Greenfield, 1988). In South Africa maize, which is a summer grain, is mostly cultivated under rain-fed conditions. According to Jury (2001) more than 100 million of the population of southern African dependent on subsistence agriculture to meet their basic nutritional needs and rainfall variability therefore has a noticeable impact on crop production, overall economic growth in terms of South Africa's Gross Domestic Production (GDP) as well as on the stream flow of major rivers (Jury, 2001). The practice of rain-fed agriculture is regarded as important for South Africa farmers because of food security (van Averbeke and Khosa, 2007). According to Klopper (1999) the uncertainty about future climate conditions on decision-making is an important retarding issue in food security, water sensitive sectors, agriculture and many other sectors of the economy.

1.5 AGRICULTURE AND CUT-OFF LOWS

Rainfall associated with the occurrence of COLs is regarded as important for the agricultural industry of the Eastern Cape Province of South Africa, since such rain might be very helpful for agricultural development and water supply, but could also be of high risk if it leads to flooding, which will cause erosion and damage to crops.

COLs contribute to both irrigated and rain-fed agriculture. Irrigated agriculture makes use of dams and rivers for irrigation. For the latter rainfall from COLs could contribute in filling dams and rivers. COLs could also initiate rainfall that is important for rain-fed agricultural practices. As mentioned before, rain-fed agriculture is important for producing food to poor communities, especially in developing countries (Wani et al., 2009). According to Reason et al. (2005) rainfall in the early season may result from mid-latitude systems such as COLs, which is also the time for germination of maize seed.

COLs can bring moderate to heavy rainfall and were also found to be extremely important to the Australian agricultural industry (Qi et al., 1999). In the southeastern Australia cropping region, COLs were found to be responsible for at least 50% of all growing-season rainfall, and the frequency of COLs were also highest during autumn and spring (Pook et al., 2005).

1.6 MOTIVATION FOR THE RESEARCH

The Eastern Cape Province is located in the southern to southeastern part of South Africa (Figure 1.1). The province is quite unique, as different climate regions with distinct characteristics occur in the province, and as the region is known for its high climate variability (Tyson and Preston-White, 2000). According to the Köppen climate classification, the eastern part of the Eastern Cape Province may be classified as a humid annual rainfall region, whereas the remainder of the Eastern Cape Province varies from humid-annual rainfall to arid summer rainfall. The Eastern Cape Province is affected by both winter and summer rainfall bearing systems. The transitional months, in particular March, is a very important rainfall-month and therefore important to agriculture as this is the period when grains are planted or when the field should benefit from the growing season (Jury and Levey, 1993a). The transitional periods (autumn and spring), are typically the periods when the occurrence of COLs are the highest (Singleton and Reason, 2007b). Note that apart from agriculture, vegetation patterns are also influenced by rainfall variation in parts of the Eastern Cape Province (Kakembo, 2001). It is therefore hypothesized that the rainfall contributed by COLs has a significant effect on the total rainfall of the Eastern Cape Province, and that rainfall from COLs contributes significantly to rain-fed agriculture in the Province.

The studies on COLs by Taljaard (1985) and Singleton and Reason (2007b) give a climatology from 1973 to 1982 and from 1973 to 2002, respectively and also descriptive the nature of the systems over southern Africa, whereas some studies of Singleton and Reason (2006) and Singleton and Reason (2007a) were aimed at addressing the processes responsible for extreme rainfall over East London and south coastal region of South Africa, respectively. In this study, an extended climatology is constructed for COLs up to 2009 over South Africa, with specific emphasis on their contribution to the total rainfall in the Eastern Cape Province, and the benefits that this rain holds for rain-fed agriculture.

1.7 AIM AND OBJECTIVES OF THE RESEARCH

The overall aim of this study was to construct an extended climatology of COLs over South Africa and to determine the contribution of COL rainfall relatively to the total rainfall of the Eastern Cape Province. The overall aim was achieved by the following objectives:

OBJECTIVE 1

The first objective of this study was to construct an extended climatology (frequency, duration and location) of COLs over South Africa and the Eastern Cape Province for the 31-year period 1979 to 2009.

a) *Data was obtained from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data (geopotential heights and air temperatures at 500 hPa as well as sea level pressure) for the 31-year period 1979 to 2009.*
b) *COLs were identified by firstly consider closed lows in the upper air (500 hPa pressure level) that are cold-cored.*
c) *Surface synoptic charts of sea level pressures were investigated to identify if the closed low-pressure systems identified on the 500 hPa pressure level extended to the surface.*

OBJECTIVE 2

The second objective was to determine the contribution of rainfall produced by the identified COLs to the total rainfall over the Eastern Cape Province, with some conclusions on how such rain could benefit rain-fed agriculture.

a) *Rainfall data for the Eastern Cape Province was obtained from the South Africa Weather Service (SAWS) and Agriculture Research Council - Institute for Soil, Climate and Water (ARC-ISCW) for the 31-year period 1979 to 2009*.

b) *Rainfall data was used to investigate the rainfall associated with each one of the COLs in order to find the rainfall contribution from each COL to the total Eastern Cape Province rainfall, and to identify both heavy and light rainfall events associated with COLs over the province.*

c) *In addition, station rainfall data was interpolated to a grid with an inverse distance method using ArcGIS software to produce maps of rainfall variability during the occurrence of COLs over the Eastern Cape Province*.

1.8 ORGANIZATION OF THE REPORT

In CHAPTER 2, a general overview of the characteristics and natural resources in the study domain of the Eastern Cape Province is provided. The chapter is divided into the following subsections: (1) the geographic location, (2) topography and drainage, (3) climate, (4) agriculture, (5) population, (6) infrastructure and (7) water availability.

In CHAPTER 3 the data collection, data processing, software and methodology used in the study are addressed.

In CHAPTER 4 the climatology of COLs over South Africa and the Eastern Cape Province is discussed. Annual frequencies, as well as monthly and seasonal distribution are compiled for both South Africa and the Eastern Cape Province.

In CHAPTER 5, the location and duration of COLs over South Africa and the Eastern Cape Province are determined. Their locations are identified from the start to the end of the occurrence of a COL. The location of COLs in four regions (Region A, B, C and D) are determined for all seasons (December-January-February: DJF, March-April-May: MAM, June-July-August: JJA and September-October-November: SON). The durations of COLs are also determined for all seasons.

In CHAPTER 6, all the COL events that contributed to average rainfall of 0 < 10 mm, 10 < 20 mm, 20 < 30 mm, 30 < 40 mm, 40 < 50 mm, and average rainfall of >50 mm in the Eastern Cape Province are identified and categories into the four regions (Region A, B, C and D). The rainfall data is interpolated with ArcGIS software and the maps of the rainfall variability (only >50 mm of rainfall) during the occurrence of COLs over the

Eastern Cape Province are produced and also the contribution of the rainfall produced by COLs to the total annual rainfall over the Eastern Cape Province is determined.

A summary, concluding remarks and recommendations are given in CHAPTER 7, which are followed by APPENDICES.

CHAPTER 2

THE STUDY DOMAIN

2.1 INTRODUCTION

This chapter provides a general overview of the characteristics of the study domain, which is the Eastern Cape Province of South Africa, as indicated in Figure 1.1. The Eastern Cape Province exhibits diverse characteristics of the general southern Africa climate, and the province stretches along the coast of the IO. The climate of the IO is the most dominant climate determiner of the Eastern Cape Province, especially of areas along the coast. The chapter is sub-divided into one section. This includes a description of the Eastern Cape Province's geographic location, topography and drainage, climate, agriculture, population, infrastructure and water availability.

2.2 THE EASTERN CAPE PROVINCE

2.2.1 Geographical location

The Eastern Cape Province extends from longitude 22.50^0E to 29.50^0E, and latitude 31.50^0S to 34.50^0S, as shown in Figure 1.1. The Eastern Cape Province is bordered in the north by the country of Lesotho, Free State and Kwazulu-Natal Provinces, west by the Northern Cape and Western Cape Provinces, and east and south by the IO. According to Jury and Levey (1993a), the Eastern Cape Province of South Africa is located along the south-eastern seaboard of Africa. The Eastern Cape Province incorporates two of the former apartheid era homelands, which are Trankei and Ciskei, and it occupies 169 580 square kilometer (km^2) of land which is 14% of the total land of South Africa (Lewu et al., 2007). The Eastern Cape Province stretches from the coast to the interior, with the great escarpment which is represented by number of locally named mountain ranges such as the Drakensberg, Stormberg, Bamboesberg, Kikvorschberg, Agter-Renosterberg and Sneeuberg mountains. Also stretches westwards of the town of Cape St Francis - approximately towards the Mbashe River (Nicol, 1988). The boundaries of the Eastern Cape Province are the Great Kei river and Mbashe river in the east, the Kromme-Gamtoos river in the west, the coast in the south and Sneeuberg-Winterberg-Stormberg escarpment in the north (Bruton and Gess, 1988).

2.2.2 Topography and drainage

According to Van Averbeke et al., (2006) the topography of the Eastern Cape Province varies because a third of the province consists of mountain ranges with large differences in location. The highest geographical points in the Eastern Cape Province are the Drakensberg, the Great Winterberg, Sneeuberg and Stormberg mountains and the lowest point falls in areas along the southern coast line (Figure 2.1). The fold mountain ridges, the escarpments, the flat Karoo plains, the incised coastal platform valleys and the coastal dunes represent great landscape variety within the physical environment in the Eastern Cape Province (Stone, 1988). Nicol 1988 explains that the greater part of the Eastern Cape Province surface areas is occupied by Beaufort Group rocks, and is intruded by Karoo dolerite sills and dykes. The Eastern Cape Province has three physiographic divisions, which are described by Nicol (1988) as follows:

- *The plateau edge region*
  “This region includes the four major river systems of the Eastern Cape Province, which are Mbashe, Kei, Fish and Sunday, while the Great Escarpment is away from the inland by some 150 km from its initial position. It forms part of the south-eastern extension and the portion of the Sneeuberg and continues in the Tandjiesberg, the Amatole Mountains, the Great Winterberg which is about 2350 m high, and the Kologha Mountains above Stutterheim. The run-off of the plateau edge is forced by the head stream of the Great Fish River and those of the Sunday River to the west, whereby in some 50 km further south it forms a smaller embayment”.
- *The extra plateau or middle land region*
  “This region includes the Hogsbacks of the Amatole Ranges north of Alice and the towering and stunning landscape of the famous Valley of Desolation near Graaff-Reinet”.
- *The southern folded belt*
  “This region lies to the west, north and east of Port Elizabeth, even to the extent of the Stormberg lavas and finished the structure as far south”.

Rennie (1946) uses the term "middle lands" instead of the "extra plateau" region, and Nicol (1988) insists that a fourth division be recognized as a coastal sub-region stretching inland to the 300 m amsl contours, which are the areas affected by the tectonic uplift of the late Pliocene. The coastal sub-region lies within about 40 km of the coastline.

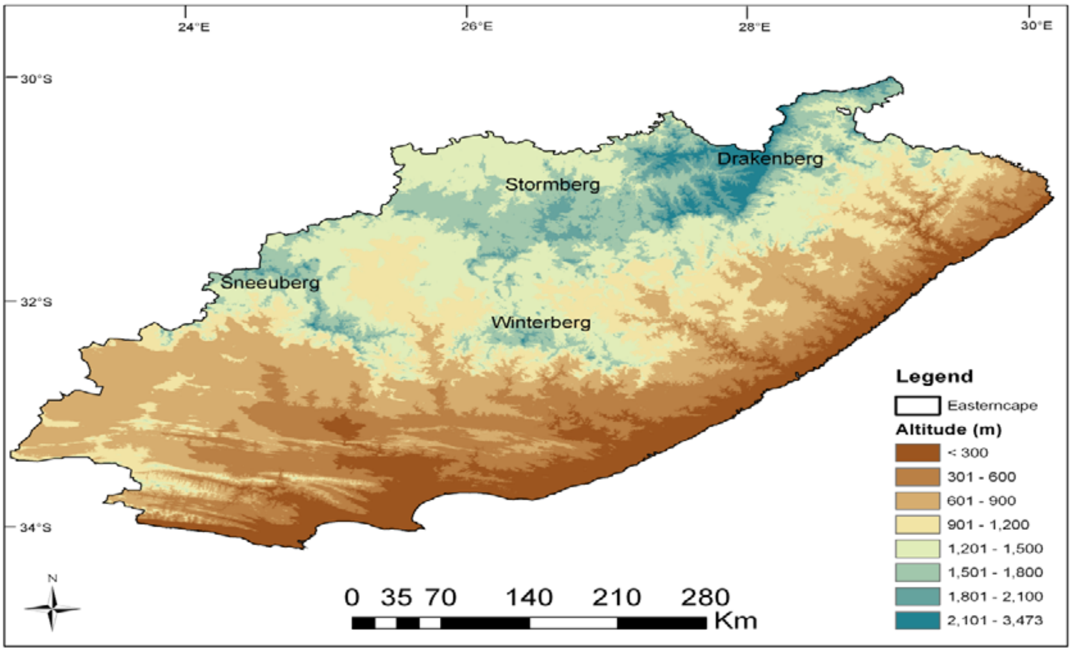


Figure 2.1: Topography map of the Eastern Cape Province with altitudes from 300 m to 3473 m above mean sea level (amsl).

Run-off of the Eastern Cape Province takes place through many of the fast flowing rivers flowing from high altitude locations in the north of the region towards the IO. According to McCallum (1988), the four major river systems in the Eastern Cape Province are the Mbashe, Kei, Sunday and Fish rivers, while the Buffalo, Black Kei, Kat and Lower Fish rivers are "border rivers" that also provide water to the neighboring countries. The Eastern Cape Province has a number of major catchments that includes the Kromme, Buffalo, Great Kei, Great Fish, Sunday, Keiskamma and Gamtoos river catchments, which provide water resources to urban areas such as Port Elizabeth, East London, King William's Town, Grahamstown and Queenstown. In the Great Fish and Sunday River valleys irrigation has been development, as shown in Figure 2.2 (McCallum, 1988).

According to Stone (1988), rivers and drainage of the Eastern Cape Province are strongly influenced by the climate and rainfall varies within the regions.

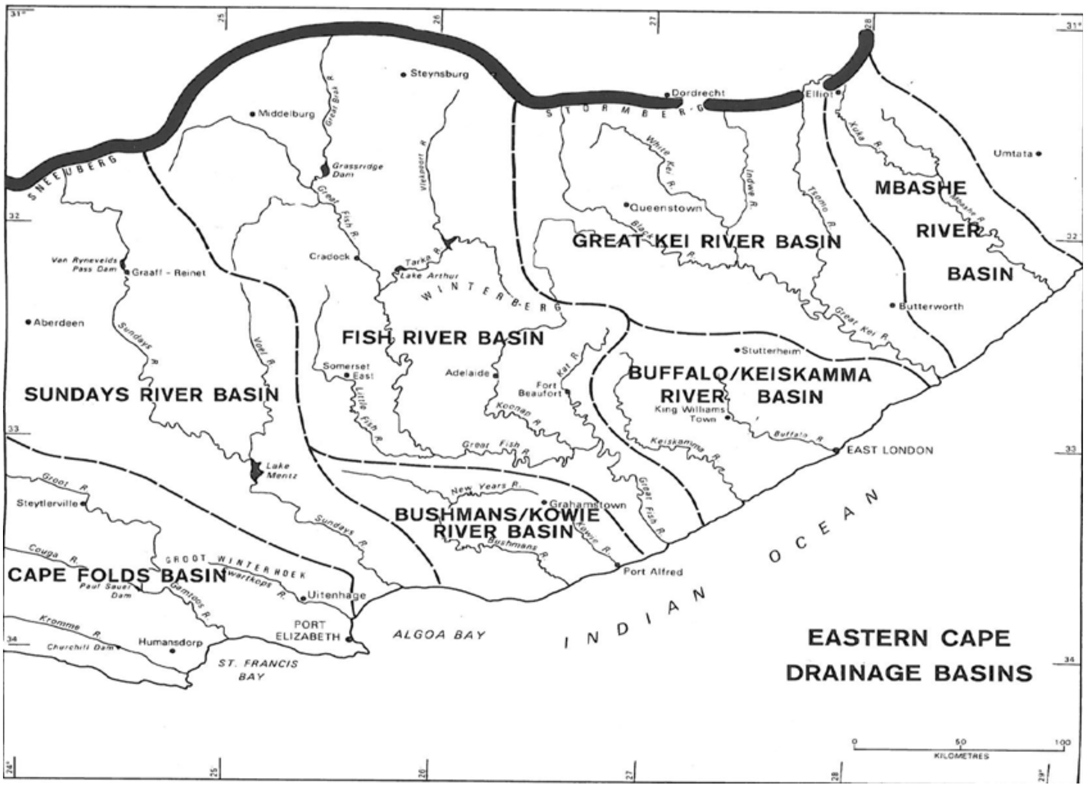


Figure 2.2: The drainage basins map of the Eastern Cape Province indicating the rivers flowing to the Indian Ocean (IO). (Acknowledgement to Bruton and Gess, 1988).

2.2.3 Climate of the Eastern Cape Province

According to Somoro (2009) the Eastern Cape Province has a diverse climate in relation to both rainfall and temperature and is comprised of 85% arid or semi-arid zones. The Eastern Cape Province is affected by both winter and summer rainfall bearing systems with high rainfall along the coast. The great Karoo to the north of the escarpment mountain range becomes gradually drier (Jury and Levey, 1993a). The eastern part of the Eastern Cape Province is a humid annual rainfall region, whereas the remainder of the province varies from humid annual rainfall regions to an arid summer rainfall region (Peel et al., 2007). According to Jury and Levey (1993a) the climate of Eastern Cape Province reflects its geographical variation, where the coast receives about 700 mm of rain annually, the great Karoo receives about 450 mm of rainfall annually, while the

Drakensberg Mountains receive over 1000 mm of rain annually. The northeastern parts of the Eastern Cape Province are characterized by convective mid-summer rainfall, while the western part is characterized by stratiform winter rainfall (Jury and Levey, 1993a).

2.2.3.1 Rainfall and temperature

The annual rainfall for the Eastern Cape Province denotes higher rainfall in the eastern parts, some parts in the interior and also in the south along the coast, as shown in Figure 2.3. This shows that along the borders of the Western Cape, Northern Cape and Free State Provinces there is less rainfall annually. Topography and orography are the main factors influencing rainfall at the local level; the effects of the IO also cause differences of several hundred of millimeters of rainfall annually over the Eastern Cape Province (Kopke, 1988; Somoro, 2009).

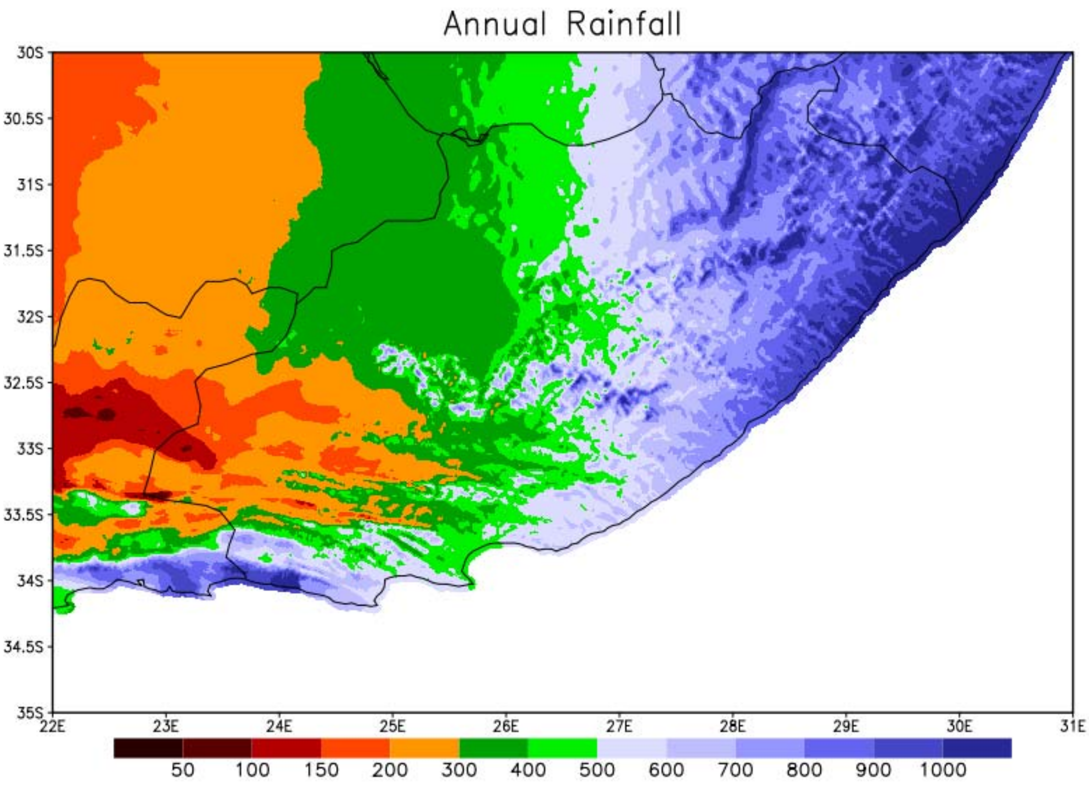
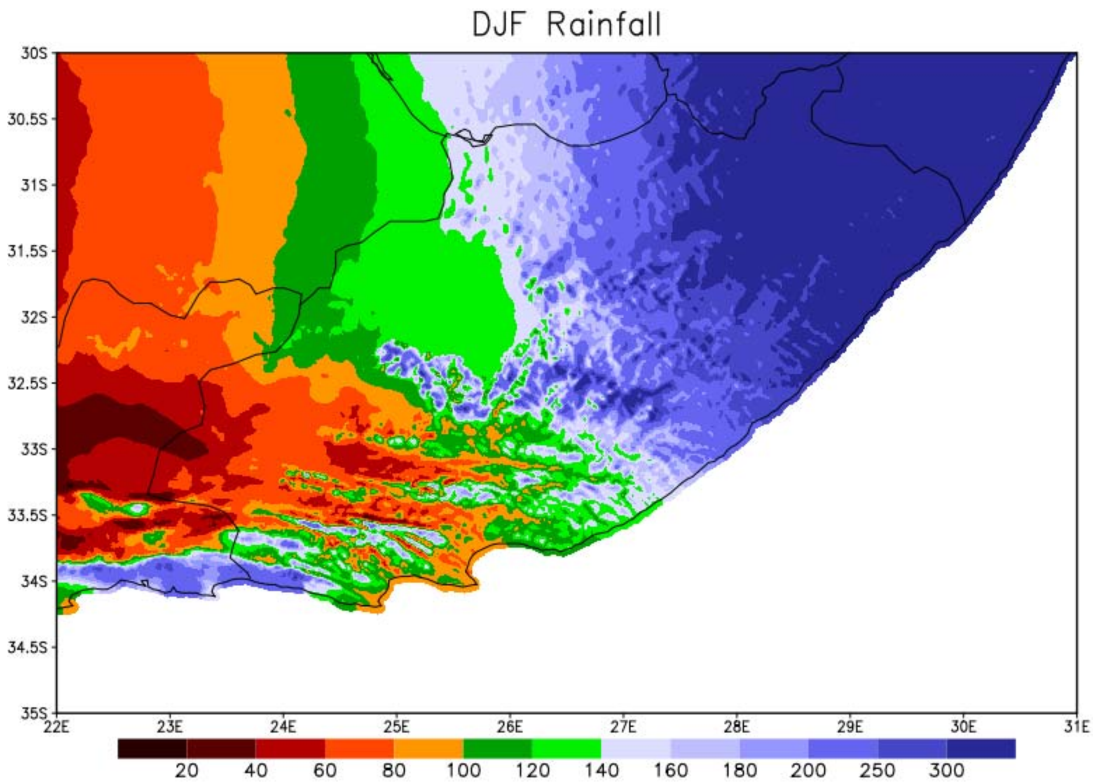


Figure 2.3: The annual rainfall, measured in mm, of the Eastern Cape Province.

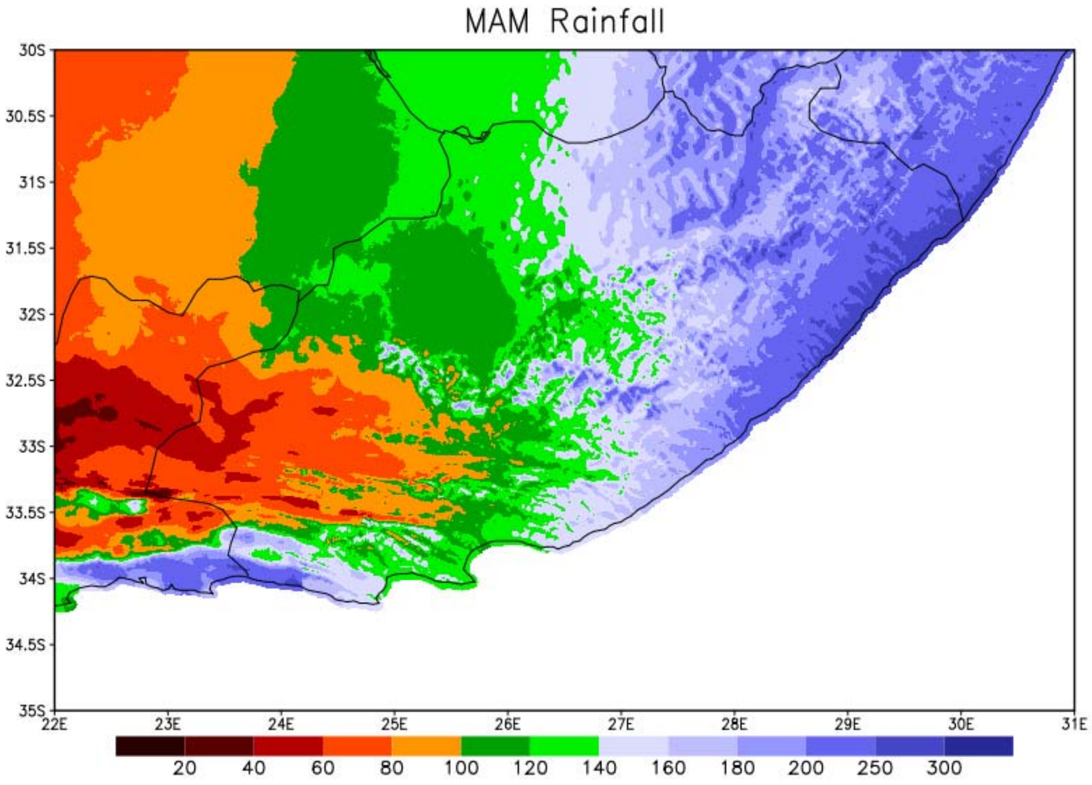
According to Roux and van der Vyver (1988) rainfall in the Eastern Cape Province is divided into four seasonal distributions:

- In the Eastern Cape Province the mean annual rain falls primarily in austral summer months (DJF), and increases from west to east with altitude. During summer in the west, annual total rainfall ranges between 250 mm to 350 mm, while the east is characterized by annual total rainfall of between 350 mm to 700 mm (see Figure 2.4(a)). The mountainous areas that extend from Komgha in the east to Katberg in the west experience higher than average rainfall which is between 750 mm to over 2000 mm annually, and the summer period is wet because of the topography in this region of the Eastern Cape Province.

- During autumn (MAM) the southeastern part and a large area lying along the coast in the east experience maximum rainfall, while the area in the north experiences less rain (see Figure 2.4(b)).



(a)

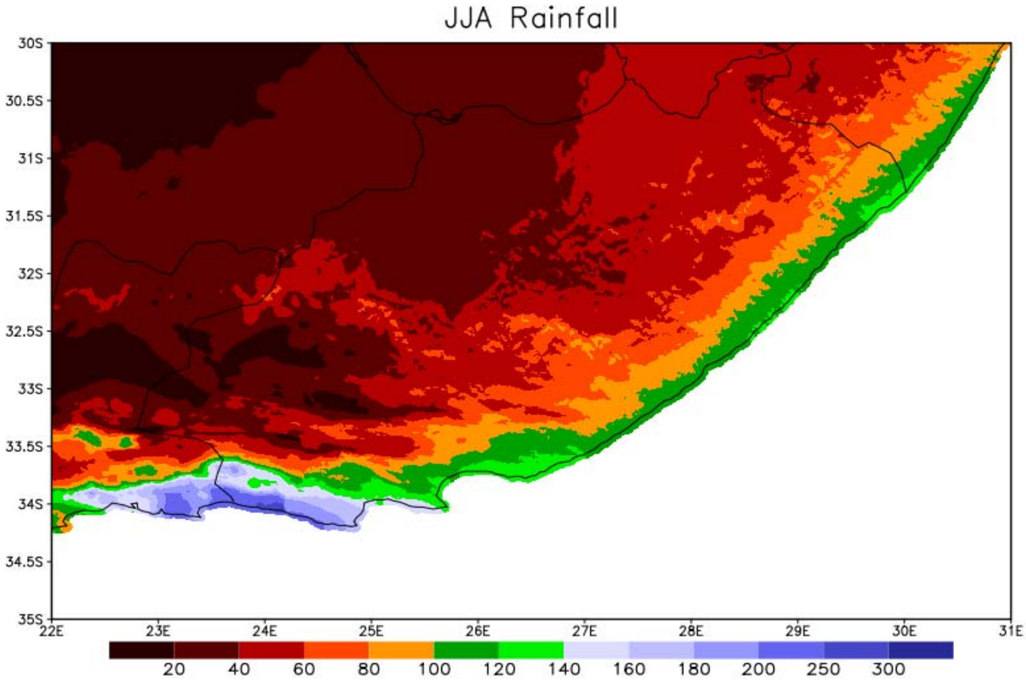


(b)

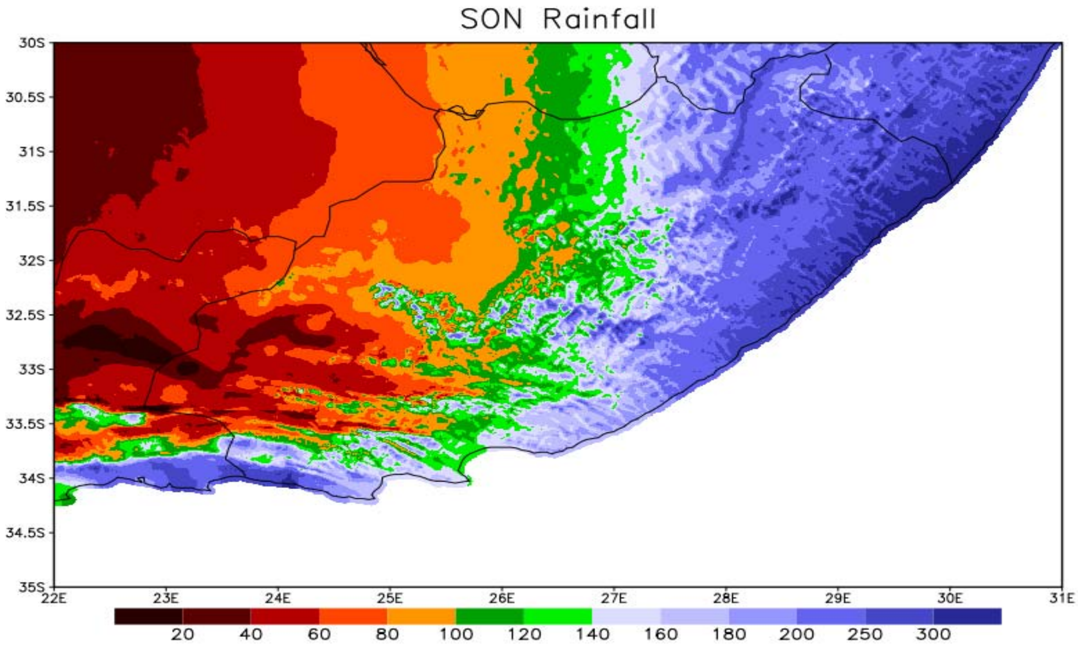
Figure 2.4: The summer (December, January, February - DJF) rainfall (a) and the autumn (March, April, May - MAM) rainfall (b), measured in mm, in the Eastern Cape Province.

- During winter months (JJA) areas that extend along the coast in the west and areas along the coast in the east experience maximum rainfall, while areas away from the coast and the northern parts experience minimum rainfall (see Figure 2.5(a)).

- During the spring months (September, October and November - SON) areas along the coast in the eastern part and a small portion of area along the coast in the south-western part of the Eastern Cape Province receive maximum rainfall, while the portion in the north receives less rain (see Figure 2.5(b)).



(a)



(b)

Figure 2.5: The winter (June, July, August - JJA) rainfall (a) and the spring (September, October, November - SON) rainfall (b), measured in mm, of the Eastern Cape Province.

Somoro (2009) provides a detailed description of the temperature of the Eastern Cape Province. The hottest months of the year are usually during DJF with a maximum temperature of up to 42.5^{0}C daily. The eastern coastal band is frost-free, whereas the north eastern mountains may experience frost duration of up to 120 days. According to Gledhill (1981), because of the prevailing winds and sea mist, certain areas of the province experience fairly humid atmospheric conditions.

2.2.4 Agriculture in Eastern Cape Province

The Eastern Cape Province produces 80% of the country's pineapples in Bathaurst and Komga near East London. The main crops, namely maize, is especially found in the Stutterheim districts and Komga near East London, and chicory is found around Alexandria and Bathurst (Roux and Van der Vyver, 1988). The agronomic production, such as crops, pasture, fodder crops and fruit, is produced by either dry land (rain-fed) farming or irrigation. In coastal areas dry land cultivation is primarily being practiced (Roux and Van der Vyver, 1988). The soil's alkalinity in the western part and acidity in the eastern part of the Eastern Cape Province limits its agricultural potential, where livestock is the dominant natural resource (Somoro, 2009). The Eastern Cape Province is dominated by large commercial and smallholder or small-scale farmers (who cultivate maize and sunflowers and farm with cattle, sheep, and goats) (Dixon el at., 2001). Agriculture is very important because there is much fertile land in the Eastern Cape Province. Sheep farming is preferred in the Karoo, while the fertile Langkloof valley in the southwest has fruit orchards. The former Transkei region is dependent on sorghum-farming, cattle and maize, while the Alexandria-Grahamstown area produces pineapples, dairy products and chicory. Coffee and tea are cultivated at Magwa (Low and Rebelo, 1996).

In the Eastern Cape Province there is a greater percentage of subsistence farmers based in a broad system which is characterized by poor management and low productivity. This system is referred to as the "communal farming system", where large areas of state rangeland (veld) are used communally by farmers for grazing domestic livestock and for harvesting natural products such as wood (Mapekula et al., 2009; Masika et al., 2003). In the central part of the Eastern Cape Province, there are many small-scale goat farmers who keep goats for slaughter during rituals and whose daily milk yield range between 0.125 and 2.01 litres per goat (Masika and Mafu, 2003). In irrigated areas dairy products, beef and fodder production have a high priority (Roux and van der Vyver, 1988).

A case study that was conducted in Grahamstown and Peddie in the Eastern Cape Province on how small-scale farmers help themselves to alleviate poverty by use of urban and peri-urban agriculture method of farming activities (Thornton, 2008). Maize production is used to help improve food security for the communities of the Alfred Nzo, OR Tambo, Chris Hani and Amathole districts, whereby 6000 hectares of maize were cultivated about 20 years ago according to the Accelerated Shared Growth Initiative of South Africa (AsgiSA) Eastern Cape (2009). In Butterworth, Matatiele, Mt Frere and Qumbu 18 000 tons of maize was harvested in 2009 on 6700 hectares, and it was intended to double the hectares to 12 000 per year to produce more maize in 2010 (AsgiSA Eastern Cape, 2009). According to Roux and van der Vyver (1988) the infrastructure in the Eastern Cape Province is favorable to agricultural practices.

2.2.5 Population

The Eastern Cape Province is home to 13.5% of South Africa's population of 51.8 million (in 2011). More than 86% of the Eastern Cape population is African, from which 48% is urbanized, 38% of the households live in traditional dwellings and 49% is unemployed (Statistics South Africa, 2012). The majority of the population is Xhosa speaking, with minorities speaking Afrikaans, English and Sotho while 65% of the population is categorized as rural (Lahiff, 2002).

2.2.6 Infrastructure

Because the highest incidence of poverty in South Africa is found in the Eastern Cape Province, with the lowest mean monthly household expenditure, 48% of the population is classified as living in poverty (Lahiff, 2002). The Eastern Cape has an infinite variety of residential areas, which could be townships large urban areas with elite surburbs and expensive holiday homes from external sectors of society, and small towns (Stone, 1998). According to Manona et al., (1998) the development of informal settlements started during 1989 and 1990 in areas such as Duncan Village and the Peddie Extension in the former Ciskei. Because of the deterioration of living conditions in the rural areas, people moved to urban areas and formed informal settlements (Manona, 1998).

2.2.7 Water availability

In the Eastern Cape Province there is great variety in the occurrence of ground water. This includes high yielding boreholes in certain parts of the Karoo, the coastal dune aquifer and the aquifer of Uitenhage. Many towns and farmers are dependent on ground water sources for their survival, while domestic and indigenous fauna depend on the ubiquitous windmills to provide water. According to Stone (1988) it will be very difficult to manage water resources in the arid climate because of low rainfall. In most cases water is exported to drier areas which have become an industry for the former Transkei and Ciskei, in particular. The use of pure, clean water for industrial, agricultural and domestic purposes at present is still in shortage (Roux and van der Vyver, 1988). Although in certain instances quality is poor, the local water resources are inadequate to meet the needs of the province. In certain areas local resources are inadequate and trans-basin diversion has been implemented to improve the water supply (e.g. the Orange River project, which diverts water into the Fish and Sunday River valleys), and is also intended to provide urban water supplies to the Port Elizabeth area (McCallum, 1988).

CHAPTER 3

[1]DATA, INFORMATION AND METHODOLODY

3.1 INTRODUCTION

This chapter addresses the data utilized in this study for identifying COLs and for studying the rainfall associated with COL systems. The methodology applied to achieve this is also presented. NCEP-NCAR reanalysis data for the 31-year period of 1979 to 2009 was used to construct a climatology of COLs over South Africa and the Eastern Cape Province. In addition to the NCEP-NCAR reanalysis data utilized in the identification of COLs on the 500 hPa pressure level, surface synoptic charts, as used by operational weather forecasters of the SAWS, were employed to obtain a more detailed surface analysis of pressure patterns over South Africa. This was done in particular for identifying the cases where COLs extended from the upper atmosphere to the surface. In order to investigate the rainfall associated with COLs over the Eastern Cape Province, daily rainfall data over the province was obtained from weather stations that were operational during the study period. The contribution of rainfall that was produced by COLs, as a fraction of the total rainfall over the Eastern Cape Province, was also determined.

3.2 OBSERVATIONAL DATA

3.2.1 Upper air data

The NCEP-NCAR reanalysis data set is a frequently updated raster data set representing the state of the Earth's atmosphere that incorporates observations and Numerical Weather Prediction (NWP) model output dating back to 1948 (Kanamitsu et al., 2002). The data is available at 6-hourly intervals at a horizontal resolution of 2.5° x 2.5° for various pressure levels in the vertical. The data is available free of charge, and may be downloaded from the National Oceanic and Atmospheric Administration (NOAA)

[1] http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.html

[2]Earth System Research Laboratory website[1]. The data is available in Network Common Data Form (NetCDF) and can be accessed using a number of libraries and tools (Kistler et al., 2001). In this study, graphical GrADS images of geopotential heights of the 850 hPa and 500 hPa pressure levels, as well as 500 hPa air temperatures for the period 1979 to 2009 were downloaded from the NCEP-NCAR website[2]. Images for 00:00 Zulu Time (Z), 06:00 Z, 12:00 Z and 18:00 Z over this 31-year period for the domain 10^0 to 40^{0}E and 20^0 to 40^{0}S were downloaded for visual inspection to identify COL events. An example of a COL event as captured in these images is illustrated in Figure 3.1. The geopotential height of the 500 hPa pressure level and 500 hPa level temperature fields for the COL event of 26 October 2009 are shown in these figures.

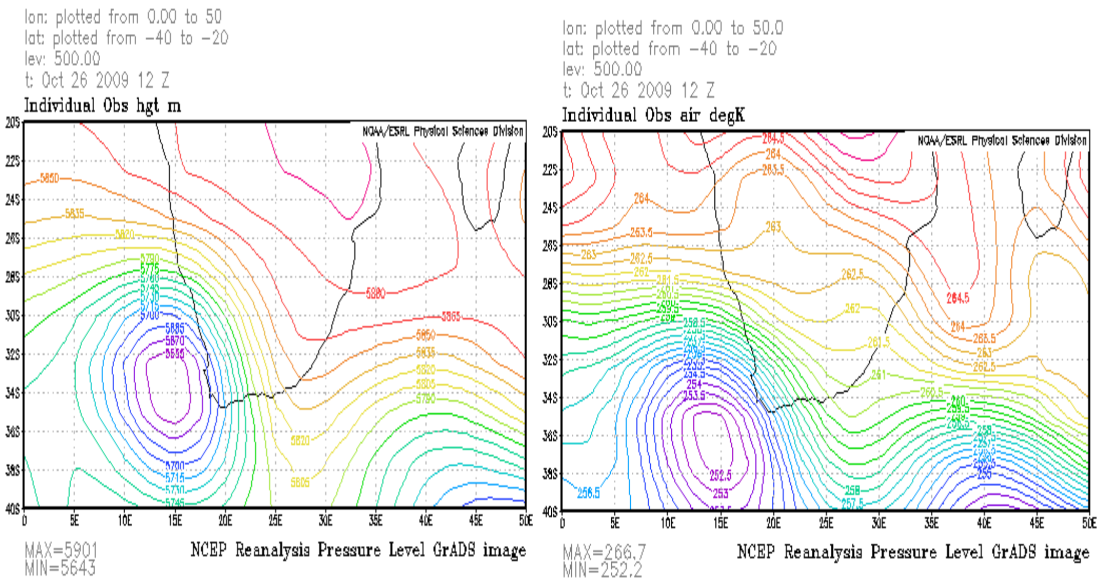


Figure 3.1: An example of the maps utilized to identify cut-off lows (COLs) over South Africa. On the left hand side are geopotential heights of the 500 hPa pressure level and on the right hand side are the corresponding air temperature valid at 26 October 2009, 12:00 Zulu Time (Z) as downloaded from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data website.

3.2.2 Surface synoptic charts

In addition to NCEP-NCAR reanalysis data of geopotential heights data and temperatures, surface synoptic charts, as used by operational weather forecasters of the

[2] http://www.cdc.gov/cdc/data.ncep.reanalysis.pressure.html

SAWS, were employed in order to study the surface circulation associated with COL events. This is done as surface lows (850 hPa) that develop in some instances in association with mid-level cut-off lows are not well resolved on a 2.5˚ x 2.5˚ resolution NCEP-NCAR data. The surface synoptic charts were obtained from SAWS for all the identified closed lows (assumed to be COL events) that occurred on the 500 hPa pressure level over South Africa over the period 1979 to 2009. From the year 2000 the SAWS analysis at 850 hPa was replaced by sea-level pressure analysis over the land, as shown in Figure 3.2. In these instances, the NCEP-NCAR 850 hPa geopotential heights were used for the surface flow analysis.

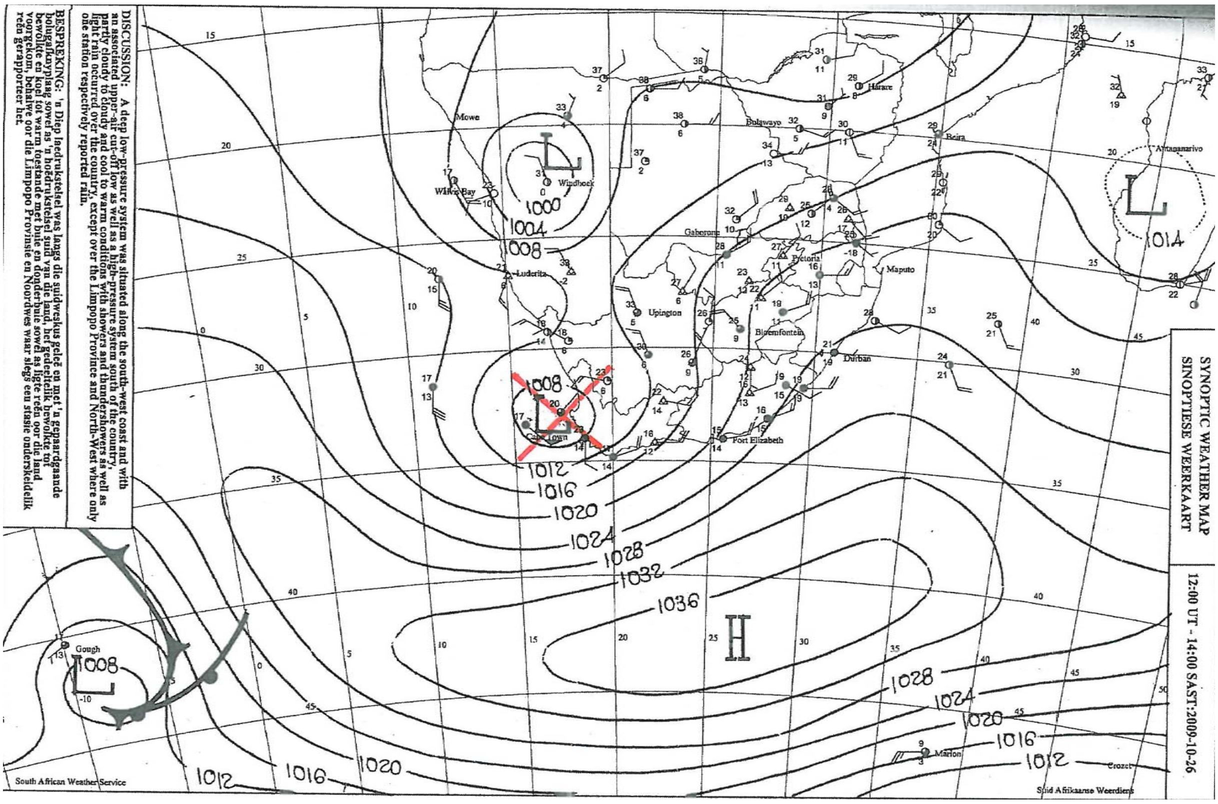


Figure 3.2: An example of a synoptic surface chart for 26 October 2009 at 14:00 South African Standard Time (SAST) during the occurrence of a Cut-Off Low (COL) over the southern African region indicated by red mark (Acknowledgement to South African Weather Bureau, 2009).

3.2.3 Station data

Rainfall data for selected Eastern Cape Province stations (listed in Table 1) were obtained from the SAWS and the ARC-ISCW for the period 1979 to 2009. The locations of the stations employed in this study are denoted in Figure 3.3. The longitude, latitude, height and information of missing data of the stations are shown in Table 1. From the 22 weather stations, 13 stations have a complete record for 31-year period. These stations include East London (EL), Engcobo Prison (EP), Gomo-Bos (GB), Humansdorp (HD), Jeffreys-Bay (JB), Klipfontein (KF), Lottering-Bos (LB), Maclear (MC), Montagu (MU), Mooredale (MD), Port Elizabeth (PE), Port Alfred (PA), and Umzoniana (UZ). Steynsburg-Pol (SB) had one month of data missing, Kendrew Estate (KE) and Groendal-Bos (GB) had two months of data missing, Rietbron (RB) and Queenstown (QT) had four months of data missing, Telpoort (TP) has five months and 16 days of missing data, Port st John (PJ) and Roussouw (RW) had eight months of data missing, and Keiroad (KR) had 33 months of data missing. Due to the long study period of 31 years, with only one station that has data missing for two years (about 9% of data), the data could be regarded as acceptable for the research.

Table 1: Weather stations across the Eastern Cape Province that have a data length of 31-year.

ID	CLIMATE_NO	STATION_NA	LAT	LONG	HEIGHT	MISSING DATA
E63	0059572B8	EAST LONDON WO (EL)	-33.03	27.83	116	NO
E91	0080072 8	KEI ROAD - POL (KR)	-32.7	27.55	711	Thirty-three Months
E67	0074363 3	KLIPFONTEIN (KF)	-32.55	24.72	673	NO
E211	0151604 4	MACLEAR (MC)	-31.07	28.35	1252	NO
E41	0037696 8	PORT ALFRED (PA)	-33.6	26.9	37	NO
E1	0017452 7	HUMANSDORP (HD)	-34.03	24.77	152	NO
E66	0073871 1	KENDREW ESTATES (KE)	-32.52	24.5	625	Two Months
E7	0031507 8	LOTTERING - BOS (LB)	-33.95	23.78	229	NO
E31	0035179 5	PORT ELIZABETH WO (PE)	-33.98	25.62	59	NO
E187	0129068 X	PORT ST JOHNS (PJ)	-31.63	29.55	47	Eight Months
E162	0123683 6	QUEENSTOWN - MUN (QT)	-31.88	26.88	1077	Four Months
E194	0146588 4	STEYNSBURG - POL (SB)	-31.3	25.83	1448	One Month
E27	0034523 4	GROENDAL-BOS (GD)	-33.72	25.3	229	Two Months
E44	0051430 7	MOOREDALE (MD)	-33.17	23.75	686	NO
E225	0173136 X	MONTAGU (MU)	-30.77	25.58	1280	NO
E218	0153631 3	GOMO BOS (GB)	-31.02	29.37	1370	NO
E171	0125880 X	ENGCOBO PRISON (EP)	-31.67	28	975	NO
E65	0071264 8	RIETBRON (RB)	-32.9	23.15	762	Four Months
E190	0145261 6	TELPOORT (TP)	-31.35	25.15	1372	Five Months & Sixteen days
E205	0149490 8	ROSSOUW (RW)	-31.17	27.28	1631	Eight Months
E3	0017723 1	JEFFREYS BAY (JB)	-34.05	24.92	6	NO
E97	0080569 4	UMZONIANA (UZ)	-32.98	27.82	168	NO

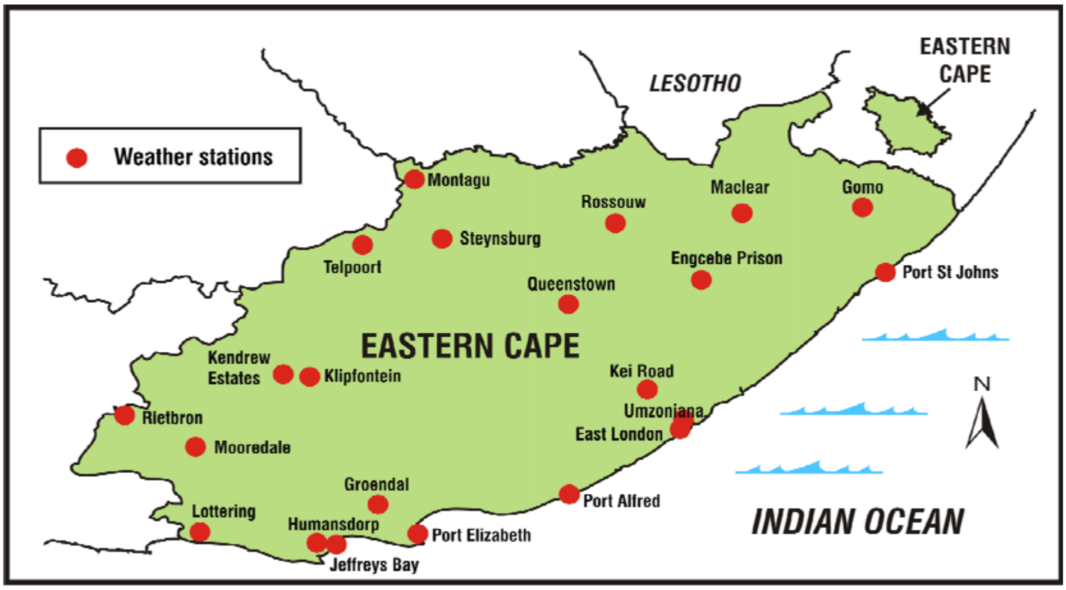


Figure 3.3: The location of the selected weather stations used in the study across the Eastern Cape Province.

3.3 METHODOLOGY

3.3.1 Identification of cut-off lows over South Africa

COLs were identified by visual inspection of the 6-hourly NCEP-NCAR reanalysis fields at the 500 hPa pressure level for the period 1979 to 2009. The study domain is bounded by 0^0E to 50^0E and 20^0S to 40^0S. All closed low pressure systems at the 500 hPa pressure level were firstly considered. To confirm that COLs were correctly identified, the temperature at the 500 hPa was also investigated by comparing the temperature of the closed low with that of the surrounding area, as shown in Figure 3.1. A COL is identified as a closed low at the 500 hPa pressure level that is accompanied with a colder core compared to the surrounding area, because COLs are associated with cold air advection that rises. Systems that satisfied this criterion, and had closed circulation for at least a period of 24 hours, had been considered to be COLs.

Because of variations in the geographical location of COLs over South Africa, the study region was divided into four sub-regions. These regions are referred to in the study as regions A, B, C, and D as indicated in Figure 1.1. The regions were selected so that the study domain which is the Eastern Cape Province must be in one region, whereby west of the study domain is region A, southwest is region C and south is region D. Region A and B contain large portion of South Africa and region C and D include part of south of AO and IO. The regions were chosen so that which location of COLs dominate and in which region that COLs have more effect on the weather of the Eastern Cape Province. Region A and B are separated from regions C and D by the latitude of 34^0S, and regions A and C are separated from regions B and D by the longitude of 22^0E, as shown in Figure 1.1. The locations of COLs in each region were selected from the center at 500 hPa of the COLs identified over South Africa. In the case where the COLs tracked over more than one region, they were counted once in each region. For South Africa as a whole, the COLs were counted once for entire region regardless whether it tracked from one region to another.

3.3.2 Identification of cut-off lows over the Eastern Cape Province

After the identification of COLs over South Africa, the surface synoptic charts from SAWS were used to investigate whether the identified 500 hPa pressure level lows extended to the surface. Prior to the year 2000, the SAWS surface analysis comprised of a sea-level pressure analysis over the oceanic regions surrounding South Africa and a 850 hPa analysis over the land. From the year 2000, the 850 hPa analysis over land was replaced by sea-level pressure analysis. Therefore, the NCEP-NCAR reanalysis at 850 hPa geopotential fields were considered for the identification of surface lows during COL cases between 2000 and 2009. For the identification of COLs over the Eastern Cape Province, all COLs with associated surface lows that were located to the west of the Eastern Cape Province were considered to be incorporated in the Eastern Cape COL data set. COLs occurring west of the Eastern Cape Province were considered on the basis that COLs typically follow a west to east path as they progress over South Africa. Further, with COLs being baroclinic synoptic-scale weather systems, rainfall is found on the eastern flanks of these systems. COLs located to the west of the Eastern Cape Province are therefore ideally located for rainfall formation over the Eastern Cape Province. The Eastern Cape Province COL data set was further scrutinized by identifying the COL events than could directly be associated with rainfall experienced over the Eastern Cape Province.

3.3.3 The duration of cut-off lows over both South Africa and the Eastern Cape Province

The duration of a COL is defined as the number of days, from the day it has been identified with closed circulation until the day the closed circulation ceased. The analysis of the duration of COLs are split into three categories, which were those that lasted for 1 to 2 (1-2) days, those lasted for 3 to 4 (3-4) days and those that lasted for more than 4 days (>4 days). According to Taljaard (1985) and Price and Vaughan (1992) COLs lasting only one to two days were regarded as short-lived systems and were mostly quick-moving and weak or ill-defined.

3.3.4 Rainfall associated with cut-off lows over the Eastern Cape Province

Eastern Cape Province COLs are by definition associated with rainfall over the Eastern Cape Province (see section 3.3.2). Daily rainfall over the Eastern Cape Province is scrutinized for all the COL events accompanied by surface lows located over and west of the province (see section 3.3.2). This is done in order to secure that rainfall was primarily caused by the COL. It is these COL systems that were defined as Eastern Cape COLs. For all of the Eastern Cape COL events, the average rainfall for 22 weather stations were calculated and classified into six categories. These categories are 0 < 10 mm, 10 < 20 mm, 20 < 30 mm, 30 < 40 mm, 40 < 50 mm, and average rainfall of >50 mm. The frequency occurrence for the various average rainfall categories over the period 1979 to 2009 is determined. This categorical Eastern Cape COL rainfall analysis was also performed within the context of the location of the Eastern Cape COLs, where the location of the Eastern Cape COLs was defined in terms of regions A, B, C and D. Additional to this analysis, the spatial distribution of heavy rainfall Eastern Cape COLs was presented. These spatial heavy rainfall maps were constructed with ArcGIS software (using the inverse distance method) to show the spatial variation of heavy rainfall over the Eastern Cape Province associated with Eastern Cape COLs. An Eastern Cape COL event is called heavy rainfall event if at least one station reported > 50 mm rainfall in one days.

3.3.5 Contribution of cut-off lows to the total rainfall of the Eastern Cape Province

The rainfall data of the 22 weather stations that were selected across the Eastern Cape Province with a data length of 31 years were used to investigate the contribution of COL associated with rainfall to the annual total rainfall received. The total rainfall, as measured at each weather station, for each Eastern Cape COL event was defined as the Eastern Cape COL rainfall, whereas the total rainfall over the Eastern Cape Province was defined as the total accumulated rainfall including the Eastern Cape COL rainfall at each weather station. The total rainfall, percentage of the Eastern Cape COL rainfall, and the total annual rainfall for each station were calculated. Averages of the Eastern Cape COL rainfall and averages of the total annual rainfall for each station for 31-year period were also calculated.

CHAPTER 4

CLIMATOLOGY OF CUT-OFF LOWS

4.1 INTRODUCTION

In this chapter, a general climatology of COLs over South Africa is presented. In addition, a second climatology of COLs that had an effect on the rainfall over the Eastern Cape Province is presented (see definition of Eastern Cape COL in Chapter 3). Various climatological frequencies, such as monthly, seasonal and annual frequencies of COLs over South Africa and the Eastern Cape Province for the period of 1979 to 2009, are also presented. The construction of a climatology of COLs for the Eastern Cape Province forms part of the objective 1 of this study (which was the construction of a climatology of COLs over the Eastern Cape Province). To put the occurrence of COLs over the Eastern Cape Province into perspective, they are presented against the background of the South Africa COL climatology which was first constructed in this study.

4.2 CLIMATOLOGY OF CUT-OFF LOWS OVER SOUTH AFRICA AND THE EASTERN CAPE PROVINCE

4.2.1 Inter-annual variability in cut-of low frequencies

The yearly variations in the occurrence of COLs over South Africa and the Eastern Cape Province for the period of 1979 to 2009 are shown in Figure 4.1. Over this period, a total of 212 COLs were identified that lasted more than 24-hours over the South Africa domain and 138 COLs of 212 were found to have effect on the total rainfall of the Eastern Cape Province and listed in Appendix A. The highest number of COLs occurred in 2001, followed by 1994 and 2008, while the least number of COL occurrences was found during 1992 and 1984 over South Africa. The average occurrence of COLs over South Africa is 6.8 COLs per year. Over the Eastern Cape Province, the highest occurrence of COLs found during 1997, 2001 and 2008, with the least occurrence in

1980 and 1991 (see Figure 4.1). The average COL occurrence over the Eastern Cape Province is 4.4 COLs per year. Therefore, amongst the many COLs that formed over South Africa, there is the possibility that some of these there had not effected on the rainfall of the Eastern Cape Province.

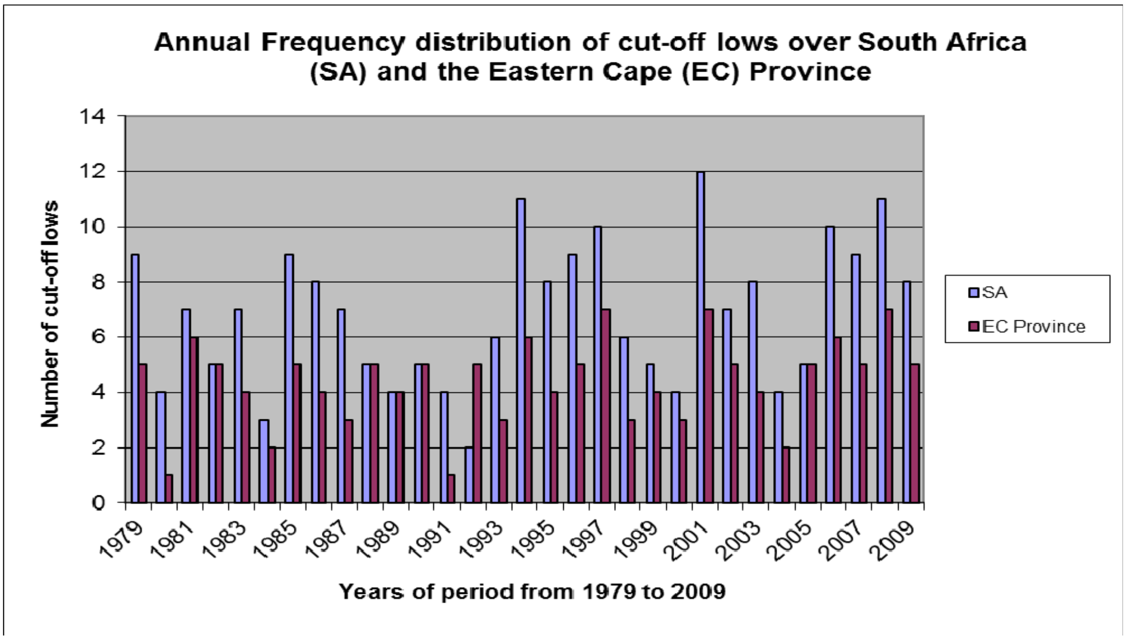


Figure 4.1: Inter-annual frequency of Cut-Off Lows (COLs) over South Africa (SA) and the Eastern Cape (EC) Province for the period of 1979 to 2009.

Figure 4.2 shows standardized anomalies in the annual frequency of COLs over South Africa and the Eastern Cape Province for the 31-year period of 1979 to 2009. By considering Figure 4.1 and Figure 4.2, it can be seen that the number of COLs varies from year-to-year over South Africa and the Eastern Cape Province. However, there are short periods where the number of COLs is above average and below average. From 1994 to 1997 and 2006 to 2009 the numbers of COLs occurrences were above average, whereas the period 1980 to 1984 was characterized by several years with strongly reduced COL numbers for both South Africa and the Eastern Cape Province. There is considerable inter-annual variability with noteworthy peaks and troughs in the number of the COLs. For example, in 2001 there were 12 COLs over South Africa, while in 1992 there were only two COLs that occurred over South Africa and that lasted for at least 24-hours.

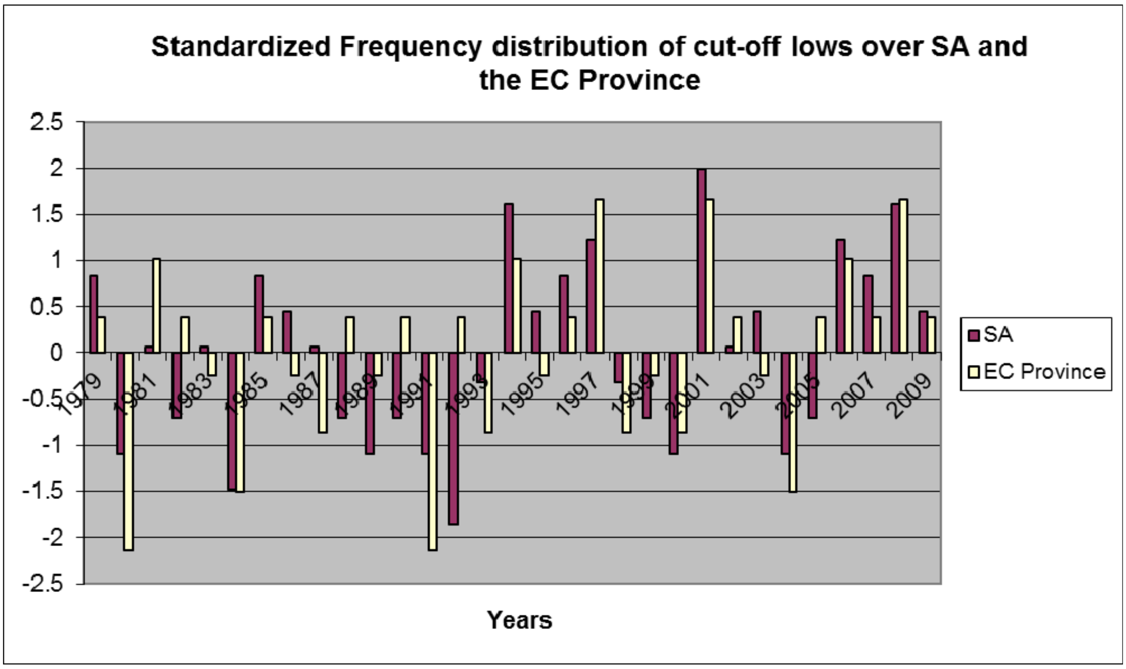


Figure 4.2: Anomalies of Cut-Off Lows (COLs) for the period 1979 to 2009 over South Africa (SA) and the Eastern Cape (EC) Province.

4.2.2 Monthly long-term average distribution

The monthly frequency distribution of COLs over South Africa for the of 31-year period shows that the maximum numbers of COLs occur during the months of April and May followed by July and October with the least occurrences in DJF (see Figure 4.3). Noteworthy is that October has a COL frequency comparable to that of June. Over the Eastern Cape Province, April followed by July are two clear peaks of COL occurrence, with the least COL occurrences during December, January and February – similar to the months of occurrence over the South Africa domain (see Figure 4.3). According to Singleton and Reason (2007) and Taljaard (1985), their climatologies of COLs show the highest monthly frequency distribution during April with the least occurrence in December and January over southern Africa. This agrees with the findings in this study. Therefore, according to the results of Singleton and Reason (2007), Taljaard (1985), and the findings in this study, April and May are the months with the highest frequency of COLs over South Africa.

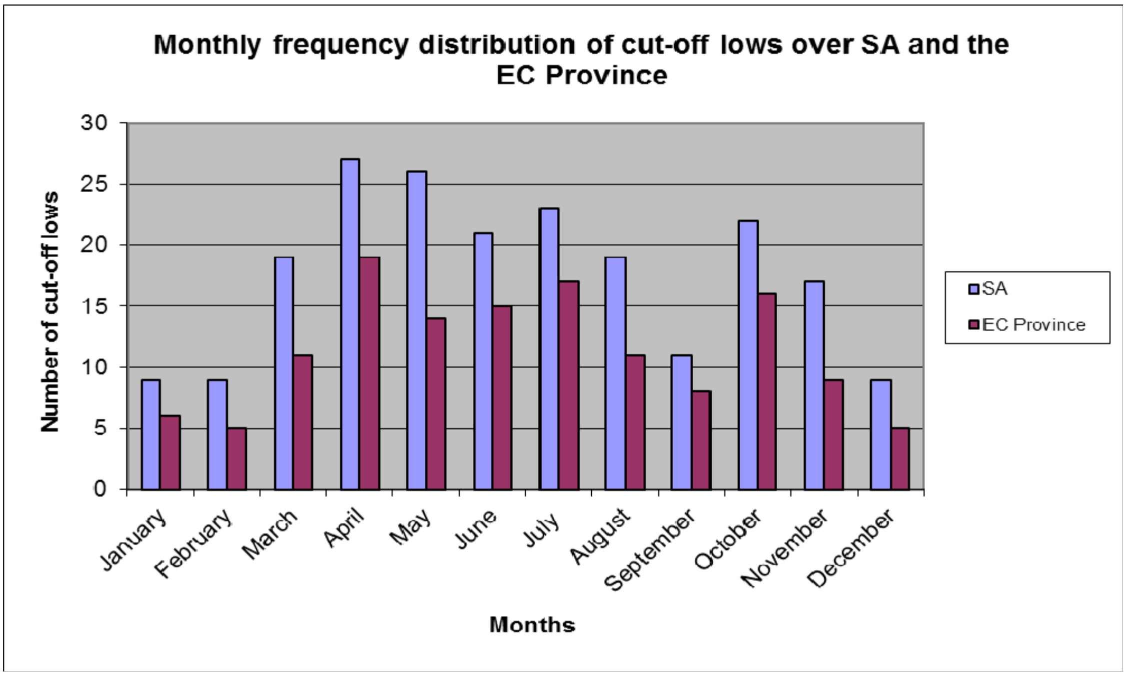


Figure 4.3: Total number of Cut-Off Lows (COLs) on a monthly basis for South Africa (SA) and the Eastern Cape (EC) Province for the period 1979 to 2009.

4.2.3 Seasonal frequency distribution of cut-off lows

The long-term average seasonal frequency distribution of COLs over South Africa and the Eastern Cape Province are shown in Figure 4.4. The highest frequencies of COLs occur during MAM followed by JJA and SON, with the lowest frequency occurs during DJF for both South Africa and the Eastern Cape Province. This is not consistent with the findings of Singleton and Reason (2007b).

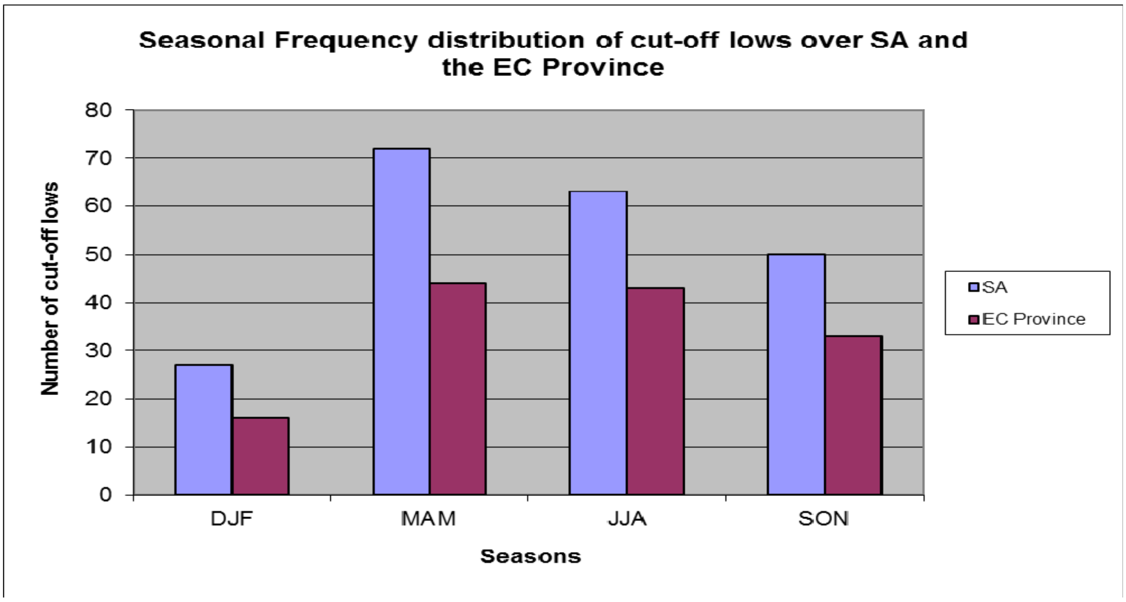
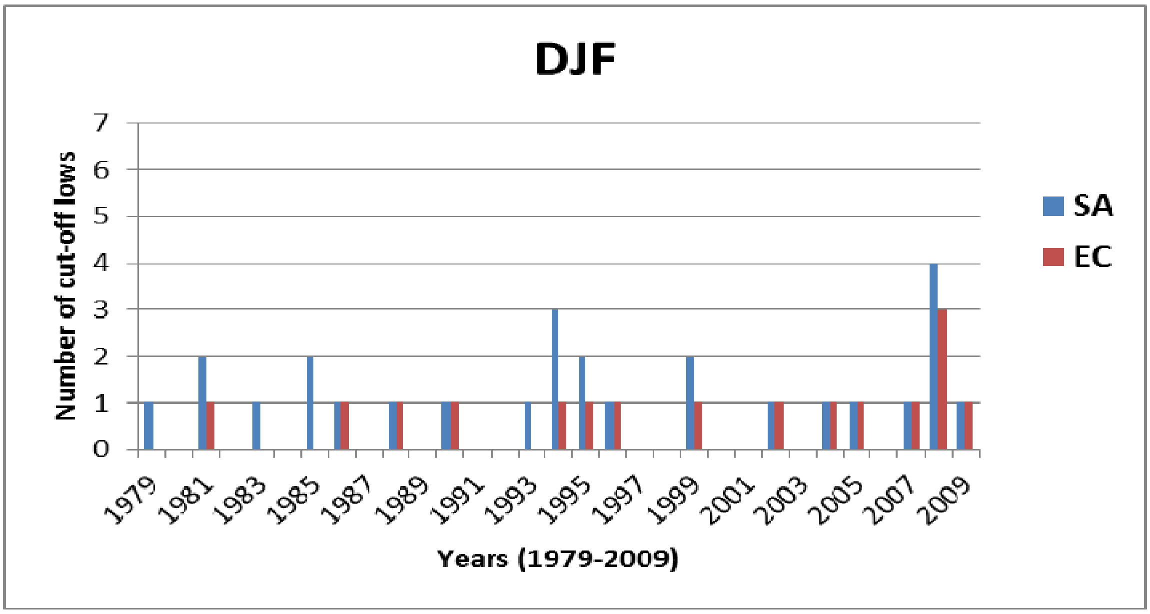


Figure 4.4: Long-term average seasonal distribution of the number of Cut-Off Lows (COLs) for the period 1979 to 2009 over South Africa (SA) and the Eastern Cape (EC) Province.

The inter-seasonal variability of COL occurrences is depicted by Figure 4.5a and b. During DJF the highest frequency of COLs occurred in 2008, while there were zero COL occurrences in 1980, 1982, 1983, 1984, 1987, 1991, 1992, 1998, 2000, 2001, 2003 and 2006 (Figure 4.5a (i)). While over the Eastern Cape Province during DJF the highest frequency of COLs occurred in 2008 with zero COL occurrence in 1979, 1980, 1982, 1983, 1984, 1987, 1991, 1992, 1993, 1994, 1997, 1998, 2000, 2001, 2003 and 2006 (see Figure 4.5a (i)). According to Singleton and Reason (2007b) the highest occurrence of COLs were found in 1990 followed by 1975, with no COL occurrences found in 1980, 1991 and 2002 during DJF over southern Africa. In this study DJF was consider as having the least COLs occurrence over South Africa and the Eastern Cape Province. During MAM, the highest occurrence of COLs was found in 1994, 1997 and 2009 with zero COL occurrences in 1984 over South Africa. While over the Eastern Cape Province the highest occurrence of COLs during MAM is found in 1981, 1982, 1994, 1997 and 2009 with zero COL occurrences in 1979, 1980, 1984, 1986 and 1996 as indicated in Figure 4.5a (ii). Both this study and Singleton and Reason (2007b) indicate that during MAM there were the highest number of COLs occurrence and also was considering as the highest COLs occurrence in comparison to other seasons over southern Africa, South Africa and the Eastern Cape Province.

During JJA the highest frequency of COLs occurred in 1986 and 2006 with zero COL occurrences in 1984 and 2005 over South Africa, while over the Eastern Cape Province the highest frequency of COLs occurred in 1986 followed by 2006 with zero COL occurrences in 1984, 2000, 2003, 2004, 2005 and 2009 (see Figure 4.5b (iii)). Singleton and Reason (2007b) report that during JJA the highest frequency of COLs also occurred in 1986 with the zero COL occurrences in 1976, 1990 and 1998 but according to this study, during JJA 1990 there was least COL occurrence. During SON the highest frequency of COLs occurred in 1996 followed by 2001 with the zero COL occurrences in 1980 and 1999 over South Africa. While over the Eastern Cape Province the highest frequency of COLs occurred in 1996 followed by 2001 with zero COL occurrences in 1980, 1986 and 1999 during SON (see Figure 4.5b (iv)). There was also a high occurrence of COLs in 2000 and 2001 and with the zero COL occurrences in 1999 during SON as reported in the article of Singleton and Reason, 2007b.



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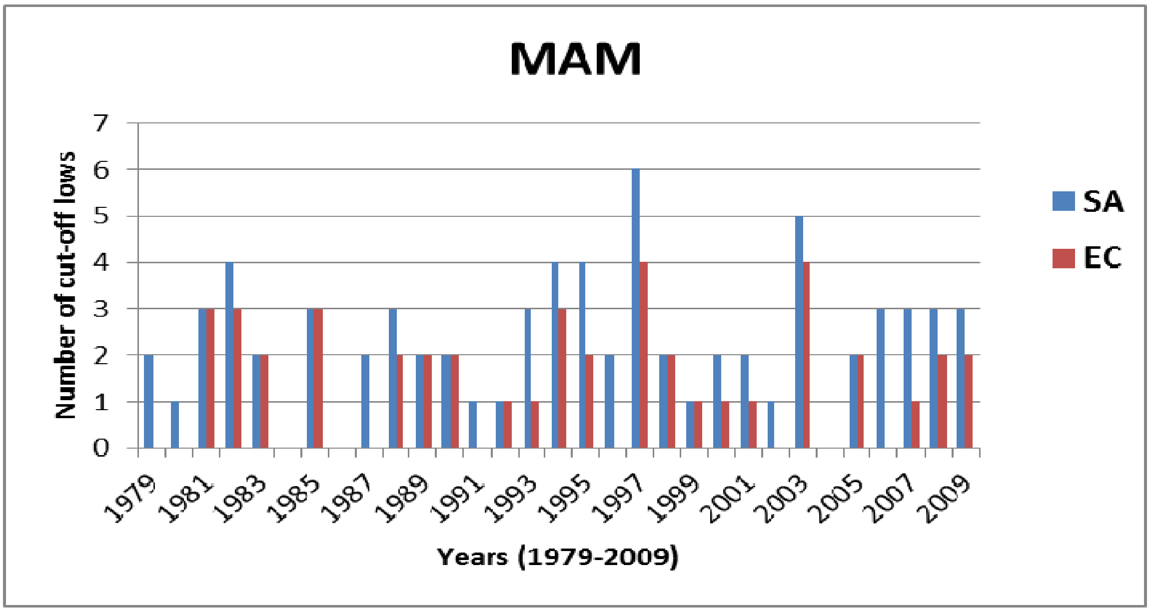
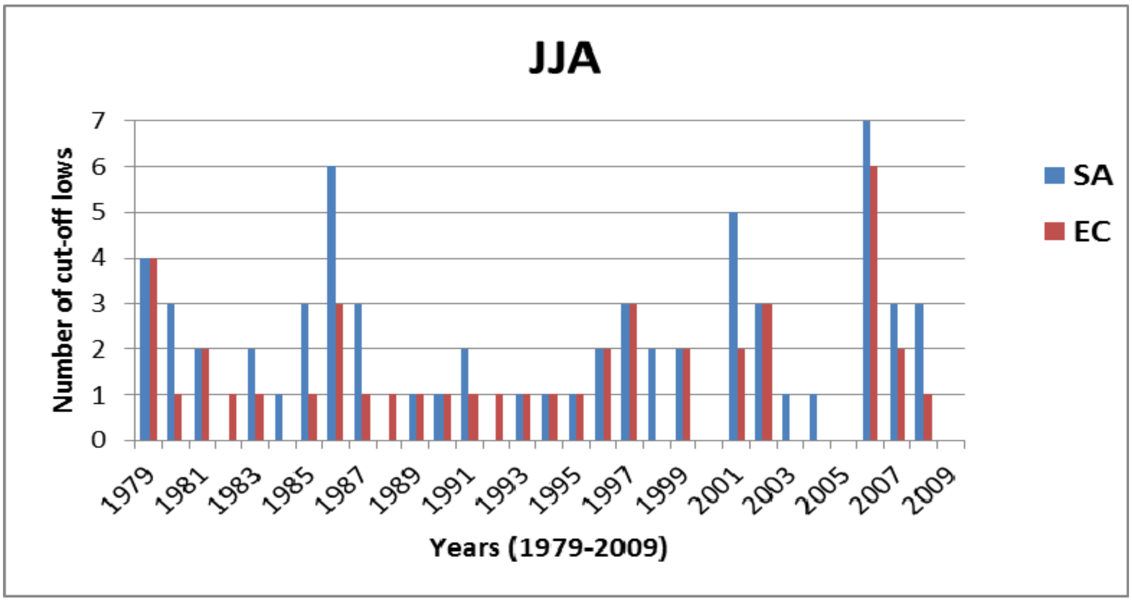


(ii)

Figure 4.5a: Frequency distribution of Cut-Off Lows (COLs) for (i) DJF and (ii) MAM for each year from 1979 to 2009 over South Africa (SA) and the Eastern Cape (EC) Province.



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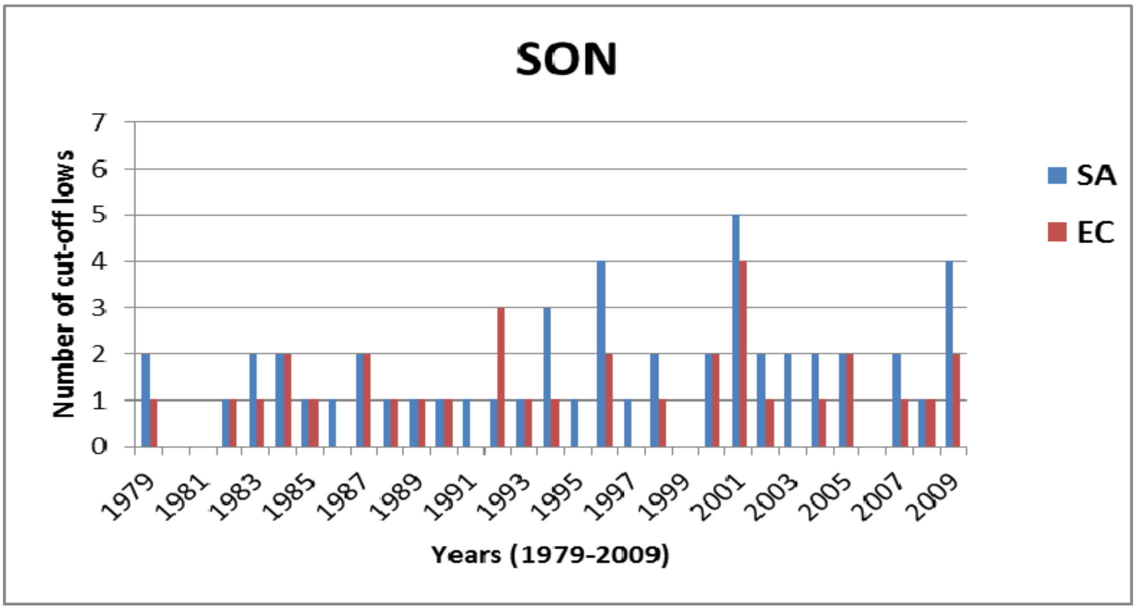


(iv)

Figure 4.5b: Frequency distribution of Cut-Off Lows (COLs) for (iii) JJA and (iv) SON for each year from 1979 to 2009 over South Africa (SA) and the Eastern Cape (EC) Province.

4.3 Summary

In this chapter, a climatology of COLs during a 31-year period over South Africa and the Eastern Cape Province is presented. This includes the annual, monthly and seasonal frequency distribution for the period of 1979 to 2009. The monthly frequency distribution of COLs over South Africa and the Eastern Cape Province for the 31-year period reveal that April and May have the highest COL occurrences while December and January have the least occurrence. The long-term seasonal frequencies distributions of COLs show the highest occurrence of COLs during MAM followed by JJA. The season with the least COL occurrences is DJF for both South Africa and the Eastern Cape Province. There is a noteworthy variation of COL frequencies on the inter-annual and inter-seasonal time-scale.

CHAPTER 5

LOCATION AND DURATION OF CUT-OFF LOWS

5.1 INTRODUCTION

In this chapter the spatial and temporal characteristics of COLs over South Africa and the Eastern Cape Province are investigated. The spatial characteristics are determined by employing a frequency analysis approach for each of the four regions as shown in Figure 1.1. The annual variability of COLs over South Africa and the Eastern Cape Province for regions A, B, C and D, as well as the seasonal frequency distribution in each of the four regions are investigated and presented. The duration of COLs (refer to Chapter 3 for definition) over South Africa and the Eastern Cape Province are categorized into 1-2 days, 3-4 days and >4 days are investigated for the period of 1979 to 2009.

5.2 LOCATION OF CUT-OFF LOWS OVER SOUTH AFRICA AND THE EASTERN CAPE PROVINCE

The preferred geographical regions of COL occurrences are different over South Africa and the Eastern Cape Province. The highest occurrence of COLs is found over region D, followed by region C and A with the least number of COLs occurring over region B over South Africa. The highest occurrence of COLs is found over region C and A, followed by region D with the least number of COLs occurring over region B over the Eastern Cape Province (see Figure 5.1). It never happened that a single COL event occurred over all four regions. There were only three events of COLs that are located over three regions. These COL events are the events of 21-25 September 1983, 04-08 May 1995 and 31 July -04 August 2006. All three of these events occurred over South Africa and have effect to the rainfall of the Eastern Cape Province. The COL event of 21-25 September 1983 developed in region A, moved over region B to region D, from where it decayed. The event of 04-08 May 1995 commenced in region C, moved to region A and ended in region D. The event of 31 July – 04 August 2006 developed over region A, moved to region B and decayed while over region D. The numbers of COLs that were active over two regions were 54 while 212 COLs were located over one region of the South Africa domain. Thirty-nine Eastern Cape COL events were located over two regions, while 138 of the events were located over one region. According to Singleton and Reason (2007b), region C is the preferred location for the occurrence of COLs over subtropical southern Africa during all seasons with more than 35% of COL events associated with this region, which is similar to the results of the Eastern Cape COLs of this study (Figure 5.1). But it is different to the results of COLs over South Africa even though the choice of domain is the same.

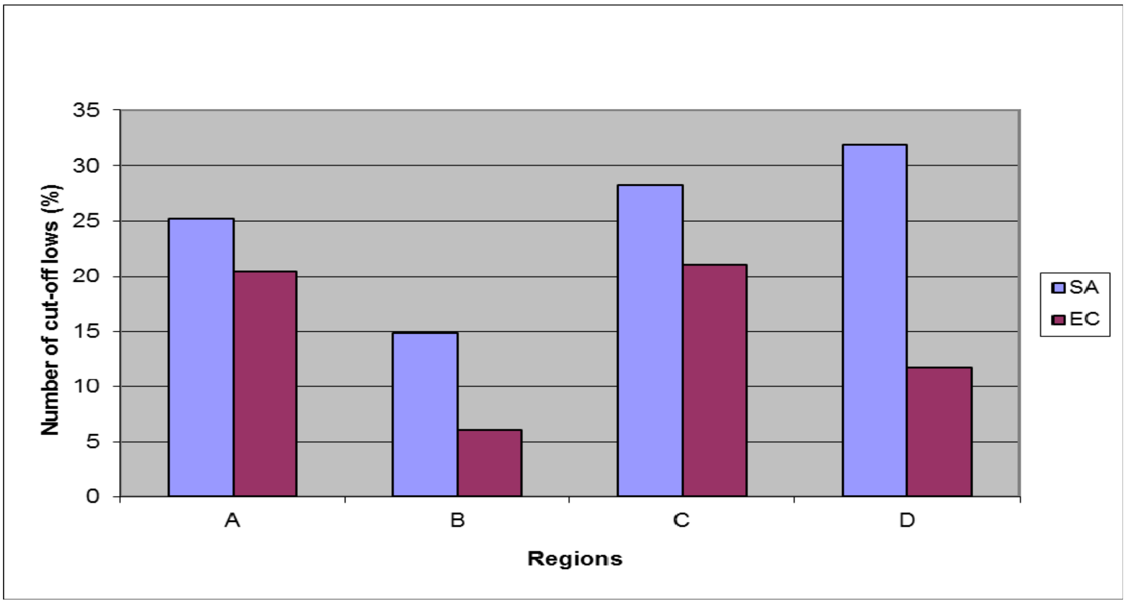
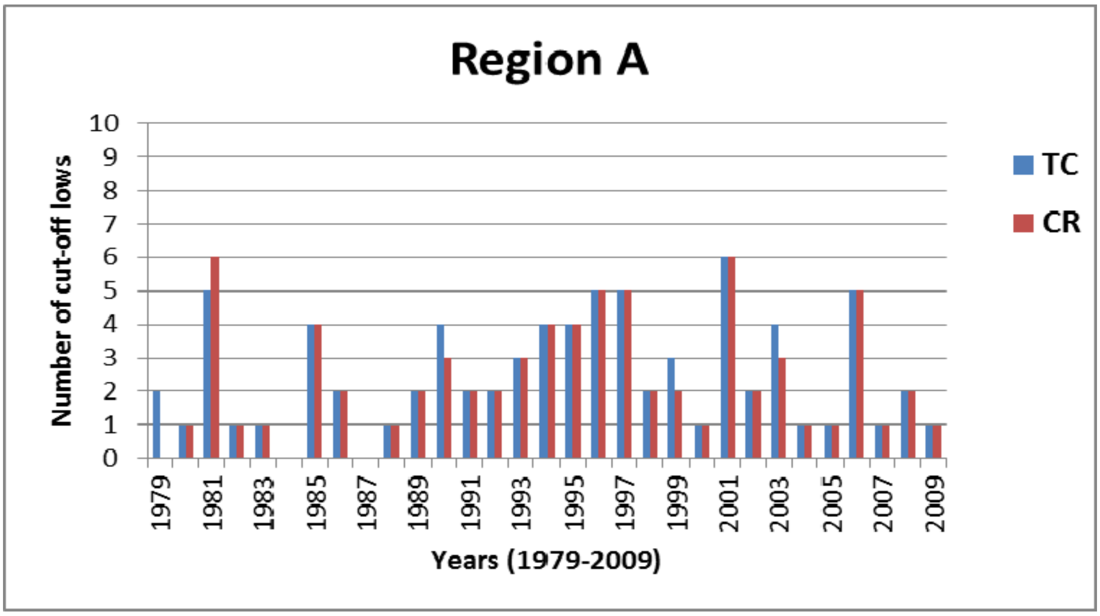


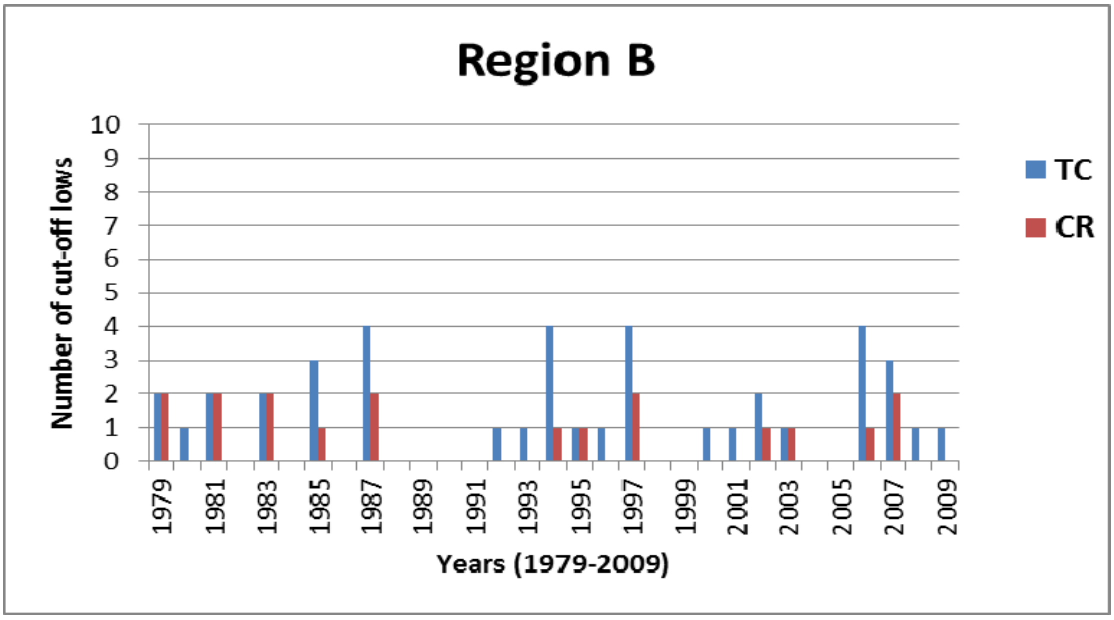
Figure 5.1: Frequency distribution of Cut-Off Lows (COLs) for region A, B, C, and D, expressed as the percentage of the total number of COL events over South Africa (SA) and the Eastern Cape (EC) Province.

5.2.1 Inter-annual variability of cut-off lows over South Africa and the Eastern Cape for regions A, B, C and D.

Further investigations on the inter-annual variability of the occurrence of COLs are done for the four regions as shown in Figure 5.2a and b. All the COLs that were located over regions and form part of COL climatology over South Africa were indicated by the abbreviation TC and all the Eastern Cape COLs that were located over regions are denoted by CR in the figures below. Region D had the highest number of occurrences of COLs over South Africa and region C has the highest number of occurrence of COLs over the Eastern Cape Province. Over region A, the highest occurrence of COLs were found in 1981 and 2001 with zero occurrences in 1980 and 1984 over South Africa, while over the Eastern Cape Province, the highest occurrence of COLs in region A were also in 1981 and 2001 with zero occurrences in 1979, 1984 and 1987 (see Figure 5.2a (i)). Most of the COLs over region A developed in this area and moved eastward. In some cases, COLs originating from region C move northwards into region A, e.g. the event of 24-27 January 1981. Region B has the least occurrence of COLs for both South Africa and the Eastern Cape Province as showed in Figure 5.2a (ii). The highest occurrence of COLs in region B were found in 1987, 1994, 1997 and 2006 with zero COL occurrences in 1982, 1984, 1986, 1988, 1989, 1990, 1991, 1998, 1999, 2004 and 2005 over South Africa. Over the Eastern Cape Province, the highest occurrence of COLs in region B were found in 1979, 1981, 1983, 1987, 1997 and 2007 with zero COL occurrences in 1980, 1982, 1984, 1986, 1988, 1989, 1990, 1991, 1992, 1993, 1996, 1998, 1999, 2000, 2001, 2004, 2005, 2008 and 2009. Most COLs in region B are originally from region A as they move from west to eastward. According to Figure 5.2b (iii), region C has the highest number of COLs over the Eastern Cape Province compared to the other regions. The highest occurrences of COLs in region C were in 2008 and with zero COL occurrences in 1980 and 1993 for both South Africa and the Eastern Cape Province (see Figure 5.2b (iii)). All the COLs found in region C developed in this region and move to other regions such as region A and D. In region D, the highest occurrences of COLs were in 1979, 1981 and 2003 with zero COL occurrences in 1987, 1988 and 1991 over South Africa. Over the Eastern Cape Province the highest occurrences of COLs were in 1981 with zero COL occurrences in 1979, 1980, 1983, 1987, 1988, 1991, 1994, 1998, 2001 and 2004 with (see Figure 5.2b (iv)). Most occurrences of COLs in region D were initially located in region A and C and some developed in region D before moving northward and eastward. There were five COL events where the COL originated in region A before moving on over region D, while nine COLs that developed over region C moved into region D.

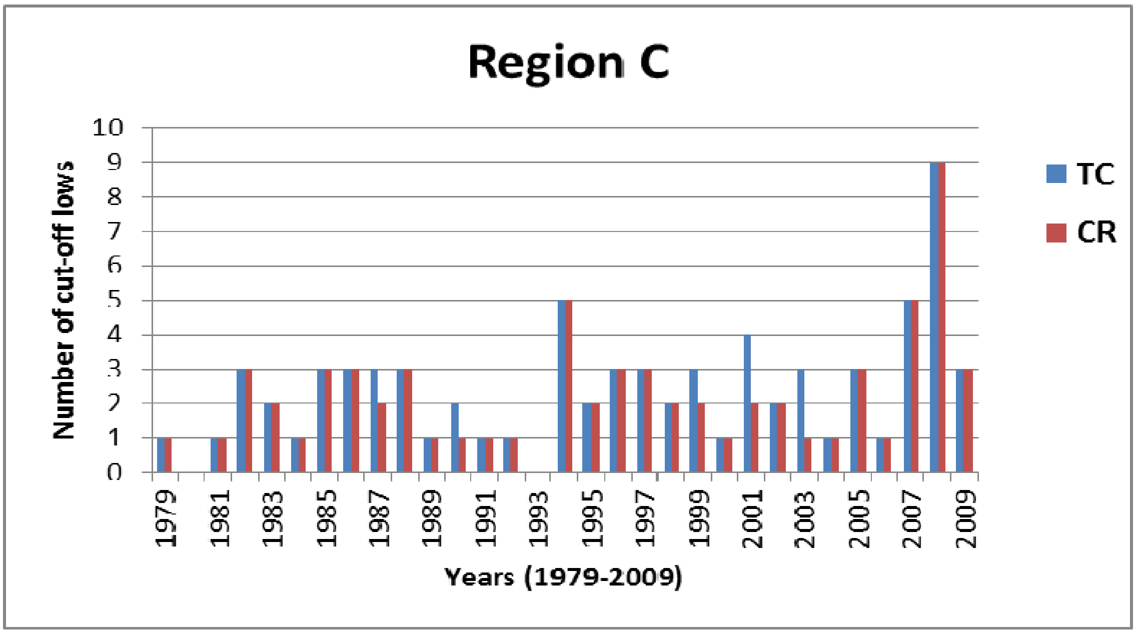


(i)



(ii)

Figure 5.2a: The number of Cut-Off Lows (COLs) per year for (i) Region A and (ii) Region B, where TC is the number of COLs located over regions over South Africa and CR is the number of Eastern Cape COLs located over regions for the period of 1979 to 2009.



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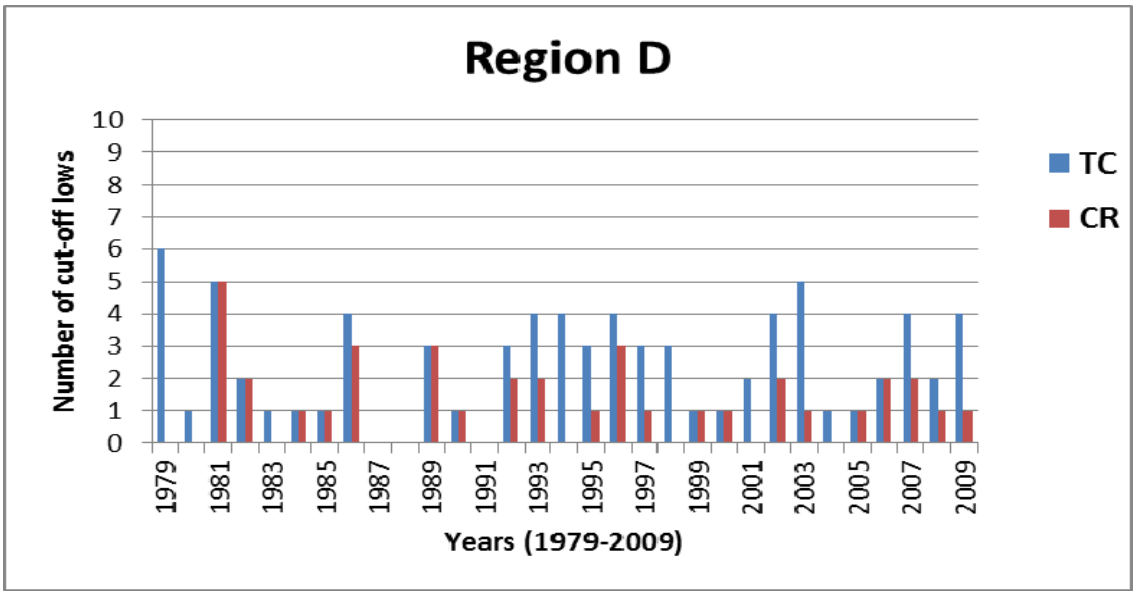


(iv)

Figure 5.2b: The number of Cut-Off Lows (COLs) per year for (iii) Region C and (iv) Region D, where TC is the number of COLs located over regions over South Africa and CR is the number of Eastern Cape COLs located over regions for the period of 1979 to 2009.

5.2.2 Seasonal distribution of cut-off lows over region A, B, C and D

Table 2: Number of Cut-Off Lows (COLs) over South Africa in each season by region in which they occur. The right hand column is the total number of COLs over the whole area.

Region	**A**	**B**	**C**	**D**	**TOTAL**
DJF	8	2	12	10	**32**
MAM	22	16	24	27	**89**
JJA	20	14	21	25	**80**
SON	18	6	19	22	**65**
Total	**68**	**38**	**76**	**86**	**266**

The total number of COL events during DJF, MAM, JJA and SON over the various regions is 266 (see Table 2). Fifty-four of these events were located over more than one region, explaining the higher number of COLs compared to the total number of 212 COL events over South Africa during the period of 1979 to 2009. The three COL events that were located over three different regions during their existence occurred during MAM, JJA and SON. According to Table 2, region D had the highest occurrence of COLs over South Africa, followed by region C and A, while region B had the least. Over region A, JJA had the highest number of COL occurrences. Over region B, MAM and JJA had the highest number of COL occurrences. Over region C MAM had the highest number of COL occurrences. Over region D, MAM had the highest number of COLs. DJF proved to have the least number of COLs over all four regions.

Table 3: Number of Cut-Off Lows (COLs) over the Eastern Cape Province in each season by region in which they occur, whereby the right hand column is the total number of COLs over the whole area.

Region	A	B	C	D	TOTAL
DJF	4	0	9	5	**18**
MAM	23	3	24	10	**60**
JJA	19	8	21	9	**57**
SON	16	4	14	8	**42**
Total	**62**	**15**	**68**	**32**	**177**

Because of the additional 39 events of Eastern Cape COLs located over more than one region, the total number of regional Eastern Cape COLs 177 (Table 3), as opposed to the total number of 138 Eastern Cape COLs otherwise. Over region A, MAM and JJA have the highest number of COL occurrences with the least occurrences during DJF. Over region B JJA, had the highest number of COL occurrences followed by SON with zero occurrences during DJF. Over region C, MAM had the highest number of COL occurrences followed by JJA with the least occurrences during DJF. Over region D, MAM, JJA and SON have the highest number of COLs with the least occurrence during DJF.

5.3 DURATION OF CUT-OFF LOWS OVER SOUTH AFRICA AND THE EASTERN CAPE PROVINCE

The duration of COLs over South Africa and the Eastern Cape Province for the period of 1979 to 2009 is shown in Figure 5.3. More than 40% of COLs lasted for 1-2 days and 2-4 days and less than 10% lasted for more than 4 days over both South Africa and the Eastern Cape Province. The duration for all the individual COL events can be seen in Appendix B. In 1997 and 2006 there were six events that lasted for more than four days over South Africa and three events lasted for more than four days over the Eastern Cape Province. During 2005 two events lasted for more than four days over both South Africa and the Eastern Cape Province. Therefore there were few COLs events that lasted for more than four days for both over South Africa and the Eastern Cape Province.

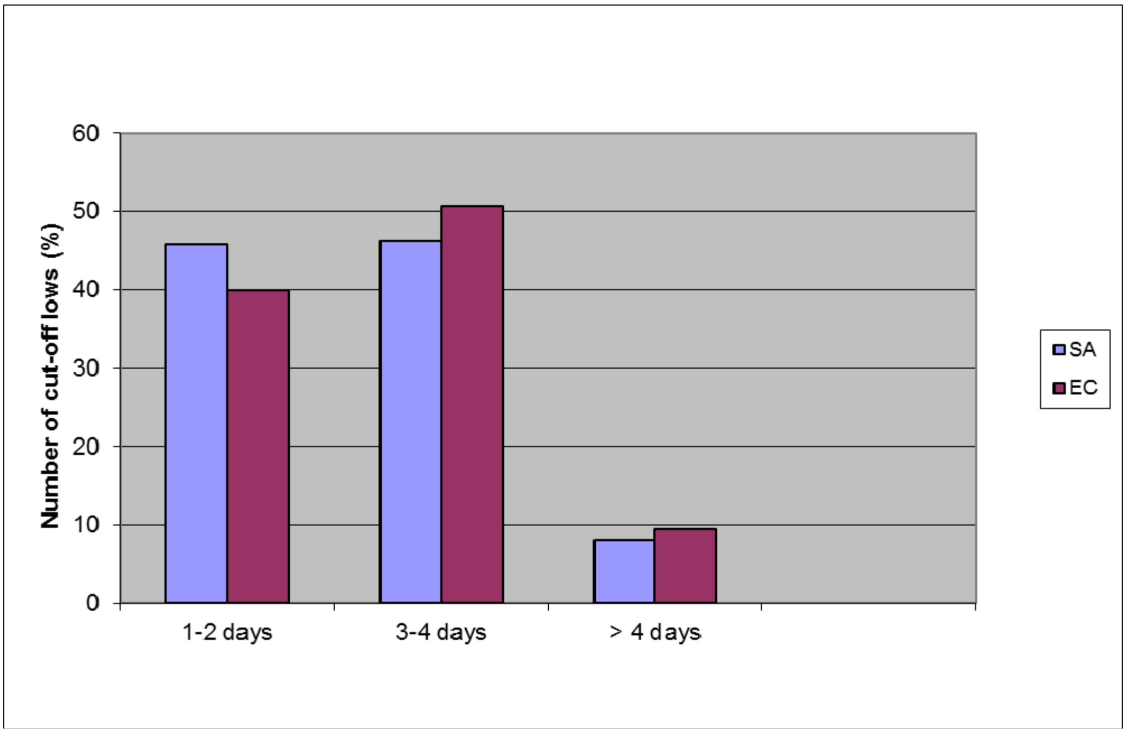


Figure 5.3: Frequency distribution of the percentage of Cut-Off Lows (COLs) in three duration categories (1-2 days, 3-4 days and >4 days) over South Africa (SA) and the Eastern Cape (EC) Province for the period of 1979 to 2009.

5.3.1 Seasonal distribution of the duration of cut-off lows over South Africa and the Eastern Cape Province

The duration of the occurrence of COLs for each season over South Africa for the period of 1979 to 2009 is shown in Figure 5.4. During DJF the highest occurrence of COLs were those that lasted for 3-4 days followed by those lasted for 1-2 days with zero occurrences for those lasted more than four days. During MAM and SON the highest occurrences of COLs were those lasted for 1-2 days followed by those that lasted for 3-4 days with the least occurrences by those lasted for more than four days. During JJA the highest occurrences of COLs were those lasted for 3-4 days followed by those lasted for 1-2 days with least occurrences by those lasted for more than four days.

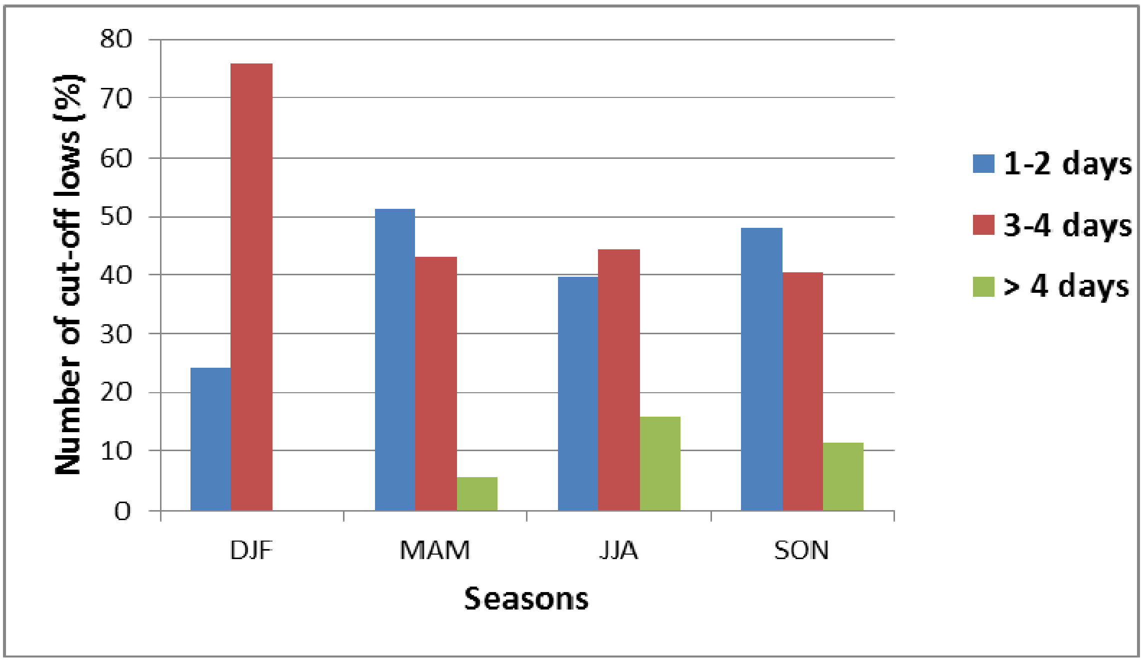


Figure 5.4: Frequency distribution of number of Cut-Off Lows (COLs) in three duration categories (1-2 days, 3-4 days and >4 days) as percentage of COLs in each season over South Africa for the period of 1979 to 2009.

Over the Eastern Cape Province, the seasonal distribution exhibits different behavior compared to that of the South Africa domain (see Figure 5.5). During DJF the highest occurrence of COLs were those that lasted for 3-4 days followed by those lasted for 1-2 days with zero occurrences for those lasted more than four days. During MAM, JJA and SON the highest occurrences of COLs were those lasted for 3-4 days followed by those lasted for 1-2 days with least occurrences by those lasted for more than four days. Over the Eastern Cape Province, during all seasons, COLs that lasted for 3-4 days have a higher frequency than those that lasted for 1-2 days and more than four days unlike over South Africa.

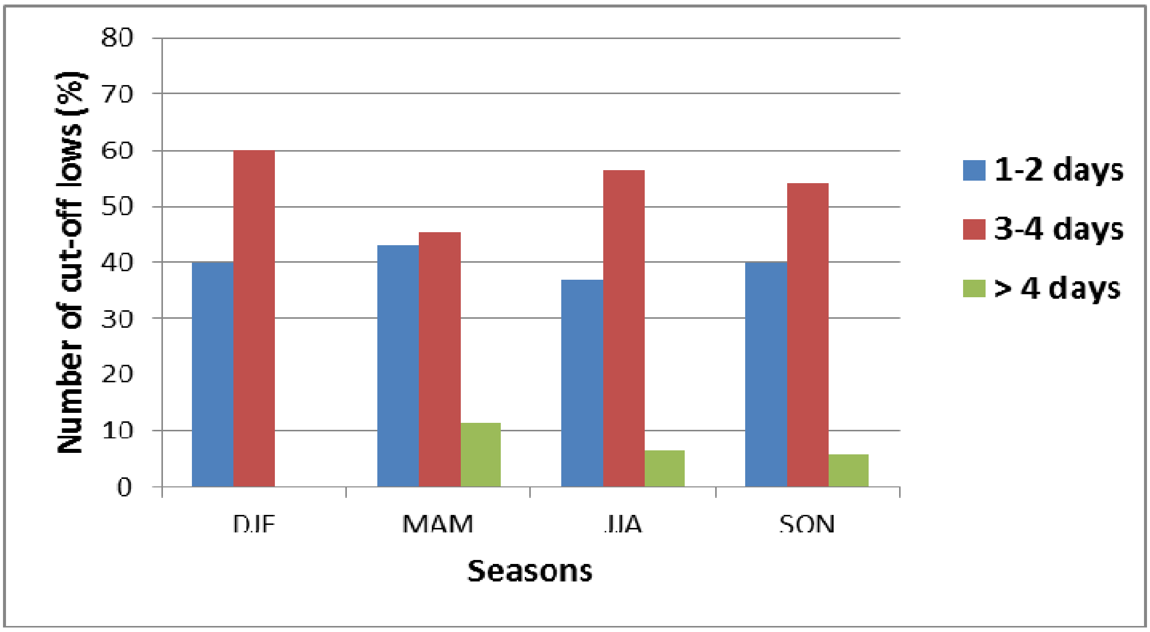


Figure 5.5: Frequency distribution of number of Cut-Off Lows (COLs) in three duration categories (1-2 days, 3-4 days and >4 days) as percentage of COLs in each season over the Eastern Cape Province for the period of 1979 to 2009.

5.4 Summary

In this chapter the location and duration of COLs over South Africa and the Eastern Cape Province are discussed in both a regional and seasonal context. The location of COLs is presented for four regions. Region D has the highest number of COL occurrences for South Africa with the least COL occurrences over region B, while region C that is located in the southwestern part of the domain has the highest number of COL occurrences for the Eastern Cape Province, with the least COL occurrences over region B. Most COLs lasted for 3-4 days over both South Africa and the Eastern Cape Province. Only three COL events during the 31-year period were located over three regions during their existence, and all of them lasted for more than four days over South Africa. The seasonal analyses of COLs show that region D has the highest number of COL occurrences over South Africa while region C has the highest number of COL over the Eastern Cape Province.

CHAPTER 6

SPATIAL RAINFALL DISTRIBUTION ASSOCIATED WITH CUT-OFF LOWS

6.1 INTRODUCTION

In this chapter, all rainfall events over the Eastern Cape Province that are associated with the occurrence of COLs are analyzed. As mentioned in Chapter 3, these COL events are referred to as Eastern Cape COLs. These rainfall events are divided into six average rainfall categories, namely 0 < 10 mm, 10 < 20 mm, 20 < 30 mm, 30 < 40 mm, 40 < 50 mm, and average rainfall of >50 mm. The duration and location of these average rainfall producing COLs are investigated and presented. The spatial rainfall distributions for heavy rainfall category events (see chapter 3) associated with the COLs are analyzed and presented. This chapter concludes with an investigation into the contribution of COLs associated with rainfall to the total rainfall for the Eastern Cape Province (see Chapter 3 for methodology).

6.2 RAINFALL DISTRIBUTION ASSOCIATED WITH CUT-OFF LOWS

From the total of 138 Eastern Cape COLs, about 36% of the events were associated with average rainfall of 0 < 10 mm, 25% with average rainfall of 10 < 20 mm, 17% with average rainfall of 20 < 30 mm, 5% with average rainfall of 30 < 40 mm, 8% with average rainfall of 40 < 50 mm and 9% with average rainfall of >50 mm (see Figure 6.1). This shows that most of the events of occurrence of COLs have average rainfall of less than 10 mm over the Eastern Cape Province. From the total number of 212 COLs over the South Africa domain, 74 of these COL events had no direct association with rainfall over the Eastern Cape Province.

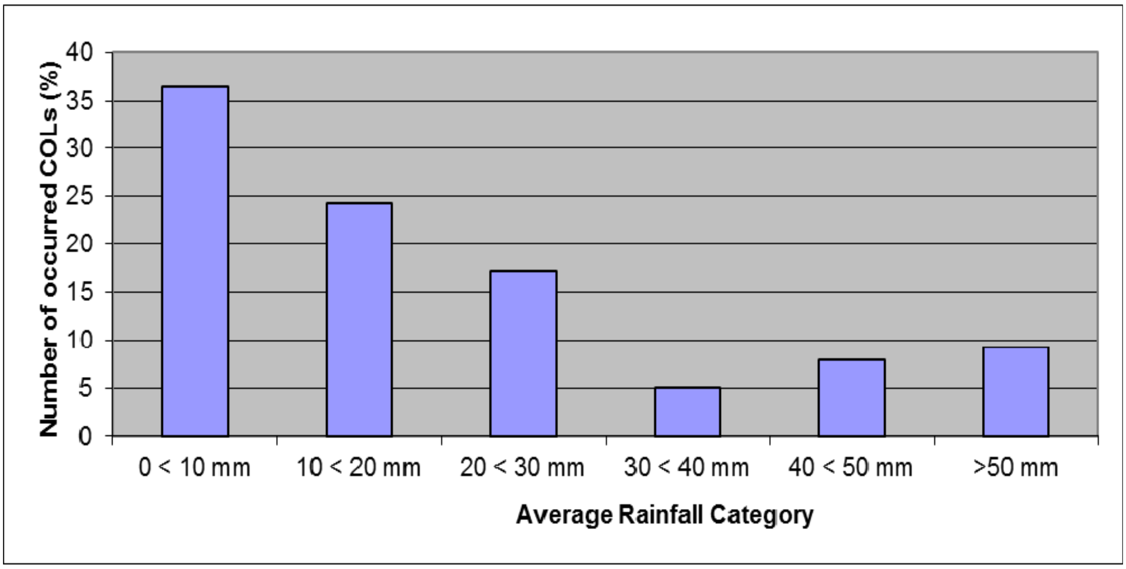


Figure 6.1: Frequency distribution of the percentage of occurred Cut-Off Lows (COLs) during average rainfall categories (0 < 10 mm, 10 < 20 mm, 20 < 30 mm, 30 < 40 mm, 40 < 50 mm and average rainfall >50 mm) for the period of 1979 to 2009 over the Eastern Cape Province

From 138 events of the occurrence of COLs with the average rainfall of 0 < 10 mm, 10 < 20 mm, 20 < 30 mm, 30 < 40 mm, 40 < 50 mm, and average rainfall of >50 mm are categories into four regions, which are region A, B, C and D as indicated in Figure 6.2. In the category of 0 < 10 mm average rainfall, region C had the highest occurrence of COLs, followed by region A and with the least occurrence in region B. In the category of 10 < 20 mm average rainfall, region A has highest occurrence of COLs events with the least occurrence in region B. In the category of 20 < 30 mm average rainfall, region A has highest occurrence of COLs events with the least occurrence in region B. In category of 30 < 40 mm average rainfall, region A has the highest occurrence of COLs events with zero occurrences in region B, C and D. Under category of 40 < 50 mm average rainfall, all regions have least occurrence of COLs events, while In the of >50 mm average rainfall, region A has highest occurrence of COLs events with zero occurrences in region C and D. Region A contains in all the average rainfall categories but with the least occurrence of COLs under category of 40 < 50 mm, 20 < 30 mm and 10 < 20 mm. There were 31 events of heavy rainfall (meaning at least one station reported >50 mm of rainfall) in region A, 12 events in region B, eight events in region C and 12 events in region D that associated with COLs. It is found that most occurrences of COLs were found in region A that had a large impact on rainfall over the province and other parts of South Africa.

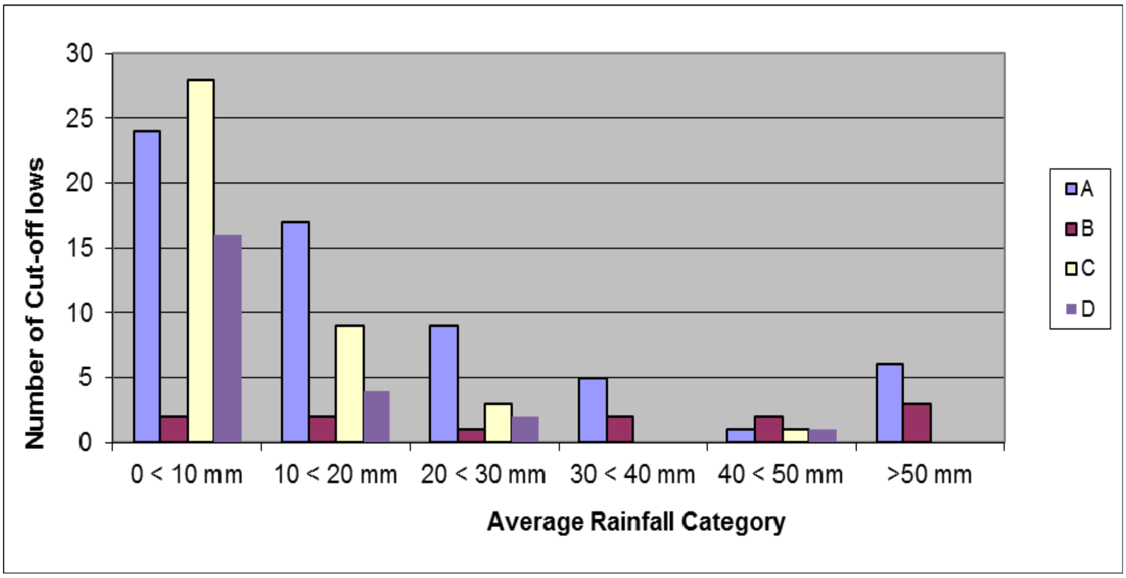


Figure 6.2: Frequency distribution of the regional distribution for six categories (0 < 10 mm, 10 < 20 mm, 20 < 30 mm, 30 < 40 mm, 40 < 50 mm and average rainfall of > 50 mm) of average rainfall during the occurrence of Cut-Off Lows (COLs) over the Eastern Cape Province for the period of 1979 to 2009.

6.3 DURATION OF CUT-OFF LOWS DURING VARIOUS RAINFALL CATEGORIES

The duration of Eastern Cape COLs for the various average rainfall categories (0 <10 mm, 10 < 20 mm, 20 < 30 mm, 30 < 40 mm, 40 < 50 mm, and average rainfall of >50 mm) is shown in Figure 6.3. For all the rainfall categories, Eastern Cape COLs with duration of 1-2 days and 3-4 days have the highest frequency under the average rainfall 0 < 10 mm with the least occurrence under the duration of more than four days. There were no events that lasted for 1-2 days under the average rainfall of more than 50 mm. As expected, the number of Eastern Cape COL events for all the duration categories decrease as the rainfall category increases except for the duration of 3-4 days under the average rainfall of >50 mm category. For the latter, there were no short-lived (1-2 days duration) COL events during heavy rainfall category. This suggests that heavy rainfall producing Eastern Cape COLs tend not to be short-lived.

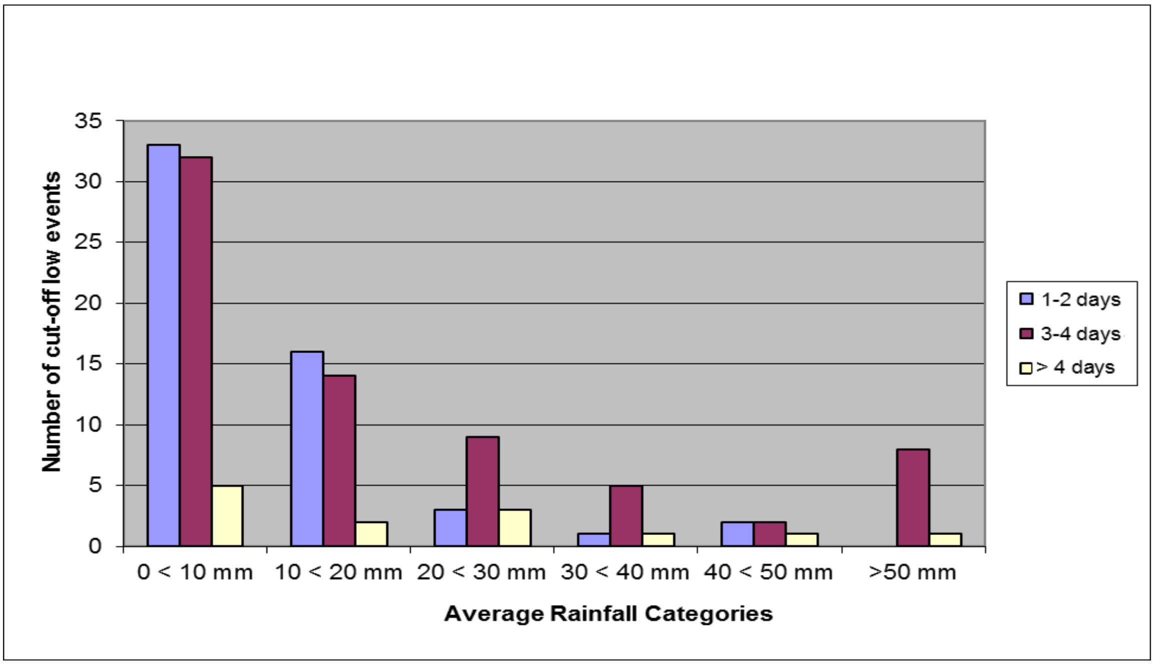


Figure 6.3: Frequency distribution of the duration of Cut-Off Lows (COLs) for six different average rainfall categories (0 < 10 mm, 10 < 20 mm, 20 < 30 mm, 30 < 40 mm, 40 < 50 mm and average rainfall of > 50 mm)for the period of 1979 to 2009.

6.4 SPATIAL RAINFALL DISTRIBUTION ASSOCIATED WITH CUT-OFF LOWS

Of the 60 heavy rainfall Eastern Cape COLs, more than 40% of these events were associated with heavy rainfall reported by only one station, 20% of heavy rainfall events were reported by two stations, 5% of heavy rainfall events were reported by three, four, five and seven stations. Less than 5% of heavy rainfall events are reported by six, eight, 10, 11 and 12 stations, indicating that such widespread heavy rainfall events were quite rare (see Figure 6.4). Three widespread heavy rainfall producing COL events were those of 19-22 July 1979 whereby heavy rainfall was reported by 11 stations (EL, GB, GD, JB, KR, LB, PE, PA, PJ, TP, and UZ), 21-24 September 1993 whereby heavy rainfall was reported by 11 stations (EL, GD, HD, JB, KR, LB, MD, PE, PA, PJ, and UZ) and 15-16 November 1989 whereby heavy rainfall was reported by 12 stations (EL, GD, HD, JB, KR, KF, LB, MD, QT, PE, TP and UZ) see section 3.2.3 for stations acronyms. There was no heavy rainfall event associated with the Eastern Cape COL that was reported by more than twelve stations in this study. Widespread heavy rainfall events occur mostly along the coastal regions.

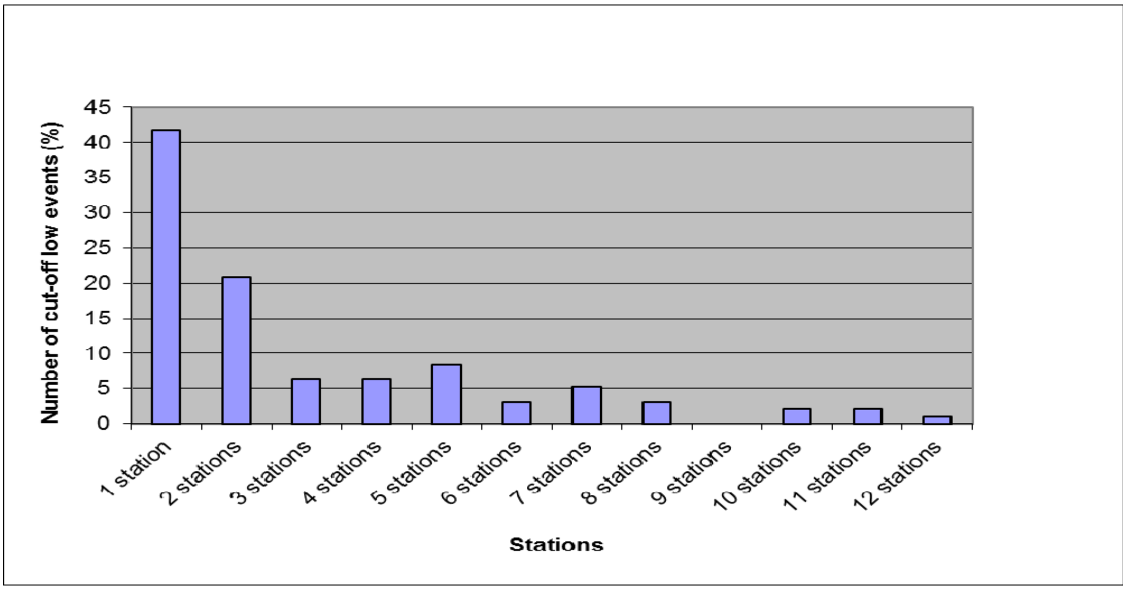


Figure 6.4: Frequency distribution of the occurrence of Cut-Off Lows (COLs) events that produced heavy rainfall (>50 mm) for each weather stations in the Eastern Cape Province.

Heavy rainfall events in this study shows more than 26% of days reported at one station, more than 8% of the days reported at two stations, more than 4% of the days reported at three stations, more than 3% of the days reported at four stations, 3% of the days reported at five stations, 1% of the days reported at six and nine stations, less than 1% of the days reported at seven, eight and nine stations during heavy rainfall events (see Figure 6.5). Because the events differed in the number of days of occurrence, all the days with heavy rainfall were counted from each event. It was found that during heavy rainfall events there are certain events that contain more than one day of heavy rainfall reported at one station, while most events contain only one day of heavy rainfall reported at one station. Therefore, with the increase in the number of stations there is a decrease in the number of days of heavy rainfall reported.

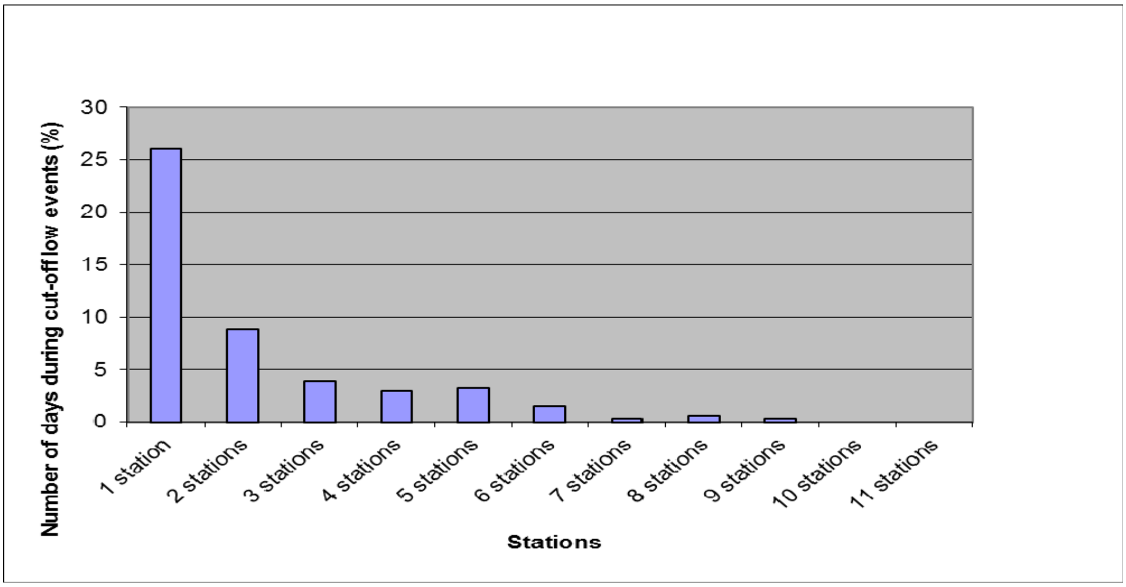


Figure 6.5: Number of days during the heavy rainfall (>50 mm) events for each weather station in the Eastern Cape Province for the period of 1979 to 2009.

Table 4: Number of stations that reported heavy rainfall (>50 mm of rainfall) during 1, 2 and 3 days in each events.

No. of Stations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
1 day	27	15	5	4	3	1	1	0	0	1	2	1	**60**
2 days	9	3	3	1	1	0	0	0	0	0	0	0	**17**
3 days	2	1	1	0	0	0	0	0	0	0	0	0	**4**

Of the 60 heavy rainfall events, there were 60 events of heavy rainfall were reported in one day with 27 events reported by one station, 15 events reported by two stations, five events reported by three stations, four events reported by four stations, three events reported by five stations, one event reported by six, seven, 10 and 12 stations and one event reported by 11 stations. Of the 17 heavy rainfall events that were reported in two days, nine events reported by one station, three events reported by two and three stations, and one event reported by four and five stations. Only four events of heavy rainfall were reported in three days with two events reported by one station and one event reported by two and three stations (see table 4). The events of heavy rainfall that were reported in three days were on 31 October - 02 November 1985 with two stations (EL and PJ) reported heavy rainfall for three days, from 21-24 September 1993 with three stations (EL, HD and UZ) reported heavy rainfall for three days, from 19-21 March

2003 with one station (PJ) reported heavy rainfall for three days and from 21-23 November 2007 one station (LB) reported heavy rainfall for three days. In this article, it is found that no heavy rainfall event was reported lasting more than four days.

This translates into 63 Eastern Cape COL events associated with heavy rainfall over 31-year period of 1979 to 2009 over the Eastern Cape Province. In this section, each of the 60 Eastern Cape COLs associated with heavy rainfall is presented according to the region in which the COL is located at the time of the heavy rainfall observations. Spatial rainfall maps are created by utilizing the inverse distance interpolation function available in the GIS ArcMap software and shown in Appendix C.

6.4.1 Region A

There are 31 events of heavy rainfall over the Eastern Cape Province associated with COLs located over region A and their spatial rainfall map are shown in Appendix C under Region A. Of these 31 events, eight events lasted 1-2 days, 19 events lasted 3-4 days and four events lasted for more than four days. There are three widespread heavy rainfall events produced by COLs with duration of 1-2 days. The first event occurred on from 10-11 May 2003 with six stations that reported heavy rainfall. During this event, on 10th May 2003 one station (PA) reported 150 mm of rainfall and on 11th May 2003 five stations reported heavy rainfall (EL reported 50.2mm, HD reported 52.5 mm, JB reported 55.9 mm, LB reported 94.5 mm and UZ reported 74 mm of rainfall). The second intense event occurred from 15-16 November 1989 with eight stations that reported heavy rainfall in one day. During this event, on 15th November 1989 eight stations reported heavy rainfall (EL reported 146.1 mm, GD reported 71 mm, HD reported 70.5 mm, JB reported 51.9 mm, KF reported 52.5 mm, LB reported 67.5 mm, QT reported 55.5 mm and UZ reported 130 mm of rainfall), while on 16th November 1989 no station reported heavy rainfall during this event. The third intense event occurred from 15-16 August 2002 with three stations that reported heavy rainfall in one day and one station that reported heavy rainfall in two days (meaning one stations has reported heavy rainfall in two consecutive days). During this event, on 15th August 2002 two stations reported heavy rainfall (EL reported 317.2 mm of rainfall and UZ reported 158.5 mm of rainfall) and on 16th August 2002 also two stations reported heavy rainfall (UZ reported 61 mm of rainfall and MU reported 70.8 mm of rainfall). This event was confirmed by the case study of Singleton and Reason (2006) in which about four times the monthly average rainfall fell in just 24-hours over EL in August and was characterized by a COL pressure system in the middle troposphere. Less intense events of COLs that lasted for 1-2 days occurred from 23-24 August 1981 RW reported 71 mm of rainfall on 23rd August 1981, 28-29 March 1992 SB reported 54 mm of rainfall on 29th March 1992. There are four intense COL events that lasted for 3-4 days in this region. The first occurred from 24-27 January 1981 with nine stations that reported heavy rainfall. During this event, on 24th January 1981 five stations reported heavy rainfall (EL reported 118.8 mm, GD reported 99 mm, HD reported 53.5 mm, KR reported 65 mm and UZ reported 141.5 mm of rainfall), on 25th January 1981 three stations reported heavy rainfall (LB reported 116 mm, TP reported 52.3 mm and JB reported 58 mm of rainfall), on 26th January 1981 only one station (RW) reported 77 mm of rainfall and on 27th January 1981 no station reported heavy rainfall. The second intense event occurred from 24-26 March 1981 with nine stations that reported heavy rainfall in one day and one station reported heavy rainfall in two days (meaning one station has reported heavy rainfall in two consecutive days). During this event, on 24th March 1981 two stations reported heavy rainfall (JB reported 174 mm and TP reported 61.5 mm of rainfall), on 25th March 1981 seven stations reported heavy rainfall (GD reported 2 274.5 mm, HD reported 122 mm, JB reported 52 mm, LB reported 160 mm, MD reported 58 mm, PE reported 224 mm and RB reported 51 mm of rainfall), on 26th March 1981 only one station (PA) reported 80 and 82.5 mm of rainfall. The third intense event occurred from 31 October - 02 November 1985 with three stations that reported heavy rainfall in one day and two stations that reported heavy rainfall in two days (meaning heavy rainfall is reported in two consecutive days in this event by two stations). During this event, on 31st October 1985 no station reported heavy rainfall, on 01st November 1985 three stations reported heavy rainfall (EL reported 50.2 mm, PJ reported 168 mm and UZ reported 58 mm of rainfall), on 02nd November 1985 four stations reported heavy rainfall (EL reported 184.6 mm, EP reported 60 mm, KR reported 257.5 mm and UZ reported 226.8 mm of rainfall). The fourth event occurred from 21-24 September 1993 with 10 stations that reported heavy rainfall in one day, six stations reported heavy rainfall in two days and two stations reported heavy rainfall in three days (meaning heavy rainfall is reported in three consecutive days in this event by two stations). During this event, on 21st September 1993 nine stations reported heavy rainfall (EL reported 53.4 mm, GD reported 58.7 mm, HD reported 74 mm, JB reported 70.5 mm, LB reported 74.5 mm, MD reported 57 mm, PE reported 62.4 mm, PA reported 61 mm and UZ reported 54.5 mm of rainfall), on 22nd September 1993 five stations reported heavy rainfall (EL reported 57.9 mm, GD reported 74.5 mm, HD reported 58 mm, PJ reported 178 mm and UZ reported 74 mm of rainfall), on 23th September 1993 five stations reported heavy rainfall (EL reported 62.8 mm, HD reported 68.5 mm, JB reported 58.5 mm, LB reported 154 mm and UZ reported 66.1 mm of rainfall) while on 24th September 1993 no station reported heavy rainfall. Less intense events of COLs that lasted 3-4 days occurred from, from 24-26 June 1985 HD reported 54.5 mm of rainfall on 24rd June 1985, from 24-26 May 1997 LB reported 52 mm of rainfall on 26th May 1997 with only one station reported heavy rainfall during each event. There is only one intense event of COL that lasted for more than four days in this region. The event occurred on 31-04 July/August 2006 with seven stations that reported heavy rainfall in one day and two stations that reported heavy rainfall in two days. During this event, on 31st July and 01st August 2006 no station reported heavy rainfall, on 02nd August 2006 seven stations reported heavy rainfall (EL reported 56.6 mm, GD reported 101 mm, HD reported 302 mm, JB reported 140.1 mm, LB reported 86 mm, PE reported 128 mm and UZ reported 127 mm of rainfall), on 04th August 2006 two stations reported heavy rainfall (PE reported 64 mm and UZ reported 61 mm of rainfall). Less intense events of COLs that lasted for more than four days occurred from 21-25 September 1983 whereby LB reported 90 mm of rainfall on 25th September 1983, from 14-18 March 1997 LB reported 59.5 mm of rainfall on 18th March 1997, and from 09-13 November 2005 LB reported 52 mm of rainfall on 12th November 2005 with only one station reported heavy rainfall in one day during each event. The heaviest falls of rain typically occurred along the coastal regions in the case of COLs that produce widespread rainfall. The heavy rainfall produced by COL events described in literature such as the January 1981 Laingsburg flooding (Estie, 1981), the September 1987 KwaZulu-Natal flood (Tyson and Preston-Whyte, 2000), the August 2002 East London flooding (Singleton and Reason, 2006) are some of the heavy rainfall producing Eastern Cape COLs located within region A as described in this study. According to Singleton and Reason (2007b), region A is a summer rainfall region and influenced by the South IO and Agulhas Current. Although region C is the region with the highest frequency of Eastern Cape COLs but it was found that region A has the highest frequency of Eastern Cape COLs that associated with heavy rainfall. During 1979, 1980, 1982, 1984, 1987, 2004 and 2009 there were no events of heavy rainfall reported by any station over this region. In this region there were nine events with more than 200 mm of rainfall reported by stations over the province. It is found that one event (31 July - 04 August 2006) that is located over three regions, lasted for more than four days and occurred during JJA. The surface synoptic maps show that there were cold fronts followed by high pressure systems as dominant surface circulation associated with the COLs in these cases. COLs occurred in this region had great impact on rainfall of the Eastern Cape Province because it is situated west of the province unlike other region.

6.4.2 Region B

In region B there are 12 events of heavy rainfall associated with COLs and their spatial rainfall map are shown under Region B in Appendix C. In this region three events lasted for 1-2 days, eight events lasted for 3-4 days and one event lasted for more than four days. The intense events of COL that lasted for 1-2 days occurred from 25-26 July 1994 with GB reported 60 mm of rainfall on 25th July 1994 and 26-27 June 2007 PJ reported 83.5 mm of rainfall on 26th June 2007 with only one station that reported heavy rainfall in one day during each event. There are two intense COLs events that lasted for 3-4 days in this region. The first intense event occurred from 19-22 July 1979 with 10 stations that reported heavy rainfall in one day and two stations that reported heavy rainfall in two days. During this event, on 19th July 1979 no station reported heavy rainfall, on 20th July 1979 seven stations reported heavy rainfall (EL reported 65.6 mm, GB reported 60 mm, KR reported 66.5 mm, PA reported 55 mm, PJ reported 70 mm, TP reported 53.5 mm and UZ reported 97.3 mm of rainfall), on 21st July 1979 three stations reported heavy rainfall (EL reported 88.8 mm, PE reported 98.5 mm and PA reported 160.6 mm of rainfall) and on 22nd July 1979 two stations reported heavy rainfall (JB reported 73 mm and LB reported 82.5 mm of rainfall). The second intense event occurred on 09-12 September 2002 with six stations that reported heavy rainfall. During this event, on 10th September 2002 no station reported heavy rainfall, on 09th September 2002 five stations reported heavy rainfall (EL reported 80.8 mm, KR reported 76.5 mm, PA reported 57 mm, PJ reported 52 mm and UZ reported 129 mm of rainfall) and on 11th September 2002 only one station (GB) reported 84 mm of rainfall. Less intense COL event that lasted for 3-4 days occurred from 16-19 June 1995 with only two stations reported heavy rainfall in one day (GB reported 132 mm and PJ reported 99.5 mm of rainfall on 18th June 1995). Over this region, none of the heavy rainfall producing Eastern Cape COL events occurred during DJF, three events occurred during MAM, seven events occurred during JJA and only two events occurred during SON. It is found that 15% of heavy rainfall category events of COLs over this province are associated with the COLs located over region B, which has the least compared to the other regions.

6.4.3 Region C

There are eight events of heavy rainfall associated with COLs that are located over region C and their spatial rainfall maps are shown under Region C in Appendix C. In this region, five events lasted for 1-2 days, three events lasted for 3-4 days and none of the events lasted for more than four days. There is only one intense event that lasted for 1-2 days in this region, which is occurred from 10-11 April 2005 with three stations reported heavy rainfall in one day (KF reported 58 mm, MD reported 57 mm and UZ reported 66.7 mm of rainfall on 10th April 2005). Less intense events that lasted for 1-2 days in this region occurred from 22-23 April 1998 with UZ reported 62.5 mm of rainfall on 22nd April 1998, 02-03 March 2000 GD reported 75 mm and UZ reported 62 mm of rainfall on 02st March 2000, and from 27-30 January 2005 UZ reported 61.5 mm of rainfall on 30th January 2005, from 05-06 January 2008 UZ reported 60.1 mm of rainfall on 04th January 2008 with only two stations reported heavy rainfall in one day during each of the event. In this region there are two intense events of COLs that lasted for 3-4 days, the first occurred from 13-15 January 2008 with five stations that reported heavy rainfall. During this event, on 13th January 2008 only one station (EP) reported 73.5 mm of rainfall, on 14th January 2008 four stations reported heavy rainfall (EL reported 51 mm, KR reported 74 mm, PJ reported 147 mm and UZ reported 67.3 mm of rainfall), on 15th January 2008 no station reported heavy rainfall. Second intense event of COL that lasted for 3-4 days occurred from 07-10 October 2008 with two stations that reported heavy rainfall in one day (HD reported 63 mm and LB reported 57 mm of rainfall on 08th October 2008). Less intense events that lasted for 3-4 days in this region occurred on 12-14 January 2004 MD reported 60 mm of rainfall on 13th January 2004, and from 25-27 October 2009 UZ reported 50.5 mm of rainfall on 26th October 2009, all with only one station that reported heavy rainfall in one day. Over region C, four COL events occurred during DJF, four occurred during MAM, no event occurred during JJA and two during SON with at least one station that reported heavy rainfall.

6.4.4 Region D

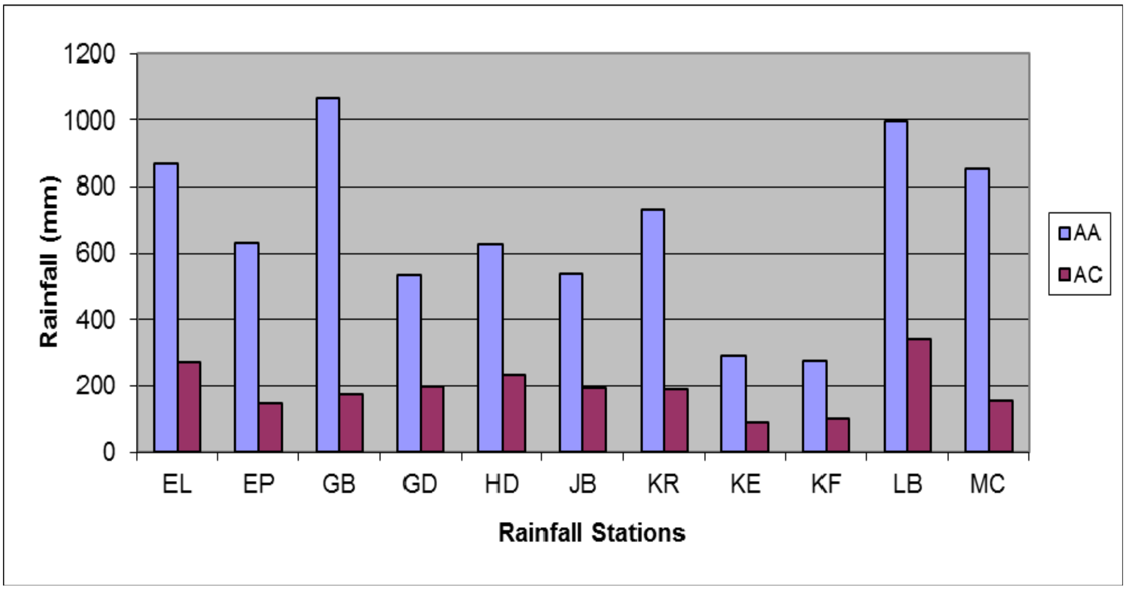
There are 12 events of heavy rainfall associated with COLs that are located over region D and their spatial rainfall maps are shown under Region D in Appendix C. Over the Eastern Cape Province in region D three COLs event associated with heavy rainfall that lasted for 1-2 days, seven events lasted for 3-4 days and two events lasted for more than four days. In this region there are two intense events associated with COLs that lasted for 1-2 days. The first intense event occurred from 11-12 June 1993 with two stations that reported heavy rainfall in one day. During this event, on 11th June 1993 no station reported heavy rainfall, on 12th June 1993 two stations reported heavy rainfall (GD reported 54 mm and PE reported 63.6 mm of rainfall. The second intense event occurred from 16-17 October 1992 with three stations that reported heavy rainfall in one day (GD reported 92 mm, HD reported 85.5 mm and LB reported 88 mm of rainfall on 16th October 1992). Less intense events that lasted for 1-2 days occurred from 25-26 May 2003 JB reported 50.8 mm of rainfall on 26th May 2003 and from 22-23 July 2006 LB reported 65.5 mm of rainfall on 23rd July 2006 with only one station that reported heavy rainfall in one day during each event. In this region there is only one intense event associated with COL that lasted for 3-4 days. The intense event occurred from 21-23 February 1990 with four stations that reported heavy rainfall in one day (HD reported 53 mm, JB reported 52.6 mm, LB reported 134 mm and PA reported 54 mm of rainfall occurred on 21th February 1990). Less intense events that lasted for 3-4 days occurred from 24-26 March 1982 LB reported 160 mm of rainfall on 25th March 1982, from 23-25 February 1986 EL reported 62.8 mm of rainfall on 24th February 1986, from 09-11 May 1998 LB reported 56 mm of rainfall on 10th May 1998. An intense event associated with a COL that lasted for more than four days occurred from 06-10 November 2005 with five stations that reported heavy rainfall in one day (EL reported 162.8 mm, GB reported 86.4 mm, PA reported 64 mm, QT reported 54 mm and UZ reported 261.5 mm of rainfall on 06th November 2005) and no heavy rainfall was reported on 7th, 8th, 9th and 10th November 2005. Less intense COL event that lasted for more than four days occurred from 30 October - 03 November 2000 with two stations that reported heavy rainfall in separate days (PA reported 68.6 mm of rainfall on 31st October 2000 and GD reported 55.4 mm of rainfall on 03rd November 2000). Over region D, four events occurred during DJF, three events occurred during MAM, two events occurred during JJA and three events occurred during SON with at least one station that reported heavy rainfall. The most affected areas in terms of rainfall are along the coast. It is found that in this region there are two events during which two stations reported more than 200 mm of rainfall (HD reported 213 mm of rainfall in one day during the 11-12 June 1993 event and UZ reported 261.5 mm of rainfall in one day during the 06-10 November 2005 event).

6.5 CONTRIBUTION OF CUT-OFF LOWS TO THE TOTAL ANNUAL RAINFALL

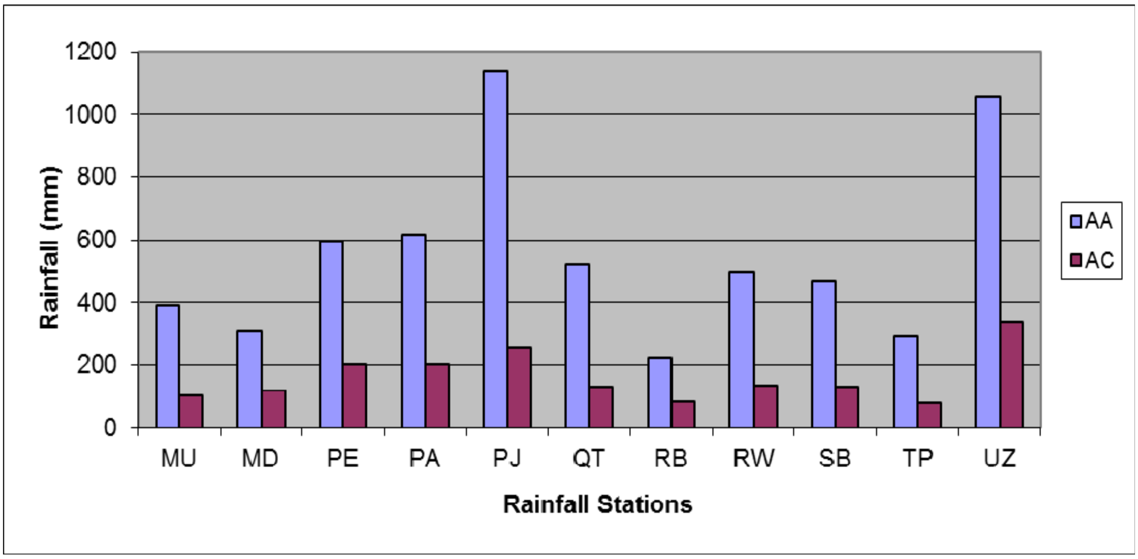
In the previous section, it is shown that areas along the coast are the most affected by the occurrence of COLs, particular with the occurrence of heavy rainfall. In Appendix D, the contribution of COLs to the total annual rainfall (expressed as a percentage of the total annual rainfall) for each of the 22 weather stations are shown. The contribution of COLs to the total annual rainfall exhibits annual variability as well as spatial variability. The highest annual contribution to rainfall by the Eastern Cape COLs occurred in 1979 with the contribution of 40% annually, 1981 with 51%, 1985 with 42%, 1993 with 40% 1993 with 40% and 1994 with 40%, the lowest annual contribution to rainfall occurred 1980 with 7.8% and 1984 with 8% annually. Increased occurrences of COLs are associated with a larger contribution to the total annual rainfall but it also depends on the intensity, duration and the location of the systems.

6.5.1 Total annual rainfall contribution

The long-term annual average rainfall and the annual average rainfall associated with COLs for each of the 22 stations can be seen in Figure 6.6(a) and (b). For each station, whereby AA is defined as the annual average rainfall for 31-year for each station and AC is defined as the annual average rainfall associated with COLs for 31-year for each station. The areas with the highest contribution of rainfall by COLs are along the coast such as EL, GB, GD, HD, JB, KR, LB, PA, PE, PJ and UZ. Stations located further from the coast such as EP, KE, KF, MC, MD, MU, QT, RB, RW, SB and TP have a smaller fraction of rainfall associated with COLs. These stations have lower total annual rainfall compared to the total annual rainfall of areas that are based along the coast. The total annual rainfall and the total annual rainfall associated with COLs for each station is calculated and shown in appendix D. It was found that during the years of highest occurrence of COLs, the contribution of COLs is 32% during 2001, 40% during 1994, 32% during 1996, 36% during 2008, 34% during 1997, 40% during 1979 and 24% during 2009 for all stations. During the years of the least occurrence of COLs the contribution was close to 8% during 1980 and 1984. The highest contribution of COLs was occurred during 1981 with 51% even though it is neither the year of the highest nor the least occurrence of COLs in this study. It was found that the total annual rainfall associated with COLs was less than 50% at all 22 stations over the Eastern Cape Province. This suggests that COLs can be one of the major rain producing weather systems over this part of South Africa. COL related rainfall is close to 37-38% along the coastal areas and less than 10% over the interior of the Eastern Cape Province. The other 62% of the rainfall result from ridging highs, cold fronts and tropical-temperate troughs along the coastal areas.



(a)



(b)

Figure 6.6: The long-term annual average rainfall (purple) and the annual average rainfall contributed by Cut-Off Lows (COLs) (red) for the period of 31-year at various weather stations.

6.6 Summary

During the 31-year period from 1979 to 2009 the numbers of COL events associated with rainfall over the Eastern Cape Province were found to be 138, of those 60 COL events were associated with heavy rainfall over the province. The spatial rainfall distribution associated with these heavy rainfalls producing Eastern Cape COLs is presented. Most Eastern Cape COLs events are located over region C, but the highest frequency of heavy rainfall producing Eastern Cape COL events are located over region A. Heavy rainfall associated with COLs usually occur along the coast and adjacent interior and majority of these systems have duration of 3-4 days. The contribution of rainfall associated with the occurrence of COLs is found to be approximate 37-38% annually along the coastal areas, while it is less than 10% annually over the interior of the Eastern Cape Province.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 SUMMARY

In this study COL climatology for the 31-year period 1979 to 2009 was constructed for South Africa. Further, COLs over South Africa that were associated with rainfall over the Eastern Cape Province were identified and in this way the Eastern Cape COL climatology was constructed. A total of 212 COLs were identified over South Africa for the 31-year period under consideration by means of visual inspection of the 6-hourly 500 hPa pressure level geopotential height and air temperature fields obtained from NCEP-NCAR reanalysis data. Surface synoptic charts from the SAWS (850 hPa heights prior to the year 2000 and sea-level pressure thereafter) and NCEP 850 hPa heights were considered to identify the surface flow associated with COLs. Daily rainfall from 22 evenly distributed rainfall stations over the Eastern Cape Province was used to determine the total rainfall over the Eastern Cape Province. Analyses on the contribution of rainfall by COLs to the total rainfall reveals in that the inter-annual rainfall variability as well as in the spatial rainfall variability by COLs are contributing more to the total rainfall along the coastal regions of the Eastern Cape Province as compared to the interior.

7.2 CONCLUSIONS

The Eastern Cape Province has experience recurring drought in recent years with an inauspicious impact on agricultural economical production (Jury and Levey, 1993b). It is also known for the occurrence of flooding events because of the occurrence of COLs over this province. According to Preston-White and Tyson (1988), in the transition seasons the Eastern Cape Province rainfall is dependent on instabilities in the mid-latitude westerlies. During the past two decades COLs as one of the main circulation systems was responsible for rainfall in South Africa (Taljaard, 1996). According to Singleton and Reason (2007b) COLs change in location from southwestern subtropical southern Africa to the northeast of the region.

During the 31-year period of 1979 to 2009 a total of 212 COLs were identified over South Africa. The highest COL frequency occurred in 2001, followed by 1994 and 2008. The lowest COL frequency occurred in 1992 and 1984. COLs over South Africa that are not associated with rainfall over the Eastern Cape Province were found to be 74 (which is about 36% of COLs over South Africa). Of the 138 Eastern Cape COLs (64% of COLs over South Africa), 60 COLs were associated with heavy rainfall over the Eastern Cape Province. Over both South Africa and the Eastern Cape Province, April is the month with the highest frequency of COLs while December and January are the months with the lowest COL frequency. The seasonal frequency distribution of COLs shows that MAM followed by JJA are the seasons with the highest COL frequency. Far less COLs occur during DJF for both South Africa and the Eastern Cape Province. According to Nieto et al., 2007, the frequency of the COLs is seasonally dependent favoring autumn but not the summer season. This is consistent with the conclusions of this study.

Region D has, with 32% the highest percentage of COL occurrence, followed by region C with 28%, region A with 25% and region B has the least COL occurrence with 15% over South Africa. None of the COL events tracked over four regions, there were 54 events that tracked over two regions and only three events (21-25 September 1983, 04-08 May 1995 and 31 July - 04 August 2006) that tracked over three regions. The frequencies of COLs over the various regions exhibit inter-annual variability. Most of the COLs develop over region A and move eastwards. Some COLs develop over region C and move northward into region A, for example the event of 24-27 January 1981. Most COL occurrences in region D are from region A and C and some that develop in region D move northward and eastward. There were five events where COLs moved from region A to region D. Over the Eastern Cape Province the highest number of COL occurrences is found over region C followed by region A and D with also the least occurrence over region B different to that of South Africa COLs. It was found that 39 COL events were located over two regions and three events (21-25 September 1983, 04-08 May 1995 and 31 July - 04 August 2006) were located over three regions. COLs located over region A contributed much to the total rainfall of the Eastern Cape Province because it is located west of the province and COLs are baroclinically extended to the surface.

COL duration was most frequent for the 3-4 day category, with more than 40% of COLs occurring in this category and also more than 40% of COLs last for 1-2 days and with less than 10% lasting for more than four days over South Africa. Over the Eastern Cape Province COL duration was most frequent for the 3-4 day category, with more than 50% of COLs occurring in this category while about 40% of COLs last for 1-2 days and with less than 10% lasting for more than four days for the period of 1979 to 2009. COLs responsible for heavy rainfall mostly lasted for more than two days. All COLs associated with heavy rainfall over large areas are associated with the 500 hPa low extending to the surface as shown by the Daily weather bulletin from the SAWS. Behind the surface low, a strong high-pressure system ridges that brings a lot of moisture into the country (e.g. Singleton and Reason, 2006). Most of the identified COLs are associated with the passing of a cold front over the country as confirmed by surface synoptic charts. It was found that during 40% of the heavy rainfall producing COL events, heavy rainfall was reported by only one station, while one event (19-22 July 1979) associated with heavy rainfall was reported by ten stations, one event (21-24 September 1993) occurred where heavy rainfall was reported by eleven stations and one event (15-16 November 1989) where heavy rainfall was reported by twelve stations. Stations that reported heavy rainfall are mostly located along the coast, for example EL, GB, GD, HD, JB, KR, LB, PA, PE, PJ and UZ. Therefore the occurrence of COLs does not affect the whole province at once in terms of heavy rainfall, but it can cause heavy rainfall over large areas, especially along the coast. Heavy rainfall events as a result from Eastern Cape COL occurred approximately 95% of the time on only one day of a COL event. Of these events, 50% reported heavy rainfall by only one station. In the cases where heavy rainfall are reported on three days of a COL event, the COL is located in region A. Based on the data utilized in this study, no COLs are identified to have caused heavy rainfall on more than three days of the duration of a COL event. In this study it is found that the contribution to the total annual rainfall by COLs for the period 1979 to 2009 is close to 37-38% along the coast and 10% over the interior over the Eastern Cape Province.

7.3 RECOMMENDATIONS

This study illustrates the importance of COLs to rainfall over the Eastern Cape Province, in particular over the coastal and adjacent interior regions. As COLs are associated with rainfall with a good spatial distribution, these rainfall events are important to water contribution, crops and veld conditions. There is potential to utilize the COL climatology developed in the study in water availability, crop or veld simulations in order to improve on the spatial component of these simulations. For example, if COLs can be forecast on agriculturally important time-scales, the regions affected by COLs as identified in the COL climatology, can be awarded a higher probability for an outcome to realize. This can potentially aid more efficient decision-making at the start of a planting season.

REFERENCES

AsgiSA EC, 2009: Four Communities lead crop charge in former Transkei. Eastern Cape Development Corporation, http://www.ecdc.co.za/.

AsgiSA EC, 2009: EC agency explores maize milling business. Eastern Cape Development Corporation, http://www.ecdc.co.za/.

Browne, N. A. K., Abiodun, B. J., Tadros, M., & Hewitson, B., 2009: Simulation of Synoptic Scale Circulation Features over Southern Africa Using GCMS. The Abdus Salam International Center for Theoretical Physics, IC, 093, http://publications.ictp.it.

Bruton, M. N., & Gess, F. W., 1988: Toward an Environmental plan for the Eastern Cape. Rhodes University, Grahamstown.

DBSA, 1994: South Africa's Provinces: A Human Development Profile Development Bank of Southern Africa. Halfway House.

Delgado, G., Redano, A., Lorente, J., Nieto, R., Gimeno, L., Ribera, P., Barriopedro, D., García-Herrera, R., & Serrano, A., 2007: Cloud cover analysis associated to cut-off low-pressure systems over Europe using Meteosat Imagery. *Meteorology and Atmospheric Physics*., 96,141-157. DOI 10.1007/s00703-006-0225-4.

Dixon, J., Gulliver, A., Gibbon, D., & Hall, M (ed.)., 2001: Farming systems and poverty: Improving farmers' livelihoods in a changing world. FAO and World Bank, Rome and Washington, D.C., 412 pp. http://www.fao.org/docrep/003/Y1860E/y1860e00.HTM.

Dyson, L. L., 2000: A dynamic forecasting perspective on synoptic scale weather systems over southern Africa. MSc thesis, Department of Earth Science, University of Pretoria.

Dyson, L.L., & van Heerden, J., 2002: A model for the identification of tropical weather Systems Over South Africa, *Water SA*, 28, 249-258.

Estie, K. E., 1981: The Laingsburg flood disaster of January 1981. *South Africa Weather Bureau Newsletter*, 383, 19–32.

Greenfield, J. C., 1988: Moisture conservation: fundamental to rainfed agriculture. http://www.metafro.be/leisa/1988/4-4-15.pdf.

Gledhill, E., 1981: Eastern Cape Veld Flowers. The Department of Nature and Environmental Conservation of the Cape Provincial Administration, Cape Town.

Harrison, M. S. J., 1984: A Generalized Classification of South African Summer Rain-Bearing Synoptic Systems. *Journal of Climatology*, 4, 547-560.

Hermes, J. C., & Reason, C. J. C., 2009: Variability in SST and winds in the tropical south-east Atlantic Ocean and regional rainfall relationships. *Int. J. Climatol*, 29, 11-21.

Hu, K., Lu, R., & Wang, D., 2010: Seasonal climatology of cut-off lows and associated precipitation patterns over Northeast China. *Meteorology and Atmospheric Physics*., 106, 37-48.

Jetton, E. V., 1966: Stratospheric Behavior Associated with the Southwestern Cut-off Low. *Journal of Applied Meteorology*, 5, 857-865.

Jury, M. R., 2001: Economic Impacts of Climate Variability in South Africa and Development of Resource Prediction Models. *Journal of Applied Meteorology*. Vol. 41, 46-55.

Jury, M. R., & Levey, K.,1993a: The Climatology and Characteristics of drought in the Eastern Cape of South Africa. *International Journal of Climatology*, Vol. 13, No. 6, 629-614.

Jury, M. R., & Levey, K., 1993b: The Eastern Cape drought. *Water SA*, Vol. 19, No. 2, 133-137.

Jury, M. R., & Majodina, M., 1997: Preliminary Climatology of Southern Africa Extreme Weather: 1973-1992, *Theoretical and Applied Climatolology*, 56, 103-112.

Kakembo, V., 2001: Trends in Vegetation Degradation in Relation to Land Tenure, Rainfall, and Population Changes in Peddie District, Eastern Cape, South Africa, Environmental Management, 28, 1, 39-46.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S. K., Hnilo, J. J., Fiorino, M., Potter, G. L., 2002: The NCEP Climate Forecast System Reanalysis. *Bull. Meteor. Soc*., 83:11, 1631-1643.

Keable, M., Simmonds, I., & Keay, K., 2002: Distribution and Temporal variability of 500 hPa cyclone characteristics in the southern Hemisphere. *Int. J. Climatol*. 22, 131-150.

Kistler, R., Kalnary, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., and Fiorino, M., 2001: The NCEP-NCAR 50-year Reanalysis: Monthly means CD-ROM and Documentation. *Bull. Amer. Meteor. Soc*., 82, 247-268.

Klopper, E., 1999: The use of seasonal forecasts in South Africa during the 1997/98 rainfall Season. Water SA, vol. 25, 3, 311-342.

Knippertz, P., & Martin, J. E., 2007: The role of dynamic and diabatic processes in the generation of cut-off lows over Northwest Africa. Meteorology and Atmospheric Physics., 96, 3-19.

Kopke, D., 1988: The Climate of the Eastern Cape, In Bruton, M. N., & Gess, F. W., ed., Towards an Environmental Plan for the Eastern Cape. Rhodes University, Grahamstown.

Lahiff, E., 2002: Land reform and sustainable livelihoods in South Africa's Eastern Cape Province. Programme for Land and Agrarian Studies Research report no. 14, University of the Western Cape, Cape Town.

Landman, W. A., & Mason, S. J., 1999: Change in the Association between Indian Ocean Sea-Surface temperatures and Summer rainfall over South Africa and Namibia. Int. J. Climatol, 19, 1477-1492.

Landman, W. A., 1997: A study of rainfall variability of South Africa as revealed by multivariate analysis. MSc Thesis, University of Pretoria, Pretoria.

Lewu, F. B., Adebola, P. O., & Afolayan, A. J., 2007: Commercial harvesting of *Pelargonium sidoides* in the Eastern Cape, South Africa: Striking a balance between resource conservation and rural livelihoods. Journal of Arid Environments, 70, 380-388.

Low, A. B., & Rebelo, A. G., 1996: Vegetation of South Africa, Lesotho and Swaziland. Department of Environmental Affairs and Tourism, Pretoria.

Manona, C., Bank, Bank, L., & Higginbottom, K., 1995: Gender, households and environmental changes in informal settlements in the Eastern Cape Province, South Africa, Institute of

Social and Economic Research. Rhodes University, No. 64.

Mapekula, M., Chimonyo, M., Mapiye, & Dzama, K., 2009: Milk production and calf rearing practices in the smallholder areas in the Eastern Cape Province of South Africa. Trop Anim Health Prod, 41, 1475-1485.

Masika, P. J., & Mafu, J. V., 2003: Aspects of goat farming in the communal farming systems of the central Eastern Cape. South Africa, Small Ruminant Research, 52, 161-164.

Mason, S. J., 1997: Seasonal Forecasting of South African Rainfall using a non-linear Discriminant Analysis Model. *Int. J. Climatol*. 18: 147-164.

Mason, S. J., Lindesay, J. A., & Tyson, P. D., 1994: Simulating drought in Southern Africa using Sea Surface Temperature Variations. *Water SA*, Vol. 20, No. 1, 15-22.

Mason, S. J., Waylen, P. R., Mimmack, G. M., Rajaratnam, B., & Harrison, J. M., 1999: Changes in Extreme Rainfall Events in South Africa, *Climatic Change*, 41, 249-257.

McCallum, D. M., 1988: The Hydrology of the Eastern Cape. In Bruton, M. N., & Gess, F. W., ed., Towards an Environmental Plan for the Eastern Cape, Rhodes University, Grahamstown.

Muller, A., Reason, C. J. C. & Fauchereau, N., 2007: Extreme rainfall in the Namib Desert During Late summer 2006 and influences of regional ocean variability. *Int. J. Climatol*.

Nicholson, S., 2003: Comments on "The South Indian Convergence Zone and Interannual Rainfall Variability over Southern Africa" and the Question of ENSO's Influence on Southern Africa. *Journal of Climate*, vol. 16, 555-562.

Nicol, I. G., 1988: The Geomorphology of the Eastern Cape. In Bruton, M. N., & Gess, F. W., ed., Towards an Environmental Plan for the Eastern Cape, Rhodes University, Grahamstown.

Nieto, R., Gimeno, L., De la Torre, L., Ribera, P., Barriopedro, D., García-Herrera, R., Serrano, A., Gordillo, A., Redano, A., & Lorente, J., 2007: Interannual variability of cut-off low systems over the European sector: The role of blocking and the Northern Hemisphere circulation modes. *Meteorology and Atmospheric Physics*. 96, 85-101. DOI 10.1007/s00703-006-0222-7.

Palmer, E., 1949: Origin and structure of high-level cyclones south of the maximum westerlies. *Tellus*, 1, 22-31.

Peel, M. C., Finlayson, B. L., & McMahon, T. A., 2007: Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11, 1633-1644.

Pook, M. J., McIntosh, P. C., & Meyers G. A., 2005: The Synoptic Decomposition of Cool-Season Rainfall in the Southeastern Australia Cropping Region. CSIRO Marine and Atmospheric Research, Hobart, Tasmania, Australia. *Journal of Applied Meteorology and Climatology*, 45, 1156-1170.

Porcù, F., Carrassi, A., Medaglia, C. M., Prodi, F., Mugnai, A., 2007: A study on cut-off low vertical structure and precipitation in the Mediterranean region. *Meteorology and Atmospheric Physics*., 96, 121-140.

Preston-Whyte, R. A., & Tyson, P. D., 1988: The Atmosphere and Weather of southern Africa. Oxford University Press, Cape Town, 207-249.

Price, J. D., & Vaughan, G., 1992: Statistical studies of cut-off low systems. Annales De

Geophysique, 10, 96-102.

Qi, L., Wang, Y. & Leslie, L. M., 2000: Numerical Simulation of a cut-off low over southern Australia. *Meteorology and Atmospheric Physics*, 74, 103-115.

Qi, L., Leslie, L. M. & Zhao, S. X., 1999: Cut-off low Pressure Systems over Southern Australia: Climatology and Case Study. *International Journal of Climatology*, 19, 1633-1649.

Reason, C. J. C., 1998: Warm and Cold Events in the Southeast Atlantic/Southwest Indian Ocean Region and Potential Impacts on Circulation and Rainfall over Southern Africa. *Meteorology and Atmospheric Physics*., 69, 49-65.

Reason, C. J. C., & Godfred-Spenning, C. R., 1998: SST Variability in the South Indian Ocean and Associated Circulation and Rainfall Patterns over Southern Africa. *Meteorology and Atmospheric Physics*., 66, 243-258.

Reason, C. J. C., Hachigonta, S., & Phaladi, R. F., 2005: Interannual Variability in Rainy Season Characteristics over the Limpopo Region of Southern Africa. *International Journal of Climatology*, 25, 1835 – 1853.

Rennie, J. V. R., 1946: The Eastern Province as a geographical region. *South African Geographical Journal*, 27, 1-27.

Roux, P. W., & Van der Vyver, J., 1988: The Agricultural Potential of the Eastern Cape and Cape Midlands. In Bruton, M. N., & Gess, F. W., ed., Towards an Environmental Plan for the Eastern Cape, Rhodes University, Grahamstown.

Sabo, P., 1992: Application of the Thermal Front Parameter to Baroclinic Zones around Cut-off Lows. *Meteorology and Atmospheric Physics*., 47, 107-115.

Singleton, A. T., Reason, C. J. C., 2006: Numerical Simulations of a severe rainfall event the Eastern Cape coast of South Africa: sensitivity to sea surface temperature and topography. *Tellus*, 58A, 355-367.

Singleton, A. T., Reason, C. J. C., 2007a: A Numerical Model Study of an Intense Cut-off Low-Pressure System over South Africa. Monthly Weather Review, 135, 1128-1150.

Singleton, A. T. & Reason, C. J. C., 2007b: Variability in the characteristics of Cut-off low-pressure systems over subtropical Southern Africa. *International Journal of Climatology*, 27, 295-310.

Somoro, L. M., 2009: The Design, Implementation and Effects of the Nguni Project in the Eastern Cape Province of South Africa. MSc Thesis, University of Fort Hare, Grahamstown.

South African Weather Bureau, 2009: Daily Weather Bulletin. October 2009, Government Printing by Weather Bureau, Pretoria.

Statistics South Africa, 2012. Census 2011 Statistical release – P0301.4. http://www.statsa.gov.za/Publications/P030142011.pdf

Stone, A. W., 1988: The Physical Environment of the Eastern Cape, In Bruton, M. N., & Gess, F. W., ed., Towards an Environmental Plan for the Eastern Cape, Rhodes University, Grahamstown.

Taljaard, J. J., 1985: Cut-off lows in the South African Region. Technical Paper no. 14, SA

Weather Bureau, Department of Transport, Pretoria.

Taljaard, J. J., 1986: Change of Rainfall Distribution and Circulation Patterns over southern Africa in Summer. *Journal of Climatology*, Vol. 6, 579-592.

Taljaard, J. J., 1994: Atmospheric Circulation Systems, Synoptic Climatology and Weather Phenomena of South Africa, Part 1: Controls of the weather and climate of South Africa. Technical Paper no. 27, SA Weather Bureau, Department of Transport, Pretoria.

Taljaard, J. J., 1996: Atmospheric Circulation Systems, Synoptic Climatology and Weather Phenomena of South Africa, Part 6: Rainfall in South Africa. Technical Paper no. 32, SA Weather Bureau, Department of Environmental Affairs and Tourism, Pretoria.

Thornton, A., 2008: Beyond the Metropolis: Small Town Case Studies of Urban and Peri-urban Agriculture in South Africa, Urban Forum. 19, 243-262, DOI 10.1007/s12132-008-9036-7

Todd, M. C., Washington, R., & Palmer, P. I., 2004: Water vapour transport associated with tropical-temperate trough systems over southern Africa and the southwest Indian ocean. *Int. J. Climatol*., 24, 555-568.

Tyson, P. D., 1986: Climatic change and Variability in Southern Africa, University of the Witwatersrand. Johannesburg, Oxford University Press, Cape Town, 122-140.

Tyson, P. D & Preston-White, R. A., 2000: The Weather and Climate of Southern Africa. Second Edition, Oxford University Press, Cape Town,196-211.

Wani, S. P., Sreedevi, T. K., Rockström, J., & Ramakrishna, Y. S., 2009: Rainfed Agriculture – Past Trends and Future Prospects. CAB International, Rainfed Agriculture: Unlocking the Potential. http://www.iwmi.cgiar.org/Rainfed_Agriculture/Unlocking_the_Potential.pdf.

Van Averbeke, W., & Khosa, T. B., 2007: The contribution of smallholder agriculture to the nutrition of rural households in a semi-arid environment in South Africa. Water SA, Vol. 33, No. 3, 413-418. http://www.wrc.org.za.

Van Averbeke, W., Harris, P. J. C., Mnkeni, P. N. S., Van Ranst, E., & Verplancke, M., 2006: Smallholder farming and Management of soil fertility in the Eastern Cape. South Africa, UNISA Press, Pretoria.

Van Heerden, J., Terblanche, D.E. and Schulze, G.C., 1988: The southern oscillation and South Africa summer rainfall. J. Climatol., **8**, 577 – 597.

Vigaud, N., Richard, Y., Rouault, M., & Fauchereau, N., 2009: Moisture transport between the South Atlantic Ocean and southern Africa: relationships with summer rainfall and associated dynamics. *Clim. Dyn*., 32, 113-123. DOI 10.1007/s00382-008-0377-7.

Vigaud, N., Richard, Y., Rouault, M., & Fauchereau, N., 2007: Water vapour transport from the tropical Atlantic and summer rainfall in tropical southern Africa. *Clim. Dyn*., 28, 113-123. DOI 10.1007/s00382-006-0186-9.

Washington, R., & Todd, M., 1999: Tropical-Temperate Links in southern African and Southwest Indian Ocean Satellite-Derived Daily Rainfall. *Int. J. Climatol*. 19, 1601-1616.

Zhao, S., & Sun, J., 2007: Study on cut-off low-pressure systems with floods over Northeast Asia. *Meteorology and Atmospheric Physics*., 96, 159-180.

APPENDIX A: List of cut-off lows events that cause rainfall over the Eastern Cape Province during a period of 1979 to 2009.

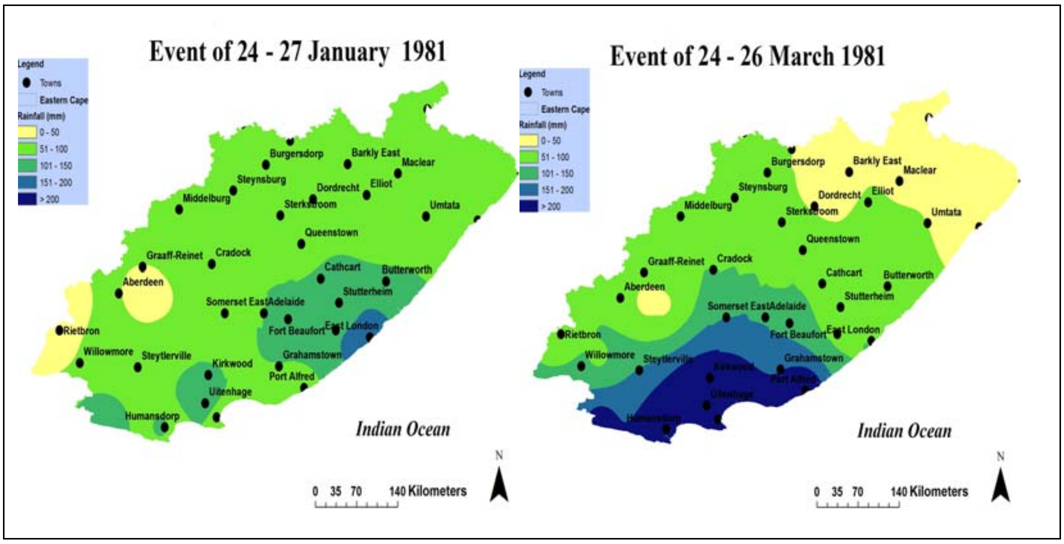
19-22 July 1979	19-22 April 1990	06-08 July 2001
24-26 July 1979	07-09 July 1990	30-31 August 2001
19-22 August 1979	27-28 November 1990	05-07 September 2001
30-31 August 1979	08-09 June 1991	16-19 September 2001
19-21 October 1979	28-29 March 1992	25-26 October 2001
29-01 July/August 1980	31-03 July/August 1992	19-20 November 2001
24-27 January 1981	09-11 October 1992	16-17 January 2002
24-26 March 1981	16-17 October 1992	11-13 June 2002
25-27 April 1981	22-27 October 1992	23-24 June 2002
28-30 May 1981	11-13 April 1993	15-16 August 2002
23-24 August 1981	11-12 June 1993	09-12 September 2002
28-30 August 1981	21-24 September 1993	19-21 March 2003
24-26 March 1982	05-07 March 1994	22-26 March 2003
18-19 April 1982	11-15 April 1994	10-11 May 2003
29-30 April 1982	19-21 April 1994	25-26 May 2003
31-01 August/September 1982	25-26 July 1994	12-14 January 2004
12-13 October 1982	04-06 September 1994	18-21 October 2004
16-17 April 1983	11-13 December 1994	28-29 January 2005
19-20 May 1983	04-08 May 1995	10-11 April 2005
25-28 July 1983	18-19 May 1995	27-28 May 2005
21-25 September 1983	16-17 June 1995	06-10 November 2005
24-25 September 1984	25-26 December 1995	09-13 November 2005
07-08 October 1984	23-25 July 1996	10-12 June 2006
01-02 March 1985	05-06 August 1996	27-29 June 2006
19-21 April 1985	09-11 October 1996	12-17 July 2006
20-21 May 1985	23-24 October 1996	22-23 July 2006
24-26 June 1985	20-22 November 1996	31-04 July/August 2006
31-02 October/November 1985	28-31 December 1996	23-24 August 2006
23-25 February 1986	14-18 March 1997	09-12 February 2007
02-04 June 1986	06-08 April 1997	04-05 March 2007
02-04 July 1986	22-23 April 1997	04-09 June 2007
05-08 July 1986	24-26 May 1997	26-27 June 2007
24-27 June 1987	13-15 June 1997	02-03 November 2007
26-29 September 1987	18-20 July 1997	21-23 November 2007
12-13 November 1987	28-31 August 1997	05-06 January 2008
03-05 April 1988	22-23 April 1998	13-15 January 2008
13-14 April 1988	09-11 May 1998	25-26 February 2008
11-12 June 1988	26-28 October 1998	22-25 May 2008
08-09 October 1988	16-19 April 1999	31-04 May/June 2008
18-19 December 1988	28-29 July 1999	18-20 June 2008
12-15 March 1989	27-29 August 1999	07-08 October 2008
21-22 April 1989	23-24 December 1999	14-16 February 2009
25-27 July 1989	02-03 March 2000	22-26 April 2009
15-16 November 1989	30-03 October/November 2000	11-14 May 2009
21-23 February 1990	15-17 November 2000	11-12 October 2009
12-14 April 1990	04-05 May 2001	25-27 October 2009

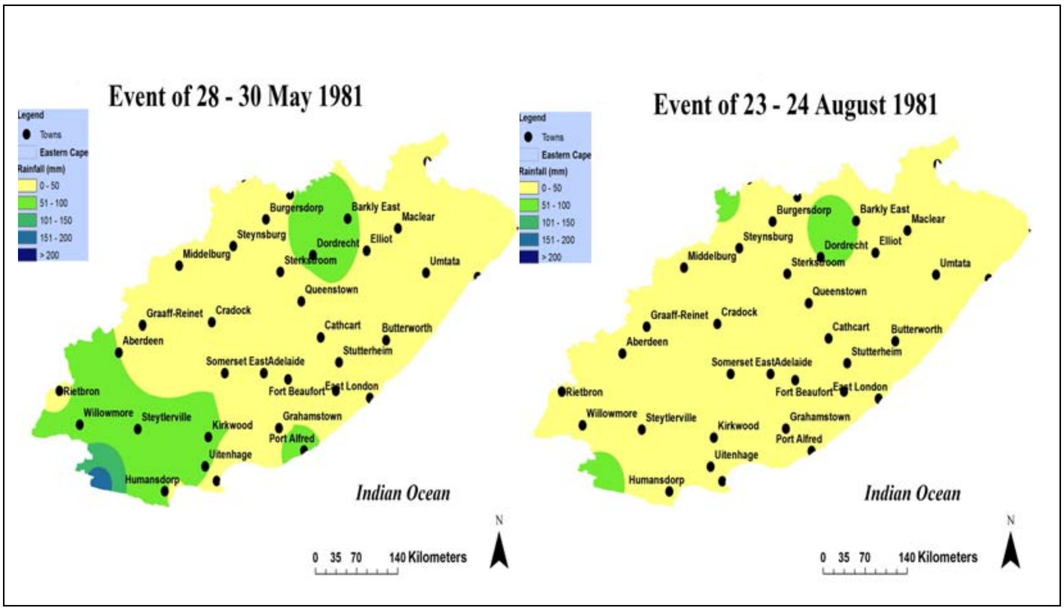
APPENDIX B: Duration of cut-off lows during the period of 1979-2009 over South Africa (SA) and the Eastern Cape (EC) Province

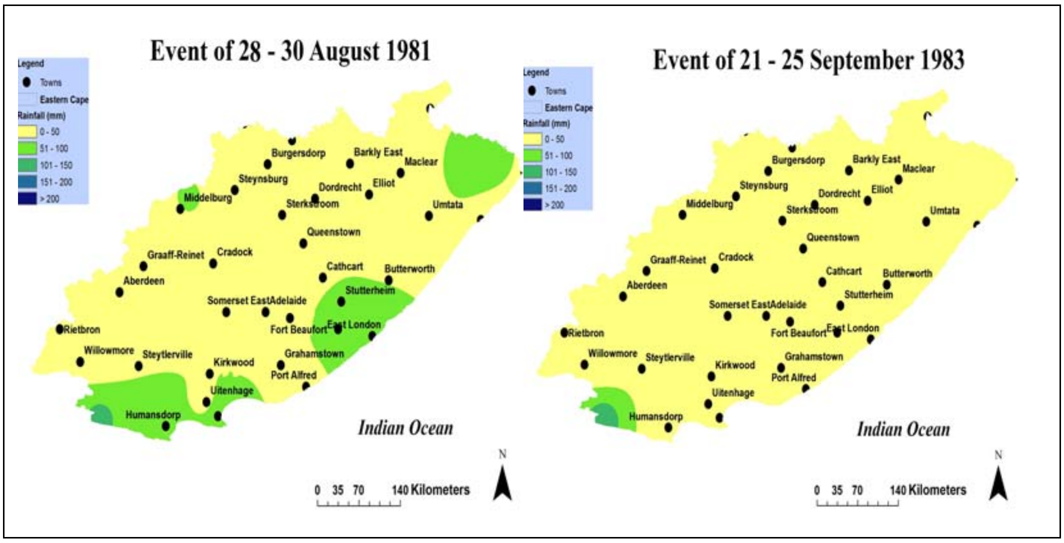
SA	1-2 days	3-4 days	>4 days	Total	EC Province	1-2 days	3-4 days	>4 days	Total
1979	2	6	1	**9**	1979	1	4	0	**5**
1980	3	1	0	**4**	1980	0	1	0	**1**
1981	1	6	0	**7**	1981	1	5	0	**6**
1982	2	2	1	**5**	1982	5	1	0	**6**
1983	5	1	1	**7**	1983	1	1	1	**3**
1984	3	0	0	**3**	1984	2	0	0	**2**
1985	2	7	0	**9**	1985	2	3	0	**5**
1986	4	4	0	**8**	1986	0	4	0	**4**
1987	5	2	0	**7**	1987	1	2	0	**3**
1988	3	2	0	**5**	1988	4	1	0	**5**
1989	3	1	0	**4**	1989	2	2	0	**4**
1990	2	3	0	**5**	1990	1	4	0	**5**
1991	3	1	0	**4**	1991	1	0	0	**1**
1992	2	0	0	**2**	1992	2	2	1	**5**
1993	1	5	0	**6**	1993	1	2	0	**3**
1994	3	8	0	**11**	1994	1	4	1	**6**
1995	4	3	1	**8**	1995	3	1	0	**4**
1996	2	7	0	**9**	1996	2	4	0	**6**
1997	2	5	3	**10**	1997	1	5	1	**7**
1998	5	1	0	**6**	1998	1	2	0	**3**
1999	1	4	0	**5**	1999	2	2	0	**4**
2000	2	1	1	**4**	2000	1	1	1	**3**
2001	7	4	1	**12**	2001	4	3	0	**7**
2002	4	3	0	**7**	2002	2	3	0	**5**
2003	6	2	0	**8**	2003	2	1	1	**4**
2004	2	2	0	**4**	2004	0	2	0	**2**
2005	3	0	2	**5**	2005	3	0	2	**5**
2006	6	1	3	**10**	2006	2	2	2	**6**
2007	3	5	1	**9**	2007	3	2	1	**6**
2008	3	7	1	**11**	2008	3	3	1	**7**
2009	3	4	1	**8**	2009	1	3	1	**5**
Total	**97**	**98**	**17**	**212**	**Total**	**55**	**70**	**13**	**138**

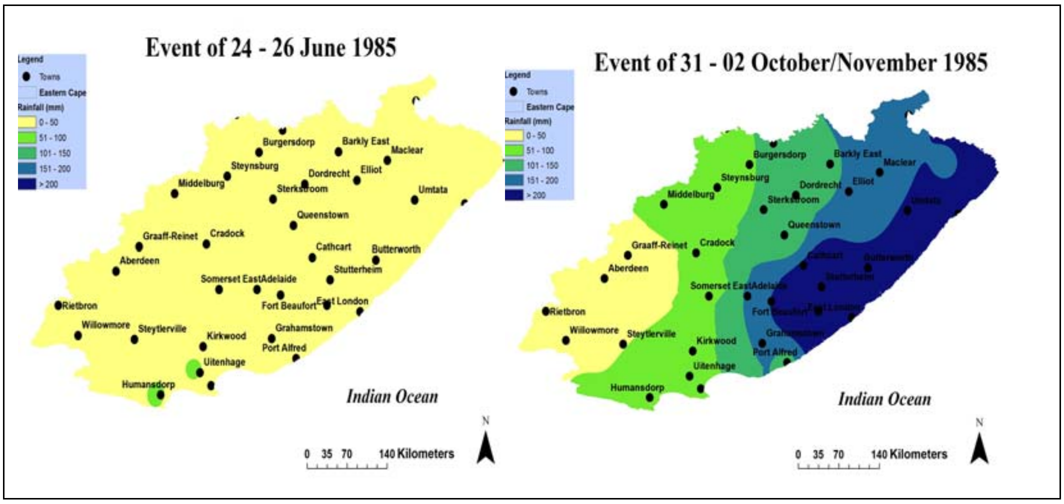
APPENDIX C: Spatial rainfall map of heavy rainfall events associated with the cut-off low over the Eastern Cape Province

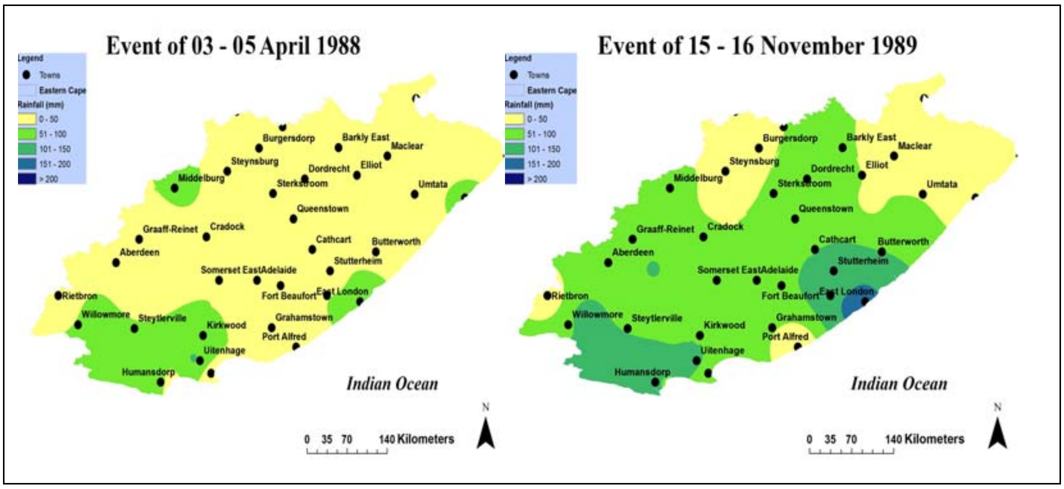
1. **Region A**

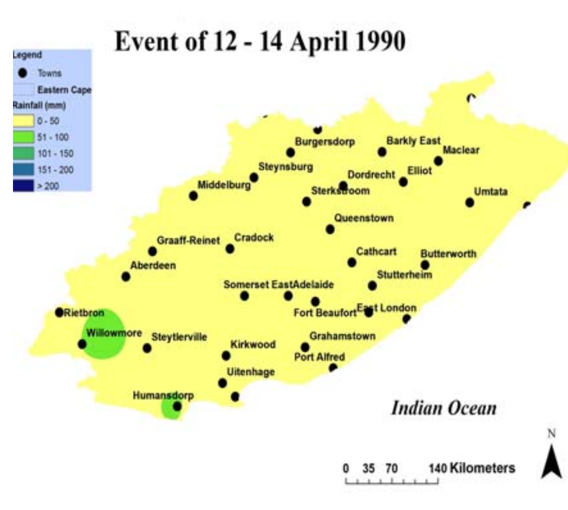


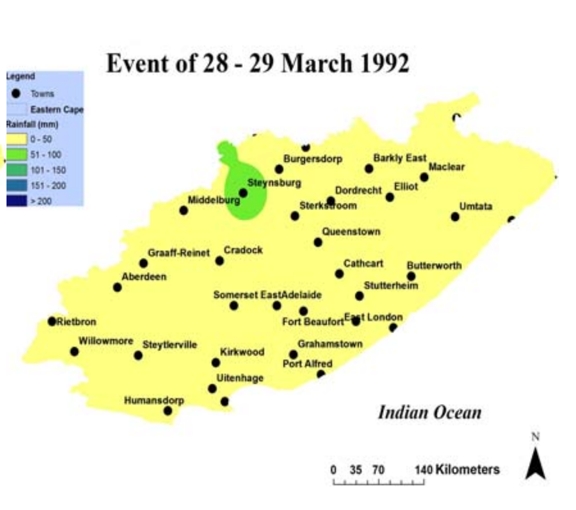


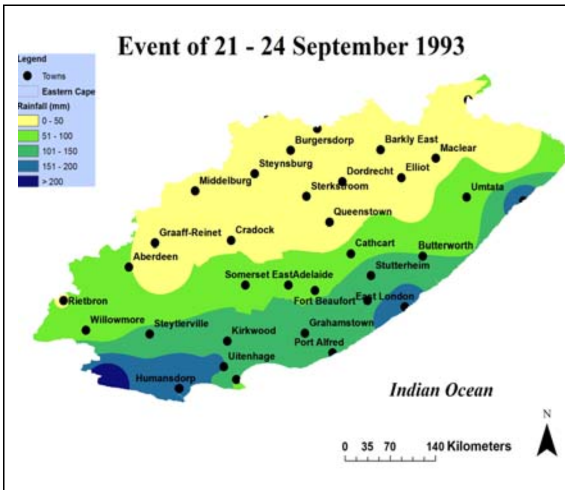

Event of 28 - 30 August 1981
Event of 21 - 25 September 1983
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
0 35 70 140 Kilometers
N

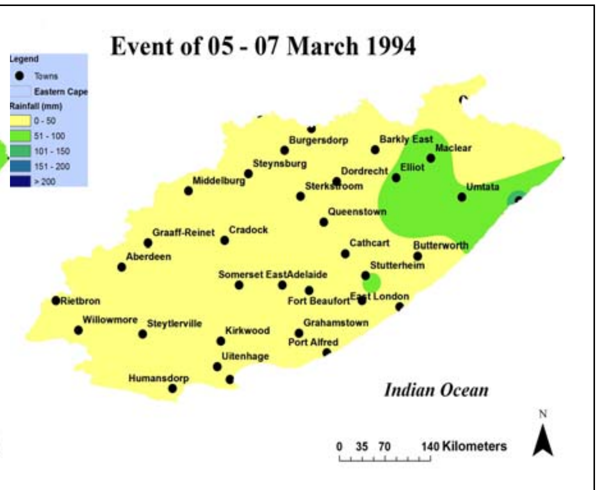

Event of 24 - 26 June 1985
Event of 31 - 02 October/November 1985
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
0 35 70 140 Kilometers
N

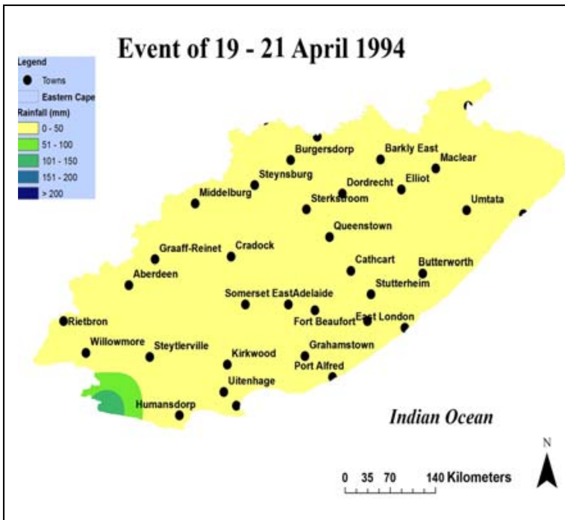

Event of 03 - 05 April 1988
Event of 15 - 16 November 1989
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
0 35 70 140 Kilometers
N

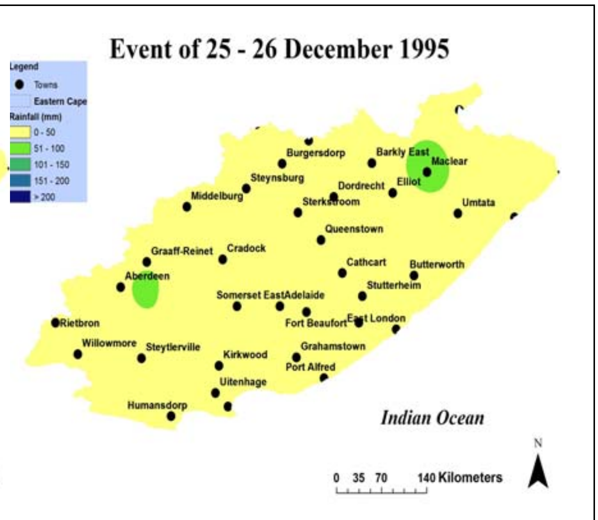

Event of 12 - 14 April 1990
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

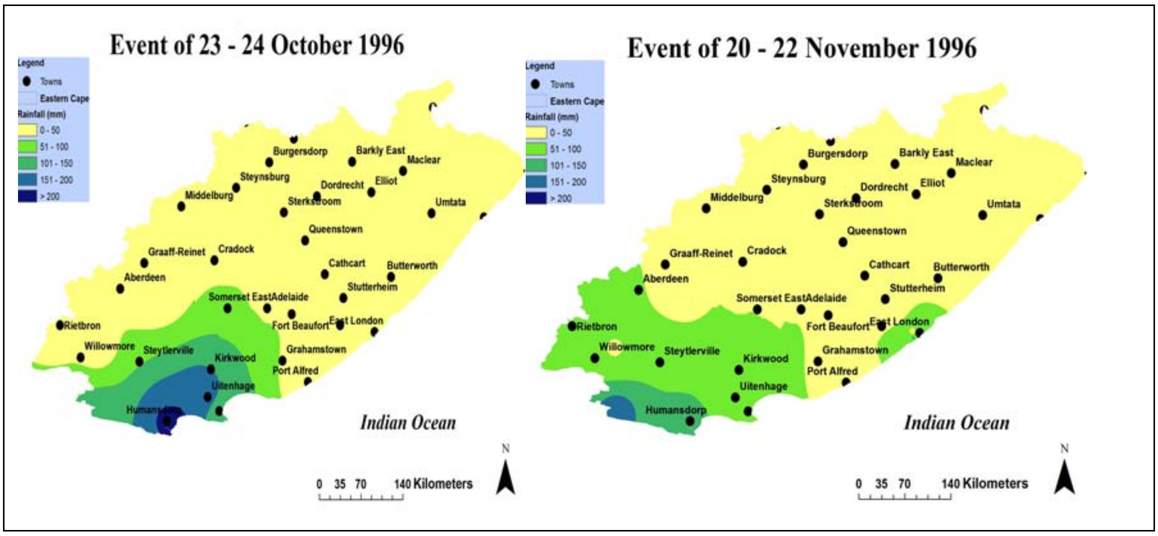

Event of 28 - 29 March 1992
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

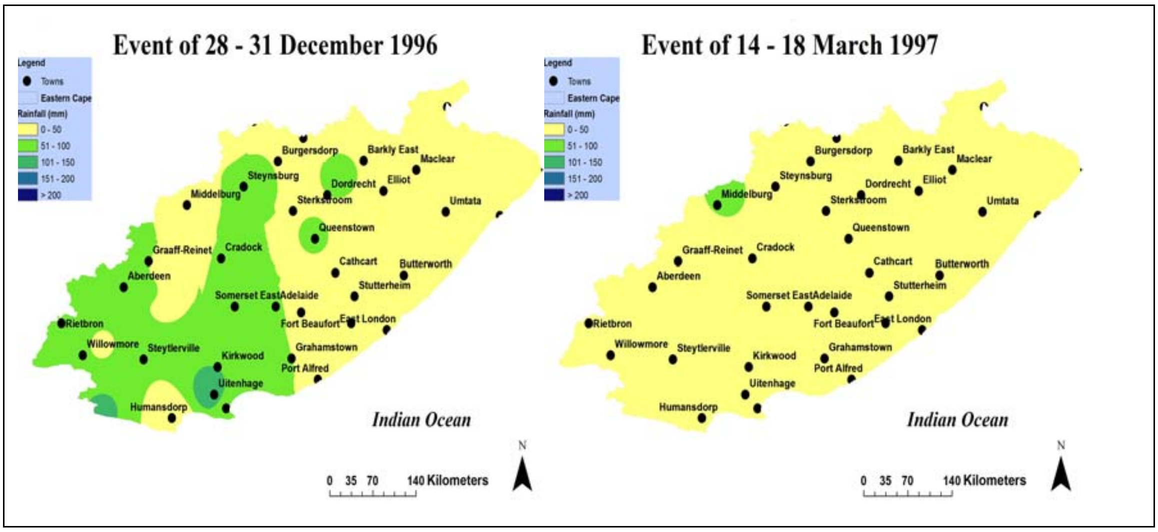

Event of 21 - 24 September 1993
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

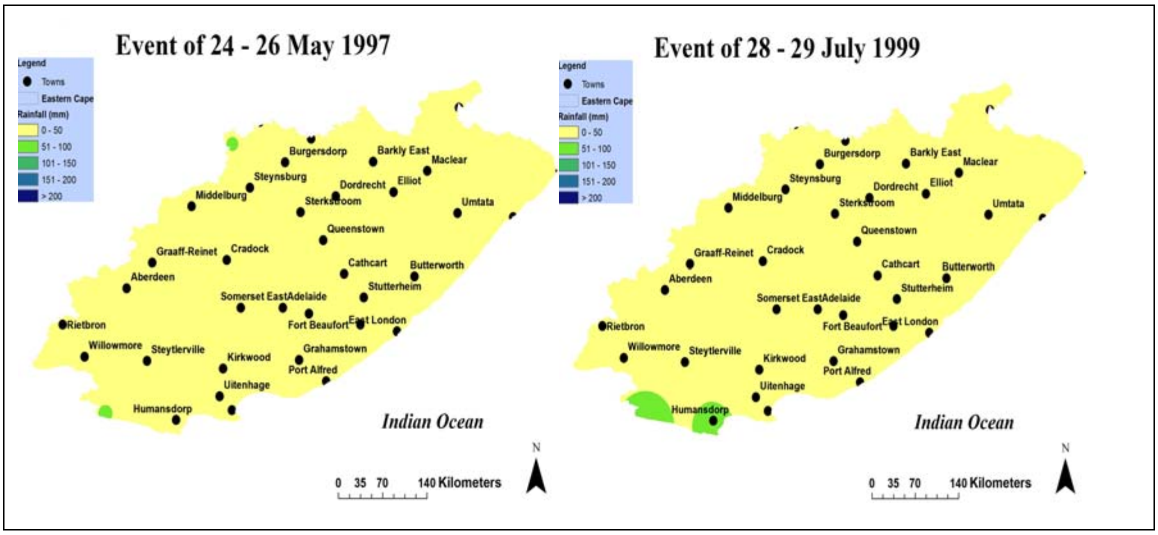

Event of 05 - 07 March 1994
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

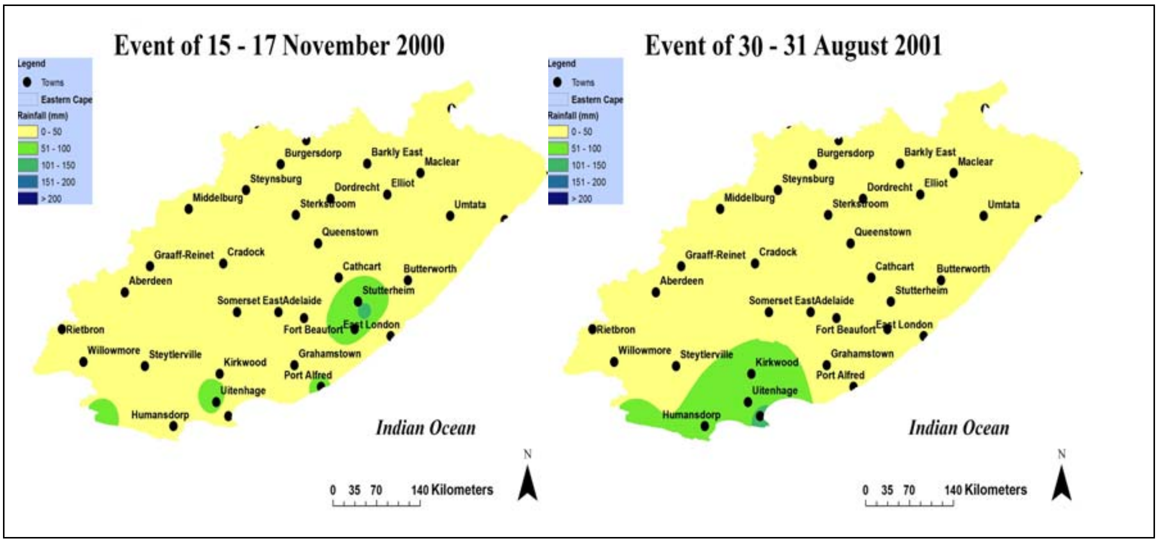

Event of 19 - 21 April 1994
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

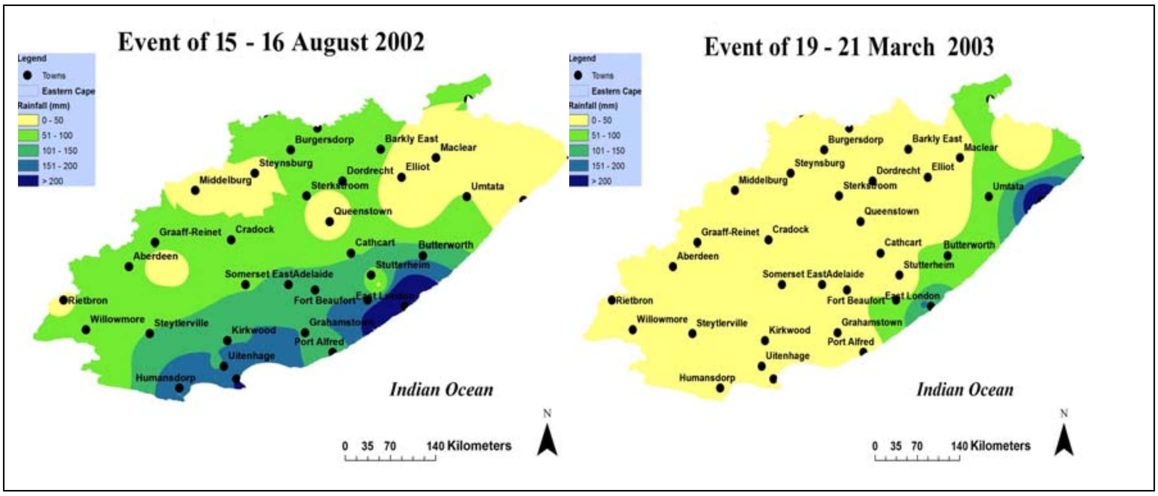

Event of 25 - 26 December 1995
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

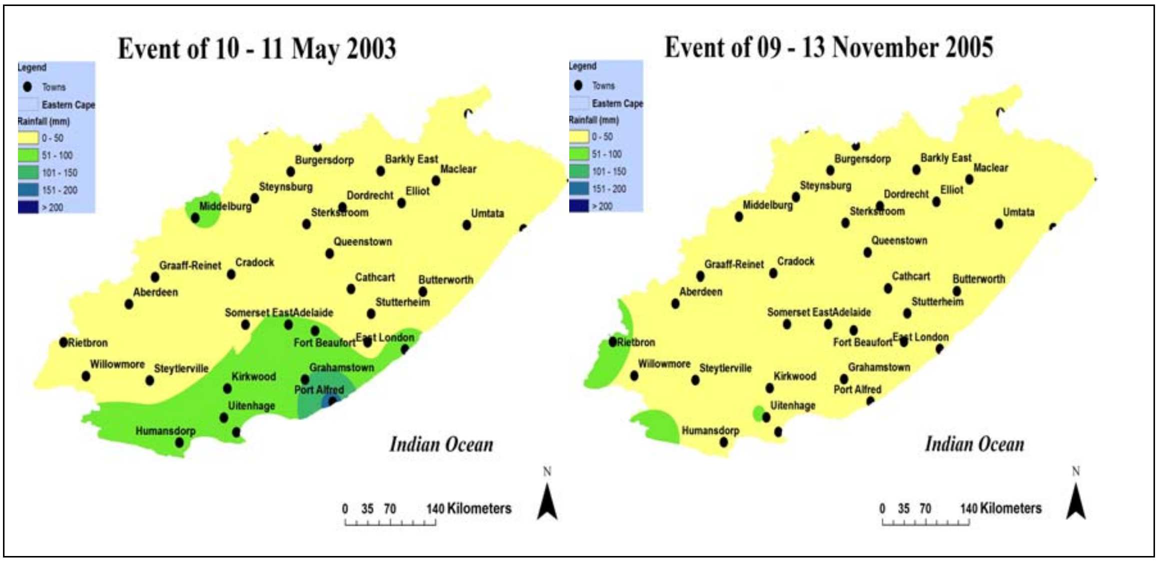

Event of 23 - 24 October 1996
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Grahamstown
Kirkwood
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N
Event of 20 - 22 November 1996
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Grahamstown
Kirkwood
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

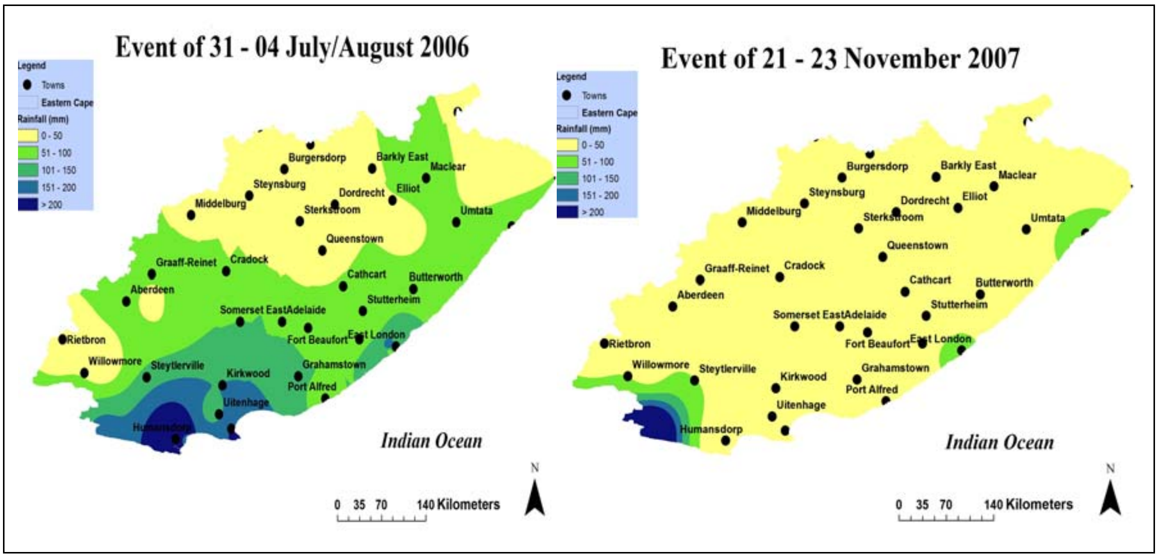

Event of 28 - 31 December 1996
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Grahamstown
Kirkwood
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N
Event of 14 - 18 March 1997
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Grahamstown
Kirkwood
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

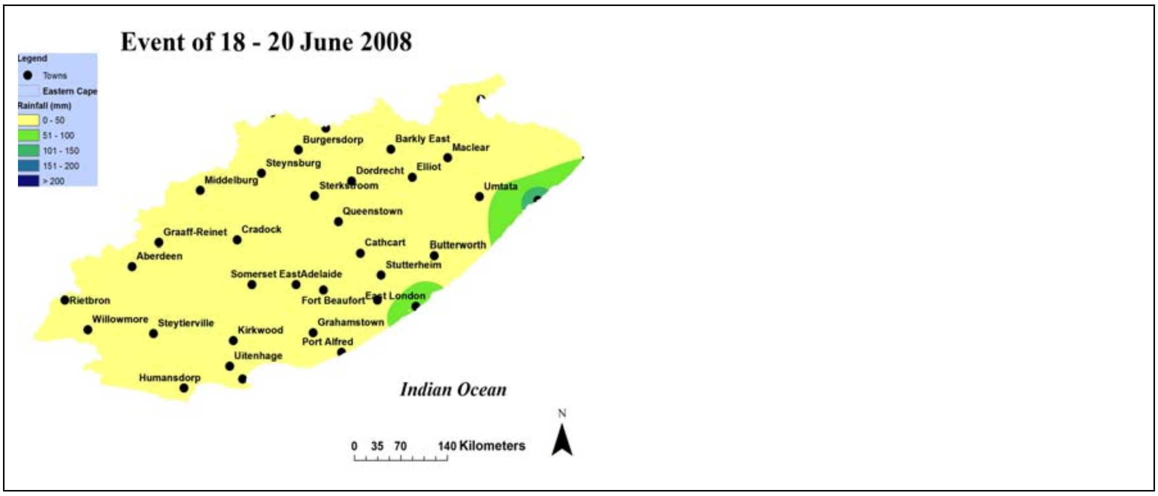

Event of 24 - 26 May 1997
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Grahamstown
Kirkwood
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N
Event of 28 - 29 July 1999
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Grahamstown
Kirkwood
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N


Event of 15 - 17 November 2000
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N
Event of 30 - 31 August 2001
Indian Ocean
0 35 70 140 Kilometers
N

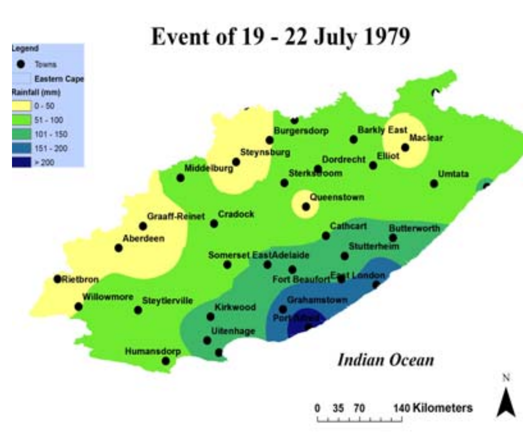

Event of 15 - 16 August 2002
Event of 19 - 21 March 2003
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
0 35 70 140 Kilometers
N

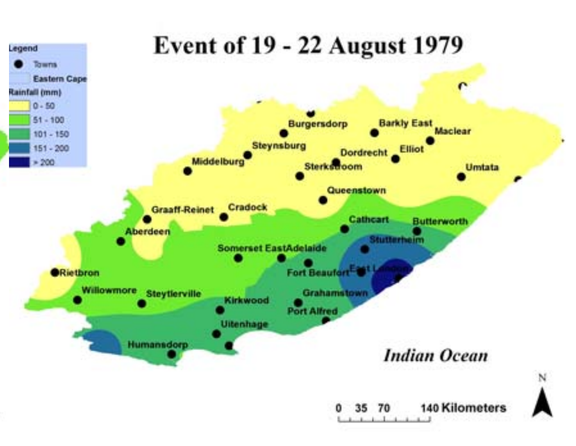

Event of 10 - 11 May 2003
Event of 09 - 13 November 2005
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
0 35 70 140 Kilometers
N

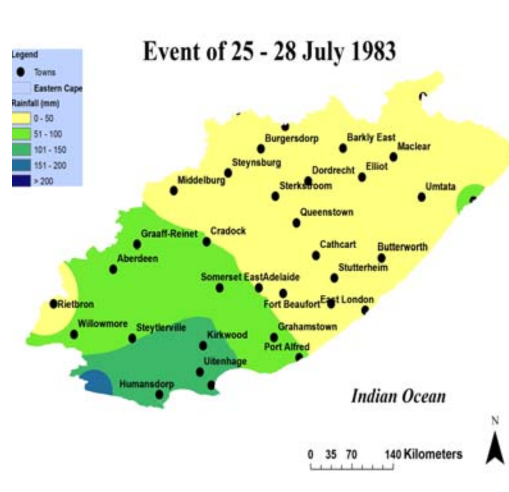

Event of 31 - 04 July/August 2006
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N
Event of 21 - 23 November 2007
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Catchcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

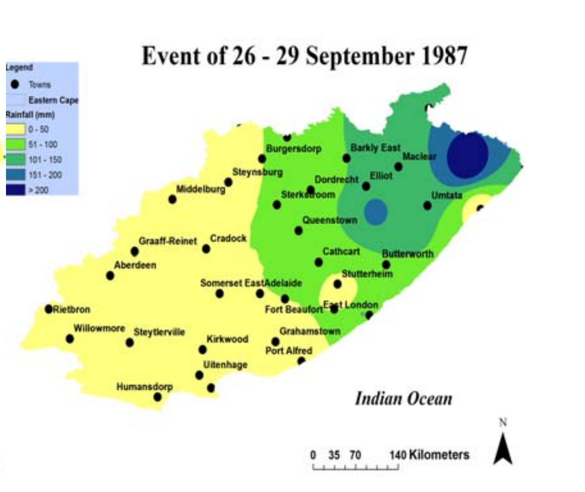

Event of 18 - 20 June 2008
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

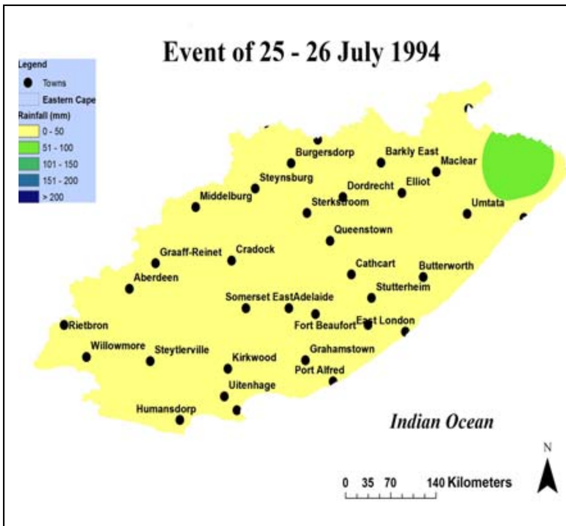
2. Region B

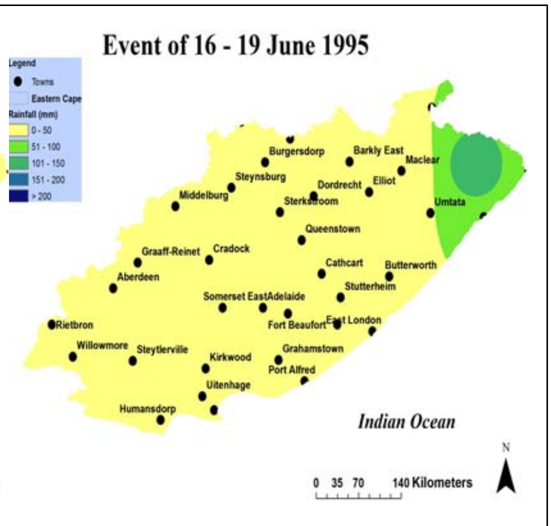

Event of 19 - 22 July 1979
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Middelburg
Dordrecht
Elliot
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Aberdeen
Cathcart
Butterworth
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
N
0 35 70 140 Kilometers

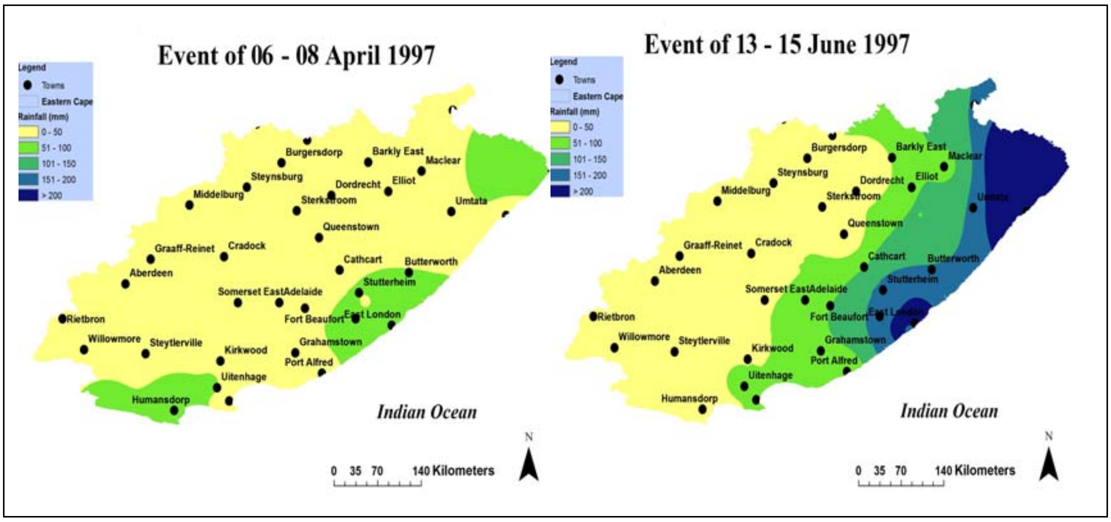

Event of 19 - 22 August 1979
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Middelburg
Dordrecht
Elliot
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Aberdeen
Cathcart
Butterworth
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
N
0 35 70 140 Kilometers

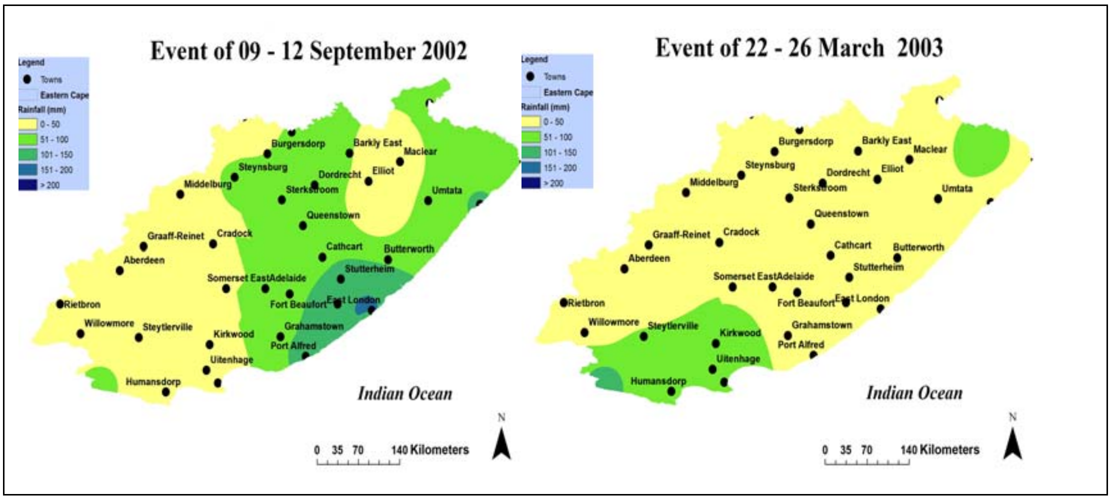

Event of 25 - 28 July 1983
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Middelburg
Dordrecht
Elliot
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Aberdeen
Cathcart
Butterworth
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
N
0 35 70 140 Kilometers

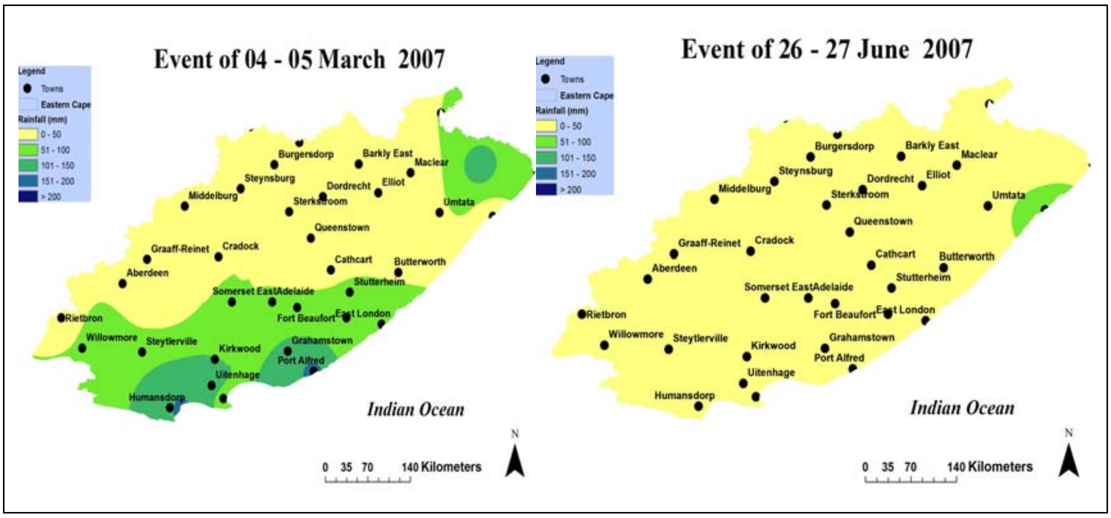

Event of 26 - 29 September 1987
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Middelburg
Dordrecht
Elliot
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Aberdeen
Cathcart
Butterworth
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
N
0 35 70 140 Kilometers


Event of 25 - 26 July 1994
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Middelburg
Dordrecht
Elliot
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Aberdeen
Cathcart
Butterworth
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
N
0 35 70 140 Kilometers

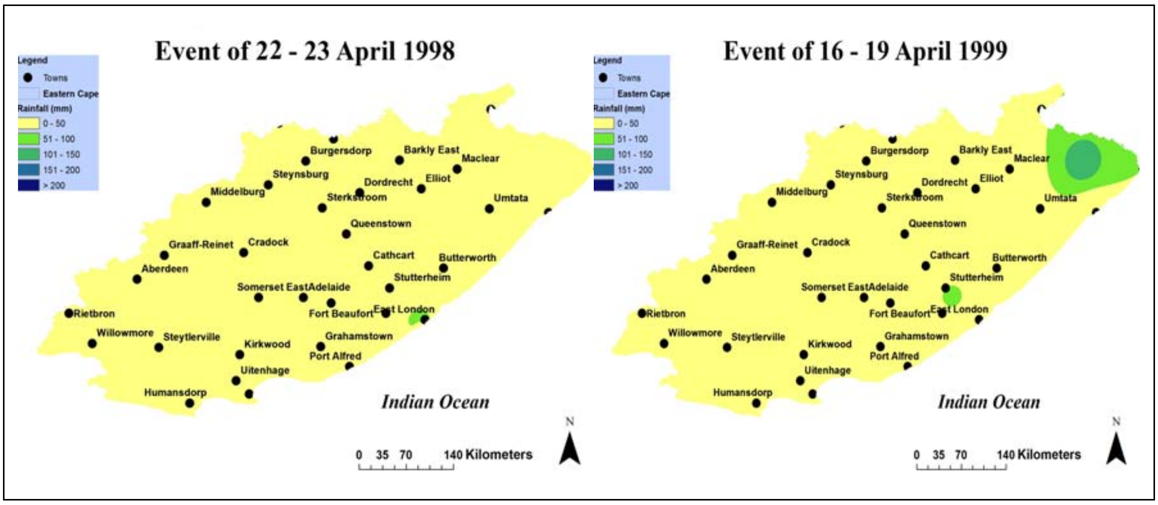

Event of 16 - 19 June 1995
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Middelburg
Dordrecht
Elliot
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Aberdeen
Cathcart
Butterworth
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
N
0 35 70 140 Kilometers

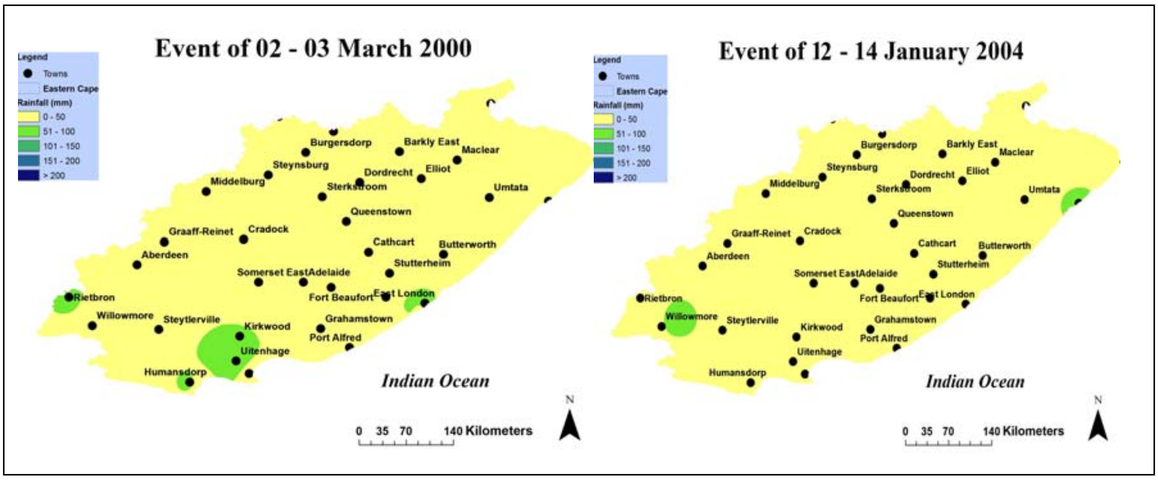

Event of 06 - 08 April 1997
Event of 13 - 15 June 1997
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Aberdeen
Cathcart
Butterworth
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
N
0 35 70 140 Kilometers

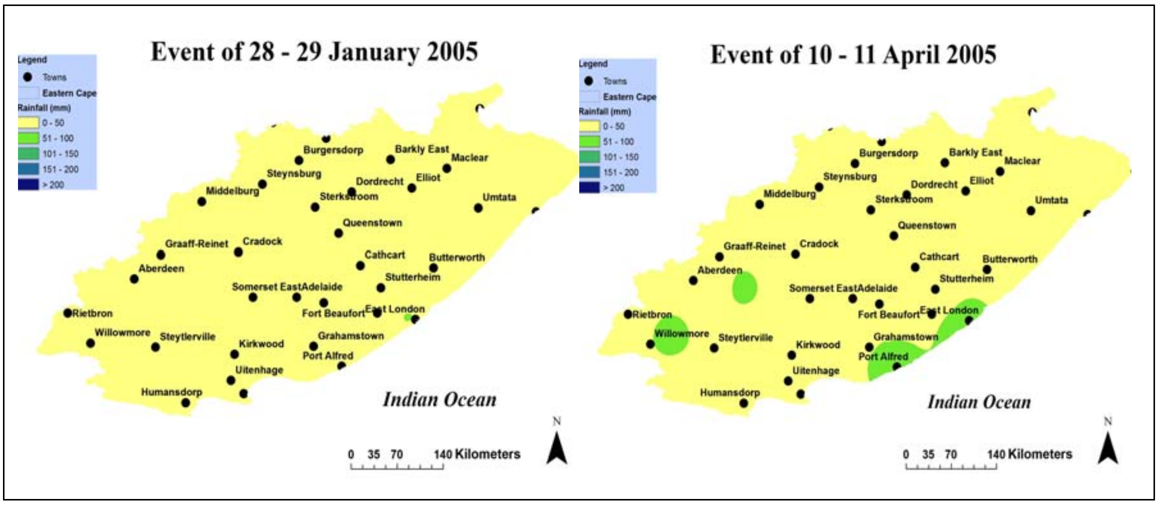

Event of 09 - 12 September 2002
Event of 22 - 26 March 2003
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
N
0 35 70 140 Kilometers

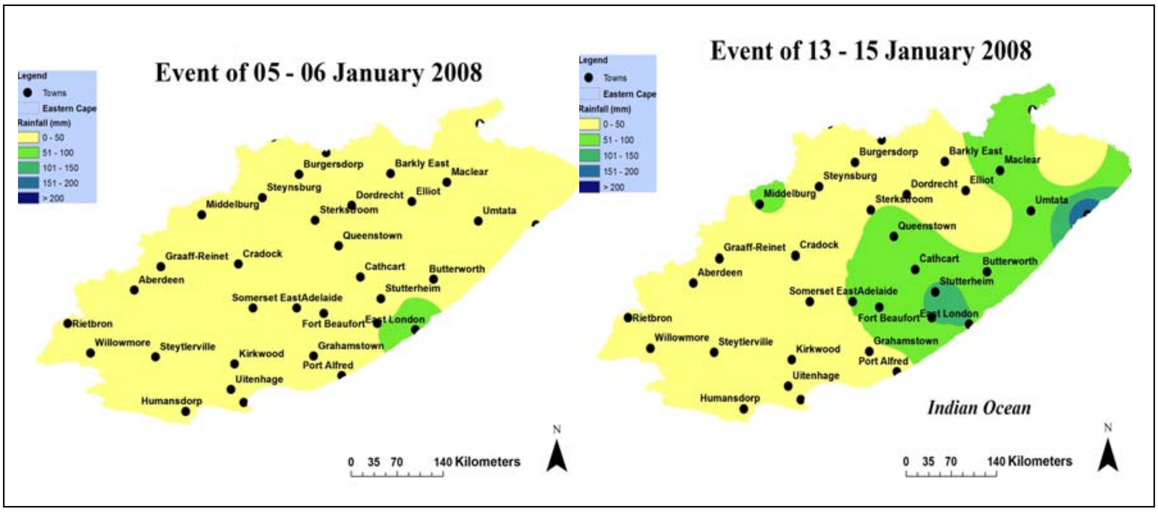

Event of 04 - 05 March 2007
Event of 26 - 27 June 2007
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
N
0 35 70 140 Kilometers

3. Region C

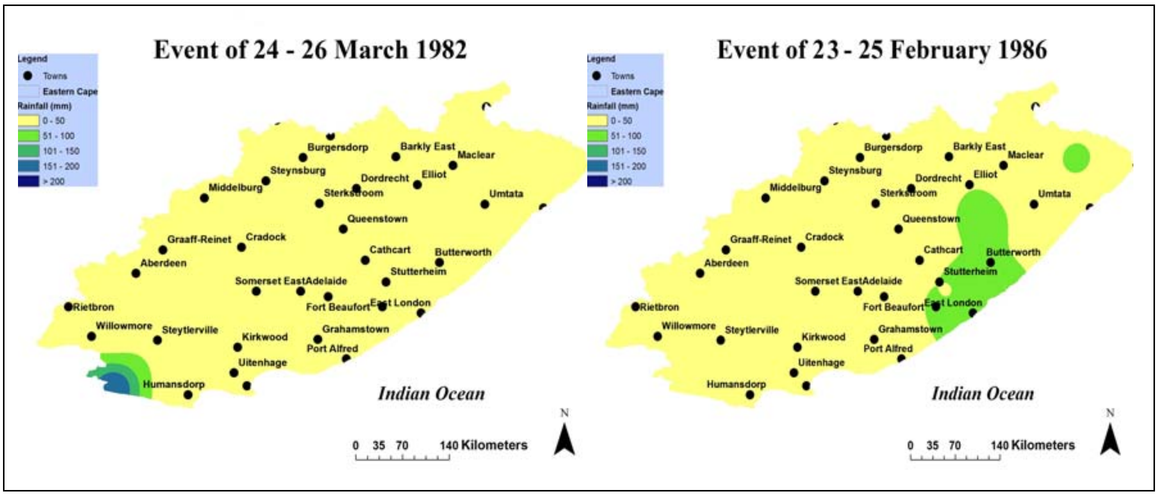

Event of 22 - 23 April 1998
Event of 16 - 19 April 1999
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

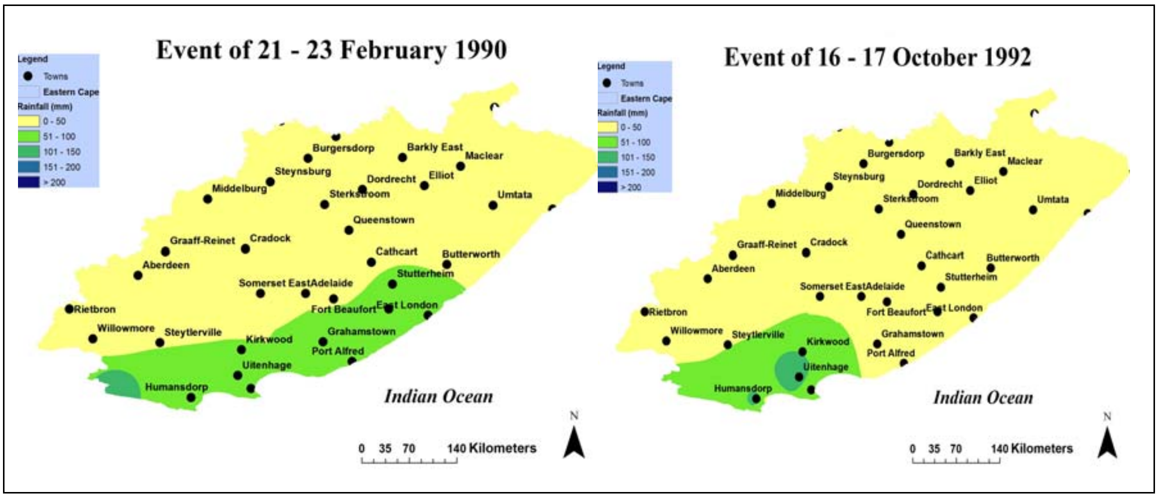

Event of 02 - 03 March 2000
Event of 12 - 14 January 2004
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

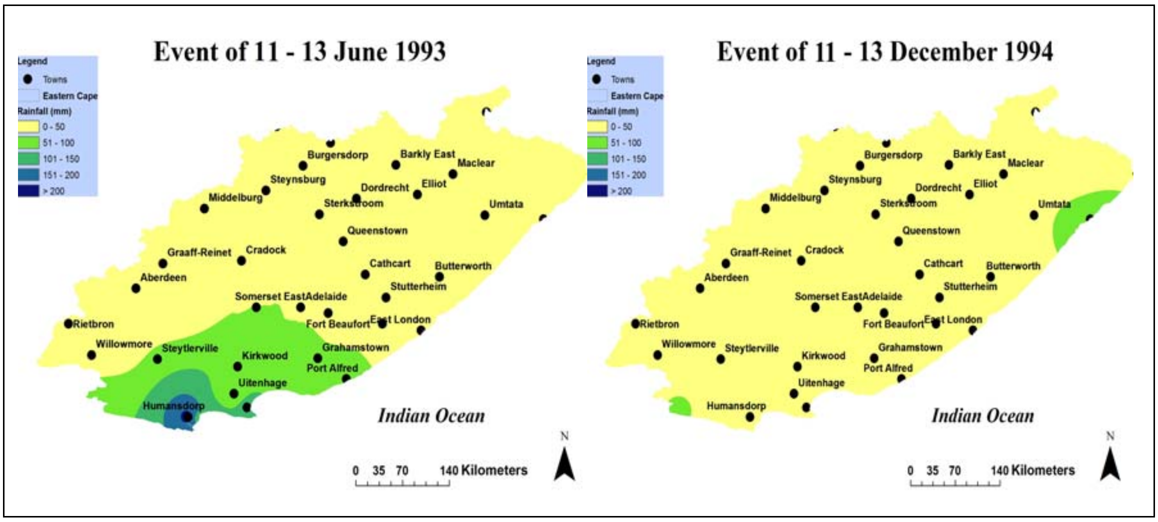

Event of 28 - 29 January 2005
Event of 10 - 11 April 2005
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N

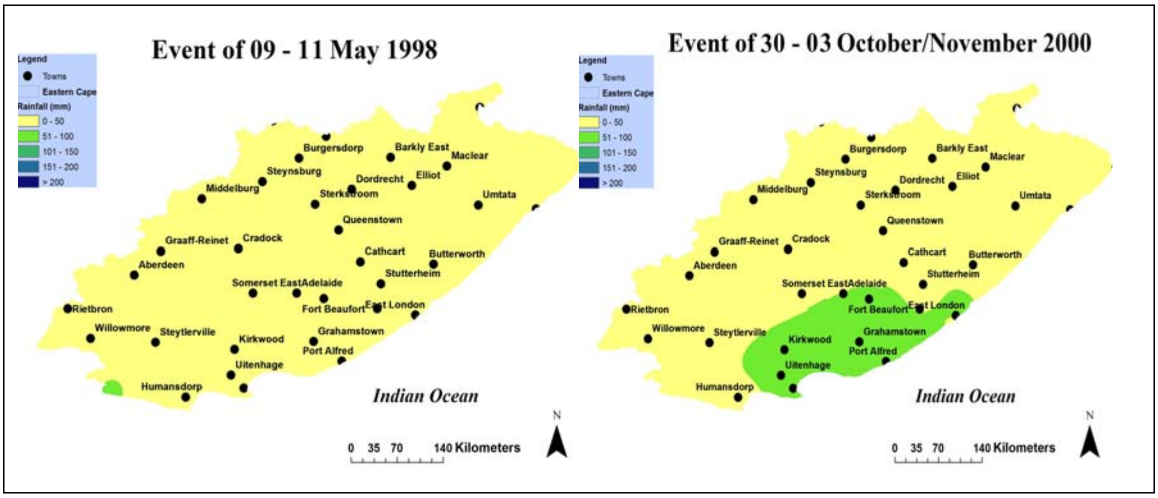

Event of 05 - 06 January 2008
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Aberdeen
Cathcart
Butterworth
Stutterheim
Somerset East
Adelaide
Rietbron
Fort Beaufort
East London
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
0 35 70 140 Kilometers
N
Event of 13 - 15 January 2008
Indian Ocean

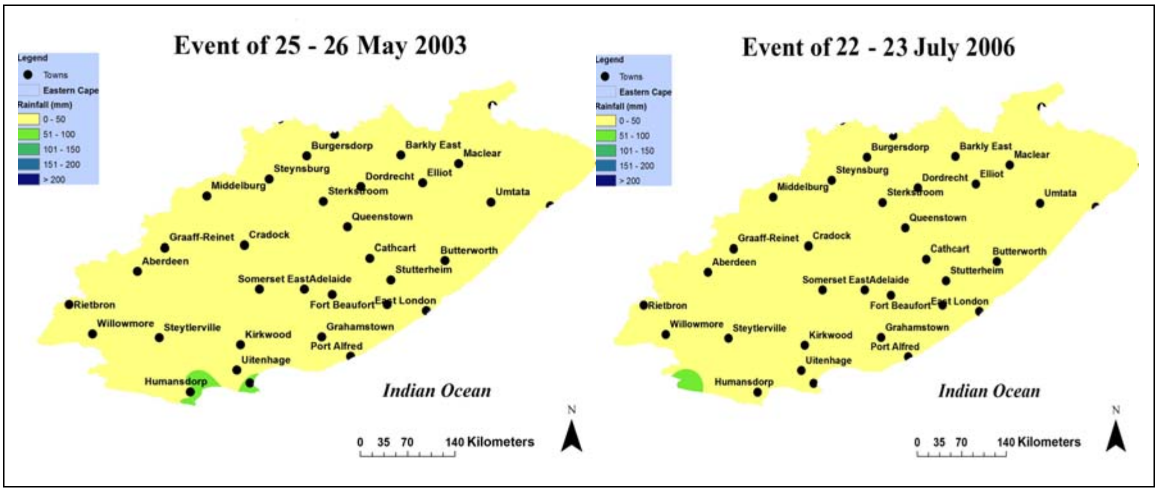
4. Region D

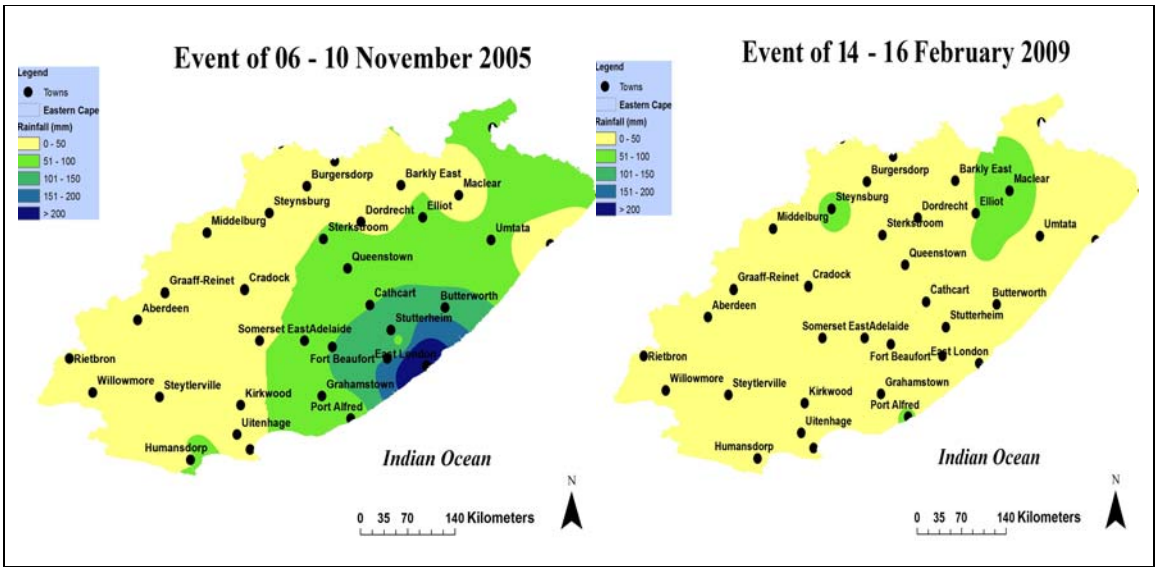

Event of 24 - 26 March 1982
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
0 35 70 140 Kilometers
N
Event of 23 - 25 February 1986


Event of 21 - 23 February 1990
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Indian Ocean
0 35 70 140 Kilometers
N
Event of 16 - 17 October 1992


Event of 11 - 13 June 1993
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N
Event of 11 - 13 December 1994
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N


Event of 09 - 11 May 1998
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N
Event of 30 - 03 October/November 2000
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N


Event of 25 - 26 May 2003
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N
Event of 22 - 23 July 2006
Legend
Towns
Eastern Cape
Rainfall (mm)
0 - 50
51 - 100
101 - 150
151 - 200
> 200
Burgersdorp
Barkly East
Maclear
Steynsburg
Dordrecht
Elliot
Middelburg
Sterkstroom
Umtata
Queenstown
Graaff-Reinet
Cradock
Cathcart
Butterworth
Aberdeen
Stutterheim
Somerset East
Adelaide
Fort Beaufort
East London
Rietbron
Willowmore
Steytlerville
Kirkwood
Grahamstown
Port Alfred
Uitenhage
Humansdorp
Indian Ocean
0 35 70 140 Kilometers
N



APPENDIX D: Total annual rainfall, total annual rainfall associated with cut-off lows with their percentage and 31-year average rainfall for each station over the Eastern Cape Province.

	East London (EL)			Engcobo_Prison (EP)			Gomo_Bos (GB)			Groendal_Bos (GD)		
YEARS	during COLs	Total	% Contr_COLs	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%
1979	488	919.9	53.0492	112.5	627.8	17.91972	175.4	989	17.735086	322	752.9	42.767964
1980	40.9	562.3	7.2737	40	579.6	6.901311	72.1	1039.3	6.9373617	15.5	499	3.1062124
1981	416.6	1050.7	39.6498	252.9	676.4	37.38912	215	940.1	22.869907	669.7	1021.8	65.541202
1982	305.2	633.9	48.1464	192.8	572.1	33.7004	153.8	1068.4	14.395358	168.7	458.4	36.80192
1983	285.2	713.8	39.9552	129.4	562.3	23.01263	121.4	824.5	14.724075	331	519.5	63.715111
1984	142.3	684.8	20.7798	9	608.4	1.47929	29.4	1142.7	2.5728538	42.7	375.3	11.377565
1985	582.7	1318	44.2109	426.7	1099.8	38.79796	440	1013.5	43.413912	314.6	644.2	48.835765
1986	223.2	882.4	25.2947	217.5	983.3	22.11939	204.9	1038.5	19.73038	98.3	451	21.796009
1987	114.3	628	18.2006	193.3	780.5	24.76618	347.9	1198.1	29.037643	6.8	259.9	2.6163909
1988	150.2	1032.5	14.5472	62	905.8	6.844778	133.5	1268.9	10.520924	171.6	636.2	26.97265
1989	506.5	938.8	53.9519	277.2	1027	26.99124	203.8	1230.8	16.558336	232.1	583.5	39.777207
1990	161.8	783.2	20.6588	112.6	647.8	17.38191	99.2	975.8	10.166018	73.7	392.3	18.786643
1991	75.5	681.3	11.0818	166.5	910.4	18.28866	69.7	917	7.6008724	43.5	399.8	10.88044
1992	183.8	615.7	29.8522	135.7	383.1	35.42156	103	523.7	19.667749	306.2	644.7	47.494959
1993	373.3	828.6	45.0519	137.8	576.6	23.89872	101.7	547.3	18.58213	367.9	675.9	54.431129
1994	285.2	725.7	39.3	245.9	640.7	38.3799	315.6	763.6	41.33054	230.7	597.2	38.630275
1995	207.7	898.3	23.1215	98.3	625.1	15.72548	213.5	1048.8	20.356598	162.5	483.9	33.581318
1996	277.3	995.7	27.8498	73.4	987.5	7.432911	122.4	1370.1	8.9336545	509.6	844.7	60.329111
1997	349.6	1383.3	25.2729	159.4	615.9	25.88082	537.5	1472	36.514946	226.8	549.4	41.281398
1998	234.4	1036.9	22.6058	126.7	909.1	13.93686	104.5	1297	8.0570547	146.2	589.1	24.817518
1999	54	854.7	6.31801	0	96	0	168.3	1032.5	16.300242	36.6	255.6	14.319249
2000	130.9	1089	12.0202	94.9	904.8	10.48851	305.4	1178.9	25.905505	230.3	682.3	33.753481
2001	323.3	982.8	32.8958	173	733.4	23.58876	183.1	860.8	21.270911	251.3	759	33.109354
2002	637.8	1207.6	52.8155	0	75	0	191.5	1128.1	16.975445	260.8	434.9	59.967809
2003	276.4	658.6	41.9678	0	0	0	92.3	1930.2	4.7818879	187.5	373	50.268097
2004	263.5	848.5	31.0548	132.3	506.5	26.12043	33.1	1045.9	3.1647385	8.5	365	2.3287671
2005	332	852.1	38.9626	129.5	456	28.39912	147	940.1	15.636634	111.6	342.2	32.612507
2006	250.3	1217.1	20.5653	233	113.7	204.9252	29.9	1503.8	1.9882963	215.9	656.8	32.871498
2007	238.6	643.6	37.0727	141.3	588.3	24.01836	344.2	1238	27.802908	200.1	472	42.394068
2008	340.9	702.9	48.4991	266.5	657.4	40.53848	59.5	642.3	9.263584	118.7	426.7	27.818139
2009	110.8	550.4	20.1308	173.5	655.7	26.46027	136.8	868.5	15.751295	112	345.9	32.3793
Average	**269.748**	**868.423**		**145.6**	**629.226**		**175.98**	**1065.75**		**199.142**	**532.003**	

	Humansdorp(HD)			Jeffreys_Bay (JB)			Kei road (KR)			Kendrew Estate (KE)		
YEARS	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%
1979	319.3	810	39.41002	261	518.5	50.337512	386.2	820	47.097561	83.4	231.6	36.010363
1980	28.1	518	5.420525	29	490.3	5.9147461	9.7	552.3	1.7562919	33.5	260	12.884615
1981	620	949	65.33881	602.9	1000.9	60.235788	352.7	833.5	42.315537	200.6	313.9	63.905702
1982	142.3	491	28.99348	86.1	401.8	21.428571	185	520.2	35.563245	71.5	190	37.631579
1983	315.6	564	55.96737	204.2	395.7	51.604751	190	570.1	33.327486	127	296.9	42.775345
1984	10.7	410	2.607848	15.2	402.9	3.7726483	67	784.1	8.5448285	41.2	160.3	25.701809
1985	290.5	620	46.88509	221.2	462.6	47.816688	654.7	1353.9	48.356599	123.3	406.6	30.324643
1986	134.6	591	22.77881	89.2	420.6	21.207798	169.1	852.4	19.838104	55.7	237	23.50211
1987	70.5	467	15.0899	67.2	411.8	16.318601	40.5	626	6.4696486	76.1	225.4	33.762201
1988	171.8	554	31.02763	89.8	376	23.882979	132.3	1090.2	12.135388	45.4	340.6	13.329419
1989	280	705	39.73886	242.1	522.4	46.343798	406.9	1014.9	40.09262	153.3	314.9	48.682121
1990	160.5	734	21.87543	118.6	511.7	23.177643	158.2	661.4	23.91896	40.7	169.1	24.068598
1991	54.5	520	10.48077	34.3	336.1	10.205296	66.2	697.3	9.4937617	21.9	202.8	10.798817
1992	420	971	43.27666	234.1	718.4	32.586303	110	473.6	23.226351	43	184.7	23.280996
1993	588	881	66.76507	439.2	774	56.744186	274.5	865.7	31.708444	87.3	290.6	30.041294
1994	234.5	623	37.64045	256	576.8	44.382802	225	557	40.394973	73.2	279.4	26.198998
1995	145	675	21.49741	91.5	533	17.166979	133.1	545.6	24.395161	229.6	406.7	56.454389
1996	455	797	57.12492	468.6	762.8	61.431568	153.5	619.7	24.77005	156.7	480.4	32.618651
1997	280.5	548	51.20482	243.5	529	46.030246	281	844.2	33.285951	63.3	205.2	30.847953
1998	112.5	517	21.76015	103.5	458.3	22.583461	62.2	849.5	7.3219541	74.6	295.6	25.236806
1999	110.5	439	25.17084	83.5	364.9	22.882982	141.3	687	20.567686	78.2	219.3	35.658915
2000	160.5	585	27.42183	108.8	514.8	21.134421	235.5	937.3	25.12536	77.7	544	14.283088
2001	240	631	38.06503	223.7	568.6	39.342244	255	925.6	27.549697	134.6	405.4	33.201776
2002	300.8	614	48.9663	374.5	724.5	51.690821	270.7	661.3	40.934523	95.8	284.3	33.696799
2003	252	569	44.32718	284.7	591.6	48.123732	0	0	0	90.3	232.5	38.83871
2004	54.5	586	9.295582	65.5	694.1	9.4366806	179.6	613.9	29.255579	30.2	292.5	10.324786
2005	136.5	428	31.89252	170.7	395.3	43.182393	170	727.2	23.377338	87.8	298.9	29.374373
2006	512.5	1014	50.56235	244.2	756.4	32.284506	63.5	1219.6	5.2066251	68.8	301.9	22.789003
2007	380.8	650	58.54859	438.6	635.9	68.973109	128.4	643.1	19.965791	38.5	297.3	12.949882
2008	142	390	36.43829	80.9	342.6	23.613543	219.7	400.5	54.856429	83	315	26.349206
2009	107.9	478	22.59213	96.6	452.3	21.357506	0	0	0	71.4	267.5	26.691589
Average	233.3	623		195.771	536.923		190.717	731.57		85.729	288.719	

	Klipfontein (KF)			Lottering (LB)			Maclear (MC)			Montagu (MU)		
YEARS	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%
1979	115	257.8	44.608223	412.7	1126	36.64861	140	660.5	21.196064	71.5	352.8	20.26644
1980	19	250.8	7.5757576	66	850.6	7.7592288	61	526.5	11.585945	32	298.7	10.71309
1981	234	344.5	67.924528	961	1589	60.482095	282.5	699.5	40.38599	265.3	532	49.868421
1982	75.4	223.6	33.72093	497.5	1027	48.432632	113	656.5	17.21249	85.5	335.8	25.461584
1983	134.2	283.9	47.270166	575.4	1283	44.855005	52.9	663.3	7.9752751	76.9	304.7	25.237939
1984	27	136.4	19.794721	21.7	671.5	3.2315711	20.5	772.1	2.6550965	0	280.6	0
1985	171	384.5	44.473342	344.6	1064	32.381131	336.5	989.6	34.003638	84.3	339.3	24.84527
1986	61	219.5	27.790433	190	812.9	23.373109	126.5	816.3	15.496754	86	378.6	22.715267
1987	45.5	118.5	38.396624	182.5	985.2	18.524158	166	871.1	19.056366	91.4	352.8	25.907029
1988	45	386.5	11.64295	294	876.6	33.538672	132	1123	11.756323	124.3	681.7	18.233827
1989	213	404	52.722772	262	891.4	29.391968	216.8	1009	21.478106	83.8	415	20.192771
1990	38.5	138	27.898551	206.7	1116	18.521505	109.8	682.4	16.09027	44.8	316.5	14.154818
1991	60	218.5	27.459954	55.7	823.3	6.7654561	94.5	914.8	10.330127	198	611.9	32.358228
1992	119.5	206.5	57.869249	525	1338	39.243534	78.2	542	14.428044	106.7	175.5	60.797721
1993	112.5	283	39.75265	594.8	1035	57.490818	187.8	941.8	19.940539	105.7	411.4	25.692756
1994	154.4	290.4	53.168044	478	1092	43.760872	309	828	37.318841	46.4	259.5	17.880539
1995	150.5	335	44.925373	268.5	1078	24.907236	209	978.1	21.367958	57.1	413.6	13.805609
1996	198	418.5	47.311828	552.6	1087	50.841844	131.5	1080	12.173672	110.5	386.9	28.560352
1997	54	206	26.213592	406.2	1015	40.003939	156.8	938.3	16.711073	130.6	298.4	43.766756
1998	64	258	24.806202	234.8	917.2	25.599651	175.5	1100	15.954545	180.6	398.1	45.365486
1999	86.3	186.5	46.273458	162.8	810.3	20.091324	11	31.5	34.920635	82.7	213	38.826291
2000	93	433	21.47806	207.5	1084	19.149133	149	1145	13.0131	76.3	433.4	17.604984
2001	168.5	343	49.125364	464.5	881.5	52.694271	204.5	1022	20.019579	180.3	505.3	35.681773
2002	99	278.5	35.547576	339.3	845.9	40.111124	107.5	961	11.186264	146.6	548.7	26.717696
2003	133	221.5	60.045147	313	908.3	34.45998	154.5	562.7	27.456904	78.1	275.7	28.327893
2004	51.5	283.5	18.165785	160.5	1064	15.091678	171.5	1205	14.232365	141.8	562	25.231317
2005	108	367	29.427793	162	711.2	22.778403	85	792	10.732323	41.3	272.7	15.144848
2006	97.5	339.5	28.718704	377.3	1253	30.114135	179.5	1243	14.44668	136.2	682.3	19.961894
2007	40.5	211	19.194313	873.2	1247	70.029674	139.5	803.7	17.357223	64.4	355.1	18.135736
2008	83	201.5	41.191067	212.9	828.1	25.709455	305.9	1069	28.610176	144.5	324.3	44.557508
2009	54.5	214	25.46729	102	575.7	17.717561	195	798	24.43609	144.3	422.9	34.121542
Average	**100.2**	**272.4**		**338.9**	**996.3**		**154.9**	**852.4**		**103.8**	**391.59**	

	Mooredale (MD)			Port Elizabeth (PE)			Port Alfred (PA)			Port st John (PJ)		
YEARS	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%
1979	157.2	229.9	68.377555	446.1	823.1	54.197546	550.1	891.8	61.684234	267	976.2	27.350953
1980	11.5	172.5	6.6666667	46	518.2	8.8768815	51	549.3	9.284544	44.5	1025.9	4.3376547
1981	433.6	629.7	68.858186	578.3	1020	56.696078	518.1	964.4	53.722522	201	1054	19.070209
1982	64	254	25.19685	135.4	512.2	26.434986	127.7	446.7	28.587419	256	1335.3	19.171722
1983	110.5	217.5	50.804598	289.6	615.7	47.035894	224.5	421.7	53.236898	182.5	990.2	18.43062
1984	19.2	169.7	11.314084	24	459	5.2287582	144.5	542.9	26.61632	136	1210.5	11.235027
1985	201.3	533.6	37.724888	260.1	545.8	47.654819	289.5	652.4	44.374617	750	1269.7	59.069071
1986	51.7	252.9	20.442863	92	493.2	18.65369	55.9	537.1	10.407745	287.3	1268.8	22.643443
1987	95.4	218.5	43.661327	57.6	514.2	11.201867	75.6	446.6	16.9279	21.4	1079.3	1.9827666
1988	75.2	254	29.606299	89.2	444.4	20.072007	65.5	575.2	11.387344	86.5	1337.8	6.4658394
1989	192.4	387.7	49.625999	229.8	602.2	38.16008	171	485.1	35.250464	340.4	1521.2	22.377071
1990	141	267.3	52.749719	60.9	441.8	13.784518	115.8	566.1	20.45575	63.2	802.2	7.8783346
1991	54.5	301.7	18.064302	60	451.7	13.283153	79.9	421.7	18.947119	115.8	899	12.880979
1992	98.8	208	47.5	193.1	619.5	31.170299	122.5	638.3	19.191603	18.5	229.5	8.0610022
1993	147	494.3	29.739025	314.4	638.7	49.224988	311.2	636	48.930818	189.3	344.2	54.997095
1994	129	327.1	39.437481	247.7	620.3	39.932291	259.4	692.5	37.458484	697.7	1126.1	61.957197
1995	112.1	352.3	31.819472	118.8	513.1	23.153381	105.1	522.9	20.099445	363.3	1435.8	25.302967
1996	211.9	437.6	48.423218	423.3	772.4	54.803211	195.5	520.5	37.560038	220.5	1352.9	16.298322
1997	105.8	189.4	55.860612	185.2	538.4	34.398217	240.2	481.6	49.875415	517.7	1716.6	30.158453
1998	138.5	334.5	41.405082	114.5	602.7	18.997843	127.8	716.7	17.831729	231	1307.3	17.670007
1999	63.5	299	21.237458	104.4	495.5	21.069627	64.5	308.3	20.921181	0	243.4	0
2000	106.5	467.7	22.771007	171.3	758.8	22.575119	190.4	687.5	27.694545	300	1264.9	23.71729
2001	163.5	329	49.696049	321.4	613.4	52.396479	232.4	649.8	35.764851	149.3	1040.3	14.351629
2002	131.5	316	41.613924	464.1	783.8	59.211534	325.8	633.9	51.396119	314.6	1202.8	26.155637
2003	85	150	56.666667	279.2	662.8	42.124321	313.1	734.6	42.621835	310.5	1038.5	29.898893
2004	97.5	321	30.373832	59.6	589.7	10.106834	149	705.7	21.113788	180.8	1207.2	14.976806
2005	106	300	35.333333	125.5	497.7	25.215994	262.5	1287.8	20.3836	50.5	901.8	5.5999113
2006	85	314.2	27.052833	283.7	821.5	34.534388	264.7	806	32.841191	430.8	1950.3	22.088909
2007	114.5	274.5	41.712204	318.9	554.6	57.500902	423.2	722.3	58.590613	340	1248	27.24359
2008	154.5	300	51.5	146.2	401	36.458853	175.5	468.1	37.491989	581.5	1583.5	36.72245
2009	79	296.5	26.644182	77.6	452.2	17.160548	90.5	406.7	22.252274	274.3	1314.1	20.873602
Average	**120.55**	**309.68**		**203.8**	**592.83**		**203.95**	**616.78**		**255.5**	**1138**	

	Queenstown (QT)			Reitron (RB)			Rossouw (RW)			Steynburg (SB)		
YEARS	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%	during COLs	Total	%
1979	196.6	522.4	37.633997	41.5	80.5	51.552795	225.5	510.8	44.14644	84.9	442.5	19.18644
1980	27.4	428.6	6.3929071	33	205	16.097561	31	264	11.74242	38.5	345.7	11.13682
1981	419.2	653.3	64.166539	193.9	253.6	76.458991	283	536	52.79851	406.6	694.8	58.52044
1982	113.4	487.7	23.251999	51.3	153	33.529412	77	327	23.5474	222.2	648.1	34.28483
1983	175.1	394.1	44.430348	81.7	173.7	47.035118	105	259.3	40.49364	135.5	483.4	28.03062
1984	6	491.4	1.2210012	19.7	125.7	15.672235	0	256.5	0	0	266.3	0
1985	245	732.3	33.456234	68.5	288.1	23.776467	253.5	571.5	44.35696	157.5	488.7	32.22836
1986	73.4	601.9	12.194717	49.9	222.3	22.447143	87	436	19.95413	80.4	493.8	16.2819
1987	168.1	444.8	37.792266	54.1	134.4	40.252976	136.5	534.5	25.53789	143	430.3	33.23263
1988	58.4	682.4	8.5580305	67.1	192.5	34.857143	109.5	863.5	12.68095	97.5	555.7	17.54544
1989	277.5	761.5	36.441234	57.8	249.8	23.138511	232.5	685.5	33.91685	109.5	250.7	43.6777
1990	33	168.5	19.58457	56.3	122	46.147541	74	465	15.91398	50	500.2	9.996002
1991	93	696.8	13.346728	21.7	130.1	16.679477	161.5	889.5	18.15627	151.1	446.7	33.82583
1992	61	306.3	19.915116	107.6	174.1	61.803561	79	209	37.79904	159	328.6	48.3871
1993	159.4	524.3	30.402441	105.3	227	46.387665	51.5	406.3	12.67536	112.2	404.5	27.73795
1994	149.9	355.5	42.165963	102.3	224.8	45.507117	86.5	331	26.13293	81.7	375.6	21.75186
1995	98.6	425.8	23.156411	92.5	298.6	30.977897	127.5	467.5	27.27273	230.5	594.3	38.78513
1996	110.2	600.5	18.351374	251.9	417.2	60.378715	186.7	641.8	29.09006	144	541.4	26.59771
1997	82.8	479.4	17.271589	56	186.7	29.994644	165.2	532.5	31.02347	141.8	449.5	31.54616
1998	161.4	555.2	29.070605	105.8	183.6	57.625272	196.5	642.9	30.56463	241.5	618.5	39.04608
1999	13.5	117.4	11.499148	90.2	350.4	25.742009	145.9	161.9	90.11736	127.9	327.9	39.00579
2000	220.5	872.6	25.26931	136.6	414.9	32.923596	71	414.8	17.11668	100.4	658.2	15.25372
2001	125.3	635	19.732283	134	286.2	46.820405	249.1	764.8	32.57061	115.2	696.7	16.53509
2002	121.7	505.8	24.060894	78.2	269.4	29.027468	160	579	27.63385	114	498.8	22.85485
2003	130.1	436.5	29.805269	77.1	214.4	35.960821	134.4	382.8	35.10972	73	264	27.65152
2004	64	629.3	10.17003	40.7	231.7	17.565818	122	593.2	20.56642	159.7	567.7	28.13106
2005	126.5	480.2	26.34319	145.6	260.2	55.956956	92.5	431.5	21.43685	84.8	370.2	22.90654
2006	115.5	790.7	14.60731	78.8	232.8	33.848797	119	820.5	14.50335	132.6	644.8	20.56452
2007	77.8	465.4	16.716803	48	158.4	30.30303	99	534.5	18.52198	89.8	336.7	26.67063
2008	213.9	548.5	38.997265	31.7	161.8	19.592089	154.6	558.8	27.66643	179	450.6	39.72481
2009	92.5	370.5	24.966262	59.7	202	29.554455	179.5	401.2	44.74078	120	349	34.38395
Average	**129.377**	**521.44**		**81.89**	**220.16**		**135.35**	**499.1**		**131.74**	**468.5**	

	Telpoort (TP)			Umzoniana (UZ)					
YEARS	during COLs	Total	%	during COLs	Total	%	Total_Annual	COL_Annual	COLs %
1979	135.3	360.3	37.552	602.6	977.1	61.6723	13881.7	5593.8	40.29622
1980	56	258.5	21.6634	56.3	600.2	9.38021	10795.7	842	7.799402
1981	408.3	676.3	60.3726	488.3	1064.2	45.8842	17497.4	9003.5	51.45622
1982	58.7	254.2	23.0921	280.3	581	48.2444	11577.9	3462.8	29.90871
1983	59	260	22.6923	267.8	629.8	42.5214	11426.8	4174.4	36.53166
1984	0	157.5	0	130	665	19.5489	10773.9	906.1	8.410139
1985	178	395.5	45.0063	650.3	1424.3	45.6575	16597.7	7043.8	42.43841
1986	42	245	17.1429	191	834.2	22.8962	13068.6	2666.6	20.40463
1987	112	217	51.6129	169.9	595.2	28.545	11539.3	2435.6	21.107
1988	148.1	511.6	28.9484	176.1	1045.4	16.8452	15734	2525	16.04805
1989	85	348.5	24.3902	526.4	953.2	55.2245	15302.1	5299.8	34.63446
1990	11	156.5	7.02875	145.7	719.6	20.2474	11337.1	2076	18.31156
1991	63.5	276	23.0072	75.7	643.4	11.7656	12389.8	1817	14.66529
1992	68.5	120.5	56.8465	199	619.6	32.1175	10229.6	3472.2	33.94268
1993	31.5	189	16.6667	398.6	901.7	44.2054	12876.2	5190.9	40.31391
1994	17	141.3	12.0311	298.9	760.7	39.2928	12188.5	4924	40.39874
1995	28.5	207	13.7681	233.9	992.1	23.5763	13830	3477.1	25.14172
1996	55	257.6	21.3509	238.9	979.2	24.3975	16351	5247	32.08978
1997	82.5	348.5	23.6729	531.3	1307.3	40.641	14834.8	4997.7	33.68903
1998	21.4	194.1	11.0252	391.6	1504	26.0372	15285.3	3349.5	21.91321
1999	68.5	229.5	29.8475	104.7	1241.1	8.43606	8964.7	1798.3	20.05979
2000	0	363.5	0	233.8	1481.4	15.7824	16915.7	3400.3	20.10144
2001	113	357.5	31.6084	544.2	1647.8	33.0259	15637.9	4949.2	31.64875
2002	67.1	261.6	25.6498	706.8	1597.1	44.2552	14412.3	5308.1	36.83035
2003	121	249.5	48.497	409.9	1064	38.5244	11519.7	3795.1	32.94443
2004	81	404	20.0495	389.5	1287.5	30.2524	14603.7	2636.3	18.05227
2005	38	259	14.6718	515.4	1383.1	37.2641	12754.2	3228.7	25.3148
2006	119	488	24.3852	440.4	2171.2	20.2837	19340.1	4478.1	23.15448
2007	0	267.5	0	321.7	984.9	32.6632	13332.1	4861	36.46087
2008	132.5	347	38.1844	595.3	1227.9	48.4811	12347.4	4422.2	35.81483
2009	78	299.5	26.0434	170.3	885.6	19.2299	10605.8	2526.2	23.81904
Average	79.980645	293.5968		338.2129	1057.058		13482.29032	3868.009677	