Extreme events: Past and future changes in the attributes of extreme rainfall and the dynamics of their driving processes

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by

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Executive Summary

Extreme rainfall events are often associated with significant societal and infrastructural impacts through human and animal fatalities, damage to or loss of property, loss of agricultural products, and flood insurance claims which are worth millions of Rands annually. Several studies have shown an increase in the intensity of extreme rainfall over many regions of South Africa as well as spatial heterogeneity in these changes, especially in the Eastern Cape, southern Free State and parts of KwaZulu-Natal. This study investigated changes in the characteristics of extreme rainfall by establishing relationships between existing station data and the daily synoptic states. We addressed the dynamical aspect of extreme rainfall in contemporary climate to provide a process based understanding of observed changes in extreme rainfall, and built a basis for understanding future projected changes. In order to do this two main objectives were set: (1) to produce a rainfall station data set that had been quality controlled according to international standards so that these data could be confidently used in achieving the second objective and (2) to identify key synoptic process that resulted in extreme rainfall based on the cleaned station data and atmospheric circulation fields and trends in these.

Station data quality control methods were applied to station data obtained from the Computing Centre for Water Research (CCWR), the Agricultural Research Council (ARC) and the South African Weather Service (SAWS). This procedure identified many errors in the station data, conflicts in the metadata between the three data sources as well as complexities around station nomenclature. However, through this procedure, we produced a quality controlled station data set that could be used in the rest of the study from which were selected stations that had 95% data present between the period 1979-2009, a process that yielded 696 stations suitable for analysis.

Daily rainfall at a point is a function of the large-scale synoptic circulation. To identify circulation stated related to extreme rainfall, a Self-Organizing Map (SOM) was used to characterize circulation stated in the 31-year period. General synoptic circulation modes over the country were generated by the SOM and those associated with seasonal extreme rainfall were identified. Summer rainfall extremes are related to a sub-tropical low pressure over the interior and winter extreme rainfall to mid-latitude cyclone types of circulations. Shoulder season extreme rainfall is associated with both summer and winter types although dominant circulation modes are not as apparent as in the core winter/summer seasons. However, South Africa experiences a number of rainfall regimes which effect different regions of the country. To investigate the regionally-specific characteristics of extreme rainfall, nine regions based on rainfall regimes were assessed. This assessment identified specific synoptic states that were associated with extreme rainfall in particular seasons. Summer recorded the highest occurrence of extreme rainfall in all regions with the exception of the South Western Cape and South Coast regions (winter and spring respectively) and was usually associated with a surface low of varying depth over the central or western interior and a high pressure over the south and/or east coast. In the Western Cape extreme rainfall occurred primarily in winter and was associated with a surface low in the mid-latitudes and over the region and an upper air trough to the south west. Extreme rainfall in the South Coast region occurred in the shoulder seasons and winter and was associated with the passage of a cold front a ridging high pressure and strong surface linkages between the sub-tropics and the mid-latitudes.

Trends in the station and circulation data identified five stations within different spatial rainfall regimes with statistically significant increases in the occurrence of extreme rainfall which was associated to circulation states that also showed significant trends, especially a circulation type associated with a surface low pressure over the west of the country and surface high over the east. Seasonal changes in the frequency of occurrence of circulation modes were very evident in the shoulder seasons and less so in summer and winter. These shoulder season trends were evident in both frequently occurring circulation modes as well as those that occurred less frequently. Although the largest number of trending circulation modes occurred in autumn and spring, trends in summer indicated more frequent summer types of circulations that were associated with extreme rainfall. It is therefore likely that regions in South Africa that experience a summer rainfall regime would have experienced more extreme rainfall between the 1979-2009 study period. Although this could not be verified explicitly in the 95th and 99th percentile station trends, trends in the Simple Daily Intensity Index (SDII) identified in 12 stations with significant positive trends in summer rainfall regions. This index may therefore be a more sensitive index with respect to examining changes in extreme rainfall characteristics in this type of analysis.

We recommend further study to (1) identify extreme rainfall regimes as opposed to general rainfall regimes we used, (2) an event-based classification procedure of extreme rainfall synoptic circulation modes, (3) a climate change study to investigate projected changes in the characteristics of extreme rainfall within the Co-Ordinated Regional Downscaling Experiment framework and (4) downscale to the station scale the new CMIP 5 general circulation model data which becomes available in 2012 for comparison with contemporary station data.

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Reference Group members:

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List of abbreviations

General

ANN	Artificial Neural Net
ARC	Agricultural Research Council
CCWR	Computing Centre for Water Research
CFSR	Climate Forecast System Reanalysis
COL	Cut Off Low
DJF	December/January/February
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	European Reanalysis
ETCCDI	Expert Team on Climate Change Detection and Indices
GHCN	Global Historical Climatology Network
ITCZ	Inter-Tropical Convergence Zone
JJA	June/July/August
NCEP	National Centre for Environmental Prediction
MAM	March/April/May
SAWS	South African Weather Service
SOM	Self- Organizing Map
SON	September/October/November
TTT	Tropical Temperate Trough

RclimDex rainfall indices

CDD	Consecutive dry days
CWD	Consecutive wet days
PRCPTOT	Total wet-day precipitation
R95 mm	Number of days above 95th %ile mm
R99 mm	Number of days above 99th %ile mm
R95p	Very wet days
R99p	Extremely wet days
RX1day	Max 1-day precipitation amount
RX5day	Max 5-day precipitation amount
SDII	Simple Daily Intensity Index

Chapter One. Introduction

1.1. Introduction

Extreme rainfall events are, while infrequent, associated with significant societal and infrastructural impacts. Extremes have two attributes – they are low frequency, prolonged events such as multi-year droughts, or short-term intense rainfall events which can lead to severe localized flooding. Both have serious impacts on society and can cause massive displacement of communities, and even fatalities. Worryingly, several studies have shown an increase in the intensity of extreme rainfall over many regions of South Africa as well as spatial heterogeneity in these changes (Groisman et al., 2005; Kruger, 2006), while low frequency changes in rainfall are less clear. All the studies indicated changes in the characteristics of extreme precipitation over the last 50 -100 years despite differing definitions of extreme rainfall.

Although South Africa has a relatively advanced capacity for climate science, flooding caused by extreme rainfall often results in fatalities, damage to or loss of property and millions of Rands (ZAR) worth of damage annually. Flooding may occur locally or over widespread regions depending on the type of weather system(s). Typical flood-causing systems are tropical, sub-tropical and/or mid-latitude systems such as tropical and extra-tropical cyclones, cut-off lows and sub-tropical convective activity (Van Heerden and Taljaard, 1998; Tyson and Preston-Whyte, 2000).

Extreme rainfall events can have consequences in a number of South African sectors. It is often detrimental to society as it causes damage to property, infrastructure and often results in massive displacement of communities. For example, in the Western Cape thousands of people in poor informal settlements are displaced every winter through flooding due to the passage of mid-latitude cyclones. Tropical cyclones affect the northern and north east regions of the country destroy dwellings and possessions and are often fatal whilst cut off lows, because of their quasi-stationary character, have resulted in flooding and fatalities in the Karoo and frequently isolate residents from the rest of the world for days. Therefore a better understanding of how the characteristics of extreme rainfall may change spatially and temporally as well as in intensity would aid in the short and long term preparedness of vulnerable communities for such events.

Flooding caused by extreme rainfall also negatively impacts the economy through human and animal fatalities, damage to or loss of property, loss of agricultural products, and flood insurance claims which are worth millions of Rands annually. For example, in 1981 an intense cut-off low system resulted in the deaths of more than 100 people and damage worth over R10 million (not adjusted for inflation) in the arid Karoo region. During February 2000, the passage of two tropical cyclones in close succession resulted in the deaths of hundreds of people in the northern parts of the country, caused damage worth more than 3 billion rand and farmers lost more than 50% of their export product. In July and August 2001 a series of severe mid-latitude cyclones cost the economy over R10 million to house people displaced from 8 000 homesteads in Cape Town and rebuild dwellings. Similarly in August 2006, a series of severe fronts resulted in more than 500 million Rands worth of damage along the south coast of the country and the deaths of nine people. People displaced by flooding also have to be housed and fed, which places further strain on provincial and municipal economies. It is therefore essential to understand the changing nature of extreme rainfall in the country for planning and budgetary purposes at the national, provincial and municipal levels to mitigate correctly for these events.

In addition to fatalities mentioned above, other health risks arise because of flooding as large bodies of standing water can place communities at risk of cholera and other water borne disease. Additionally, flooding often results in the release of agricultural and industrial pollutants into local water sources with consequences for local populations and livestock. This situation is often exacerbated through lack of drinking water as a result of damaged water pipes. An understanding of changes in extreme weather characteristics is thus necessary to identify communities at risk and put in place relevant infrastructure.

Environmental risks associated with high water volumes during flooding usually include soil erosion. This often results in surface denudation of plant material and local slope slippages, which are potentially fatal. Eroded material is often deposited on the floor of a valley and may result in the diversion of a water-course with consequent impacts on the local ecology and hydrology.

In order to mitigate or prepare for extreme rainfall events, it is therefore necessary to understand the spatial and temporal characteristics of extreme rainfall in terms of intensity, frequency, seasonality and understand any changes that may have occurred within these attributes. Many studies have addressed this. Groisman *et al.* (2005) provide an overview of studies which documented changes in extreme and heavy precipitation at a global and regional scale. This following paragraph repeats much of the information provided in this paper but also lists additional studies to provide a context for the growing need to identify systems associated with extreme precipitation and correctly forecast them, especially in South Africa.

1.2. Observed and projected changes in the characteristics of extreme precipitation in South Africa

Iwashima & Yamamoto (1993) were the first to document changes in the characteristics of heavy precipitation. Using long-term station data, they examined the number of extreme precipitation events at meteorological stations in Japan and found an increasing tendency in the number of extreme precipitation events. Additionally they found that more stations recorded their highest precipitation events in recent decades. Using data from 1910 to 1995 across the contiguous United States, Karl and Knight (1998) demonstrated an increase in the frequency of extreme precipitation events as well as the amount of rainfall associated with these. Groisman et al. (1999) used a model that was fitted to daily precipitation data from eight countries (Australia, Canada, China, Mexico, Norway, Poland, the United States and the former USSR) and found a disproportionate (usually positive) change in precipitation intensity whenever the mean precipitation changed. This disproportionate change was also theoretically demonstrated by Katz (1999).

Easterling et al. (2000) summarized the work of many studies to determine the change in the probability of heavy precipitation using daily data for many regions of the earth. They identified regions that experienced statistically significant changes in heavy and very heavy precipitation compared to the change in annual or seasonal precipitation and showed an increasing probability of intense precipitation events for many extratropical regions. Groisman et al. (2005) extended this work and provided more information for the Americas (Fig. 1.1). Notable for the purposes of this study are the significantly positive changes at the three southern African stations.

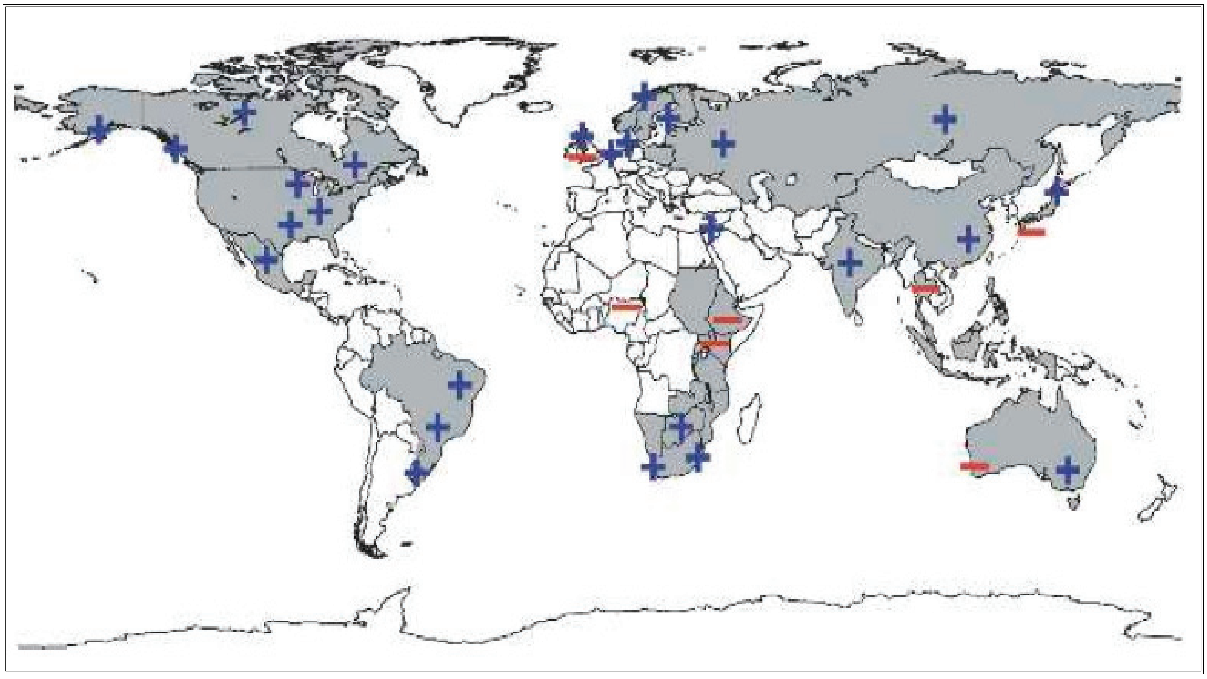

Figure 1.1. Regions where disproportionate changes in heavy and very heavy precipitation during the past decades were documented compared to the change in the annual and/or seasonal precipitation. Plus and minus signs indicate regions where significant changes in heavy precipitation have occurred during past decades. Shaded regions indicate statistically significant changes. From Groisman et al. (2005).

Frich et al. (2002) investigated a global dataset of derived extreme climate indicators and found those derived from wet spells and the number of heavy rainfall events (based on daily precipitation data) displayed significant increases in the extreme amounts. This type of increase has been observed over many regions of the earth, e.g. the United Kingdom (Osborn et al. (2000) and Osborn and Hulme (2002)), Europe (Klein-Tank and Koennen (2003)), Nigeria (Tarhule and Woo, (1998)), Australia (Suppiah and Hennessy (1998)), China (Zhai et al. (1999)), the USA (Groisman et al. (2001)), Canada (Zhang et al. (2001)) and India (Roy and Balling (2004)). These studies also indicated that at a regional scale, statistically significant changes in the rainy season have generally been accompanied by relative changes in heavy precipitation that are of the same sign of and stronger than changes in the mean.

More recently, Groisman et al. (2005) empirically assessed the observed changes of intense precipitation in the twentieth century. They found that in the mid-latitudes there was a widespread increase in the frequency of very heavy precipitation over the last 50-100 years. Their results for South Africa were in agreement with Mason et al. (1999) who found significant increases in the intensity of extreme rainfall events between 1931 and 1990 over about 70% of the country. Additionally, they reported that the intensity of the 10-year high rainfall events had increased by over 10% over large areas of the country with the greatest percentage increases in the intensity of high rainfall events being for the most extreme. Easterling et al. (2000) showed a statistically significant positive trend in extreme precipitation over the south-western region of South Africa. In examining daily climate data over southern and western Africa, New et al. (2006) found evidence of statistically significant positive trends in extreme precipitation in regionally averaged daily rainfall intensity. They also found that although there was an indication of decreasing total precipitation, this was accompanied by increased average rainfall intensity which was concentrated on extreme precipitation days. Kruger (2006) examined the rainfall characteristics at 138 rainfall stations across South Africa with records of almost a century long and demonstrated an increase in the number of extreme rainfall days in the Eastern Cape, southern Free State and parts of KwaZulu-Natal. Thus there is evidence that the characteristics of extreme precipitation both globally and over South Africa has changed over the last 50-100 years to have become more frequent and intense in most extra-tropical regions. Many studies have documented the cause of this as an overall increase in intensity of extra-tropical cyclones in the southern hemisphere through a pole-ward shift of baroclinicity (e.g. Lambert, 1995; Kushner et al., 2001; Lin and Simmonds, 2002; Fyfe, 2003; Gillet et al., 2006). It is also likely that the characteristics of extreme precipitation over the region will continue to change in intensity, frequency and duration as a result of global warming.

In addition to the evidence of the observed change in the extreme precipitation characteristics, there is also a growing body of literature that indicates that as the global temperature increases as a result of the increase in greenhouse gas concentrations in the atmosphere, further changes in the characteristics of heavy precipitation are likely. Groisman et al. (2005) also analysed output from three GCM simulations that had transiently increasing greenhouse gases during the twenty-first century and indicated an increased probability of heavy precipitation events for many extra tropical regions, including South Africa. An increasing number of model projections have demonstrated this globally as well as regionally, e.g. Zwiers and Kharin, (1998); Meehl et al. (2000); Cubash et al, (2001); Allen and Ingram, (2002); Semenov and Bengtsson, (2002); Giorgi et al. (2004); Kim (2005), Tebaldi et al. (2006). Over the southern African region, Mason and Joubert (1997) showed the frequency and intensity of extreme daily and prolonged (five-day) rainfall events increased under doubled-CO_2 conditions over the southern African region, even in areas where decreases in mean annual rainfall were simulated. Most recently Engelbrecht et al. (2011) showed the potential increase of the occurrence of cut-off lows over South Africa in the future using a cubic conformal model.

In the Intergovernmental Panel on Climate Change IPCC's Fourth Assessment Report (IPCC AR4) has also noted long-term changes in extreme rainfall as an increased frequency of heavy precipitation events over most land areas (IPCC, 2007). The report further states that it is "very likely" (a likelihood of an occurrence of 90%) that extreme events will become more frequent in the future with increased greenhouse gas concentrations.

Although there is a wealth of literature documenting the changes in the characteristics of rainfall and particularity of extreme rainfall, there has been little effort to understand the forcing dynamics of the observed long term changes at the synoptic and hemispheric scales. The daily weather characteristics of a region, including extreme rainfall, are conditioned primarily by the synoptic scale atmospheric state so changes in the characteristics of synoptic scale circulation are likely to result in changes to local weather. It is possible to relate extreme rainfall events to particular circulation states and examine the attributes of past and future extreme rainfall events from a synoptic perspective. Flood-causing synoptic states include tropical temperate troughs, tropical and mid-latitude cyclones, cut-off lows as well as interactions between these and the attributes of these inform the likelihood of the occurrence of extreme rainfall. Understanding extreme rainfall synoptically has the benefit of gaining dynamical explanations for climate features related to these. Additionally, as these studies used station data only, regionally specific statements are difficult to make. In this context several questions emerge: Can the driving synoptic conditions that cause extreme rainfall in South Africa be identified? Have extreme rainfall events become more or less frequent, during which season, and in which regions? Are these changes reflected in the driving synoptic?

In order to address some of these questions, this study builds on previous work through investigating changes in the characteristics of extreme rainfall by establishing relationships between existing station data and the daily synoptic states. The study will address the dynamical aspect of extreme rainfall in contemporary climate to provide a process based understanding of observed changes in extreme rainfall, and build a basis for understanding future projected changes. It is envisaged that this work will lay the foundation for a larger study dedicated to past and future extreme rainfall.

1.3. Objectives

This study had two main objectives as set out in the proposal. The first was to produce a rainfall station data set that had been quality controlled according to international standards so that these data could be confidently used in achieving the second objective. The second objective was to identify key synoptic process that resulted in extreme rainfall based on the clean station data and atmospheric circulation fields.

Within these two main objectives were sub-objectives that aided the study.

Objective 1 – Produce a quality-controlled rainfall station data set

1.1 Update the station data set using data from a number of sources

1.2 Identify the attributes/characteristics of extreme rainfall (e.g. intensity, duration, seasonality, etc.) in the station record, and the historical trend of these attributes.

Objective 2 – Identify key synoptic process that resulted in extreme rainfall

2.1. Identify synoptic circulations associated with extreme rainfall within the context of all synoptic circulations that effect South Africa

2.2. Identify key synoptic circulations associated with extreme rainfall using only atmospheric data associated with extreme rainfall days in the station record.

2.3. Identify regionally specific extreme rainfall and the synoptic drivers of these and seasonal attributes of these.

2.4. Identify regions in South Africa that have experienced any changes in the frequency of occurrence of extreme rainfall as well as the synoptic drivers.

This report is constructed in the following way in order to most logically address these objectives. Chapter Two describes the methods employed in the quality control procedures as well as the method used to relate extreme rainfall in the station data to atmospheric data fields. Chapter Three describes the station data quality control methodology and gives a number of examples demonstrating problems in the station data. Chapter Four presents the results of the association of extreme rainfall with the driving atmospheric circulation fields for the whole of South Africa. Chapter Five presents the synoptic drivers of extreme rainfall at a regional scale. Chapter Six presents trends in the station and synoptic data and discusses the importance of these. Chapter

Seven presents the summary and conclusion as well as suggested research avenues to pursue based on this work.

Chapter Two. Methods

2.1. Introduction

In order to relate extreme rainfall records in the station data to the driving synoptic states there are two requirements: an accurate station data record and a methodology to relate the station data to synoptic circulations. For the former, a quality controlled selection of station data was generated for an assessment of extreme rainfall. In making statistically defensible statements about extreme rainfall, a suitably long record of reliable daily rainfall data, appropriately quality controlled and homogenized, was needed. To reach the desired data standard, station data obtained from various sources was quality controlled for a number factors such as adequate length of record the record, step jumps, errors in magnitude, amounts of missing data, anomalously extreme recordings, negative precipitation, automated searches for outliers. Visual inspection of flagged data was performed as alternative check for erroneous data points, using local meteorological knowledge to assess large precipitation outliers. The standardized homogenization routines of the international Expert Team on Climate Change Detection and Indices (ETCCDI) procedures were used.

The latter requirement of relating synoptic scale characteristics to local scale responses requires the reduction of a large number of variables into a smaller set of data that still represent the original data. For example, precipitation is a function of many variables, e.g. pressure, temperature, humidity, etc. Interactions between these variables have to be preserved in relating synoptic sale characteristics to the local scale precipitation response. Self-organizing maps (SOMs) use multivariate atmospheric data to produce a number of generalized weather circulations over a chosen time period. The SOM technique is used for clustering, visualization and abstraction of data. The process uses a non-linear projection of the probability density function of high-dimensional input data onto a two-dimensional array of nodes while spanning the full continuum of data space. The SOM identifies nodes within a given data space such that the nodal distribution represents the observed distribution, providing a means for data to be generalized into a number of arch-types. The archetypal circulations can then be associated with extreme rainfall in the station data record and attributed to particular events.

The steps taken produce a usable observational data set and the SOM procedure is described below.

2.2. Station data quality control

The first deliverable of the project, as set out in the contract, was the production of a defensible station data set to be used in the extreme rainfall analysis. This involved updating the station data record at the Climate Systems Analysis Group (CSAG) and formulating a host of tests for the data to ensure the highest possible quality data will be used in the analysis phase of the project.

2.2.1. Updating the weather station data record at CSAG

The Climate Systems Analysis Group has South African weather station data from the Agricultural Research Council (ARC), Computing Centre for Water Research (CCWR) and the South African Weather Service (SAWS). However, the data are not current and we requested 3 years of daily rainfall and temperature records from SAWS to update our record. The request was made on 10 March 2010 and once terms were agreed upon the data were supplied on the 20 April 2010. Furthermore, on discovering errors in minimum temperature data between 1988 and 1996 we made a second request for data in August which was promptly supplied this in early September. We would like to acknowledge and thank Elsa de Jager and Colleen de Villiers at SAWS for their kind assistance in facilitating this process.

2.2.2. Quality control of station data

This was the primary activity undertaken in the first year of the project as set out in the proposal. The process entailed updating the station data that CSAG already had, error-checking all the data and then merging duplicate data to generate long-term station data record that could be confidently used in the rest of the study. This involved the setting up of a suite of quality assurance checks based on the Global Historical Climatology Network (GHCN) tests[1] . Rainfall and temperature data were error checked based on GHCN criteria and these criteria checks were automated for easy application to other station datasets. The checks consist of several types of carefully evaluated tests that detect duplicated data, climatological outliers, and various inconsistencies (internal, inter-variable and temporal). A manual review of random samples of flagged values was used to set the

[1] Global Historical Climatology Network – daily http://www.ncdc.noaa.gov/oa/climate/ghcn-daily

threshold for each procedure such that the false-positive rate of the testing procedure was minimized. In addition, the tests were performed in a deliberate sequence to enhance the performance of the later checks by detecting errors with the checks applied earlier in the sequence.

In many cases multiple records for a single location exist. Either data were available for limited time periods in each record or the data from different sources spanned overlapping time periods. In these cases the different stations were merged to generate a single record of a long recording period which could then be subject to the quality control process. The results of the quality control and concatenation process as well as a documentation of difficulties encountered in setting up these procedures are presented in Chapter Three.

2.3. The SOM procedure

The large scale synoptic circulation establishes the environment for the regional daily weather response. These dominant circulations often have smaller scale circulations associated with them (such as coastal lows, convective systems, land and sea breezes, etc. – described exhaustively in Tyson and Preston-Whyte (2000)). So a quantification of the large scale circulation-regional response would assist in identifying synoptic states associated with extreme rainfall. Achieving this involves the reduction of a large number of variables into a smaller set of data that should still represent the original data. For example, precipitation is a function of many variables (pressure, temperature, humidity, etc.) so the relationship between these variables must be preserved when relating synoptic scale process to the local scale precipitation response. To this end, self-organizing maps (Kohonen, 1997) were employed to reduce multivariate atmospheric data and produce generalized modes of synoptic circulation over South Africa. Self-organizing maps (SOMs) are a form of artificial neural net (ANN) that reduce high dimensional data space to a lower dimensionality (usually two-dimensional), discretized representation of the input data and produces a map of discretized data archetypes. They are a data description and visualization tool that extracts and displays the major characteristics of the multidimensional data distribution function (Hewitson and Crane, 2006) to produce an array of generalized data archetypes.

The application of SOMs to atmospheric circulat33ion reduces the degrees of freedom in the data by forming archetypal circulations and facilitates identification of dominant modes of circulation within the data set as well as the visualization of this array of atmospheric states. These are easily visualized as an array of archetypal synoptic states that span the data continuum. The method allows the user to define the degree of generalization required by defining the dimension of the SOM, without losing the ability to visualize the results. In using this technique, daily synoptic atmospheric data are categorized into a number of characteristic synoptic circulations. With this information it is possible to relate extreme precipitation events to their associated modes of driving circulation and examine events within this context. This allows for not only a documentation of changes in extreme precipitation but for an investigation into the dynamical drivers of the change. Annual and seasonal attributes of the synoptic states were examined and related to the extreme rainfall station record and changes in these attributes were investigated.

The study period was determined by the availability of daily synoptic atmospheric data that was used in the SOM. This data was the new, high-resolution reanalysis dataset produced at National Centre for Environmental Prediction (NCEP), namely the Climate Forecast System Reanalysis[2] (CFSR). It was decided to use this dataset as the resolution of the reanalysis is 50 km – higher than the resolution of other reanalyses such as the NCEP 1 & 2 (2.5 degrees), European Centre for Medium-Range Weather Forecasts (ECMWF) ERA 40 (2.5 degrees) and ERA Interim data (0.75 degrees). At the resolution of the CFSR dataset it should be possible to identify and investigate the characteristics of synoptic scale features such as cut-of lows, west coast troughs, tropical temperate troughs – all circulations systems that are often associated with extreme rainfall. The period of this data is from 1979 to current therefore the study period was set from 1979 to 2009, a 31-year period.

The SOM software used in this study is SOM_PAK version 3.1[3] which has three distinct stages in the data mapping routine in which (1) the type and size of the SOM is set, (2) the training occurs and (3) error is evaluated and results are visualized.

Each of the steps listed produce resultant data on which the following step acts. It is therefore more useful to place a detailed explanation of the workings of the SOM procedure in the results chapter to see the sequential outcomes of each step. Chapter Four therefore describes and demonstrates the methodology in the context of the results generated.

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2 http://dss.ucar.edu/pub/cfsr.html
3 Software and documentation available online at http://www.cis.hut.fi/research/som_lvq_pak.shtml

Chapter Three. Quality control and merging of station data

3.1. Introduction

In producing a quality controlled, optimal dataset for the project, station data from a number of different institutions were sourced. These included the ARC, the now defunct CCWR and the SAWS. This involved updating the station data record at the Climate Systems Analysis Group and formulating a host of tests for the data to ensure the highest possible quality data will be used in the analysis phase of the project. As mentioned in Chapter Two, we would like to acknowledge and thank Elsa de Jager and Colleen de Villiers at SAWS for their kind assistance in this facilitating this process.

3.2. Duplicate datasets

The primary data used in this work is obtained from the now defunct CCWR. However, this dataset extends only up to the year 2000 therefore data from the SAWS was used to update the records to the present as well as to replace erroneous data within the CCWR dataset. Data was also obtained from the Agricultural Research Council for the period 2000-2004.

SAWS and the ARC datasets have records for many of the same stations. This has resulted in duplication or overlapping records in the CCWR dataset as well as in the more recent records. Unfortunately the records were not always identical in their overlapping periods and it was not always possible to determine which of the more accurate version of the record was.

Another problem encountered was in the station location information metadata where often the CCWR and SAWS latitude, longitude and altitude information were not always identical between records. The differences were also not always consistent; i.e. it was not just a simple rounding or truncation to two decimal places. Additionally, the list of station locations from the data provided were to only two decimal places and this was not precise enough to correctly locate a station which presented difficulties where were multiple records in a small geographical region like a city existed.

A final problem to deal with was that SAWS and CCWR use a 9 digit long station ID code which geographically determined. Unfortunately, this code does not allow one to distinguish between two closely situated stations if one station had undergone a major upgrade.

Below are two examples illustrating these spatial/locational problems encountered in the station data. These situational problems had to be overcome in order to continue to the next phase of the project which was to perform the error checking on the data itself.

The South African Weather Service has a unique way to reference stations which is reflected in the station identity code. In referencing a station, the map and inset below (Figures 3.1a and 3.1b) were used in the following way:

1. A reference number consisting of two parts is allotted to every climate and rainfall station e.g. 145/470.
    - The first part of the number refers to the section in which the station falls as shown on the map of climate and rainfall station reference numbers (red cube).
    - The second part of the number indicates the position of the station within a specific section – each section consists of half a degree latitude by half degree longitude, and is further divided into one-minute intervals of latitude and longitude (see figure below).
2. The 900 inter-sections are numbered from top to bottom and in progressive longitudinal order, as indicated on the grid to the left.
3. As these intersections are about 1 mile apart in South Africa and provision has been made for the possible numbering of one station per square mile.
4. Where more than one station falls within the square mile A, B, C, etc. is added to the second part of the station reference number to differentiate between the stations, e.g. 145/470 145/470A, 145/470B, etc.
5. When a station is moved or undergoes significant changes/ upgrades, it is thought of as being a new station and therefore gets a new suffix e.g. 145/470A changes to 145/470B.
6. The circles in the figure on the left show the position of stations in section 145.

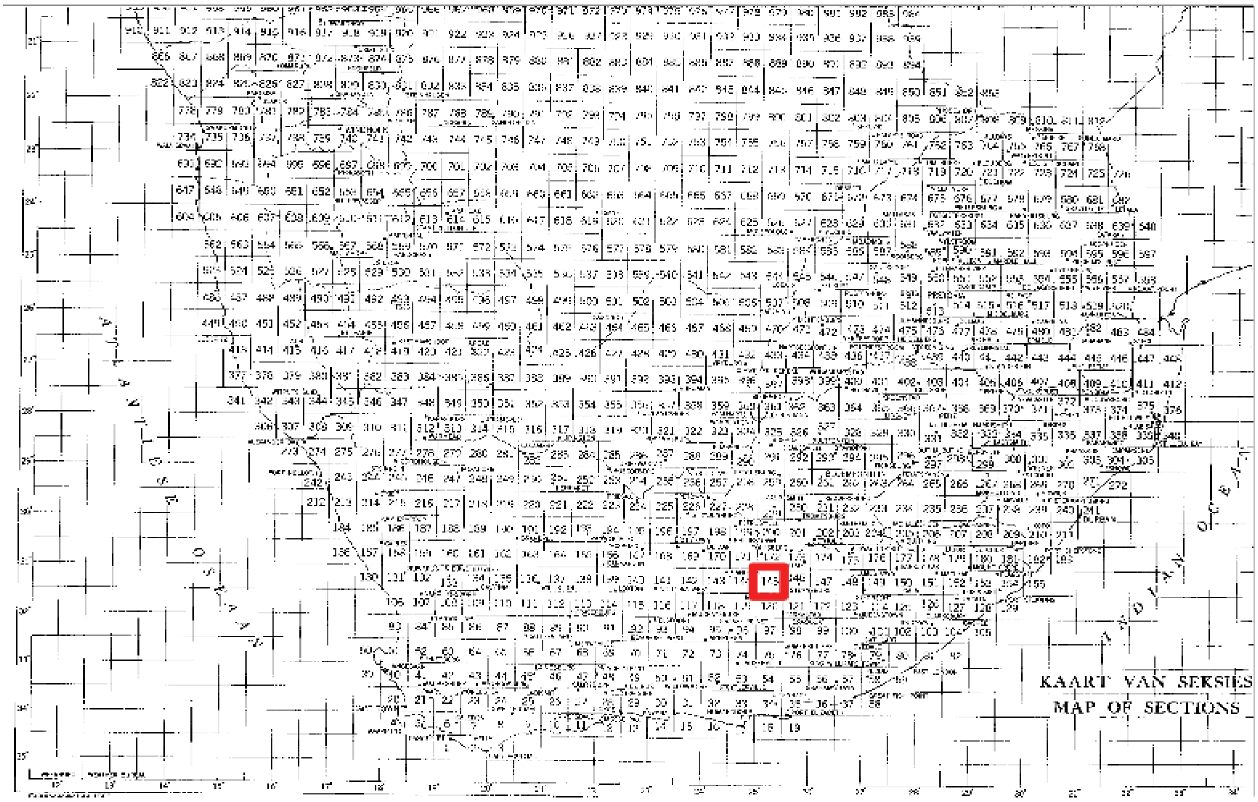


Figure 3.1a Climate station nomenclature scheme of the South African Weather Service.

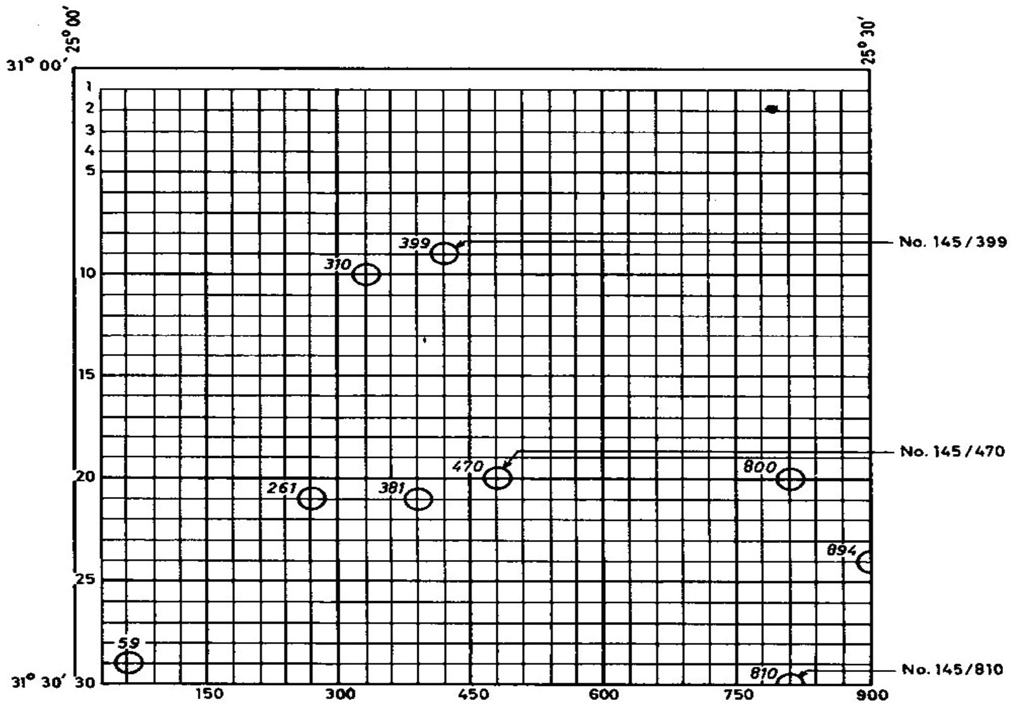


Figure 3.1b Climate station nomenclature scheme of the South African Weather Service.

The codes can now be written as a 9 digit ID. The original values are padded with zeros at the beginning and have a space if there is not an "A, B, C, etc." followed by a final number at the end (not sure what this last number represents). In the CCWR and cleaned data the space is replaced with an underscore. Below are some examples that demonstrate this procedure and some problems encountered in working with these data.

Example 1:

Langebaan is in Grid box 40/005 and is written as 0040005 6 (SAWS) or 0040005_6 (CCWR):

0040005 6	LANGEBAAN	-33.08	18.02	8	WESTERN CAPE	9291	1923/08/01	RAINFALL

Gansbaai is in Grid box 1/517 so is denoted 0001517 8 (SAWS) or 0001517_8 (CCWR); Danger Point is in the same 1 mile area and therefore is 1/517A and becomes 0001517A2 in both SAWS and CCWR records:

0001517 8	GANSBAAI DANGER POINT	-34.63	19.3	25	WESTERN CAPE	6	1959/04/01	RAINFALL
0001517A2	DANGER POINT	-34.61	19.3	28	WESTERN CAPE	9287	1985/08/28	ELEC_TEMP

Messina is in grid box 810/080 (0810080_1). The station was upgraded but not moved in 1955 and therefore it became 810/080A (0810080A6):

0810080 1	MESSINA	-22.33	30.05	538	LIMPOPO PROVINCE	8612	1955/06/30	CLOSED
0810080A6	MESSINA	-22.33	30.05	538	LIMPOPO PROVINCE	8612	1955/07/01	FIRST

The above is the original SAWS station history file that provides metadata about the station as well as the code format. The CCWR modified the code template slightly as they received data from sources additional to SAWS. They replaced the last value in the code with a letter representing the original source (e.g. W for SAWS, S for Sugarcane South Africa), e.g. 0091288_W, 0759116AP.

Example 2:

Sometimes there were multiple files for the same location that came from different sources. For example, in the table below (Table 3.1) is the header information of three stations from the CCWR dataset that appear to be the same station. Both the _A and _W stations had the same latitude and longitude; however, the altitude and station name differed. The station name indicated that this station was in fact an agricultural station and SAWS was not the primary data source. On inspecting the ARC data a station with the same station name as name 0079811_A in a similar position with a similar altitude was found for a short time period between 2000 and 2004 (last row).

Table 3.1. Metadata for the same station from the CCWR and ARC sources.

Station ID	*Latitude*	*Longitude*	*Altitude*	*Start Date*	*Close Date*	*Name*
0079811_A	-32.52	27.47	840	1939040112	2001080512	DOHNE_NS
0079811_W	-32.52	27.47	870	1959010112	2001123112	HAZELDENE
0079811AW	-32.52	27.47	870	1976120112	2000073112	HAZELDENE
11157	-32.51	27.46	899	2000010112	2004043012	_DOHNE_-_AGR

When the header metadata above from the CCWR were compared to the station history file from SAWS (see Table 2.2 below) more information could be gleaned and inconsistencies detected:

- Both CCWR header information and SAWS history indicate the station opened on 1939/04/01
- The CCWR had all three stations being within the same 1 mile area, while the SAWS list shows the _A0 station being in a different latitude location and different height.
- The CCWR _A and _W records continue until 2001 (the end of the CCWR record), while the SAWS list indicated that the station closed in 1977/12/01.
- The CCWR AW station record begins at the correct time, but differs in the lat- and altitude and name to that of the SAWS list.
- The ARC whose latitude and longitude were only 0.01 of a degree removed from the three stations above was also present and overlapped temporally for most of 2001.

Table 3.2. Metadata for the same station from the SAWS

0079811 6	DOHNE - AGR	-32.52	27.47	899	EASTERN CAPE	1057	1939/04/01	SECOND
0079811 6	DOHNE - AGR	-32.52	27.47	899	EASTERN CAPE	1057	1977/12/31	CLOSED
0079811A0	DOHNE - AGR	-32.54	27.47	901	EASTERN CAPE	1057	1976/12/01	FIRST
0079811A0	DOHNE - AGR	-32.54	27.47	901	EASTERN CAPE	1057	2007/03/01	ELEC_MANU
0079811A0	DOHNE - AGR	-32.54	27.47	901	EASTERN CAPE	1057	2008/02/01	ELEC_TEMP

3.3. Error Checking

The daily data were subject to a suite of quality assurance checks based on the GHCN tests[4]. The checks consist of several types of carefully evaluated tests that detect duplicated data, climatological outliers, and various inconsistencies (internal, inter-variable and temporal). A manual review of random samples of flagged values was used to set the threshold for each procedure such that the false-positive rate of the testing procedure was minimized. In addition, the tests were performed in a deliberate sequence to enhance the performance of the later checks by detecting errors with the checks applied earlier in the sequence.

A list of the quality assurance checks and the specific variables evaluated by each check is provided below. Temperature data were also checked for potential use later in the study.

Rainfall:

- *99 check* – Checks for incorrect assigning of undefined values (-99, -9.99, 9.99, 99, 999).
- Streak check – Checks for unrealistic sequences of identical values in time series of non-missing/non-zero values. Flags sequences of 10 or more consecutive identical values in time series of non-missing and nonzero precipitation observations.
- *Frequent-value check* – Checks for clusters of 5-9 identical moderate to heavy daily totals in time series of nonzero precipitation observations (values over 5mm/day).
- *World (continental) record exceedance check* – Identifies values that fall outside the world extremes for the highest and lowest ever observed (daily ppt > 1825 mm). This threshold is set too high for South Africa and was reset to 600 mm for our purposes.
- *Percentile-based climatological outlier check* – Checks for daily precipitation totals that exceed the respective 29-day climatological 95th percentiles by at least a certain factor (6 standard deviations).

Temperature:

- *99 check* – Checks for incorrect assigning of undefined values (-99, -9.99, 9.99, 99, 999).

[4] Global Historical Climatology Network – daily http://www.ncdc.noaa.gov/oa/climate/ghcn-daily

- Streak check – Checks for unrealistic sequences of identical values in time series of non-missing values. Flags sequences of 10 or more consecutive identical values in time series of non-missing daily maximum, minimum, and observation-time air temperature.
- *World (continental) record Exceedance check* – Identifies values that fall outside the world extremes for the highest and lowest ever observed (between -34.00°C and 67.80°C in Africa)
- *Naught check* – Checks for days on which maximum and minimum temperature are both equal to 0°C.
- *Z-score-based climatological outlier check* – Checks for daily surface air maximum and minimum temperatures that exceed the respective 15-day climatological means by at least six standard deviations.
- *Temporal consistency check (spike or dip)* – Checks whether a daily maximum (minimum) temperature differs from the maximum (minimum) temperatures on the preceding **and** following days by more than 25°C (both up and down).
- *Lagged temperature range check* – Identifies maximum temperatures that are at least 40°C warmer than the minimum temperatures on the preceding, current, and following days as well as minimum temperatures that are at least 40°C colder than the maximum temperatures within the three-day window.
- *Tmin >= Tmin* – daily minimum surface air temperature that are greater or equal to that day's maximum surface air temperature.
- *Duplicate data check* – Checks for duplication of the data between entire years, different years in the same calendar month, different months within the same year. In the case of precipitation at least three non-zero precipitation values must be available during the month (zeros are ignored).
- *Spatial consistency check (corroboration of anomalies)* – checks for temperatures whose anomalies differ by more than 10°C from the anomalies at neighbouring stations on the preceding, current, and following days.
- *Spatial consistency check (corroboration of precipitation amounts and percentiles)* – checks for precipitation totals that differ significantly from totals (and percentiles) reported at neighbouring stations on the preceding, current, and following days.

Many stations were represented in multiple datasets at different time periods so it was possible to concatenate these into one longer time series. This was done in the middle of the cleaning procedure before the tests where the values were compared to the climatologies. The length of records was checked before the climatological tests and only those that had at least 3650 valid values (10 years) were retained.

A number of common errors were identified in the records, these include:

- Undefined values set to the wrong value – most of these errors were set to some variety of 99 (999, -99 being the most common).
- Undefined values set to zero. For temperature this error can be identified by comparing the maximum and minimum temperature records but it not possible to identify these errors in the precipitation record.
- Negative minimum, and to a lesser degree maximum temperatures were incorrectly assigned to zero between 1988 and 1997. It appears that a precipitation negative value check was performed on this data. Replacement data for this period has been acquired for all the SAWS stations, but some stations were still uncorrected.
- Many of the earlier records showed a 1 day lag between the day the maximum and minimum temperatures were recorded. For example, for values observed at 8am on the January 2^{nd}, the maximum temperature was recorded on January 1^{st}, while the minimum temperature was assigned to the 2^{nd} of January. These errors are not consistent through the whole record so it was not possible to correct. Where this was encountered data were set to undefined.
- The maximum and minimum temperatures were sometimes swapped or the same values were recorded for both records. Both the variables are set to undefined in these cases.
- The values for a whole month (normally December) were incorrect and seemed to be taken from another station, or from a previous year. This error is identified by comparing the records from different sources (e.g. SAWS and ARC). In these cases data were set to undefined.

3.4. Concatenation procedures

The concatenation or merging of data from different datasets and sources was a challenging problem and needed an iterative methodology to determine the best way to address the problem. The SAWS provided a list of all their stations with metadata including the station name, latitude, longitude and altitude. It also provided information on when they started and if they were changed, moved, upgraded or closed. This information, however, did not always agree with the data found in stations in the CCWR dataset and it required automatic and manual checking on these records to correctly merge the data.

The initial method simply concatenated stations if their latitude and longitude were the same which worked most of the time. However, the newer SAWS and ARC data often had slightly different locational metadata to that of CCWR and therefore the code written to perform the merging of the stations incorrectly assumed these records were for different stations. Another problem with this method was that there were times when there are multiple stations within close proximity (e.g. in cities) and initially these records for different stations were incorrectly merged together.

To address this, a second methodology then used the station ID in order to identify records for a specific station. The basic method is described below and was performed in two stages. Results were also manually checked to determine whether two records represented a single station which had undergone an upgrade (which does not significantly alter the values), or if it represented two separate stations.

The code checked if the station ID of records were identical excluding the last digit. If they were, the records were assumed to be for the same location. The records often had overlapping periods, which could be used to check whether these records represent two versions of the same record. Only if 80% of the valid values were identical in this overlap period were the records merged together. Unfortunately, there were often small differences between the records. Some of these differences were because only one version contained recorded data whereas the other was filled with undefined values. A further problem occurred when small differences were scattered throughout the record where the differences do not seem to follow a clear rule (rounding up, truncation, underestimation, etc.). Records displaying these characteristics were flagged and inspected manually after which a subjective decision was made how to concatenate the data. In the case where there was no overlap in two consecutive time slices in SAWS stations for the same location, the records were assumed to be for the same station since all the meta data (ID, name, latitude, longitude and altitude) were identical.

The records were merged in a specific order, with data from the more recent SAWS datasets being given preference over the older CCWR data. Within the CCWR there was also a need for an order in determining to how duplicate records were merged. Here the ID suffix was used to determine the ordering. From observations, it seemed that the A suffix, followed by W, P, X and S was the most logical ordering. This ordering was employed except when the higher preference station had a missing value whereas the other version recorded a valid value. In this case the valid record was inserted into the merged record.

After this first iteration of the concatenation there were stations identified that required further manual investigation, these were largely stations that had undergone upgrading. In these cases, where the IDs were identical except for the last two digits, the records either represented two closely situated stations, or a station that had been upgraded. To determine if the records should be concatenated together or left as separate stations, the overlapping periods and station names were compared, the names were checked against the SAWS station list and the Rh-test was run on the data to test for differences. Stations were concatenated assuming that the latest data/files were the most reliable and were used as priority over the others. If there was an overlap in time the more recent data was used unless the newer file had undefined values and the older file had overlapping valid data. If it turned out the values were invalid or had errors, these errors would be captured in the final stage of cleaning. Figure 3.2 below illustrates the concatenation of different versions of data record together. The top two rows represent two CCWR stations that have the same station ID but a different last digit – here the _A file (second row) was deemed more reliable than the _W file (top row) and therefore the _W file was only used for the period when there was no other data available (see black period in bottom row). The third and fourth rows indicate a similar situation for SAWS sourced data where the most recent data are shown in the fourth row. The final multiple sourced product of the concatenation is shown in the last row.

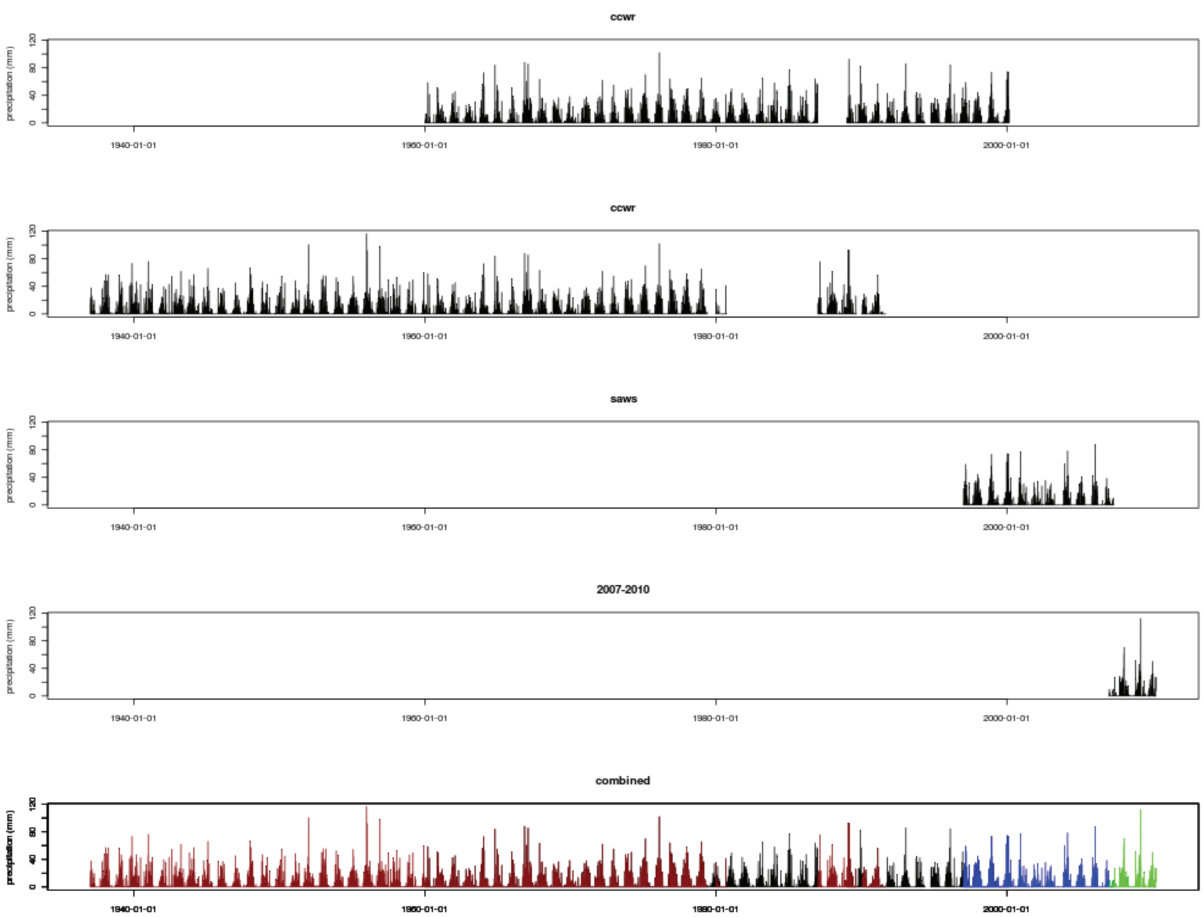


Fig. 3.2. Concatenation of multiple data sources into one record.

As mentioned above, the concatenation of stations occurred in the middle of the error checking sequence before tests against climatological values were performed. Once a station had been concatenated, the length of the record was checked before the climatological tests and only those that had at least 3650 valid values (10 years) were retained.

Below is another, more complex example of how data were concatenate to form a continuous record for a station.

3.4.1. A complex concatenation example

The same station as above is used to demonstrate difficulties encountered in merging data files due to small but important differences. Below are examples of errors encountered in the data records illustrate the difficulties encountered in this process. The text is illustrated by the tables below and the columns represent the date, _A, _W and _AW stations respectively.

The _A file is the oldest file with the earliest start date of 1939/04/01. The _W file began in 1959/01/01, however, the first value was actually for the day before and therefore there is a 1-day time slip, this slip is corrected on 1960/01/01. The same error is found from 1962/04/01 – 1962/07/01 and 1974/01/01 – 1975/12/31:

58/12/30	13.3	
58/12/31	13	
59/01/01	4.7	13
59/01/02	0	4.7
59/01/03	3.7	0
59/01/04	3	3.7
59/01/05	6.2	3
59/01/06	0	6.2

For the month of January 1976 the _A all values were set to zero while _W had the actual values:

76/01/01	0	0.1
76/01/02	0	0
76/01/03	0	17.8
76/01/04	0	6.5
76/01/05	0	0
76/01/06	0	0.1
76/01/07	0	0
76/01/08	0	0
76/01/09	0	32.5
76/01/10	0	0
76/01/11	0	11

From 1976/10/13 the values for the two records were slightly different. It appears the _W values are actually for the new station AW which is located in a slightly different location (see table on the right). This is supported by the fact that the values are identical to the new record when it begins on 1976/12/01 (far right column):

76/10/09	0	0
76/10/10	1.4	1.4
76/10/11	2.5	2.5
76/10/12	1	1
76/10/13	1	0.8
76/10/14	9	9
76/10/15	6.8	6.7
76/10/16	0.6	0.6
76/10/17	5.2	5
76/10/18	0	0
76/10/19	2.2	2
76/10/20	9	8.2

76/11/24	4.7	4.5	
76/11/25	0	0	
76/11/26	0	0	
76/11/27	0	0	
76/11/28	0	0	
76/11/29	0	0	
76/11/30	0	0	
76/12/01	0	0	0
76/12/02	0.6	0.6	0.6
76/12/03	30	30.5	30.5
76/12/04	0	0	0
76/12/05	0	0	0
76/12/06	0	0	0
76/12/07	0.5	0.4	0.4
76/12/08	0	0	0
76/12/09	2	2	2

The AW station stopped reporting from 1977/01/01 (till 1978/01/01) and the _W station recorded the same values as _A until 1977/02/24 after which it again differed from _A by a small amount relatively often (as illustrated above):

76/12/27	6.3	6.4	6.4
76/12/28	0	0	0
76/12/29	0	0	0
76/12/30	0	0	0
76/12/31	1.3	1.3	1.3
77/01/01	0	0	-999
77/01/02	0	0	-999
77/01/03	3.5	3.5	-999
77/01/04	7.5	7.5	-999
77/01/05	0	0	-999

On 1978/01/01 AW resumed reporting and _W stopped. _A and AW do reported slightly different values from time to time:

77/12/29	31.5	31	-999
77/12/30	100.8	-999	-999
77/12/31	8.6	8.5	-999
78/01/01	4.8	-999	0
78/01/02	0	-999	0
78/01/03	0	-999	0
78/01/04	8.5	-999	8.2
78/01/05	2.6	-999	2.6

From 1987/01/01 till 1988/12/31 AW also stopped reporting and was again almost identical to _A, but every now and again they differed.

From 1989/07/01 to 1989/12/31 _A stopped reporting. From 1990/01/01 all three records were reporting identical values, until 1991/08/01 when _A stopped reporting. In 1992/02/01 _W also stopped reporting:

89/12/29	-999	-999	0.3
89/12/30	-999	-999	0
89/12/31	-999	-999	2.1
90/01/01	4.2	4.2	4.2
90/01/02	2.1	2.1	2.1
90/01/03	0	0	0
90/01/04	0.5	0.5	0.5
90/01/05	0.2	0.2	0.2
90/01/06	27	27	27

On 1997/01/01 a new SAWS A0 version of the station started and data were identical to that of AW. In 2000/01/01 _W resumed reporting values identical to AW and A0.

On 2000/08/01 A0 stopped reporting (fourth column from the left). _A resumed reporting from 2000/08/01 till 2000/11/01, but was 7 days late for the first month. _A0 resumed again from 2001/05/28, but ended on 2001/08/05 and _W ended on 2001/12/31when A0 resumed and continued reporting until 2010:

00/07/29	-999	0	0	0
00/07/30	-999	0	0	0
00/07/31	-999	0	0	0
00/08/01	0	0		0
00/08/02	0	0.9		0.9
00/08/03	0	0		0
00/08/04	0	0		0
00/08/05	0	0		0
00/08/06	0	0		0
00/08/07	0	0		0
00/08/08	0	0		0
00/08/09	0.9	0		0
00/08/10	0	0		0

Additionally, there was also ARC data for this station from 2000-2004 as well as data for this period from SAWS. Upon inspection it was determined there were more errors in the ARC data than in the SAWS data so the ARC data was not used in the concatenation.

3.5. Summary

Station data cleaning (based on GHCN criteria) and concatenation procedures were applied to station data obtained from the CCWR, SAWS and ARC. This procedure identified a many errors in the station data, conflicts in the metadata between the three data sources as well as complexities around station nomenclature. However, through this procedure, we were able to identify stations that could be used in the rest of the study. Two simple steps were taken in determining which stations would be used for this analysis. The study period is restricted from 1979 to 2009 (see Chapter 3), so the first step identified stations with records that included observations throughout this 31 year period to be selected. This reduced the sample of stations from the initial 4011 stations to 1034. The second step entailed filtering out stations based on how much missing data there was during the study period. The amount of missing data present during the study period was checked for each station and stations with less than 95% of data missing were excluded. This reduced the number of stations further down to 698 stations covering South Africa from which to make a selection.

Chapter Four. Identifying synoptic circulations associated with extreme rainfall

4.1. Introduction

The large-scale synoptic circulation establishes the environment for the regional daily weather response. These dominant circulations often have smaller scale circulations associated with them (such as coastal lows, convective systems, land and sea breezes, etc. described exhaustively in Tyson and Preston-Whyte (2000)). So a quantification of the large-scale circulation-regional response would assist in identifying synoptic states associated with extreme rainfall. Achieving this involves the reduction of a large number of variables into a smaller set of data that should still represent the original data. For example, precipitation is a function of many variables (pressure, temperature, humidity, etc.) so the relationship between these variables must be preserved when relating synoptic scale process to the local scale precipitation response. To this end, self-organizing maps (Kohonen, 1997) were employed to reduce multivariate atmospheric data and produce generalized modes of synoptic circulation over South Africa. Self-organizing maps (SOMs) are a form of artificial neural net (ANN) that reduces high dimensional data space to a lower dimensionality (usually two-dimensional), discretized representation of the input data and produces a map of discretized data archetypes. They are a data description and visualization tool that extracts and displays the major characteristics of the multidimensional data distribution function (Hewitson and Crane, 2006) to produce an array of generalized data archetypes.

This study uses SOMS to categorize daily atmospheric data for 31 years into a number of archetypal circulation modes from which it is possible to infer local weather characteristics. The circulation modes can be easily visualized as an array of synoptic states spanning the continuum of weather causing events. The relationship between synoptic scale circulation modes and the local scale responses can then be investigated using rainfall data from stations. In South Africa, flooding caused by extreme rainfall may be a function of individual synoptic states or interactions between different states. For example a single cut-off low system caused severe flooding and loss of life in Montagu in the Western Cape in March 2003 whereas a in February 1996 widespread flooding throughout almost the entire summer rainfall region was caused by the interaction between tropical lows, two strong mid-latitude cyclones and two ridging anticyclones (Edwards, 1997; Crimp and Mason, 1999).

Two SOM analyses were performed. The first assessed all days in the 31 year time period to categorized the archetypal synoptic states that represented this period. This assessment was used to identify general synoptic states affecting the region as well as those that can be associated with extreme rainfall. The second analysis used data only from days that experienced extreme rainfall during the 31 year period. This facilitated an in-depth assessment of extreme rain causing synoptics and the characteristics of these.

The section below presents a detailed explanation of the SOM procedure as well as how it is used in this study. The configuration of the SOM and the input (training) method is described data and some results are shown. All results shown in this section are derived from the first SOM assessment of the full 31 year period.

4.2 The SOM method

This technique classifies input data into a predefined number of reference patterns or modes using an unsupervised artificial neural network (ANN). The ANN facilitates a non-linear projection of the probability density function of high-dimensional input data onto a two-dimensional array of nodes while still spanning the full continuum of the data space. The SOM identifies nodes within a given data space such that the nodal distribution fully represents the observed distribution, providing a means for data to be generalized into a number of arch-types. The main advantage of the SOM technique is that it can be applied to non-linear data (such as the continuum of atmospheric conditions) and it does not force orthogonality (as for example in principal component analysis (PCA)). The application of SOMs to atmospheric circulation reduces the degrees of freedom in the data by forming archetypal circulations and facilitates the identification of dominant modes of circulation within the data set. In addition, the results can be directly physically interpreted as an array of atmospheric states, unlike, for example the PCA approach which produces patterns of variance rather than direct physical states of the atmosphere (see Reusch et al., 2005). The SOM software used in this study is SOM_PAK version 3.1[5] which has three distinct stages in the data mapping routine in which (1) the type and size of the SOM is set, (2) the training occurs and (3) error is evaluated and results are visualized.

[5] Software and documentation available online at http://www.cis.hut.fi/research/som_lvq_pak.shtml

4.2.1. SOM architecture

The SOM architecture is comprised of an output layer of nodes in a single or multi-dimensional lattice, which can be arranged in a rectangular or hexagonal topology. The rectangular lattice is used in this study as it facilitates easier visual display and analysis, although the choice of lattice has little effect on the end product (Openshaw, 1994).

The size of the map is chosen subjectively according to the degree of generalization desired and has a strong bearing on the range of synoptic situations represented. A fewer number of nodes in the SOM array would result in more generalized circulation archetypes, while a greater number of nodes would represent a wider range of circulations. Although South African synoptic systems have been categorized into six to eight main types of circulation (Tyson and Preston-Whyte, 2000), in assessing synoptic states associated with extreme rainfall it was decided to use a large map in an attempt to tease out and identify specific synoptic states associated with extreme rainfall. Then a random distribution of nodes within the data space is defined during which the reference vectors of the map are initialized with either random or linear values. In the latter, reference vectors undergo an orderly initialization along a two-dimensional subspace spanned by the two principal eigenvectors of the input data vectors. The former allocates random numbers to the reference vectors equally across the data space. Both initializations are equally effective, although more care needs to be taken with input data preparation when using the latter. A random initialization was chosen for the SOMs in this study.

Although South African synoptic systems have been categorized into six to eight main types of circulation (Tyson and Preston-Whyte, 2000), in assessing synoptic states associated with extreme rainfall it was decided to use a much larger map to tease out and identify specific synoptic states associated with extreme rainfall. On testing various SOM sizes a 40-node SOM was selected that adequately represent all the expected synoptic types. Using a larger number of nodes did not contribute any more information to this chosen size.

4.2.2. SOM training

The second stage of the SOM is the map training process. Training the SOM is an iterative process in which the weights on a node are adjusted toward the training vectors such that they span the variance structure of the data space. Training vectors are obtained from a set of predictor variables that are, in this case, obtained from a climate reanalysis (described below). Mean Sea Level Pressure (MSLP) and the 500 hPa geopotential height (z500) were used as training variables for the SOM as these are able to give a good indication of processes associated with the regional atmospheric circulation. The former provides information about the surface circulation and is also used to identify circulations like cold fronts, low pressure troughs, tropical temperate troughs and sub-tropical systems. The latter variable can be used to provide information about the upper air characteristics like depth of a particular system as well as to identify cut off lows.

The training data used was the new, high resolution reanalysis dataset, namely the Climate Forecast System Reanalysis[6] (CFSR) produced at National Centre for Environmental Prediction (NCEP). It was decided to use this dataset as the resolution of the reanalysis is 50 km – higher than the resolution of other reanalyses such as the NCEP Reanalysis 1 & 2 (2.5 degrees), ERA 40 (2.5 degrees) and ERA Interim data (0.75 degrees). At the resolution of the CFSR dataset it should be possible to identify and investigate the characteristics of synoptic scale features such as cut-of lows, west coast troughs, and tropical temperate troughs – all circulations systems that are often associated with extreme rainfall. Daily data were extracted for a domain over southern Africa whose latitudinal extent encompasses synoptic circulations from the sub-tropics to the mid-latitudes and whose longitudinal extent would capture the evolution and translation of mid-latitude cyclones. The resultant domain stretched from 20^{o}S-40^{o}S and 15^{o}E-35^{o}E and consisted of 61x45 grid cells. Training data were standardized using the means and standard deviations of the 61x45 grid time series to preserve the local gradients in each field. In doing this each six-hourly atmospheric state over the region was represented by a 2745-element vector which formed the training data for the SOM.

During the training process, the node whose weight matches the input vector most closely (having the minimum Euclidian distance between node vector and data vector) is chosen as the 'winning' node for the particular vector. Unlike most clustering techniques, not only is the winning node updated but the nodes surrounding the winning node also benefit from the learning process by adjusting their weights such that each vector converges to the input pattern. These form an update neighbourhood, at whose centre the winning node lies. Two important parameters are set in this process – the radius of influence and the learning rate. The radius of influence determines how many nodes surrounding the winning node are updated. This can be thought of as the "stiffness" of the SOM. This parameter should start off quite high to ensure that the topology of the map is

[6] http://dss.ucar.edu/pub/cfsr.html

maintained strongly while it aligns itself with the data. It is then slowly reduced to unity to allow individual nodes the freedom to achieve a final stable position within the data space. A proper ordering of the map is achieved if the radius is initially set to a higher value, as a value set too low at this stage may cause various types of error on the map (Kohonen, 1997). The learning rate determines how fast the weights move towards the data points. Should this parameter be set too high, so that the map moves rapidly towards the data distribution, it may lead to an unstable solution, while too small a learning rate results in the analysis taking longer to converge on a solution. However, the computational needs of the SOM analysis are very modest so a small learning rate is usually set and an arbitrarily large number of iterations are made. The learning rate decreases to almost zero towards the end of the training to allow the map to stabilise and settle on a final solution. The vectors adjust during the iterative training process such that they span the whole data space (unlike other clustering techniques) where the number of iterations is chosen such that final convergence (the fine adjustments of the nodes in the data space) can be achieved by the end of the training. Hewitson and Crane (2002) note that, unlike a feed-forward type of artificial neural network, a function is not fitted so the SOM cannot be over-trained or over-fitted, facilitating a redundantly large number of training iterations.

A two phase training process was employed in which the initial phase first developed a broad-base mapping of the SOM (orders the map) and the second phase developed the finer aspects of the array to capture the maps final convergence. The SOM procedure then identifies archetypes that span the data space, such that the two diagonals of the node array are analogous to the first two principal components, or EOFs of the data (although they are not necessarily orthogonal to each other). The nodes in between represent the transition states between these 'extremes' (Hewitson and Crane, 2002). For precipitation data this results in the one axis capturing the very dry to very wet states, and the second axis captures spatial variation in the dominant precipitation patterns. For sea level pressure, one axis would capture the dominant high to dominant low pressure systems and the second axis the spatial variation in pressure states across the region.

In the first training phase the radius of influence was set to 4, the learning rate to 0.1 and the number of iterations to 10 000. In the second, refining phase, the radius of influence was set to 1, the learning rate to 0.01 and the number of iterations to 1 000 000. The result of the training is a two-dimensional map of nodes whose weight vectors span the data space continuum as represented by the input data. Each node represents a position that is the approximate mean of the nearby data samples, or 'archetypal' points in the data space. This procedure places nodes most dissimilar from each other furthest from each other and locates nodes most similar to each other closely.

4.2.3. Evaluation of error and visualization

The third stage of the process evaluates the quantization of error in order to attain the best SOM. For each input vector, the winning node is selected through an assessment of the Euclidean distance to the node vectors. The shortest distance between nodes, or quantization error, is calculated and the input vector is allocated to that node. In this way each day in the 31 year time period is associated with a particular node. The best SOM is attained when the averaged minimum Euclidean distance is obtained (the smallest average quantization error). Detection of error in the SOM can be monitored easily through the use of Sammon maps (Sammon, 1969). Sammon maps use a non-linear mapping technique that allows the mapping of high dimensional data space to a lower dimensional data space whilst maintaining the structure of the data. It does so by creating a two-dimensional image of the reference vectors where distance between the node image vectors approximate the Euclidean distances in data space. The training of the SOM produced a very ordered Sammon map which made for an easy interpretation of nodal relationships (Fig. 4.1). The SOM places more nodes in regions of the data space where there are more data elements so where nodes in the Sammon map are close together this would indicate a denser data space. As each individual data element is associated with the best matching node in the map, the individual quantization error can be used for calculating the frequency that each node was mapped to over the 31-year period (Fig. 4.2). The mapping frequency is homogeneous across the map indicating that days in the 31-year time period were evenly distributed across the synoptic archetypes, which is a characteristic result.

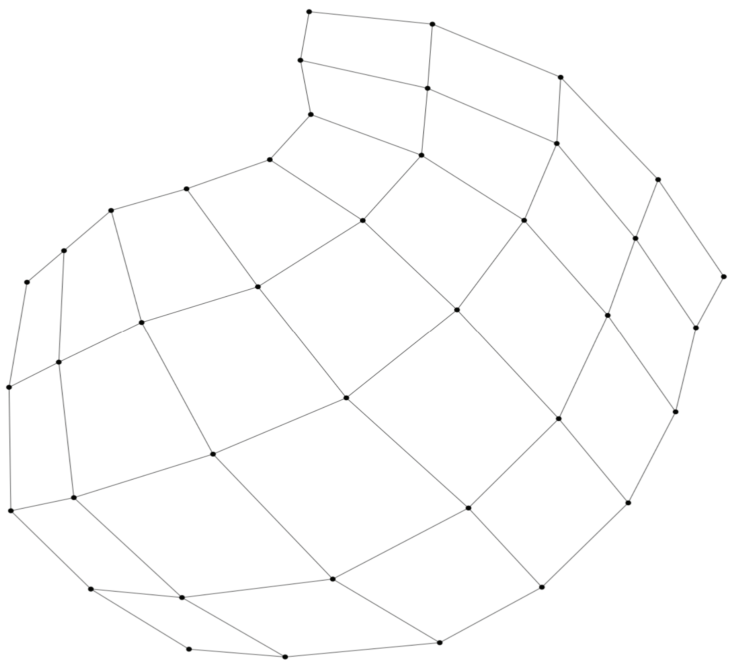


Figure 4.1. Sammon map indicating the relationship between nodes in the SOM. Nodes closer together indicate a denser region of the data space.

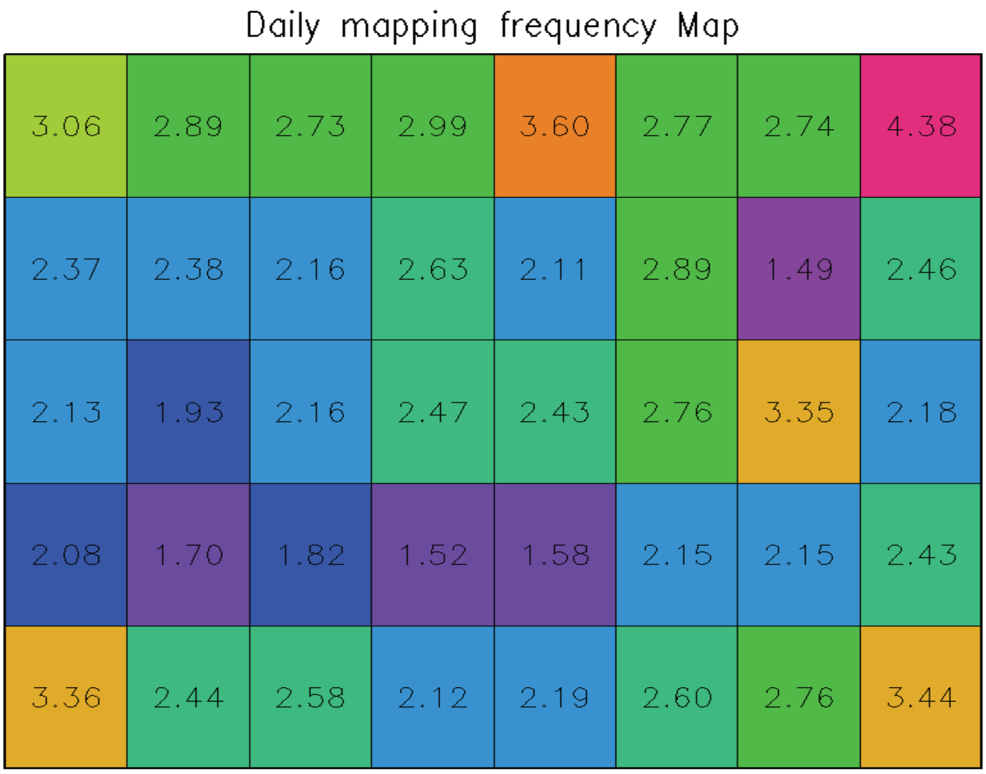


Figure 4.2. Frequency map indicating in percentages the frequency each node was mapped to over the 31 year time period.

Once the average quantization error has been minimized, the relationships between the predictor data and the nodes can be investigated. Each individual data element used in the training procedure is associated with the best matching node in the map and used to create representative archetypes for the input data. The 40 archetypal MSLP and Z500 states produced by the SOM for the 31 year period are shown in Fig. 4.3. These circulation modes/archetypes/states range from node 6 which represents a high pressure regime dominating most of the country to node 33 which represents a low pressure regime over most of the country. It is a characteristic of SOMs to place greatly dissimilar states on opposite sides of the map. From the frequency map above it can be seen that high frequencies are at the corner nodes (typical of the SOM procedure) where daily circulations represented by e.g. node 40 occurred 4.38% of the time in the 31 year time period . A general synoptic assessment of the SOM results indicates transient low pressure systems at relatively low latitudes are evident on the lower left of the SOM; towards the top and left of the SOM are nodes representing circulations associated with the sub-tropical low pressure trough; that link with the mid-latitudes; a ridging high pressure is evident in the bottom right nodes and in the middle of the map are synoptics that indicate a sub-tropical low in the north and transient highs in the south.

4.3. Seasonal analysis

In order to examine the seasonal distribution of synoptic circulations seasonal data were passed through the trained SOM and mapped to each node to produce seasonal frequency maps (Fig. 4.4). Immediately evident is the mapping of summer days to the top and left of the SOM and winter days to the bottom and right. The most frequently mapped to node in summer was node 37 followed by nodes 36, 35, 34 and 33. These were all associated with a subtropical low pressure over the interior and a high pressure over the south of the country. These synoptic states are associated with rainfall in the interior of the country. In winter the highest mapped to node is node 8, which is associated with a surface high over most of the country and an upper air ridge, typical of winter synoptics here. The next most frequently mapped to node is node 23, which is associated with an approaching upper air trough in the mid-latitudes and a surface low. Other frequently mapped to nodes are nodes 1, 2 and 3 which are associated with a surface and upper air trough in the mid-latitudes and a surface ridging high in the case of node 3. These nodes are likely associated with rainfall in the south western and southern Cape caused by the passage of mid-latitude cyclones. Autumn mappings are predominantly to nodes in the top and right of the SOM and are associated with a surface trough over the western parts of the country, a surface high over the east and in the upper air a high over the interior with indications of a trough in the mid-latitudes. These synoptics indicate a weakening of the sub-tropic low as the Inter-Tropical Convergence Zone (ITCZ) moves northward in this season. Spring mappings are towards the centre of the SOM which represent a sub-tropical low over the interior and high pressure to the south at the surface which is demonstrated well by the most mapped to node, node 21.

The SOM generated archetypal circulations that correspond to the expected mappings based on South African seasonal circulation characteristics described in, for example, Tyson and Preston-Whyte (2000). Additionally the SOM identified characteristic seasonal circulations successfully.

As each day that was used in generating the SOM mapped to a particular it is possible to match daily observational station data with corresponding daily data that were used to train the SOM. Data in the station records can therefore be matched with the circulation modes produced by the SOM to examine the relationship between the circulation modes and extreme rainfall data. Therefore days that recorded extreme rainfall in the station data record could be assigned to a node to investigate if particular synoptic circulations were associated with extreme rainfall. These results are presented in the next section.

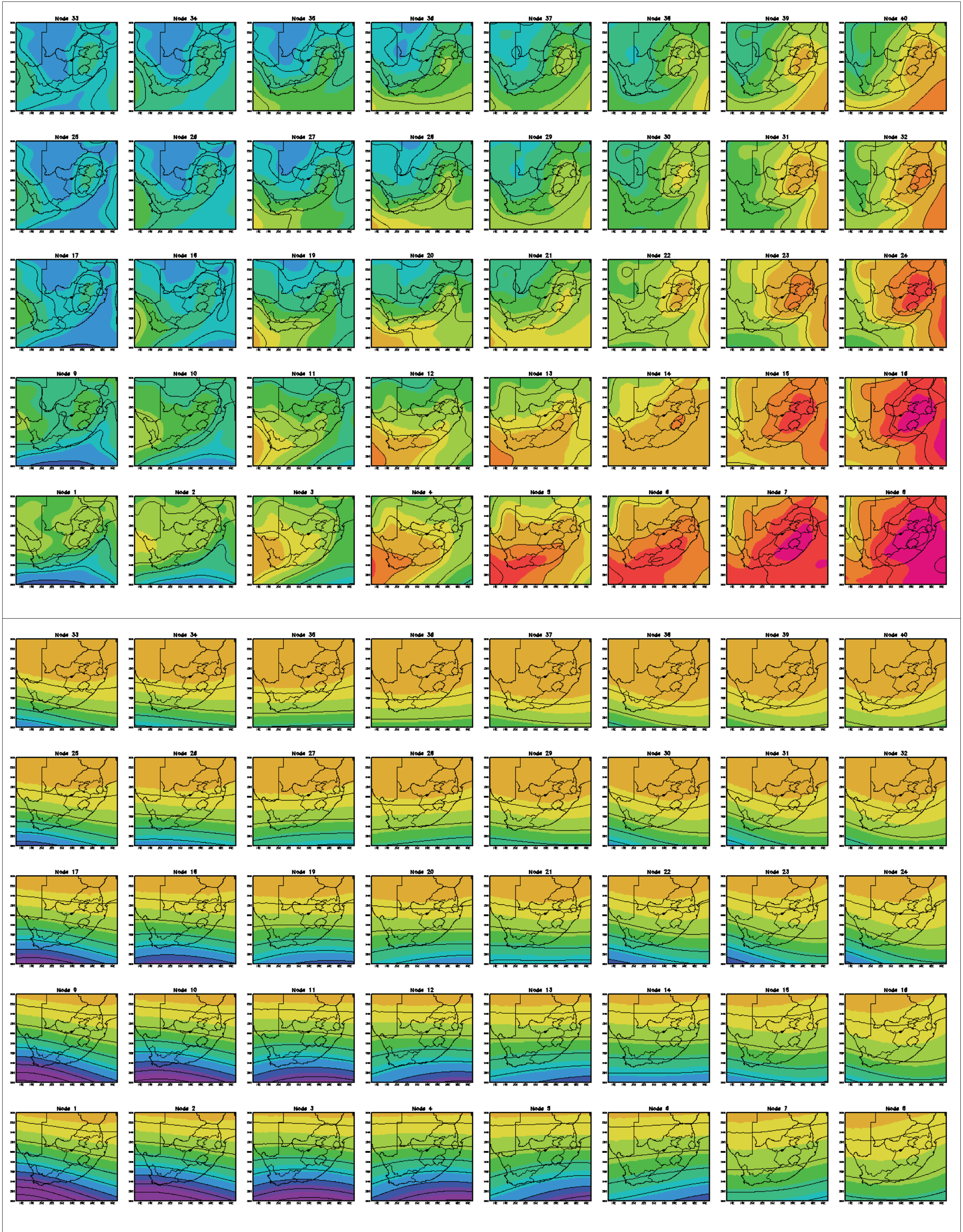


Figure 4.3. Forty archetypal MSLP (upper panel) and Z500 (lower panel) circulation states produced by the SOM for the period 1979-2009.

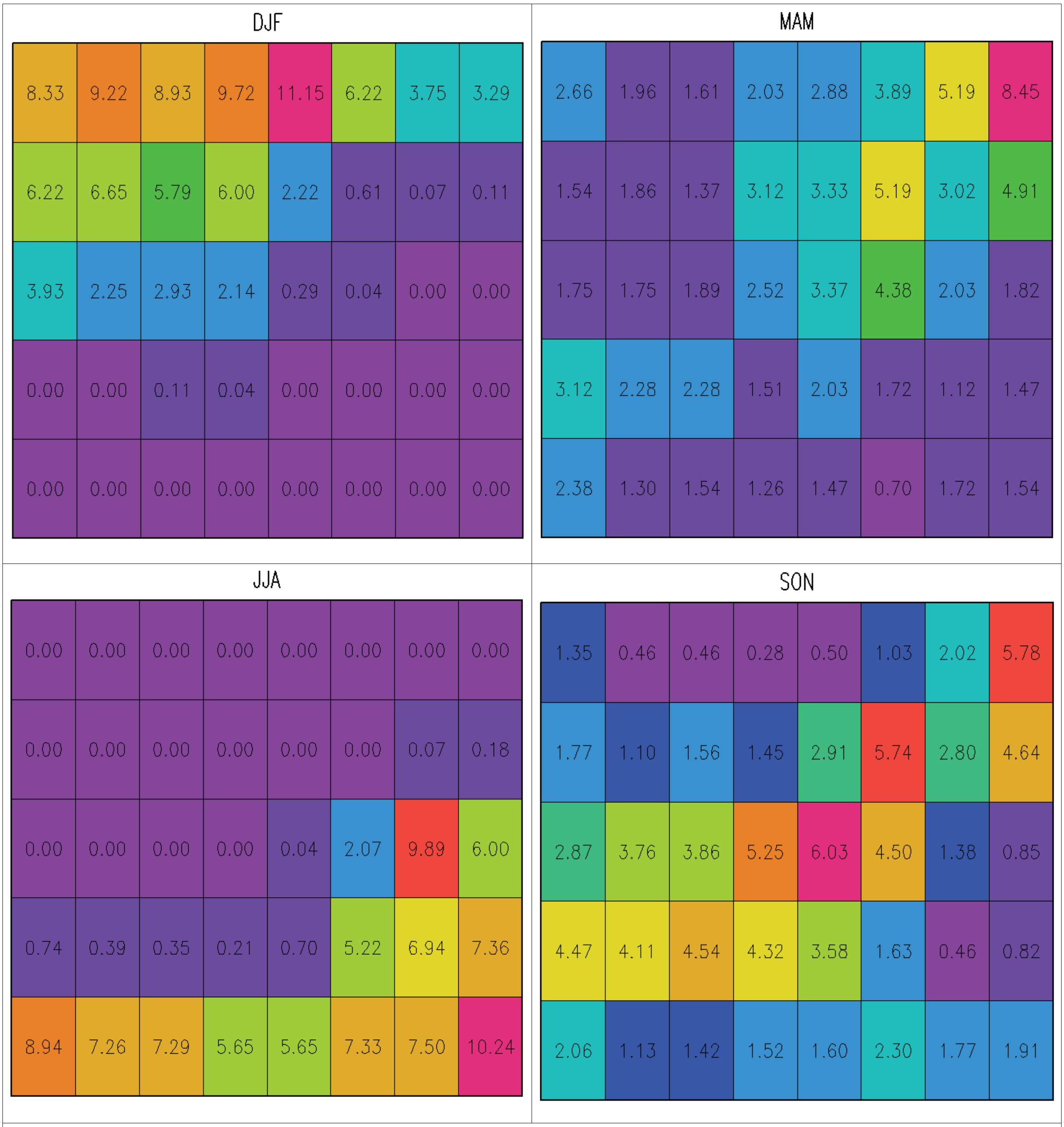


Figure 4.4. Seasonal frequency mappings for the 31 year period.

4.4. Identification of synoptic states associated with extreme rainfall

4.4.1. Extreme rainfall synoptics in the full study period

South Africa has a rather wide spatial coverage of rainfall stations throughout the country consisting of more than 4000 available stations to select from. However, as described in the data quality control section earlier, not all this data was usable. Two simple steps were taken in determining which stations would be used for this analysis. As the reanalysis data is only available from 1979 to 2009, the first step identified stations with records that included observations throughout this 31 year period to be selected. This reduced the sample of stations from the initial 4011 stations to 1034. The second step entailed filtering out stations based on how much missing data there was during the study period. The amount of missing data present during the study period was checked for each station and stations with less than 95% of data missing were excluded. This reduced the number of stations further down to 698 stations covering South Africa from which to make a selection.

Having identified stations with a usable record, an extreme rainfall threshold was set as the 95th percentile level in each station and all days in the record that matched or crossed this threshold were extracted. The circulation data for each day that experienced extreme rainfall was then extracted from the reanalysis and passed through the trained SOM to associate extreme rainfall with circulations identified in the SOM.

The results indicated that, compared to the rest of the nodes, one node was highly mapped to (Fig. 4.5). The synoptics associated with this node (node 25) are an approaching trough in the mid-latitudes in the upper air associated with surface low over the central interior and south east coast. In other frequently mapped to nodes around node 25 (e.g. 33, 34, 35, 36, 26, 27, 28) the surface trough over the interior is present throughout. Extreme rainfall in the 696 station is therefore predominantly associated with summer types of circulations where a deep surface low pressure exists over the interior of the country. The frequency mapping to winter types of circulations is relatively low largely as a result of the high station density in the summer rainfall region compared to the winter rainfall region (Fig 4.6).

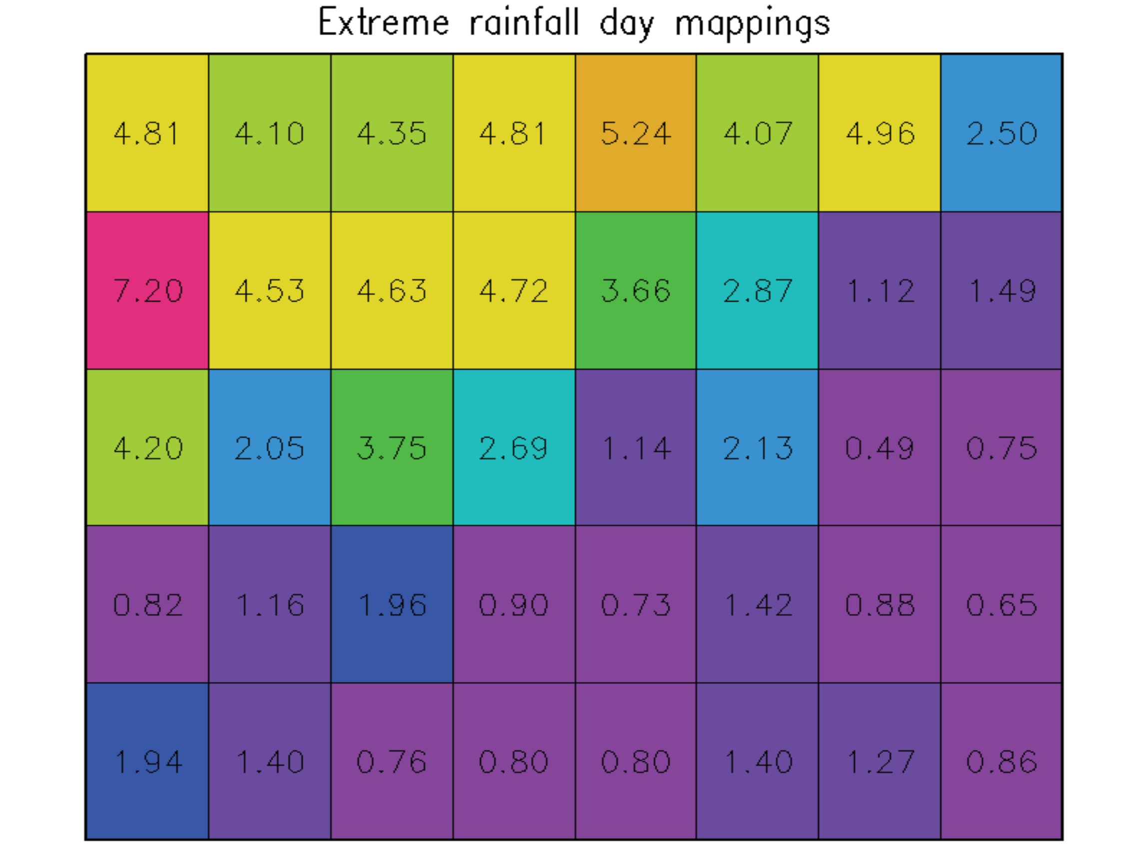


Figure 4.5. Frequency mapping of extreme rainfall days to nodes of the trained SOM.

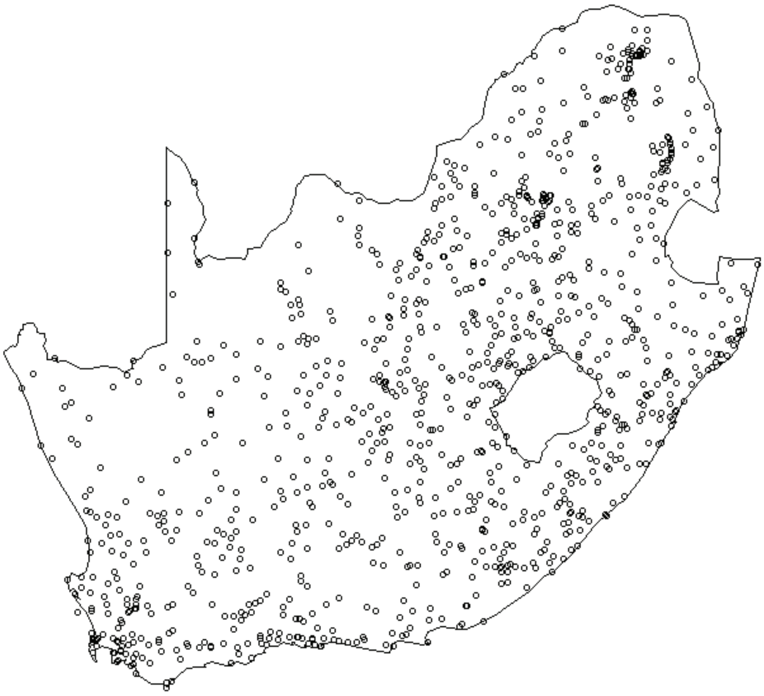


Figure 4.6. Station distribution of the 696 stations.

4.4.2. Extreme rainfall SOM analysis

To further identify the synoptic states associated with extreme rainfall a new SOM was generated using only circulation data associated with extreme rainfall. For each of the 696 stations, days which experienced extreme rainfall were identified and the corresponding synoptic data extracted from the CFSR reanalysis data. Circulations associated with sub-tropical lows, mid-latitude cyclones, tropical-mid-latitude linkages and ridging high pressure systems were identified (Figure 4.7). In the upper air mid-latitude low pressure troughs reach into the northern regions of the domain are evident as well as a suggestion of cut-off low types of circulations in nodes 1 and 2. The frequency map indicates highest mappings to nodes 17 and 40 and also nodes 3, 19, 33 and 36 (Figure 4.8). Node 17 s associated with a low pressure over the interior and a ridging high (similar to node 22 and 30 in the first SOM) and node 40 is associated with a surface low pressure system to the south-west of the country. Node 3 is associated with an upper air trough over the eastern parts of the country and a surface trough over the interior.

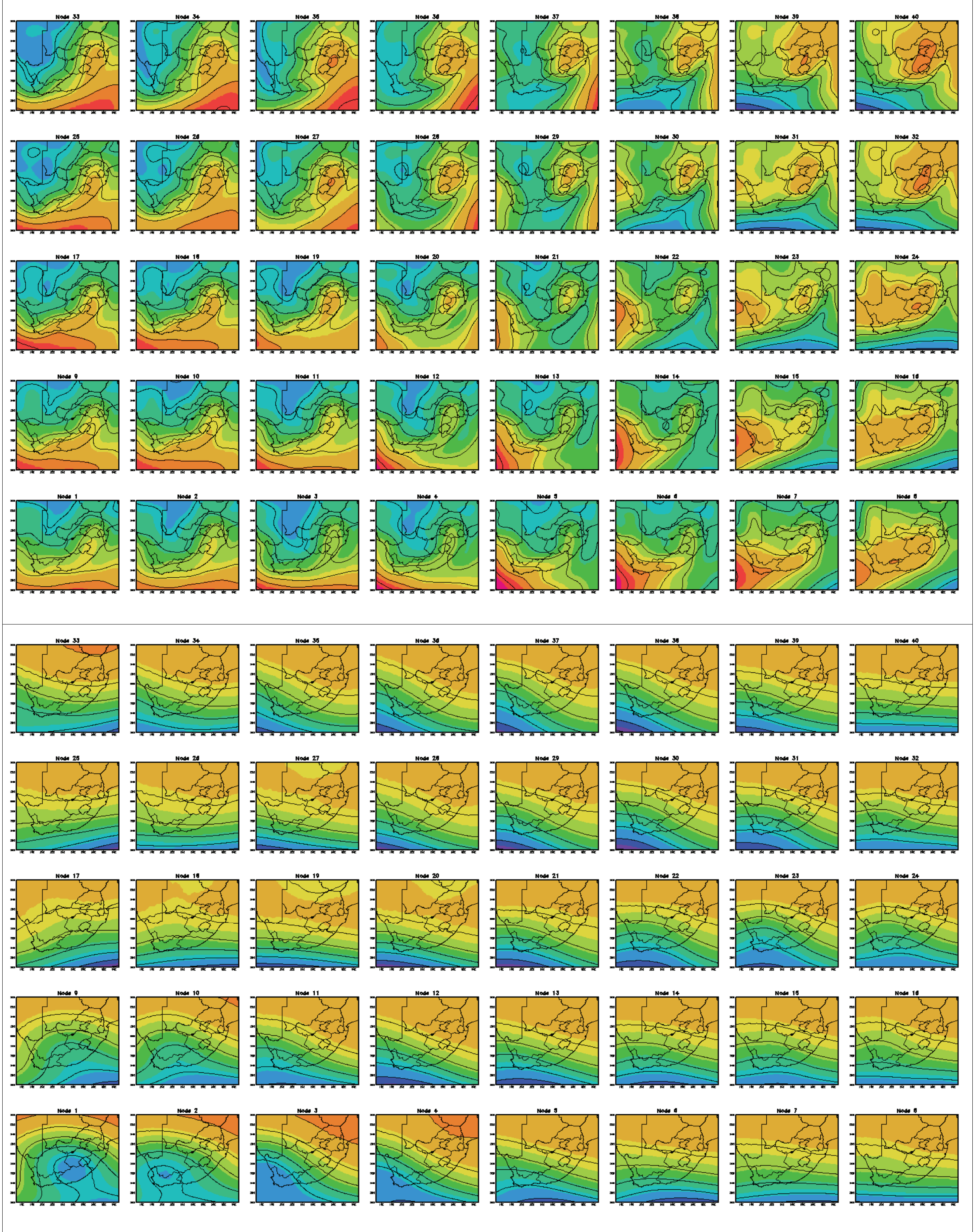


Figure 4.7. Sea level (top) and 500 hPa height (bottom) circulations associated with extreme rainfall.

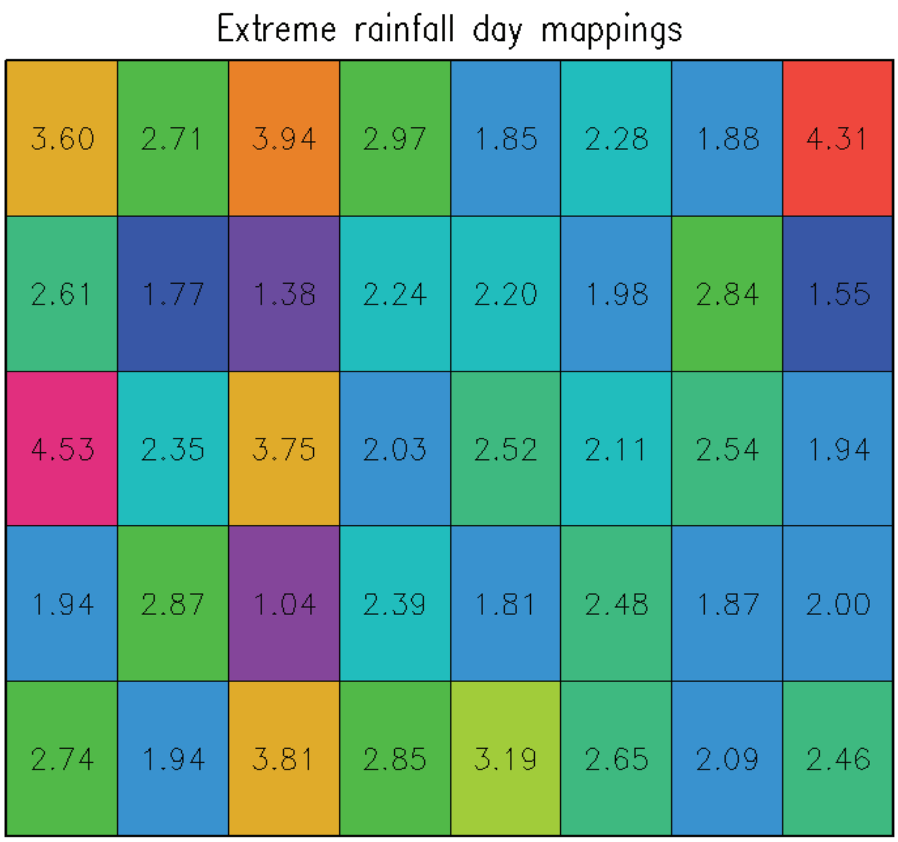
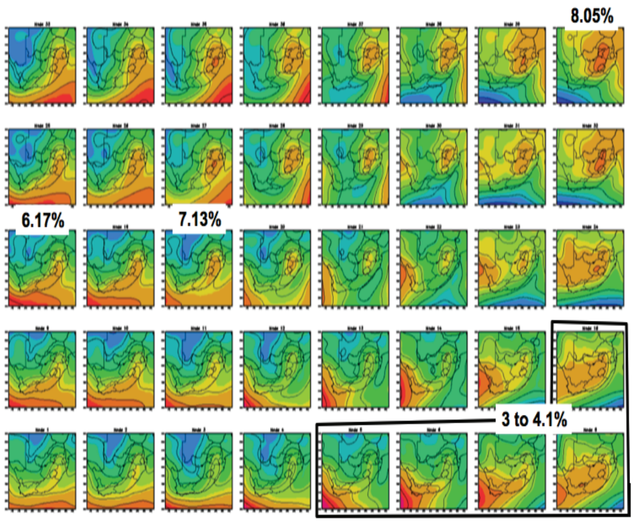


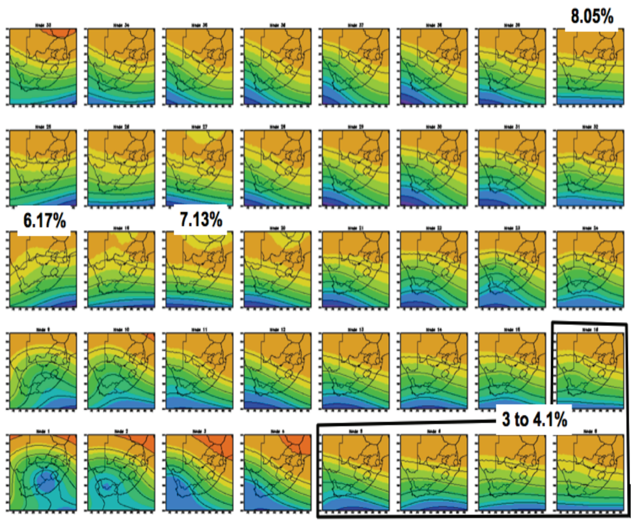
Figure 4.8. Frequency mapping of extreme rainfall days.

A seasonal assessment was performed on the new SOM and distinct summer and winter circulations that were associated with extreme rainfall were identified (Figure 4.9). Frequency maps are not shown in this figure but nodes that were most frequently mapped are marked out with either percentages and coloured boxes where appropriate, these are then referred to in the text. Summer extreme rainfall was most frequently associated with circulations represented by nodes 40, 19 and 17 (top row). The circulations associated with these indicate an onshore flow over the south and east of the country (node 40) and the effect of a surface low pressure trough over the western interior (nodes 19 and 17).

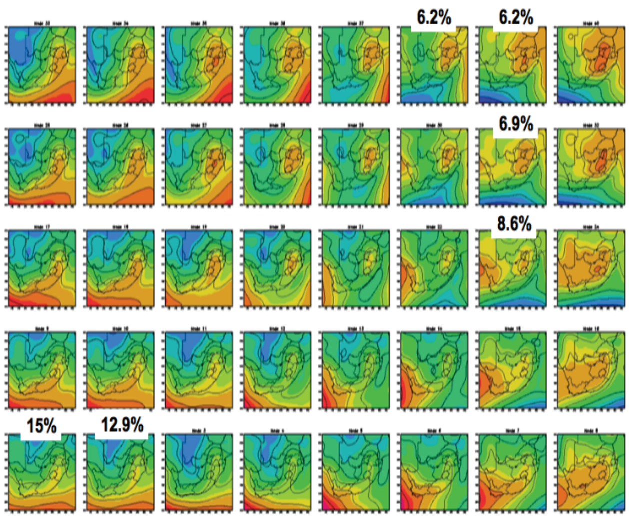
Winter extreme rainfall is associated most strongly with nodes 1 and 2 – 28% of winter extreme rainfall days map to these 2 nodes. They show circulations with a relatively high pressure over the interior (the thermal low has a more northerly context) and a deep trough in the upper air that give indications of cut-off characteristics. A further 27% of extreme winter rainfall map to nodes 23, 31, 38 and 39 which are associated with a passage of mid-latitude cyclones at both the surface and upper air – the latter two nodes indicate a more wide-spread high pressure system over the interior



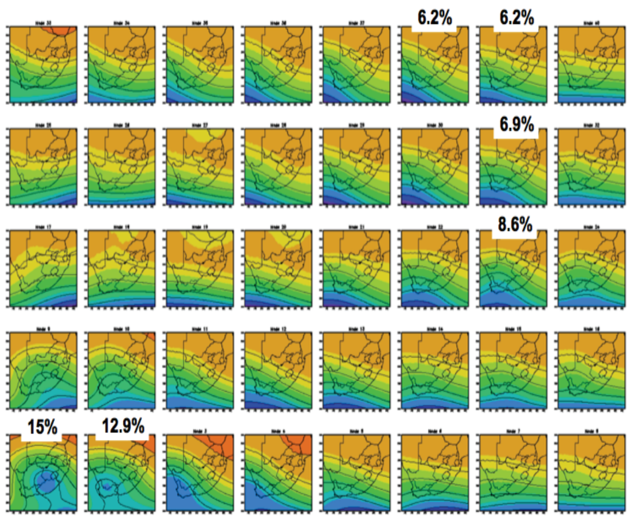
Sea level pressure frequency mapping for DJF



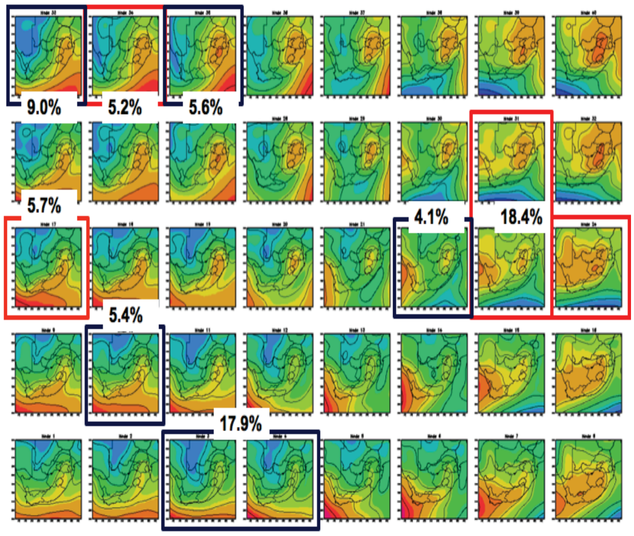
Z500 frequency mapping for DJF



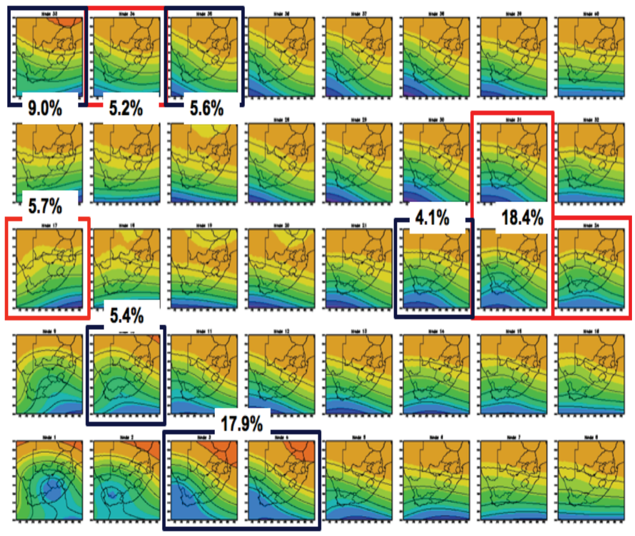
Sea level pressure frequency mapping for JJA



Z500 frequency mapping for JJA



SLP frequency mapping for SON (blue) and MAM (red)



Z500 frequency mapping for SON (blue) and MAM (red)

Figure 4.9. Seasonal frequency mapping of extreme rainfall days.

than the former 2 nodes. Thus two dominant circulation types have been identified as being associated with more than half of the extreme rainfall during winter.

During spring (SON) extreme rainfall is associated primarily with nodes 3, 4 and 10 (23.3%) which represent an upper air mid-latitude trough and a surface trough over the western parts of the country. Nodes 33 and 35 (14.6% of the mapping with the former being the second highest mapped to node) represent a surface trough over the western parts of the country. These 5 nodes account for 38% of the spring extreme rainfall day mapping.

During autumn (MAM) nodes 23, 24 and 31, which represent onshore flow along the south and east coast of the country coupled with an upper air mid-latitude trough are mapped to most frequently. Together with node 34, which represents a surface trough on the extreme west of the country (a West Coast Trough), these nodes account for the greatest number of extreme rainfall days (32%). These nodes are also mapped to frequently by winter extreme rainfall days that are associated with mid-latitude cyclones.

4.5. Summary

General synoptic circulation modes were generated by the SOM and those associated with seasonal extreme rainfall were identified. Not surprisingly summer rainfall extremes are related to a sub-tropical low pressure over the interior and winter extreme rainfall to mid-latitude cyclone types of circulations. Shoulder season extreme rainfall is associated with both summer and winter types of although dominant circulation modes are not as apparent as in the core winter/summer seasons.

At this stage, it is difficult to perform a useful regional assessment of the drivers of extreme rainfall. Even though we have a temporal seasonal disaggregation, spatially there is not clear association of extreme rainfall drivers with a particular region. As mentioned earlier, Tyson and Preston-Whyte (2000) describe six to eight main circulation types responsible for rainfall and the large-scale dominant circulations often have smaller-scale circulations associated with them that influence the local weather response. In the next chapter we present a regional scale analysis of extreme rainfall based on rainfall regimes identified in the literature to identify specific synoptic states responsible for extreme rainfall in each particular regime.

Chapter Five. Analysis of extreme rainfall characteristics at the regional scale

5.1. Introduction

In general it is widely accepted that the South Western region of South Africa is characterized by winter frontal precipitation, while the eastern and interior plateau regions experience summer convective rainfall. Large parts of the Northern Cape and central interior are characterized by a dry arid climate with very low rates of precipitation and the Eastern Cape along with parts of the southern coast experience rainfall from a number of synoptic drivers with minimal seasonal distinction. So across the spatial extent of South Africa a number of different rainfall regimes, from tropical to frontal, affect different regions of the country. This means any regional attributes of synoptic drivers of extreme rainfall would be lost in the generalizations made when considering the extreme rainfall data across all the rainfall regimes affecting the country. To address this extreme rainfall within specific rainfall regimes was examined and the synoptic states associated with these elucidated at the seasonal scale.

5.2. Regional rainfall regimes in South Africa

In order to investigate the regional characteristics of extreme rainfall regions within Southern Africa were identified based on Landman and Mason (1999) and Landman *et al*. (2001). They identified nine characteristic regions that capture the large variability and types of rainfall received from various synoptic patterns throughout South Africa and provide a spatial criteria necessary for analysing regionally specific extreme rainfall events. The regions used in this study include the south-western Cape, the south coast, Eastern Cape, KwaZulu-Natal coast, the Lowveld, the north-eastern Highveld, the central interior, the western interior and the northern/western Botswana (Figure 5.1). The northern/western Botswana region is not considered in this study as it falls outside the borders of South Africa.

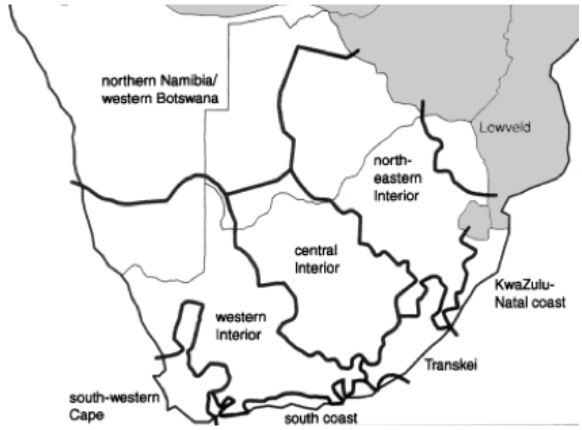


Figure 5.1. Nine rainfall regions considered in this study (from Landman *et al*. (2001)).

5.3 Regional station selection

For each of these rainfall regions a number of stations have been selected as being representative of the region. The criteria on which the stations were selected included factors such as spatial representativeness, effect of the topography, data quality and the number of extreme rainfall days experienced. These criteria are described in detail below.

5.3.1. Data quality

The steps in determining which stations were used are described earlier which reduced the number of stations based on overlap with the reanalysis data and amount of missing data from 4011 stations to 698 stations.

5.3.2. Spatial representativeness

There are many variables apart from the dominant large-scale circulations that are also responsible for the regional characteristics of rainfall such as ocean currents and their associated sea surface temperatures and topographical relief that in in some regions is relatively flat and mountainous in others. These factors are evident in the South African domain and therefore had to be taken into consideration when in selecting stations to maintain an representative sample in each of the eight rainfall regions. Each station has a set of metadata as described in Chapter 1. These geographical metadata provided information on latitude, longitude and altitude which was used to assess the best spatial representation of the various rainfall regions of South Africa from the 698 stations. Although at least 5 stations per region were selected, more stations were selected for the larger regions of the interior and the mountainous coastal regions. For example, the coastal regions such as the South

Western Cape, South coast and Eastern Cape are made up of lower altitude coastal plain as well as high mountainous areas. The coastal plains and mountains usually occurred within the same rainfall region and were in close proximity to each other. We included stations from both high and low-lying areas within the regions such that the rainfall of those particular regions is well represented.

The rainfall of the western half of South Africa is influence by the mid-latitude cyclones mostly during the winter months of June, July and August (JJA). Out of the eight specified rainfall regions this would affect the South Western Cape, South coast, Western interior (mostly the southern parts) and the Eastern Cape. Spatially, the Eastern Cape and eastern parts of the South coast region are a transition zone between the mid-latitude driven winter rainfall from the west and the thermally driven summer rainfall regime.

The eastern parts of South Africa inland from the KwaZulu-Natal coast are characterized by very high mountains that form a plateau creating an influential weather barrier into the central parts of the country. Here the North Eastern interior receives greater influx of moisture from the east coast region during the warmer summer months of December, January and February (DJF) and coupled with the intense over land heating leads to large convective systems driving rainfall over the region. These conditions also tend to spread out over towards the Lowveld in the east as well as to the Central interior region to the west.

Through testing the representativeness of stations in particular regions against the full station record (described below), we selected 69 stations to base the assessment of regional extreme rainfall characteristics within Southern Africa. These stations are shown in Figure 5.2.

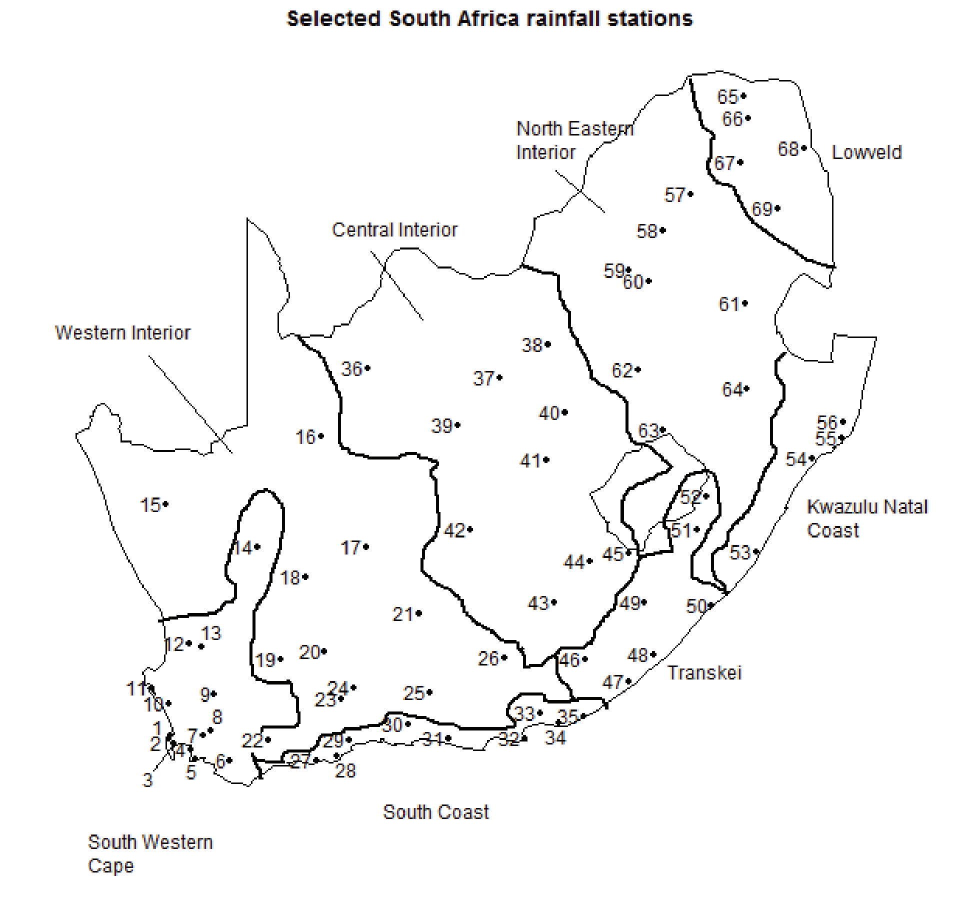


Figure 5.2. Map showing the 69 selected rainfall stations throughout South Africa within each of the eight rainfall regions.

5.3.3. Data representativeness

In conjunction with the task of selecting stations with the best spatial representation of the rainfall regions of South Africa it is also important for the stations actual rainfall data to closely resemble that of the particular region and South Africa as a whole. Percentile thresholds and averages were used to compare the selected 69 stations characteristics against the full 698 stations. These include the 95th percentile rainfall amount along with the number of 95th percentile rainfall occurrences and the 99th percentile rainfall amount with the number of 99th rainfall occurrences during the 31-year study period. The maximum rainfall recording within the 31-year period for each station is also identified (Table 5.1). The average for each threshold was calculated from the initial selection of stations throughout South Africa as well as for each of the eight rainfall regions. These averages were then compared to those of the entire sample of 698 stations (Table 5.2).

It is clear from these thresholds that there are no obvious discrepancies amongst the selected stations for each region and the combined selection of 69 stations throughout South Africa. The higher number of 95th and 99th percentile rainfall events in the 69 stations is to be expected as the selection process sought to optimize this number through acquiring the maximum number of extreme rainfall events. The actual 95^{th} and 99^{th} percentile rainfall amounts remain very similar to that of the whole sample.

This selection process yielded 69 stations whose extreme rainfall characteristics were representative of stations in the 8 rainfall regions and could be used to assess the synoptic drivers of the extreme rainfall in each region. For each of the 69 stations, extreme rainfall days were identified and the corresponding daily synoptic data extracted from the reanalysis data. These data were passed through the trained extreme rainfall SOM in order to identify synoptic states associated with extreme rainfall in each region based on the driving synoptics of all 698 stations. Thereafter, a SOM was generated for each region based on the extreme rainfall recorded by stations in the particular region to disaggregate regionally specific synoptic states associated with extreme rainfall.

Table 5.1. Extreme rainfall profile for each of the selected stations used in this study with reference to the map in Figure 5.2.

Regions	Labels	StationID	Name	Latitude	Longitude	Altitude (m)	Missing data	95th percentile (mm)	95th percentile events	99th percentile (mm)	99th percentile events	Maximum recording (mm)
	1	0020746A	MOLTEN	-33.93	18.42	93	20	30	156	50	31	95
	2	0020719B	WOODHEAD_DA	-33.98	18.41	733	45	49	176	80	36	152
	3	0004874_	RONDEVLE	-34.06	18.5	8	71	27	146	49	30	115
	4	0005611A	STEENBRAS	-34.18	18.85	380	4	33	174	59	35	176
	5	0005771_	BETTYS_BAY_HEROLD_PORTE	-34.35	18.93	34	46	36	171	63	34	222
	6	0007263_	BOSKLOO	-34.39	19.65	128	67	28	81	46	16	100
South Western Cape	7	0022148_	FRANSCHHOEK_ROBERTSVLE	-33.93	19.08	256	181	74	136	127	27	278
	8	0022440_	STETTYNSKLOO	-33.84	19.26	451	18	46	132	95	27	191
	9	0042582_	BOKVELDSKLOO	-33.19	19.33	1035	49	45	82	68	17	115
	10	0040682_	DARLIN	-33.37	18.38	120	14	21	106	33	21	66
	11	0040035_	LANGEBAA	-33.09	18.03	14	124	20	74	32	16	59
	12	0084558_	ELANDSFONTEI	-32.3	18.82	457	0	30	90	44	20	96
	13	0085112_	ALGERIA_-_BO	-32.37	19.06	517	21	43	86	69	18	106
	14	0162366_	BRANDVLEI_KAN	-30.6	20.22	953	30	27	23	47	5	96
	15	0215559_	SPRINGBOK_DABEE	-29.82	18.32	856	0	17	42	37	9	66
	16	0284008_	THORNLE	-28.63	21.52	884	0	29	35	46	7	58
	17	0166755_	OORLOGSHOE	-30.58	22.43	1204	20	34	41	55	12	170
	18	0137337_	GROOTFONTEIN_WILLISTO	-31.12	21.19	1188	0	29	27	50	7	66
	19	0066304_	SUTHERLAND_GUNSFONTEI	-32.57	20.68	1529	16	30	47	46	9	100
Western Interior	20	0090176_	GROOTFONTEIN_MERWEVILL	-32.44	21.59	808	1	41	25	82	5	132
	21	0117047_	LOSKO	-31.78	23.52	1219	82	29	37	45	8	86
	22	0008751_	MARLOT	-34.01	20.44	247	23	38	138	68	28	149
	23	0047765_	DAMASKU	-33.27	21.94	666	33	27	36	54	8	63
	24	0048275_	ZACHARIASFONTEI	-33.09	22.17	823	48	28	29	46	6	112
	25	0051430_	MOOREDAL	-33.17	23.75	630	6	31	63	52	14	94
	26	0075483_	STRUISHOE	-32.55	25.28	914	65	27	82	49	17	127
	27	0010742_	STILBAAI_SAP	-34.38	21.41	20	34	26	102	46	20	98
	28	0011617_	DIE_EILAN	-34.28	21.84	49	3	21	113	51	23	95
	29	0028150_	MOSSELBAAI_KWEPERTUI	-34.01	22.08	220	29	35	87	68	17	212
	30	0030524_	WELGELEGE	-33.73	23.29	853	18	32	88	63	18	238
South Coast	31	0032209_	WITELSBOS_-_BO	-33.99	24.12	227	73	49	116	94	24	191
	32	0035299_	HUMEWOOD_-_GOLF_CLU	-33.98	25.67	15	46	24	127	47	26	139
	33	0033871_	TYGERHOE	-33.55	25.99	457	17	33	56	66	12	146
	34	0036642_	ALEXANDRIA_-_BO	-33.7	26.37	198	70	35	119	70	24	213
	35	0037696_	PORT_ALFRE	-33.6	26.88	61	32	37	94	69	19	161
	36	0391834_	WHYENBA	-27.41	22.48	1372	4	35	44	68	9	100
	37	0361277_	WELKO	-27.6	25.17	1310	1	36	61	66	13	116
	38	0399241_	LEEUKO	-27.01	26.15	1219	0	34	85	54	17	89
	39	0323535_	DELPORTSHOOP_-_PO	-28.42	24.3	1030	80	37	50	77	10	141
Central Interior	40	0327883_	GROOTKUI	-28.22	26.5	1280	0	35	75	56	15	132
	41	0261183_	BAINSVLEI-MU	-29.06	26.13	1372	69	40	69	70	12	135
	42	0199107_	GROOT_-_ARENDSKRAA	-30.28	24.57	1295	0	26	83	50	16	93
	43	0122514_	WILDEPERDEHOE	-31.57	26.3	1707	2	28	108	46	21	115
	44	0176523_	HELVELLY	-30.85	27.02	2034	65	39	117	64	24	102
	45	0177552_	FUNNYSTON	-30.7	27.82	2286	38	29	144	44	29	86
	46	0078755_	HOGSBACK_-_BO	-32.59	26.93	1375	73	41	141	67	29	228
	47	0080569_	UMZONIAN	-32.98	27.82	168	0	38	183	79	37	262
	48	0103570_	KENTANI_-_BO	-32.5	28.32	488	101	45	114	91	23	268
Transkei	49	0126245_	ENGOBO_MANINA_PLANTATIO	-31.58	28.15	1067	307	49	107	82	22	182
	50	0129007_	SILAKA_NATURE_RESERV	-31.62	29.52	256	184	56	102	101	21	331
	51	0208406_	THE_MEADOWS_FAR	-30.27	29.22	1460	0	28	142	48	29	95
	52	0237731_	COBHAM_-_BO	-29.68	29.42	1675	41	33	201	55	43	181
	53	0182730_	THE_VALLEY	-30.67	30.42	183	46	47	156	98	32	245
Kwazulu-Natal Coast	54	0272121_	GINGINDHLOV	-29.03	31.57	100	67	37	160	85	32	296
	55	0305308_	KWAMBONAMBI-BO	-28.66	32.17	30	64	56	130	112	26	337
	56	0339352_	KANGEL	-28.37	32.2	76	2	35	153	80	31	305
	57	0634140_	DOORNFONTEI	-24.33	29.08	1219	1	38	80	61	16	107
	58	0590028_	ILLAWARR	-24.97	28.51	1062	0	33	105	54	21	116
	59	0512580_	DE_KROON_-_IR	-25.67	27.83	1152	8	40	60	76	12	110
	60	0513382_	IREN	-25.87	28.22	1448	0	31	135	55	27	111
North Eastern Interior	61	0480377_	CHRISSIESMEER_-_PO	-26.28	30.21	1675	374	40	73	70	16	166
	62	0402866_	DRIEFONTEI	-27.44	28	1626	0	38	85	59	17	100
	63	0298031_	KOEBER	-28.51	28.53	1767	57	26	155	48	29	105
	64	0371437_	WATERVAL_-_TN	-27.79	30.25	1190	14	38	93	65	19	111
	65	0766276_	TSHIPIS	-22.6	30.17	579	7	44	38	74	8	100
	66	0766480_	ENTABENI_BO	-23	30.27	1376	0	66	136	138	27	360
Lowveld	67	0679197_	ZOMERKOMST-BO	-23.78	30.12	792	18	55	108	121	22	340
	68	0681691_	LETABA_MOOIPLAA	-23.52	31.4	305	1	46	65	84	13	174
	69	0594635_	MARIEPSKOP_-_BO	-24.58	30.87	914	8	56	111	130	24	387

Table 5.2. The average for each rainfall threshold and for each of the rainfall regions, the 69 selected stations and the entire sample of 698 stations.

Region	**95th percentile (mm)**	**95th percentile events**	**99th percentile (mm)**	**99th percentile events**	**Maximum recording (mm)**
South Western Cape	36	117	62	24	133
Western interior	30	50	53	11	102
South coast	32	100	64	20	166
Central interior	34	84	59	17	111
Eastern Cape	45	141	75	29	221
KwaZulu-Natal coast	44	150	94	30	296
North Eastern interior	36	98	61	20	116
Lowveld	53	92	109	19	272
South Africa (69 selected stations)	**36**	**99**	**67**	**20**	**155**
South Africa (698 stations)	**36**	**80**	**62**	**16**	**144**

5.4. Drivers of extreme rainfall in the 8 rainfall regions

The 95th and 99th percentile rainfall data were used to generate SOMs for each region so that the regions synoptic drivers of each percentile's rainfall could be identified and contrasted. The analysis was performed on the seasonal scale given the seasonal nature of rainfall across South Africa. The section following is structured so that for each region there is a general description of the archetypal circulations generated by the SOM, a description and brief discussion of the seasonal frequency mappings and once this has been done for each of the 8 regions there is a general discussion. Images for the sections 5.4.1 to 5.4.8 relate to 95th and 99th percentile rainfall events. The 95th percentile images are shown in the appropriate sections and the 99th images are contained in the Appendix.

5.4.1. South Western Cape

Archetypal circulations identified by the SOM in this region in the upper air were mid-latitude troughs associated with meridional air flow (Fig. 5.3). At the surface a number of circulation states were evident: a low pressure trough to the south of the country was evident in all nodes, towards the upper right of the array a strong high pressure system over the interior and eastern parts of the country was present while the nodes on the left side of the array indicate signs of a linkage between low pressure troughs over the interior and mid-latitude trough in the south.

The winter months of June, July and August (JJA) recorded the highest number of extreme rainfall days in the 31-year study period. Nodes 20 and 12 of JJA have the highest frequency (15.06 and 13.48 respectively), accounting for 28% of extreme rainfall days. Nodes 15, 16 and 8 represent a further 28% of extreme rainfall occurrences so 56% of extreme rainfall days were associated with synoptics represented by these five nodes. The synoptics of these nodes are very similar as they are all situated towards the upper right of the SOM array and are characterized by the passage of mid-latitude cyclones to the south of the country and a high pressure over the interior.

In DJF most 95th percentile rain days map to nodes on the right of the SOM (nodes 5, 9, 13 and 17) which are associated with a low pressure over the interior of the country and a mid-latitude cyclone to the to the south west of the country. The mid-latitude cyclone is evident in the upper air and is not a very deep system. The surface fields in these nodes show a linkage between the subtropical regions with the mid-latitudes which indicate the potential the existence of tropical temperate troughs (TTTs). Tropical Temperate Troughs causes approximately up to 30% of mean rainfall between October-November-December season and 60% in January over South Africa (Jury & Pat hack, 1993). Todd & Washington (1999) suggest that TTT events are a major mechanism for pole-ward transfer of energy and momentum.

The extreme rainfall mapping for the shoulder seasons is different to the winter months in that the majority of extreme rainfall days are attributed to nodes mostly on the left hand side of the SOM array. Nodes 1, 5 and 9 are common in each season and nodes 2 and 13 are have high mapping frequencies in MAM and SON respectively. These nodes are characterized by a linkage between the mid-latitude low pressure systems and the sub-tropics over the interior of the country and within the SOM are more closely related to summer types of extreme rainfall. The combined occurrence of MAM/SON extreme rain days is about two-thirds the winter number and indicates a clear seasonal distinction between the synoptic patterns of extreme rainfall in the winter and autumn months in this region.

The 99th percentile SOM shows a similar pattern both in terms of the synoptics identified by the SOM and the seasonal characteristics between JJA and MAM. The synoptics are, however, more exaggerated – the upper air troughs are deeper and have a more northerly extent implying stronger mid-latitude cyclones, the surface lows are also deeper and the linkages between the mid-latitudes and the sub-tropics are more pronounced.

In order to quantify the frequency of TTTs in the region, information kindly provided by Mr Neil Hart at the Oceanography Department at the University of Cape Town, whose Ph.D. examined the occurrence and drivers of TTTs, was examined. Although many TTTs were identified during this period over the SW Cape region, most were not associated with extreme rainfall. During summer 14 TTT days were recorded in the 95th percentile data and mapped to nodes 5, 9 and 13. Four DJF TTT days were recorded in the 99th percentile dates and similar synoptic states were noted, however, the upper air trough was deeper and had a more northerly extent and the surface trough was also deeper. During JJA only one TTT was associated with extreme rainfall and this was only present in the 95th percentile data of station 6. During MAM, 35% (40%) of all 95th (99th) percentile rain days were associated TTTs and in SON this was 46% (42%). All the TTT dates provided that experienced extreme rainfall mapped to either nodes 1, 5, 9 or 13. It should be noted that even though extreme rainfall can be associated with a TTT, this is exceptional; most rainfall from a TTT did not fall into the extreme percentiles.

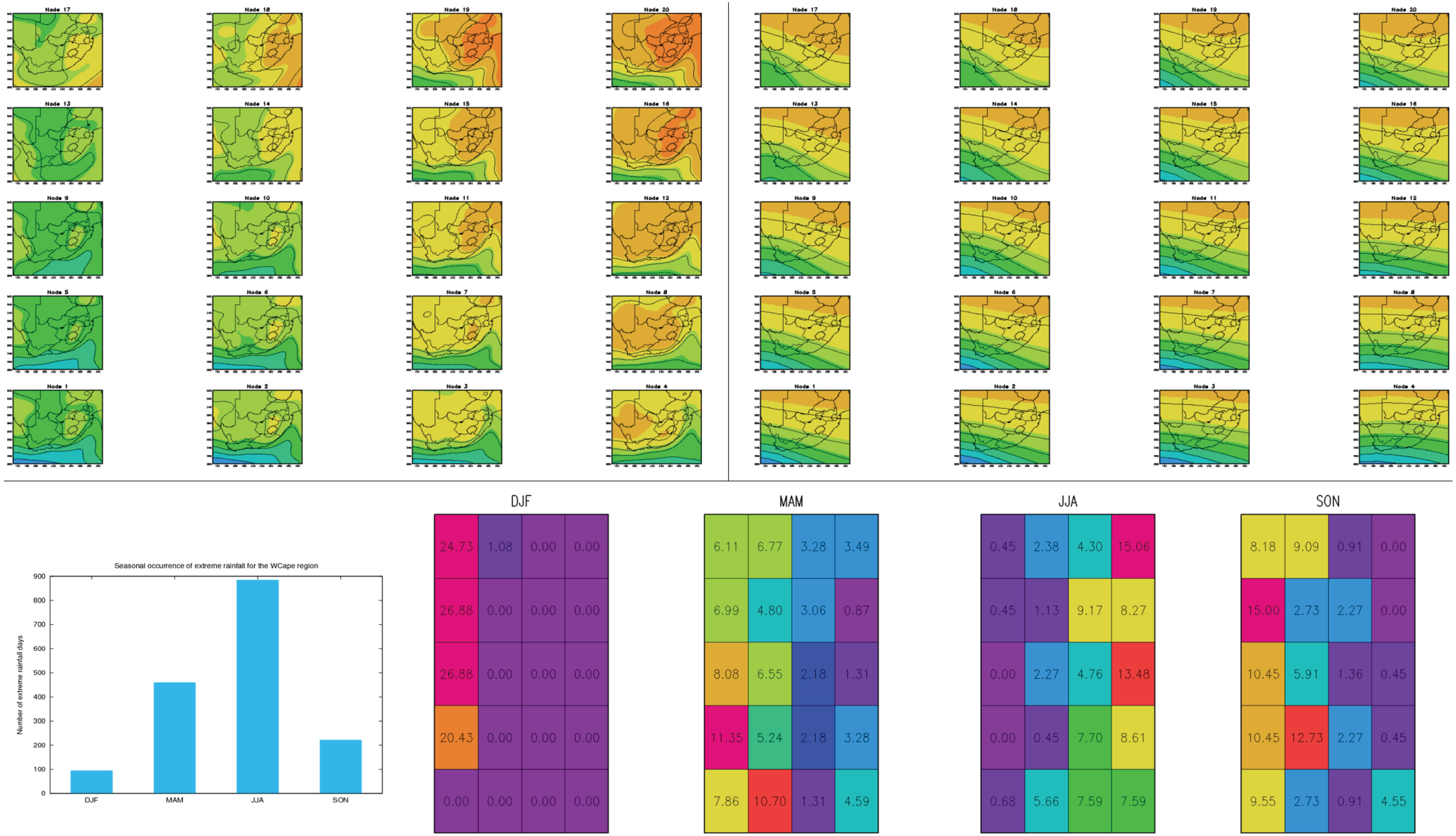
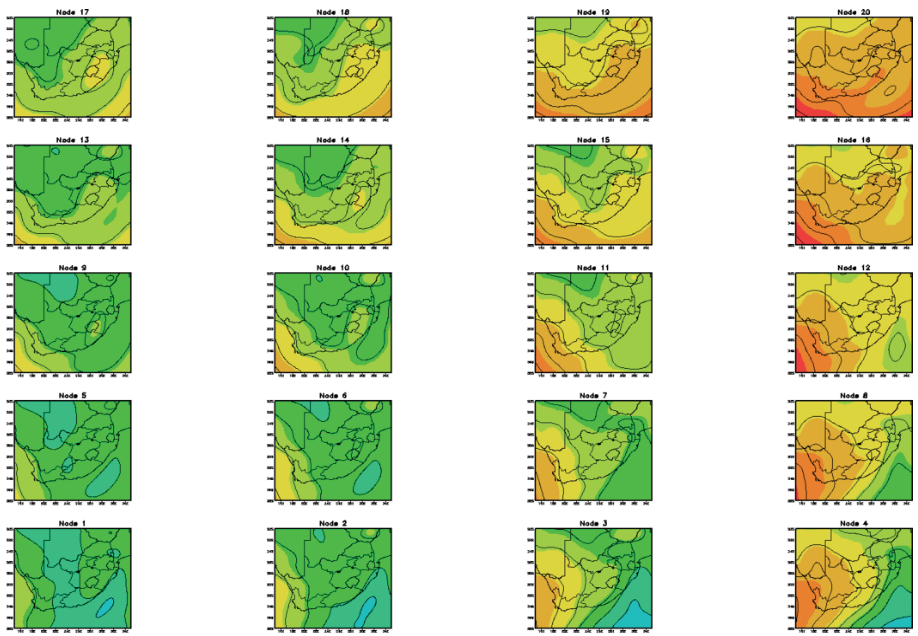


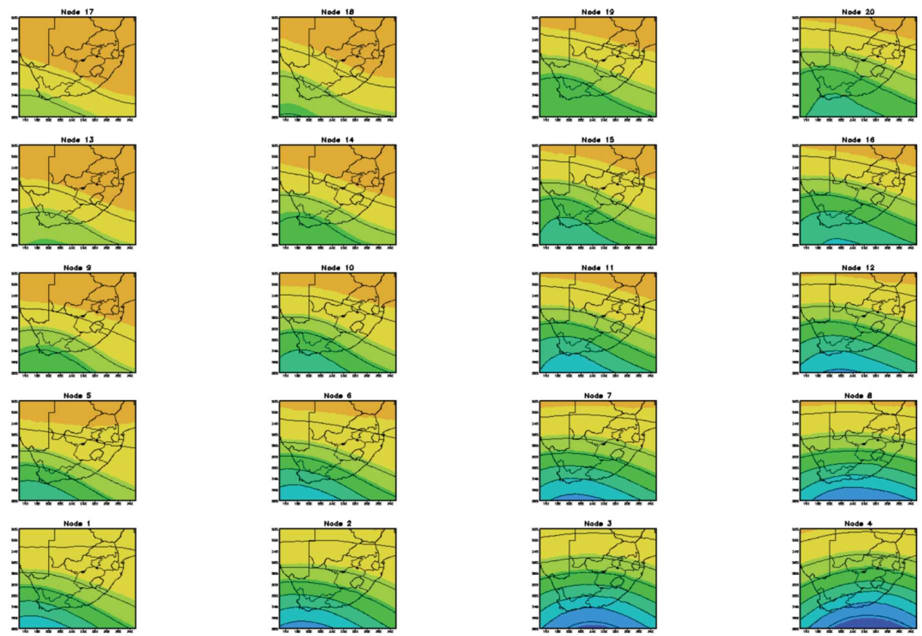
Figure 5.3. Seasonal 95th percentile SOMs of the SW Cape. The SLP and z500 archetypes are top left and right respectively. The bottom row shows the seasonal distribution of seasonal extreme rainfall on the left and frequency maps which are for the shown seasons.

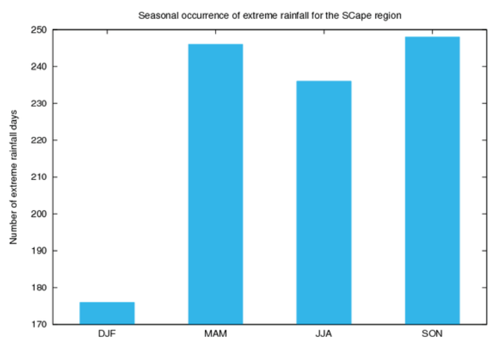
5.4.2. Southern Cape

The 95th and 99th percentile SOMs of the Southern Cape region have characterised a number of synoptic features at the surface: ridging high pressure systems and clear linkages between low pressure troughs over the interior and mid-latitude cyclones, possibly indicating tropical temperate troughs (Fig. 5.4). In the upper air deep mid-latitude cyclones are identified with some weak evidence of cut-off low pressure systems in the 99th percentile maps.

The 95th percentile SOM has a relatively even seasonal distribution of the occurrences of extreme rainfall days between MAM, JJA and the spring months of September, October and November (SON). SON seems to have only slightly more extreme rainfall days than MAM with both falling just fewer than 250 days in the 31-year period. SON extreme rainfall was most frequently associated with circulations represented by nodes 6, 11, 14 and 15, these nodes accounting for 52% of SON extreme rainfall days. Node 6 is characterized by a wide spread surface low pressure linkage across the majority of the country with a surface high pressure system moving in the west. Nodes 11, 14 and 15 are characterized with a surface trough over the northern parts of the domain with a more established ridging high pressure system to the south west. In the upper air these 4 nodes are exhibit a mid-latitude trough to the south of the country. The extreme rainfall for the autumn months of MAM in the 95th percentile SOM are dominated by nodes 9, 13 and 18 accounting for just over 30%. These nodes are characterized by a deeper surface trough extending from the sub-tropics over most of the country.







DJF

22.86	4.00	0.00	0.00
16.57	5.71	0.00	0.00
17.71	1.14	0.00	0.00
14.29	3.43	0.57	0.00
13.14	0.00	0.57	0.00

MAM

4.90	9.39	4.08	0.82
10.61	5.71	6.53	0.00
10.61	0.82	5.71	0.82
2.86	6.94	2.04	2.04
5.31	7.76	7.76	5.31

JJA

0.00	0.00	5.53	22.98
0.00	0.00	2.13	14.47
0.00	0.00	2.55	18.30
0.00	0.85	4.68	11.91
0.00	0.85	5.96	9.79

SON

1.62	4.86	4.45	0.40
0.40	12.15	13.36	0.00
0.81	9.31	12.15	1.21
4.05	14.17	6.07	0.40
4.86	7.29	2.43	0.00

Figure 5.4. As for Figure 5.3 but for the South Coast region.

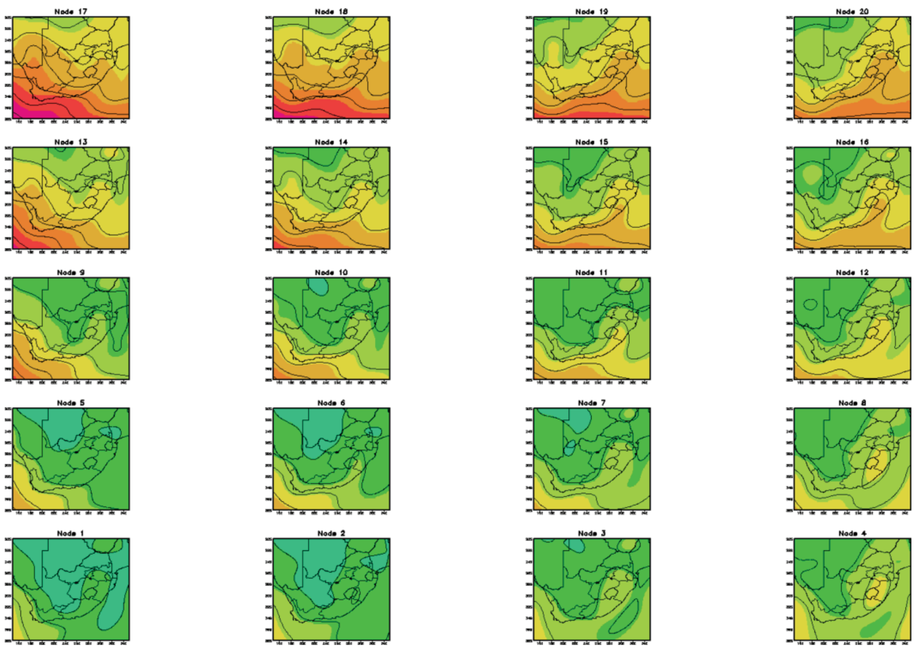
The majority of extreme rainfall during JJA is attributed to the nodes down the right hand side of the SOM array with node 20 experiencing 23% of extreme rainfall alone. These nodes are primarily characterized by strong surface ridging high pressure systems moving in behind upper air mid-latitude troughs. A general overview of the seasonal node placement shows a movement of the distribution from right to left from JJA to SON to DJF across the SOM and them MAM extreme rain days being quite well distributed across most nodes which again indicates a seasonal distinction between circulations that cause extreme rainfall in the region with the exception of MAM.

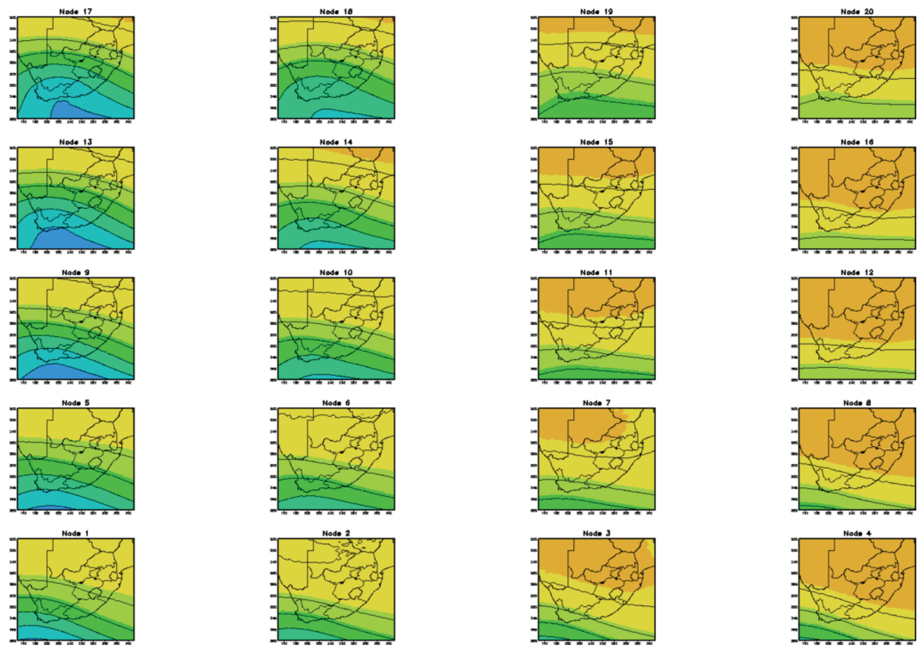
The 99th percentile SOM has a slightly different seasonal make-up of extreme rainfall with a more clear distinction between the number of occurrences for MAM, JJA and SON, with SON maintaining the highest frequency. Node 6 represents 18% of extreme rainfall for SON and is characterized by a strong linkage between the sub-tropics and mid-latitudes in the surface layers and a mid-latitude trough to the south west of the country in the upper air flow. A further 25% of extreme rain days is attributed to nodes 12 and 16. These two nodes are characterized by a surface high pressure system to the south of the country and a trough over the interior. The upper air circulations of these two nodes are characterized by mid-latitude troughs with node 16 showing signs of a weak cut-off low pressure system. A similar seasonal movement of the distribution across the nodes is evident except here the movement is from the top to the bottom of the SOM going from JJA to SON to DJF with a more homogeneously spread across the SOM for the MAM days.

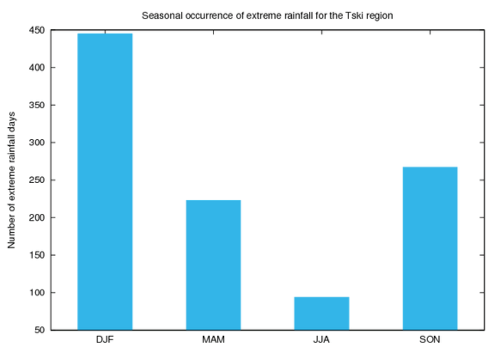
5.4.3. Eastern Cape

The 95th and 99th percentile SOMs for the Eastern Cape have identified nodes with surface troughs over the interior of the country and others dominated by strong high pressure systems over the south (Fig. 5.5). In the upper air nodes tend to indicate either a weaker trough or zonal isobars over the interior or a deep trough with a large northward extent, in the case of the 99th percentile map circulations like this have a deeper trough.

The summer months of December, January and February (DJF) have the highest number of extreme rainfall days in the study period for both the 95th (450) and the 99th (80) percentile SOMs followed by SON with about 270 and 66 days respectively. The majority of 95^{h} percentile rainfall during DJF maps to the bottom right had side of the SOM array with nodes 3, 6, 7, 8 and 12 accounting for 53%. The synoptics of these nodes are generally characterized by a surface trough over the interior and a high pressure system off the east coast. These synoptic circulations and the resultant onshore flow would advect moisture from the warm Agulhas current into the region which would interact







DJF

0.00	0.00	0.00	1.35
0.00	0.00	3.38	6.31
0.00	4.28	8.33	11.71
1.35	10.36	10.36	10.36
5.86	9.23	10.36	6.76

MAM

0.90	0.90	4.50	12.16
3.60	4.50	11.26	5.86
3.60	9.91	7.21	5.41
1.35	2.70	2.25	4.95
1.80	1.35	4.50	11.26

JJA

50.54	20.43	1.08	0.00
19.35	0.00	0.00	0.00
7.53	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	1.08

SON

3.38	6.39	9.02	2.63
9.02	13.53	3.76	0.75
15.04	6.39	1.50	0.00
10.90	3.38	2.63	1.88
2.26	0.00	1.88	5.64

Figure 5.5. As for Figure 5.3 but for the Eastern Cape region.

with the topography to cause rainfall. The characteristics of the nodes (9 and 14) representing the extreme rainfall for SON are different in which they have a ridging high pressure system at the surface and a mid-latitude trough in the upper air. Similar characteristics are evident in the 99th percentile rainfall events SOM.

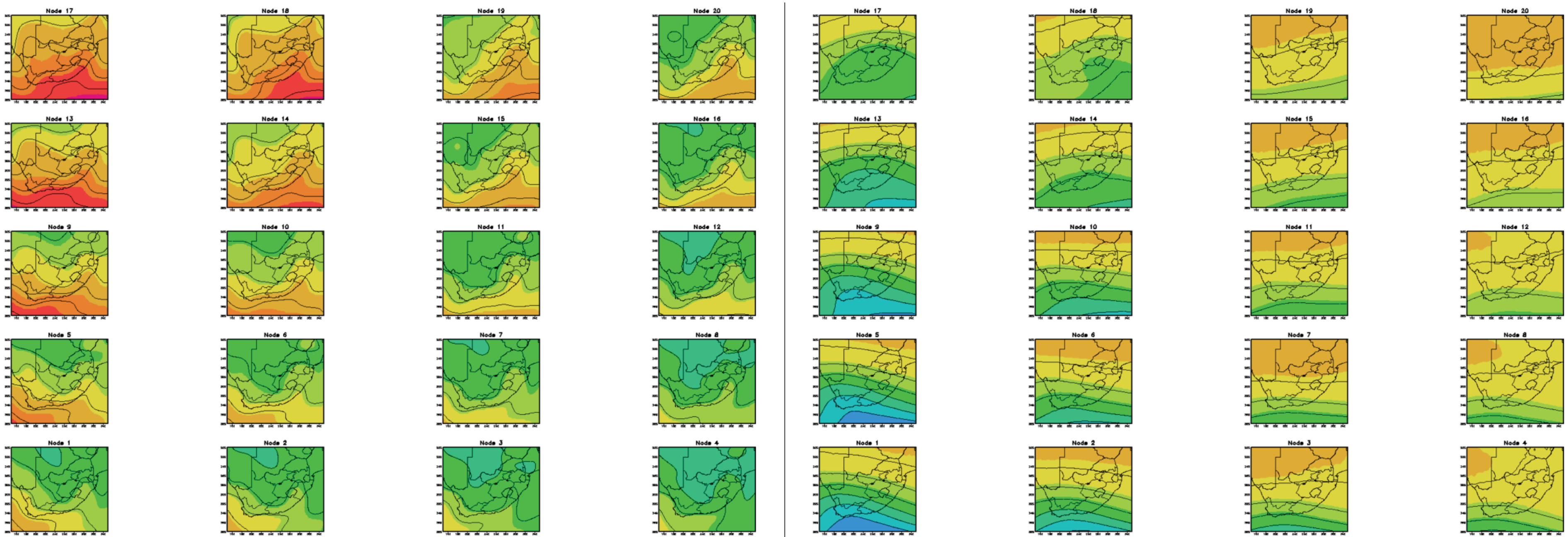
It is worthwhile to note that although JJA experiences the least amount of extreme rainfall, 50% of the extreme rainfall is attributed to node 17 in the 95th percentile SOM as well as 70% is attributed to node 4 of the 99th percentile SOM. These nodes in each case have very similar synoptic characteristics consisting of a very strong ridging high pressure system at the surface moving behind a deep mid-latitude cyclone in the upper air flow. These synoptic circulations are similar to the extreme rainfall synoptics for the Southern Coast region during the same winter months.

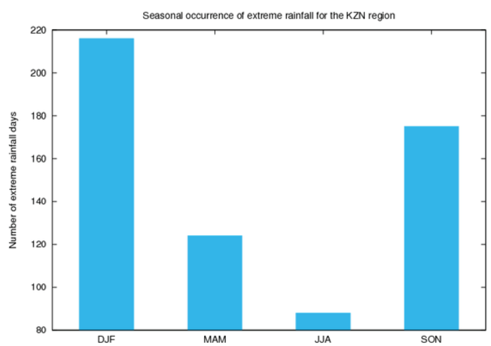
5.4.4. KZN Coast

The 95th and 99th percentile SOMs for the KZN coastal region have identified strong surface high pressure systems to the south and south east of the country, surface troughs over the interior and a variety of upper air circulations (Fig. 5.6). These upper air circulations range from nodes with relatively deep mid-latitude cyclones and some evidence of cut-off low pressure systems in the 99th percentile SOM to weaker, more zonal upper air patterns.

The KZN Coastal region has a similar seasonal distribution of extreme rainfall occurrences as the Eastern Cape with the largest being attributed to the summer months of DJF followed by SON. The 95th percentile rainfall for DJF mapped primarily to the bottom left of the SOM, the nodes 4, 7, 8 and 12 accounting for 56% of the days. These nodes are characterized by a surface trough extending from the sub-tropics covering the interior as well as most of the country and zonal upper air flow. In SON extreme rainfall days map to the right-middle of the SOM (nodes 5, 9 and 10 accounting for 34% of the days) which have different characteristics from DJF circulations with evidence of a ridging high pressure system at the surface and a weak mid-latitude trough in the upper layers.

The 99th percentile SOM DJF and SON again have a different synoptic drivers of extreme rainfall. The summer nodes are to the right of the map as well as node 10 whereas for SON there is a more widespread mapping across the SOM with nodes 2 and 17 accounting for 22% of occurrences. Node 2 is characterized by a strong surface high pressure system to the south of the country and a closed low pressure system in the upper air. Node 17 shows at the surface a ridging high pressure system to the south west of the country and low pressure trough over the interior accompanied by a very deep mid-latitude cyclone in the upper air. These features are similar to those of the winter months of the Eastern Cape and South Coast regions





DJF

0.00	0.00	0.47	11.63
0.00	0.00	2.79	9.30
0.00	0.00	5.12	13.02
0.00	0.47	13.95	12.09
0.00	5.58	8.84	16.74

MAM

0.00	11.38	8.94	10.57
0.00	3.25	10.57	4.07
0.81	6.50	9.76	0.81
2.44	8.13	7.32	4.07
2.44	6.50	2.44	0.00

JJA

28.74	16.09	0.00	0.00
26.44	1.15	0.00	0.00
12.64	2.30	0.00	0.00
5.75	0.00	0.00	0.00
5.75	1.15	0.00	0.00

SON

1.72	4.02	2.30	0.57
4.60	8.62	6.90	1.15
12.64	11.49	6.32	3.45
10.34	6.32	4.60	0.57
8.05	3.45	0.57	2.30

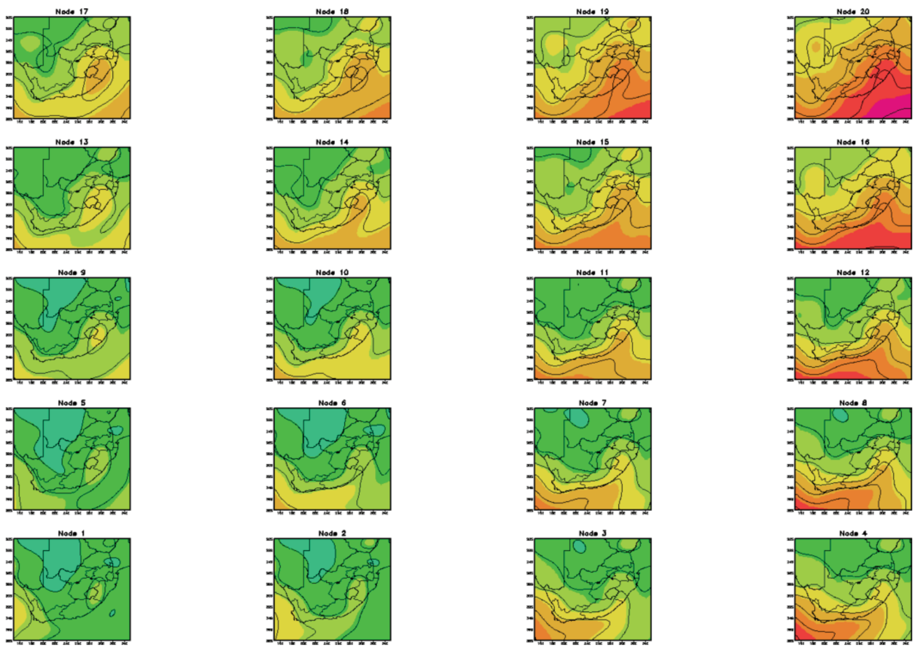
Figure 5.6. As for Figure 5.3 but for the KwaZulu-Natal region.

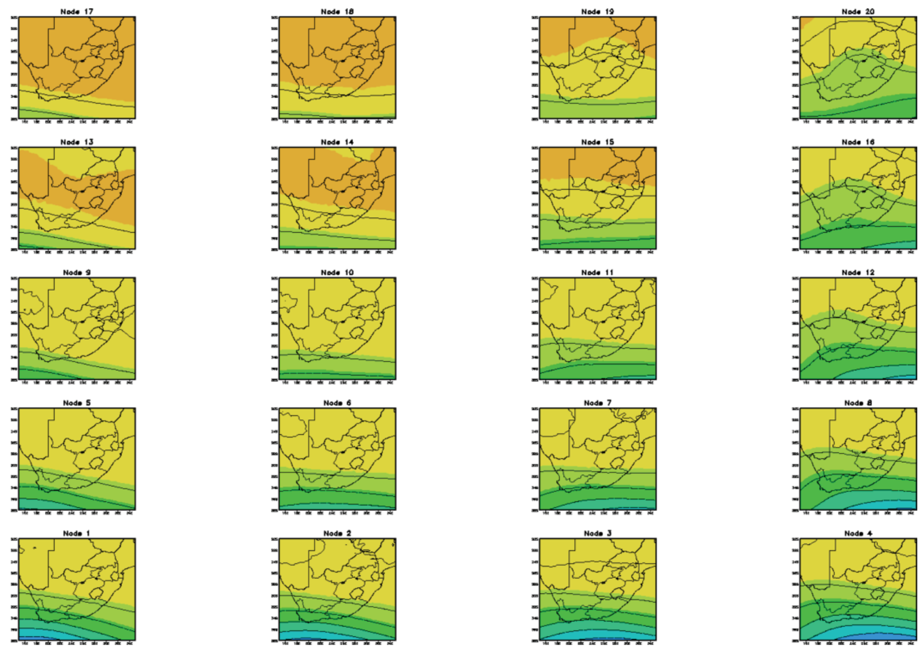
5.4.5. Lowveld

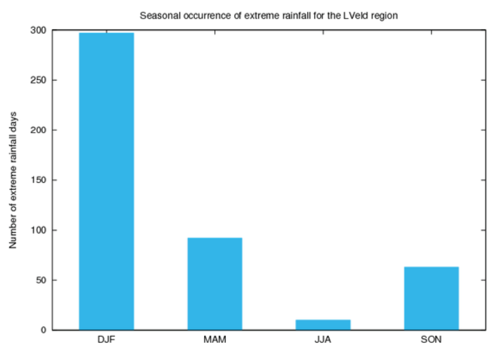
The extreme rainfall synoptics represented by the 95th and 99th percentile SOMs for the Lowveld are generally driven by the surface forcing. These circulations are characterized by high pressure systems to the south of the country that also extend northward along the east coast of South Africa as well as low pressure troughs over the central interior parts of the country (Fig. 5.7).

The seasonal distribution of the extreme rainfall events follows the summer rainfall regime of the Lowveld. This is evident in the 95th percentile SOM with the months of DJF experiencing the highest number (300) of extreme rainfall days. The frequencies of the nodes for DJF are widely distributed across the SOM array, however, tending to occur more towards the left hand side. Nodes 1, 7, 9, 10 and 18 have the highest amount of occurrences together totalling a little over 43%. With the exception of node 18, these nodes are all characterized by a deep low pressure trough over the interior and a high pressure system over the east coast of South Africa. Node 18 is characterized by a weaker surface low but stronger high pressure to the east and likely enhanced onshore flow. The high pressure systems provide on-shore air flow from the warm ocean current resulting in a large influx of moisture inland and the surface thermal low provides the uplift need for precipitation. In winter al extreme rainfall days mapped to node 20 which is associated with the strongest high pressure system to the east of the country as well as a weak trough in the upper air. I the shoulder seasons MAM extreme rain days map broadly across the SOM whereas SON days tend to map to the right of the SOM and are associated with a weak upper air trough and a high pressure to the east of the country.

The seasonal distribution of the 99th percentile rainfall events showed SON experienced the highest number of extreme rainfall days (120) while DJF followed with 90 days, this is different to the 95th percentile seasonal distribution. During SON seven of the 20 nodes account for all the extreme rainfall events with 27% attributed to node 1 and 36% to nodes 9 and 19. Node 1 is characterized by a ridging high pressure system that extends from the south of the country up the east coast. Node 9 is similar to node 1 but with a more prominent low pressure trough over the interior and weaker high pressure over the east coast. Node 19, unlike nodes 1 and 9, does not exhibit a strong ridging high pressure but a sub-tropical trough over the interior and western half of the country that looks to extent to the mid-latitudes as well as a an upper air tough to the south west of the country. The







DJF

6.08	9.12	1.01	0.00
7.77	3.72	3.04	0.34
9.80	8.11	5.41	5.07
5.41	6.08	8.11	2.03
8.11	5.41	3.38	2.03

MAM

2.20	4.40	13.19	3.30
3.30	6.59	14.29	2.20
2.20	1.10	4.40	4.40
2.20	0.00	3.30	13.19
9.89	3.30	3.30	3.30

JJA

0.00	0.00	0.00	100.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00

SON

0.00	0.00	4.84	11.29
1.61	1.61	4.84	20.97
0.00	1.61	3.23	8.06
1.61	0.00	3.23	3.23
0.00	6.45	9.68	17.74

Figure 5.7. As for Figure 5.3 but for the Lowveld region.

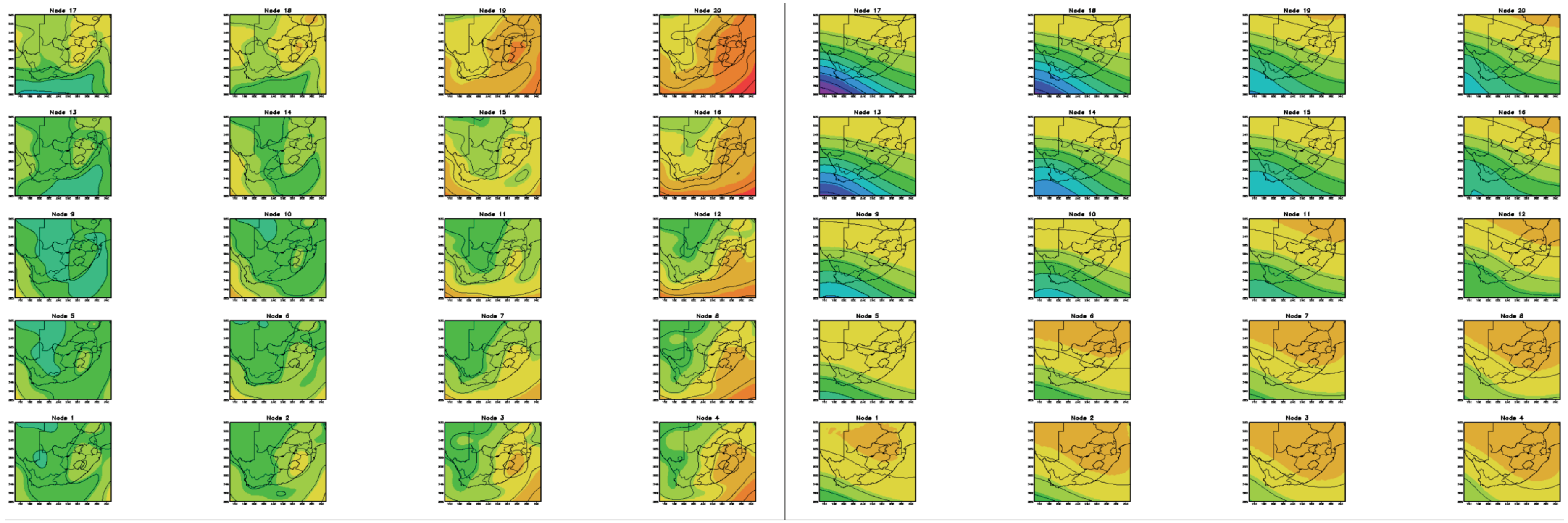
summer month nodes are associated with a deeper sub-tropical low pressure system and generally weaker high pressure systems to over the east coast of the country. It appears likely that the high pressure systems are important in extreme rainfall in this region as through the advection of moisture into the region.

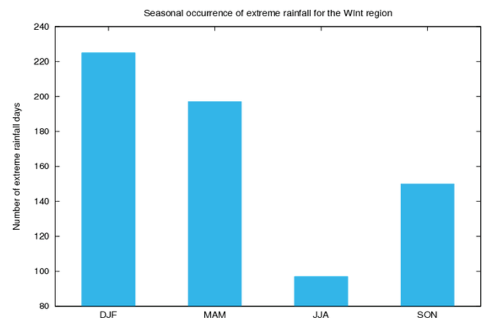
5.4.6. North East Interior

The North Eastern Interior has a very similar rainfall regime as the Lowveld that is evident in the synoptics characterized by the 95th and 99th percentile SOMs. The synoptics can be generalized as high pressure systems at the surface level to the south and east of the country with low pressure troughs extending from the north covering the interior (Fig. 5.8).

The seasonal distribution of extreme rainfall are also very similar to the Lowveld with DJF experiencing the highest number of 95th percentile extreme rainfall days (423) followed by SON with 217 days. The frequency of extreme rainfall for the 95th percentile events during DJF are distributed across the top part of the SOM array with nodes 19 and 20 accounting for 21% of the events. These nodes are characterized by a low pressure trough over the interior with a weak high pressure system towards the eastern parts of the country. Node 20 has slight evidence of a linkage between the low pressure trough and the mid-latitudes. The upper air layers of these nodes are characterized predominantly by zonal flow. The extreme rainfall of SON is represented largely by the bottom half of the SOM array where the synoptic circulations are characterized by stronger high pressure system across the south of the country and extending northward up the eastern half.

Differing to the Lowveld for the 99th percentile extreme rainfall, the North Eastern Interior experiences a similar seasonal pattern for the 99th percentile events to the 95th percentile events with DJF recording the highest number of days (85) followed by SON (40 days). The summer mappings are to nodes on the right and middle-right of the SOM and are associated with the thermal low and varying intensities of the high pressure over the east coast. In SON the mappings are to the left of the SOM which feature a surface thermal low and a high pressure over the east coast much like the like nodes mapped to in DJF, however, these nodes are also associated with a upper air trough to the south east (especially nodes 13, 17 and 18). This might suggest that in SON the upper air circulation is important for enhancement of extreme rainfall into the 99th percentile.





DJF

0.00	0.00	0.00	0.00
0.45	0.00	0.00	0.00
5.80	5.36	1.34	1.79
11.16	9.82	11.61	4.46
12.05	14.29	12.95	8.93

MAM

6.12	3.06	4.08	3.06
7.14	5.61	6.12	2.04
5.10	4.59	2.04	2.55
2.04	8.16	6.63	5.10
4.08	4.08	4.08	14.29

JJA

27.08	6.25	12.50	30.21
3.12	5.21	7.29	8.33
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00

SON

1.34	3.36	4.03	5.37
3.36	12.08	10.07	4.03
8.05	8.72	8.05	10.74
2.01	0.67	3.36	4.70
2.68	2.01	0.67	4.70

Figure 5.8. As for Figure 5.3 but for the Eastern Interior region.

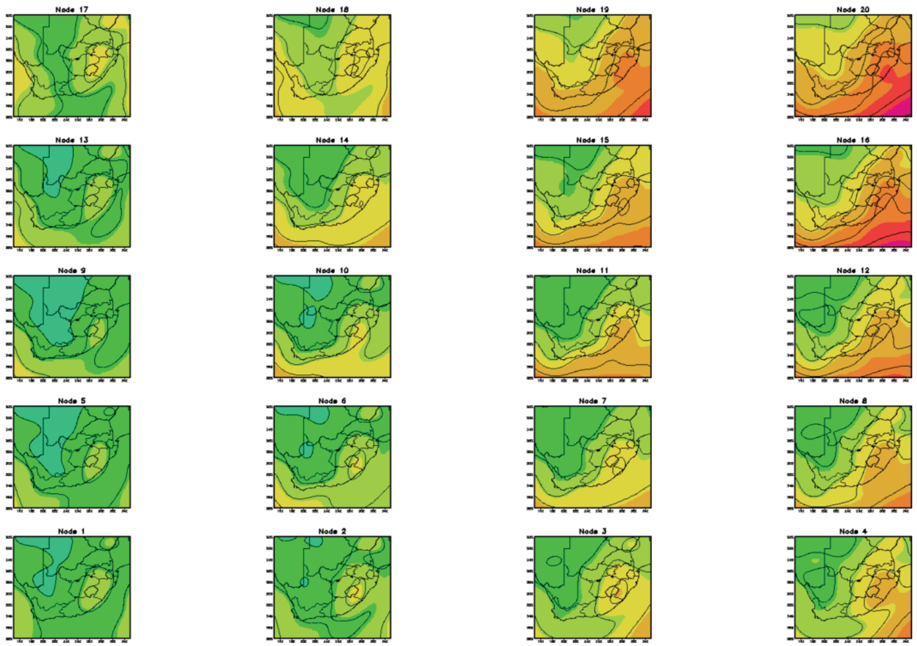
5.4.7. Central Interior

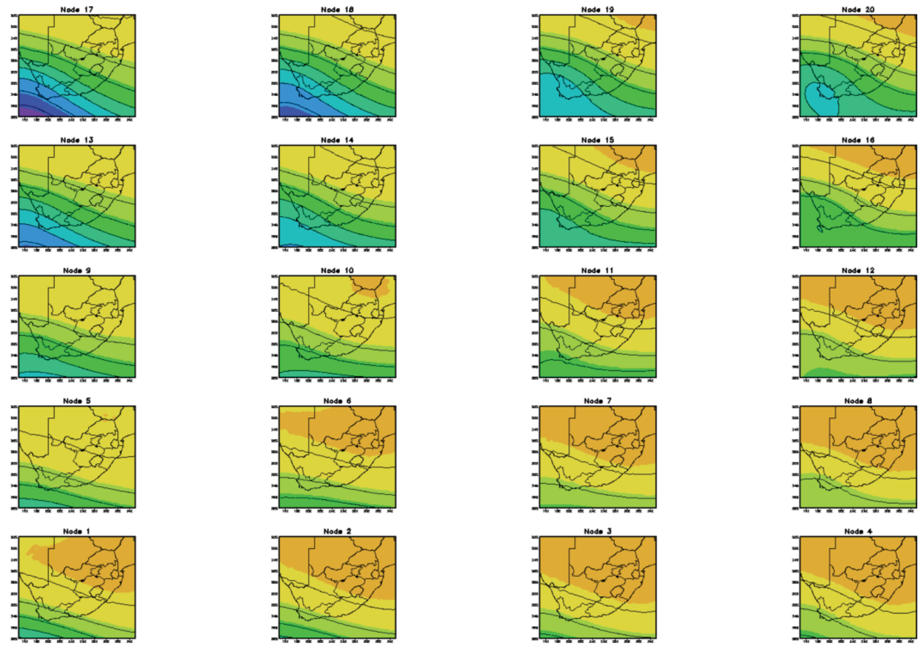
Over the Central Interior synoptic circulations identified by the SOM for the 95th and 99th percentile extreme rainfall events show a low pressure trough over the interior and high pressure systems towards the eastern half of the country (Fig. 5.9). A number of nodes indicate a linkage between the sub-tropics and the mid-latitudes and are one of the most common synoptic states responsible for extreme rainfall to the region. They are evident in the nodes of the 95th percentile evens towards the left side of the SOM (nodes 1, 5 and 17) and in nodes 1-4 of the 99th percentile events SOM. The 99th percentile SOM shows a more pronounced linkage with a stronger low pressure state at the surface level coupled with evidence of a deep mid-latitude cyclone in the upper air flow.

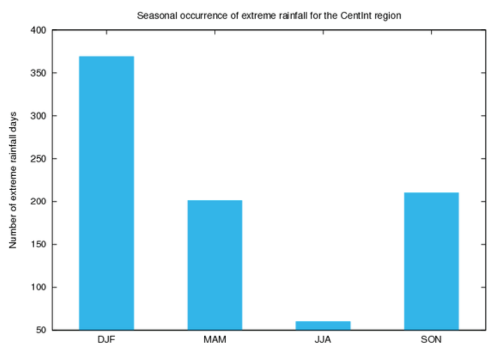
The seasonal distribution of 95th percentile extreme rainfall indicates the summer months of DJF experienced the highest number of days (371) followed by the shoulder seasons with a similar number of occurrences. Nodes 1, 6 and 7 are the most significant nodes representing 34% of 95th percentile extreme rainfall events. The synoptic circulation of these nodes are characterized by a surface trough over the interior with node 1 showing signs of a linkage to the mid-latitudes in the south, while nodes 6 and 7 do not show this linkage but have a stronger high pressure system over the eastern parts of the country. This high pressure together with the trough over the interior during the warmer summer months form similar circulations patterns driving the extreme rainfall to the region. In MAM, there is wide-spread mapping across the SOM, however, node 12 is mapped to most frequently and is associated with a thermal trough over the west of the country and a relatively strong high pressure system over the east. In JJA all days map to the top row of the SOM and are associated with a strongly developed upper air trough with evidence of a closed low in node 20. Surface features indicate a high pressure to the east of the country and weak low over the north-western interior (nodes 19 and 20) and to a lesser degree linkages between the sub-tropical low and mid-latitudes (nodes 17 and 18). The SON season also has 95th percentile rain days mapping predominantly to the top two rows of the SOM which are characterised by an upper air trough and surface high over the eastern parts of the country.

The 99th percentile extreme rainfall events are more common during DJF (66) followed by SON (34) and MAM (25). Summer 99th percentile rain days mapped to nodes on the left of the SOM where nodes 5 and 10 had the highest frequency mappings of 17and 14% respectively. The synoptics of these nodes are characterized by strong surface trough extending from the northern sub-tropics and covering a large part of the country with weak signs of a linkage to the south and a high pressure over the east coast region. Spring 99th percentile rain days mapped to the right of the

SOM where 17.65% were attributed to node 8. This extreme rainfall is represented by a surface low pressure trough extending over the Central Interior region and linked to a deep upper air mid-latitude cyclone.







DJF

0.27	0.00	0.00	0.00
0.00	0.00	0.54	1.09
7.61	4.62	5.43	3.80
8.70	11.68	10.60	7.07
12.77	8.42	8.42	8.97

MAM

5.50	3.50	3.50	1.50
4.00	5.50	5.00	3.00
1.00	4.00	5.00	15.50
3.00	4.50	3.00	8.50
3.00	6.50	5.50	9.00

JJA

11.86	16.95	32.20	38.98
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00

SON

7.18	9.09	4.78	7.66
6.70	10.53	13.88	10.53
2.39	4.31	6.70	1.44
0.48	1.44	0.96	1.44
2.87	1.44	1.44	4.78

Figure 5.9. As for Figure 5.3 but for the Central Interior region.

5.4.8. Western Interior

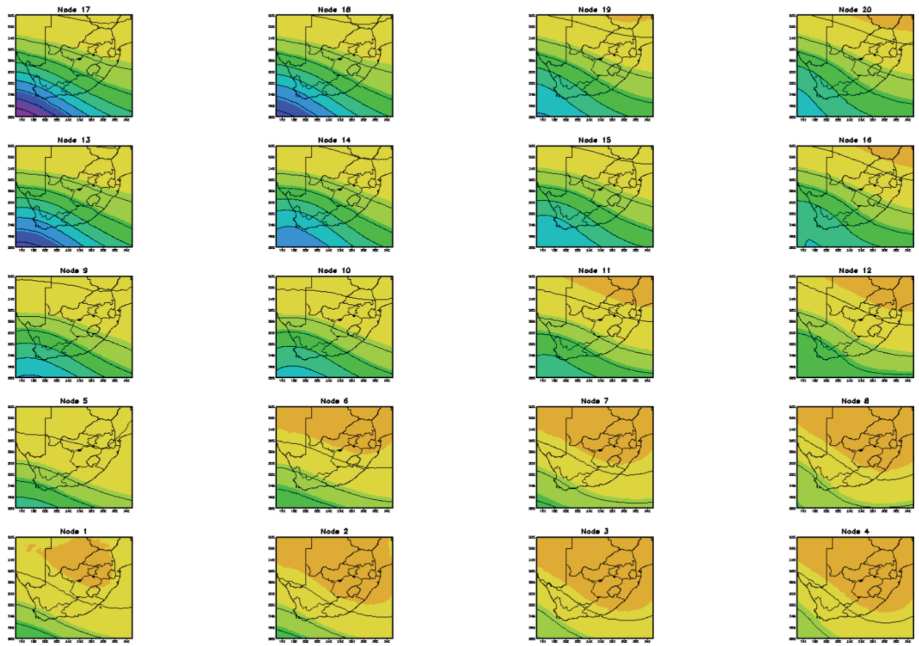
It is evident in the 95th and 99th percentile SOMs that the Western Interior experiences extreme rainfall from synoptic conditions similar to the Central Interior. This is in part due to its inland spatial coverage similar to the Central Interior; however, it is also situated west enough for its rainfall to be influenced by deep passing mid-latitude cyclones (Fig. 5.10). The SOM has identified surface troughs over the interior with high pressure systems to the south and east of the country (nodes 2, 3, 6, 7, 11 and 12 of both SOMs), low pressure systems to the south of the country at the surface as well as in the upper air (nodes 13, 17 and 18 of the 99th percentile SOM) and linkages between the sub-tropics and the mid-latitudes (nodes 5, 9, 13 and 14 of the 95th percentile SOM and nodes 13-20 of the 99th percentile SOM).

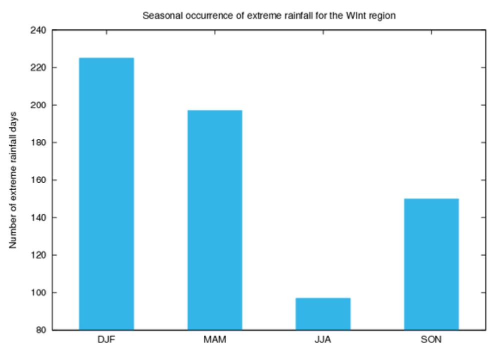
The seasonal distribution of the extreme rainfall events for both the 95th and 99th percentile indicate that the summer months (DJF) experienced the highest number of days (about 225 and 42 respectively). MAM experienced the next highest with about 200 days (95th percentile) and about 34 days (99th percentile).

The most significant nodes representing the synoptics responsible for the 95th percentile extreme rainfall events during DJF occur towards the bottom left corner of the SOM array with nodes 1-3 and 5-7 accounting for 72% of events. These nodes identify a surface trough over the interior with nodes 1 and 5 having a deeper surface low and signs of a linkage to the mid-latitudes whereas nodes 3 and 7 show a stronger high pressure system over the eastern parts of the country. The frequency distributions of the 95th percentile rainfall events for MAM are widely spread across the SOM array with only node 4 showing a significantly higher attribution of 14.29%. The synoptics of node 4 indicate a weak surface trough extending down the west coast and a stronger surface high pressure over the eastern parts of the country. The upper air flow of node 4 indicates a high pressure ridge extending over the eastern parts of the country. The difference between this node and those immediately surrounding it is not obvious, however, on inspection it was noted the mid-latitude low pressure trough is very poorly developed. These very weak synoptic forcings likely facilitate a very strong surface forcing through the thermal low, the formation of a deep west coast trough and subsequent extreme rainfall. During SON highest mapping frequencies are found in the middle of the map (nodes 9-12, 14 and 15), which are associated with an upper air trough in the mid-latitudes if varying strengths. At the surface the sub-tropical low over the interior and linkage with the mid-latitudes characterize nodes 9 and 14 whereas nodes 10-12 and 14 show a high pressure to the south and east of the country to varying degrees and do not show the sub-tropic mid-latitude linkage. In

JJA most days mapped to 17, 19 and 20, which exhibit different synoptic states. Node 17 has a low pressure at the surface to the south of the country associated with a low pressure trough in the upper air indicating a strong mid-latitude cyclone. Nodes 19 and 20 have a weaker upper air trough and a weak surface trough present. This would indicate the 95th percentile rainfall associated with these synoptics not to be frontal but more likely convective.

The 99th percentile extreme rainfall event SOM for DJF is largely attributed to node 20 with 27.5% of the mapping. The synoptics characterizing node 20 indicate a strong surface low pressure linkage between the sub-tropics and the mid-latitudes and a trough in the upper air. Interestingly the highest frequency distribution of MAM is also largely attributed to one node (node 4) which has a surface low pressure over the western interior and a surface high pressure over the eastern parts of the country. The rest of the extreme rainfall in MAM is attributed to the opposite end of the SOM array (apart from node 12 with 9%) and are grouped mostly around nodes 13-16 and 17-19. These nodes have a synoptic circulation pattern characterized by a deep mid-latitude cyclone in the upper air and wide spread low pressure systems at the surface level covering large parts of the country. The JJA 99th percentile rainfall mapped primarily to 2 nodes with distinctly opposite synoptics: node 17, which has a deep surface low to the south of the country and an associated deep upper air trough (frontal characteristics) and node 17, which has a shallower upper trough and a very weak surface trough over the interior. Each of these 2 nodes accounted for 6 of the 17 99th percentile rain days in this season.





DJF

0.00	0.00	0.00	0.00
0.45	0.00	0.00	0.00
5.80	5.36	1.34	1.79
11.16	9.82	11.61	4.46
12.05	14.29	12.95	8.93

MAM

6.12	3.06	4.08	3.06
7.14	5.61	6.12	2.04
5.10	4.59	2.04	2.55
2.04	8.16	6.63	5.10
4.08	4.08	4.08	14.29

JJA

27.08	6.25	12.50	30.21
3.12	5.21	7.29	8.33
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00

SON

1.34	3.36	4.03	5.37
3.36	12.08	10.07	4.03
8.05	8.72	8.05	10.74
2.01	0.67	3.36	4.70
2.68	2.01	0.67	4.70

Figure 5.10. As for Figure 5.3 but for the Western Interior region.

5.5. Discussion

The SOM identified key synoptic circulations associated with extreme rainfall within each of the defined regions. Furthermore the seasonal distribution of extreme rainfall events is also evident in the seasonal SOM mapping – summer rainfall regions had the highest number of extreme rainfall days map to typically summer circulation patterns and in winter rainfall regions winter synoptics.

5.5.1 Seasonal rainfall synoptics

The most notable synoptic circulations associated with extreme rainfall events identified by the SOMs often involved an interaction between circulation patterns. In the summer rainfall regions these included a surface level trough extending from the north covering large parts of the interior together with a ridging high pressure system to the south and/or south east of the country. These synoptics would facilitate the advection of moisture inland derived from the warm Agulhas current. In addition, over the central and interior regions a linkage at the surface level between the sub-tropic low pressure trough and mid-latitudes is present. These linkages, which are also often associated with a mid-latitude trough in the upper air, facilitate the advection of moisture into the interior and may also result in tropical temperate troughs. However, without cloud data it is difficult to identify TTTs and thus fully assess the role of TTTs in each region.

During winter, extreme rainfall synoptics affecting the South Western Cape were identified as the passage of low pressure systems bringing frontal rainfall to the region during the winter months (JJA). These synoptic conditions were also associated with extreme rainfall during the winter months for the coastal regions from the South Coast, Eastern Cape and KZN coast. The latter 3 regions showed an additional characteristic of a ridging surface high that together with deep mid-latitude cyclones in the upper air. The interaction of these two features and the topography are able to result in the observed extreme rainfall. The upper air trough in the mid-latitudes would create unstable synoptic conditions through generating cyclonic vorticity and therefore surface convergence and uplift while the surface high would advect moist air from the Agulhas current into the region which then interacts with the escarpment to result in further uplift. There is also evidence of a closed low pressure system over the KZN coastal regions, however, on inspection of literature for the occurrence of cut-off lows (COLs) in the region (Singleton and Reason, 2006a, 2006b, 2007; Reboita et al., 2010, Favre et al., 2011) this is not associated with cut-off lows.

Outside of the core summer and winter rainfall seasons there are a number of extreme rainfall events evident throughout all the regions. The summer rainfall driven eastern parts of the country as well as the Southern Coastal region experience a higher number of extreme rainfall events during SON than MAM, while the western regions of the South Western Cape and the Western Interior experience a higher number of extreme rainfall events during MAM compared to SON. Singleton and Reason (2007) show the occurrence of COLs, which are known for their ability to cause extreme rainfall, to peak in MAM in the South Western Cape, South Coast and the Western Interior regions which may be an explanation for this observation. However, COLs have been poorly characterized in the regional SOMs.

5.5.2. Characterization of cut-off lows

All discussion in this section refers to the 99th percentile SOM and the 500 hPa geopotential height. Although the regional SOMs have identified synoptics of the associated extreme rainfall days, there is a lack of clearly visible cut-off low pressure systems. The closest synoptic pattern to that of a cut-off low for the Southern Coastal region is identified in node 16 and similarly nodes 1 and 2 of the KZN Coastal region. Although the KZN nodes could not be associated with known cut-off low caused extreme rainfall, node 16 of the south coast was associated with one COL event on 22 August 2006.

Cut-off low systems that are known to have been associated with extreme rainfall were identified (e.g. 24/25 January 1981, 22/23/24 August 2006, 11/12/13 November 2008) primarily in the Western Interior, South-western Cape and South Coast. The positioning of these systems is consistent with the findings of the above authors who all show that these regions experience the highest occurrence of cut-off lows per year. However, these systems were placed in nodes that did not exhibit characteristic closed circulations usually associated with a COL, which indicates a potential problem with w.r.t. extreme rainfall and the rationalization scheme chosen.

In the Western Interior 99th percentile map, nodes 1-3, 5-7, 10 and 14 had known COL days map to them. The highest rainfall event from a COL in the region was recorded by station 22 on 11, 12 and 13 November 2008 – the days mapped to nodes 10, 6 and 7 respectively and resulted in the daily rainfall amounts of 127, 149 and 116 mm respectively. Over the South Coast region nodes associated with COLs were nodes 2, 3, 6, 7, 9, 12 and 13. Here the highest rainfall event was recorded at station 30 (238 mm) on the 22nd November 2007 and the day mapped to node 6. This is also the most frequently mapped to node during SON. In the SW Cape region cut-off lows associated with extreme rainfall mapped primarily to nodes 13 and 17 in the 95th percentile SOM and 1, 2 and 5 in the 99th percentile SOM.

As mentioned above, the nodes to which COLs generally mapped in the regional maps did not exhibit characteristic closed circulations which suggest a deficiency in the method. It would be expected that a COL type of circulation would be captured especially in the seasonal maps where data points are fewer and thus the characterization of synoptic types is less generalized. This may be due to a number of reasons: the extreme rainfall regimes are likely different to the general rainfall regimes of the country used in this study. In looking more closely at where COLs occurred, it was found they spanned the 3 regions of the South Western Cape, South Coast and Western Interior. This suggests a more event-based regionalization might be more successful in producing circulation patterns associated with COLs. A SOM of one region that experienced e.g. 12 COLs would more likely produce a node with characteristic COL circulations than 4 regional SOMs that split the 12 COL events between them. In this way it may be possible to map out extreme rainfall-specific regions of South Africa ultimately providing a more precise description of the extreme rainfall causing synoptics in each region. Secondly, extreme rainfall may occur the day before the COL forms, an event this type of analysis would miss. Lastly, the characteristics of COL in summer and winter are different. During summer strong COLs are associated with a high pressure to the south of the system whereas in winter the surface circulation has deep frontal characteristics. The latter circulations are present in COL-related nodes in the SW Cape region and the former evident in the South Coast region. However, these characteristics are very generalized, a situation that would be addressed in an event-based analysis. This would also aid future studies in characterizing changes in these.

5.6. Summary

The regional assessment identified specific synoptic states that were associated with extreme rainfall in particular seasons. Summer recorded the highest occurrence of extreme rainfall in all regions with the exception of the South Western Cape and South Coast regions (winter and spring respectively) and was usually associated with a surface low of varying depth over the central or western interior and a high pressure over the south and/or east coast. The surface thermal low would facilitate moisture transport from the sub-tropics as well as surface convergence and convection and the high pressure a measure of moisture advection into the interior. In the Western Cape extreme rainfall occurred primarily in winter and was associated with a surface low in the mid-latitudes and over the region and an upper air trough to the south west, the upper air trough was deeper in 99th percentile events. Extreme rainfall in the South Coast region occurred in the shoulder seasons and winter and was associated with the passage of a cold front a ridging high pressure and strong surface linkages between the sub-tropics and the mid-latitudes. However, circulation characteristics of cut-off lows were not reproduced in regions that experienced extreme rainfall as a result of these systems and we suggest an event-based analysis would be more likely to identify these.

Chapter Six. Trends in extreme rainfall

6.1. Introduction

Trends in extreme precipitation are important to understand in order to understand the effect these events may have as well as in the formulation of adaptation and coping strategies. Regional station data was assessed for trends in extreme rainfall indices listed in the RClimDex classification set to identify regions that have experienced changes in the characteristics of extreme rainfall. The RclimDex software identifies GHCN indices in the R statistical package. Any statistically significant changes in the station data were related to changes in the frequency of occurrence of circulation archetypes identified in the regional SOMs in to relate the station trends to circulation trends. The station trends were also placed in the context of full 31-year daily record so identify frequency changes in these synoptics. Additionally a seasonal assessment of regional changes was carried out to identify any shifts in the synoptic drivers of the extreme rainfall, e.g. between summer and shoulder season drivers, which were different.

6.2. Regional trends in the station data

The RClimDex software was used for calculating climate indices from daily station data. This study used 10 of the RClimDex extreme rainfall indices specific to rainfall to investigate regional trends in extreme rainfall. Each station within each rainfall region of South Africa had these indices calculated and their associated trends were analysed. A description of the 10 RClimDex extreme rainfall indices is listed in Table 1 after which each region is assessed.

Table 6.1. RClimDex extreme rainfall indices used in this analysis. The 95^{th} and 99^{th} percentile indices amounts are calculated based on the study period 1979 to 2009. RR is the daily rainfall rate.

Index code	**Name**	**Definition**	**Units**
CDD	Consecutive dry days	Annual maximum number of consecutive days with RR <1.0mm	Days
CWD	Consecutive wet days	Annual maximum number of consecutive days with RR >=1.0mm	Days
PRCPTOT	Total wet-day precipitation	Annual total precipitation from wet days (RR>=1.0mm)	mm
R95 mm	Number of days above 95^{th} %ile mm	Annual number of days when RR >=95^{th} percentile rainfall amount	Days
R99 mm	Number of days above 99^{th} %ile mm	Annual number of days when RR >=99^{th} percentile rainfall amount	Days
R95p	Very wet days	Annual total precipitation from RR >95^{th} percentile	mm
R99p	Extremely wet days	Annual total precipitation from RR >99^{th} percentile	mm
RX1day	Max 1-day precipitation amount	Annual maximum precipitation in 1 day	mm
RX5day	Max 5-day precipitation amount	Annual maximum precipitation in 5 consecutive days	mm
SDII	Simple Daily Intensity Index	Annual total precipitation divided by the number of wet days (RR >=1.0mm) in the year	mm/day

6.2.1. South Western Cape

The stations clustered around the Cape Town area at lower altitudes (1 and 3) identify a steeper positive trend for the very extreme 99^{th} percentile rainfall indices compared to the 95^{th} percentile rainfall indices (Fig. 7.1). Station 6 has positive trends similar to these and both the R99mm (days) and R99p (mm) indices of station 6 are significant with R99p at the 5% level.

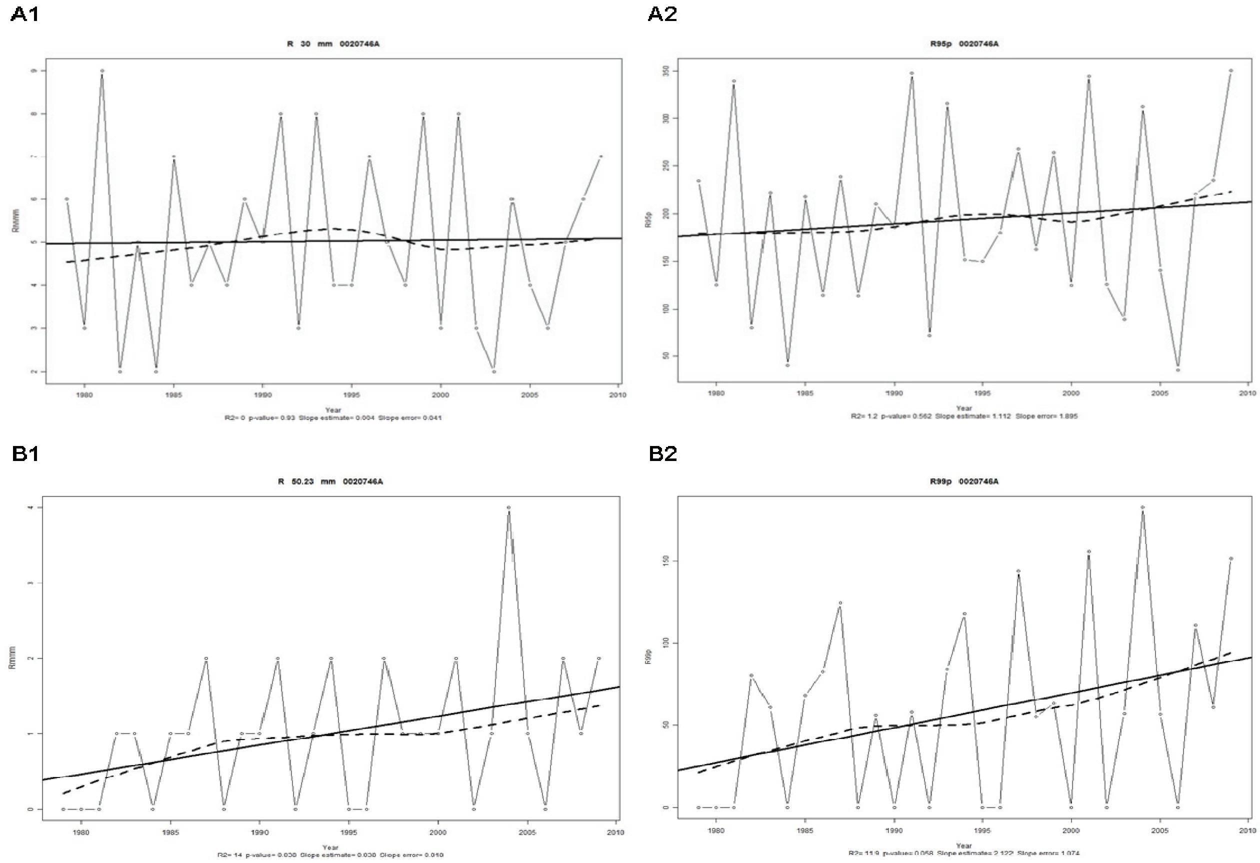


Figure 6.1. Annual precipitation from 95th percentile rainfall events (A1 and A2) and 99th percentile rainfall events (B1 and B2) for Station 1 in the Cape Town area showing a steeper positive trend in the more extreme 99th percentile rainfall compared to that of the 95th percentile rainfall.

Further up the west coast (station 11), has experienced significantly positive trends throughout all the extreme rainfall indices (Fig 7.2). This is primarily due to an increase in these indices since the year 2000. However, the SDII index has a decreasing trend (not significant), which is due to the increase in annual total precipitation together with the decrease in the CDD and increase in the CWD indices. Therefore the annual total rainfall is increasing due to the increase in rainfall contributed by the 95th and 99th percentile events.

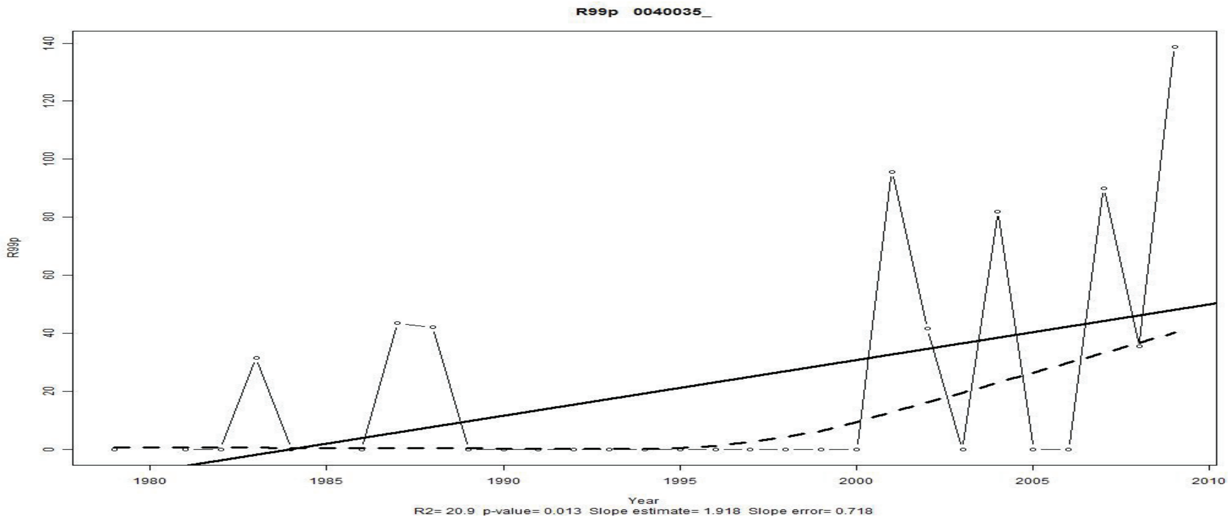


Figure 6.2. Annual precipitation from 99th percentile rainfall events for Station 11 on the West Coast showing the significantly (p-value = 0.013) increasing trend influenced by the extreme rainfall years post 2000.

The mountainous regions of the South Western Cape represented by stations 7, 8, 9 and 13 identify a mix in positive and negative trends in their 95th and 99th percentile indices. They do, however, agree with non-significant positive trends for the CWD index and apart from station 8 they identify negative trends in the SDII index.

Summary:

- It is generally noted that most of the stations around the Cape Town area experience a greater increase in the very extreme 99th percentile indices compared to the 95th percentile indices. This pattern does not hold for the stations further outside of the Cape Town region.
- There are generally mixed trends with very little significance.
- The further inland mountainous parts of the region identify positive trends in the CWD index and negative trends in the SDII index, which may identify a general trend towards less extreme and more consistent rainfall here.
- Some mountainous stations that indicated significant trends did not have nearby stations displaying a similar profile. The topography of the region may affect these differences in stations with close proximity and more stations may need to be sampled to confirm the identified trends.
- The short 31-year period likely caused the trends to be heavily influenced by 1 to 4 years of extreme rainfall years clustered together in the time period.

6.2.2. South Coast

Stations 27 to 29 display a similar pattern to the lower altitude stations around the Cape Town area in which they experience steeper trends in the very extreme 99th percentile indices compared to the 95th percentile indices (Fig. 7.3). These stations are located closer to the South Western Cape region along the South Coast and also occur at lower coastal altitudes. Station 27 and 35 both experience significantly positive trends in the SDII. Their profile throughout the indices are very similar and this significant trend in the SDII index may be due to the positive trends in the extreme rainfall indices along with the positive CCD index trend and negative CWD index trend. Stations 27 and 35 occur on the coast at low altitudes, while station 27 is on the far west side of the South Coast region station 35 is on the far, east side. These trends are not as evident in the other stations in the South Coast region. There are no clear signs of trends in the indices or agreement between the stations further eastwards along the South Coast region.

Summary:

- The South Coast region identifies a similar profile in the indices throughout the stations to that of the South Western Cape region with mixed trends and little significance.
- It is clear that a link between a positive CDD index, negative CWD index and a positive SDII index exists and the stronger these trends are the more significant the SDII trend becomes.

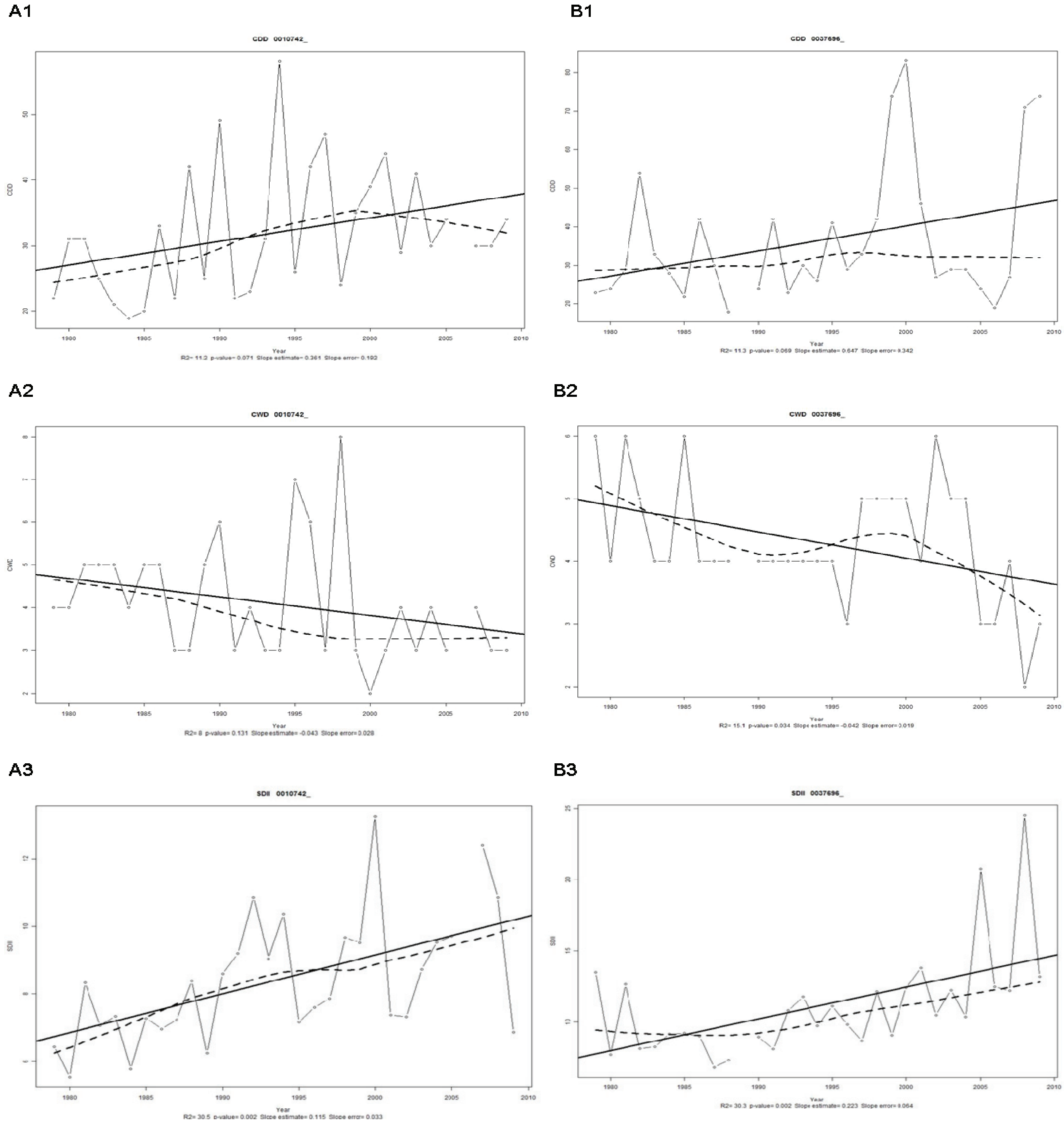


Figure 6.3. Relationship between the CDD index (A1 and B1), CWD index (A2 and B2) and the SDII index (A3 and B3) for stations 27 (A) and 35 (B). The SDII is significant for both stations at the 5% level.

6.2.3. Eastern Cape

The 3 stations along the coast have similar patterns in their trends for the extreme rainfall indices. Station 47, which is situated the furthest south and closer to the South Coast region identifies trends similar to some of the stations of this region with positive 95th and 99th percentile indices trends. The 95th percentile indices and the SDII index for station 47 are positive and significant at the 5%

level. Further up the coast station 48 has few trends throughout all its indices. While even further up the coast and nearer to the KwaZulu-Natal Coast region station 50 identifies a pattern of trends similar to that region in which the 95th and 99th percentile extreme rainfall indices are all negative.

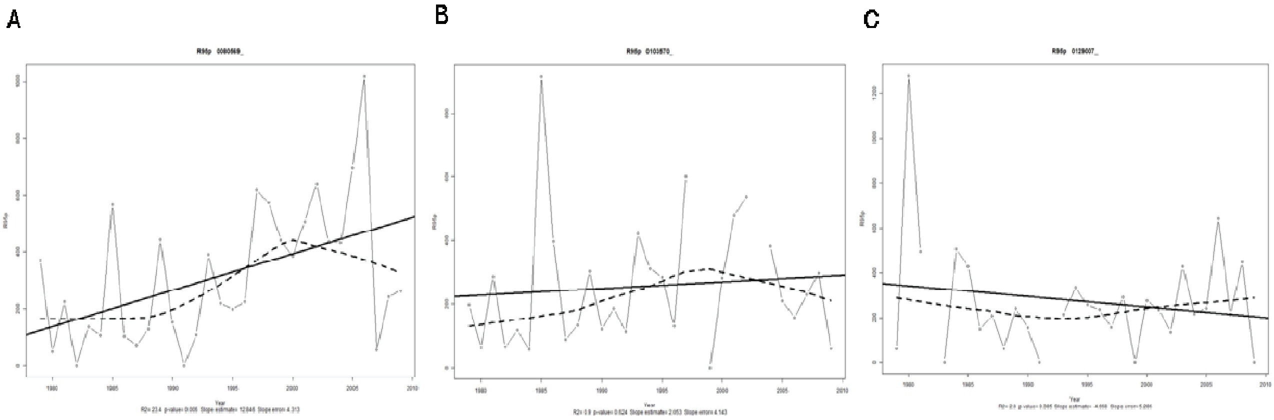


Figure 6.4. The change in extreme rainfall trends represented by the R95p index along the Eastern Cape coastal stations from station 47 (A) further south with a positive trend to station 48 (B) in between with a flatter trend to station 50 (C) further north with a negative trend.

The 4 stations further inland and at higher altitudes identify a mix of trends. Stations 46 and 52 both identify negative trends in their 95th and 99th percentile rainfall indices and no clear trends in the other indices. Stations 49 and 51 identify positive trends in their 95th and 99th percentile rainfall indices and in this scenario station 49 has significantly positive trends at the 5% level for 99th percentile indices (R99mm and R99p) and the SDII index. Station 51 also has a significantly positive trend at the 5% level for the SDII index. These trends are similar to those identified in stations 44 and 45 of the Central Interior region.

Summary:

- There is a spatial transition between the pattern of trends identified between the stations along the coast from the southern parts near the South Coast region and the northern parts nearer the KwaZulu-Natal Region. This is exemplified in station 48 with few clear trends and situated roughly between station 47 and station 50, which have very different pattern of trends in their indices.
- The 4 stations situated inland from the coast and higher above sea-level are evidently different to those stations on the coast with no agreement amongst their trends.
- The higher altitude stations with positive extreme rainfall trends are also mostly significant at

the 5% level.

6.2.4. KwaZulu-Natal Coast

Most of the 95th and 99th percentile extreme rainfall indices trends are negative throughout all the stations (Fig. 6.7). Station 55 identifies a significantly positive trend at the 5% level for the SDII index. This is primarily due to the strong negative trend also at the 5% level for the CWD index, as this does not agree with the negative trends identified for the extreme rainfall indices, the RX1day and RX5days indices.

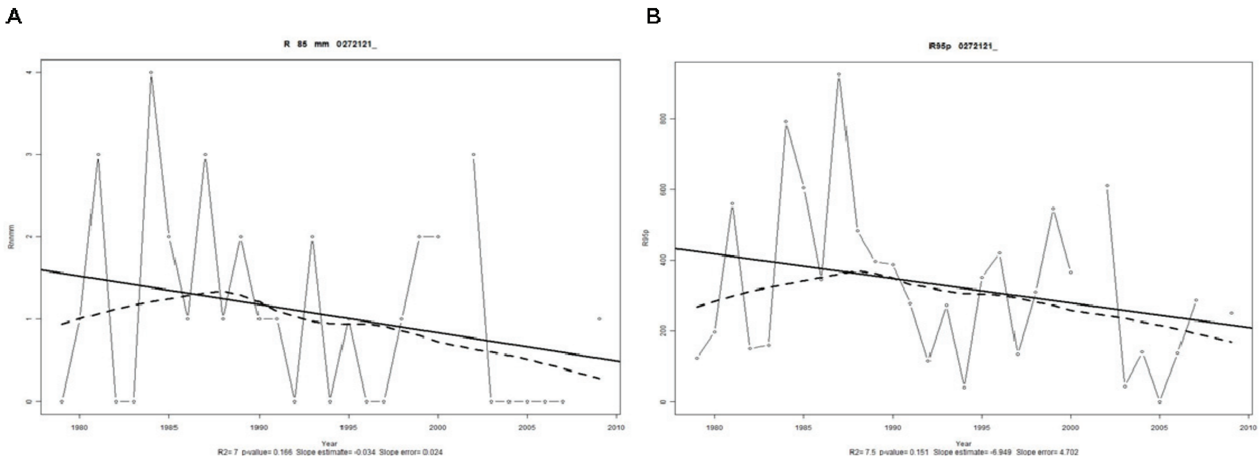


Figure 6.5. Extreme rainfall indices R99mm (A) and R95p (B) representing the negative trends for the KwaZulu-Natal Coast region.

Summary:

- The stations in the region agree in identifying negative trends in the CWD and positive trends in the CDD indices. These are not accompanied with a significant trend in the SDII index as seen in other regions above due to the general negative trends identified throughout the 95th and 99th extreme rainfall indices.
- A trend towards less extreme rainfall is identified throughout the region.

6.2.5. Lowveld

The only indices that identify a pattern in their trends throughout the stations of the Lowveld region are those relating to the 95th and 99th percentile rainfall indices. None of these are significant; however, they are all slightly positive. The other index trends are mixed between being either positive or negative and no trend at all. Station 66 identifies a significantly positive trend at the 5%

level for the CDD index, while most of the other stations either identify no trend or slightly negative trends for this index that are not significant. Station 67 identifies a positive trend for the SDII index significant at the 5% level, while the other stations identify a mix of trends or no trends as well as no significance for this index.

Summary:

- The region experiences few significant trends apart from a general agreement between the positive trends of the 95th and 99th percentile extreme rainfall indices indicating a trends towards slightly more extreme rainfall over the region.
- These extreme rainfall indices have very high thresholds in this region with the 99th percentile rainfall thresholds ranging between 73mm and 137mm.
- Station 67 is situated near the regional boundary and identifies a similar pattern in trends throughout its indices as the stations in the northern parts of the North Eastern Interior region.

6.2.6. North Eastern Interior

Station 58 experienced positive trends in the 95th and 99th percentile extreme rainfall indices with R99p significant at the 5% level. This trend is characterized by a notable increase in the amount of precipitation from 99th percentile rainfall events in extreme years after 1995 shown in Figure 5 below.

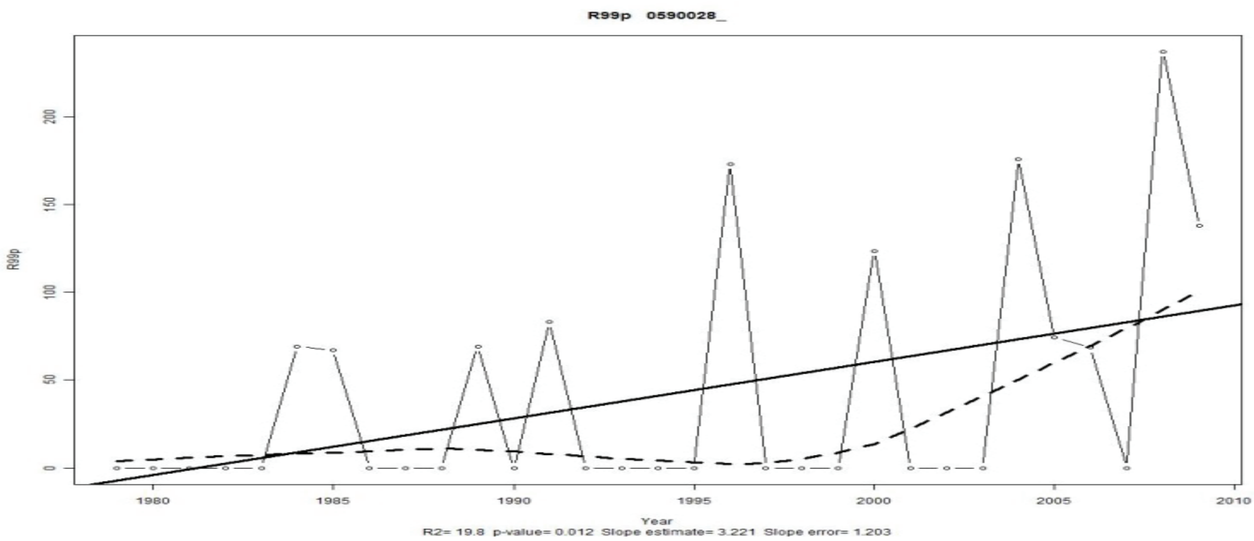


Figure 6.6. Contribution of rainfall in mm from extreme events greater than the 99th percentile with a clear increase in extreme years from 1995 for station 58.

The same pattern occurs for station 58 as various inland stations described above in which the extreme rainfall indices are all positive as well as a positive CDD and negative CWD resulting in a significantly positive trend in the SDII at the 5% level. These trends are also identified in stations 59 and 60 (except station 60 has a positive CWD trend that is, however, not significant). The North Eastern Interior region shows similar attributes as the other two interior regions in that the stations further southward identify fewer significant trends. Station 61 does, however, identify a significantly positive trend in the SDII at the 5% level similar to the stations further northward due to its significantly positive trend in the CDD index. The rests of station 61's indices show no real trends. (Fig. 6.6). Station 64 also shows no real trends except for the SDII index, which in the scenario is opposite to all the other stations in this region and is negative with a p-value of 0.057.

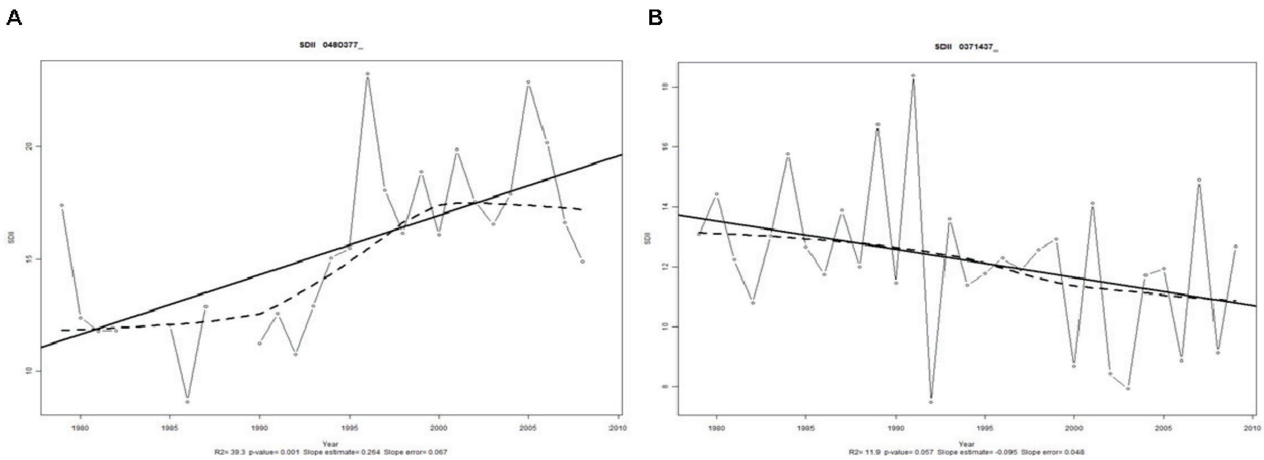


Figure 6.7. The negative trend for the SDII index for station 64 (B) compared to the positive trend for station 61 (A), which is more representative of the stations spread throughout the North Eastern Interior region.

Summary:

- The northerly positioned stations have a similar pattern of trends to the stations situated in the northern parts of the Western and Central Interior regions.
- Stations 58, 59 and 60 have the most convincing trends throughout their indices.

6.2.7 Central Interior

Stations 36, 39 and 42 are situated towards the western parts of the Central Interior region and identify very similar trends to the stations in the northern region of the Western Interior (stations 15 to 18) discussed above.

In the central and eastern parts of the region the extreme rainfall trends of the 4 stations (37, 38, 40 and 41) are flatter and less significant identifying a mix between positive and negative trends. Station 43 identifies no sign of trends throughout its indices. Stations 44 and 45 both identify positive trends for the 95th and 99th percentile indices. Both these stations have a significantly increasing trend at the 5% level for the RX1day index.

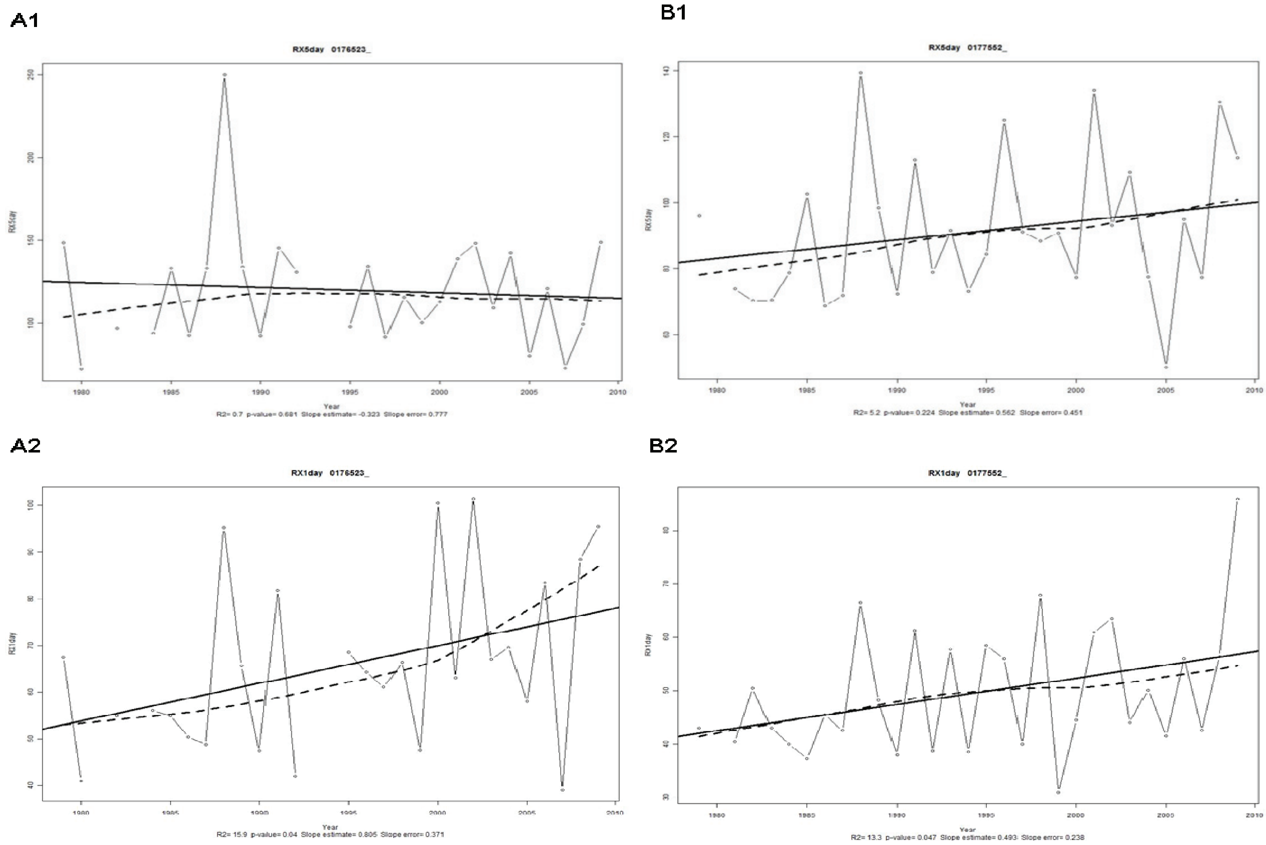


Figure 6.8. The difference between the extreme rainfall trends for the RX5day (A1 and B1) and the RX1day (A2 and B2) for stations 44 (A) and 45 (B). The RX1day index identifies a significantly positive trend at the 5% level both stations 44 (A2) and 45 (B2).

Summary:

- It is difficult to identify a pattern between the extreme rainfall trends for stations 37, 38, 40 and 41 when there are differences in the trend directions between the 95th and 99th percentile indices, while stations 36, 39 and 42 identify positive trends throughout the 95th and 99th indices and therefore have a higher level of significance.
- The significantly positive trends of stations 44 and 45's RX1day index and less clear trends in the RX5day index may indicate the rainfall becoming more extreme over a shorter period of time in the higher altitudes as both these stations are occur above 2000 meters above sea-level.

6.2.8. Western Interior

The stations in the northern parts of the region (15 to 18) extreme rainfall trends identify slightly positive trends that are not significant. In this case for the Western Interior opposed to the South Western Cape (Figure 1), the 95th percentile rainfall indices show a steeper positive trend compared to the very extreme 99th percentile indices. These stations have a significantly positive trend for the SDII index accompanied with the positive CDD index and negative CWD index similar to that identified for the South Coast region stations of 27 and 35. The stations in the southern parts of the region (19 to 26) display mostly negative trends in the extreme rainfall indices that are also not significant.

Summary:

- There is a clear spatial division between the stations in the northern parts of the region (stations 15 to 18) to the stations in the southern parts of the region (stations 19 to 26) in which the northern stations identify more clear trends in the extreme rainfall indices as well as significantly positive trends for the SDII index, while the southern stations display mixed trends.

6.2.9. Summary and Conclusions

The short 31-year study period posed difficulties in the identification of significant trends in extreme rainfall as there were relatively few data points per station. The nature of extreme rainfall and definition of such as 95th or 99th percentiles should ideally have a much longer time series when examining trends such as in Kruger (2006). The trends are also heavily influenced by a few extreme rainfall years and therefore do not provide an accurate representation.

However, some general observations could be made. Throughout all the stations across the country, apart from the KwaZulu-Natal Coast region, positive trends were identified in the 95th and 99th percentile extreme rainfall indices, although, very few of these were significant at the 5% level. There was also a general feature where many of the stations experiencing a positive SDII index related to a positive CDD index and a negative CWD index. The SDII index identified the highest number of significant trends throughout the regions and stations. This significance was closely linked to the trends for the significant trends identified to be positive for the CDD index and negative for the CWD index. The southern parts of the Central Interior and the inland parts of the

Eastern Cape form a region that identifies this trend pattern and agrees with the results identified by Kruger (2006) for this region apart from the SDII index, which was not included in his analysis.

Inland regions identify steeper increasing trends in the 95th percentile extreme rainfall indices than the 99th percentile extreme rainfall indices, while the coastal stations identify the opposite. A greater number of stations displayed an increase in RX1day events than RX5days events. This, together with the SDII trends may indicate that extreme rainfall has begun to occur over a shorter time period. Significant trends in R95p, R99p, SDII and RX1day are summarized in Figure 6.9.

Spatially, there was a difference within the coastal rainfall regions of the South Western Cape, South Coast and the Eastern Cape between the higher altitude stations situated inland and the lower altitude coastal stations. Stations that were situated close together but at very different altitudes usually had very different patterns of trends. In these regions there was also a transition along the coast from the generally positive trends in the 95th and 99th extreme rainfall indices occurring more in the winter frontal driven rainfall regions towards the south west to the negative trends identified in the summer rainfall region towards the north east along the KwaZulu-Natal Coast region.

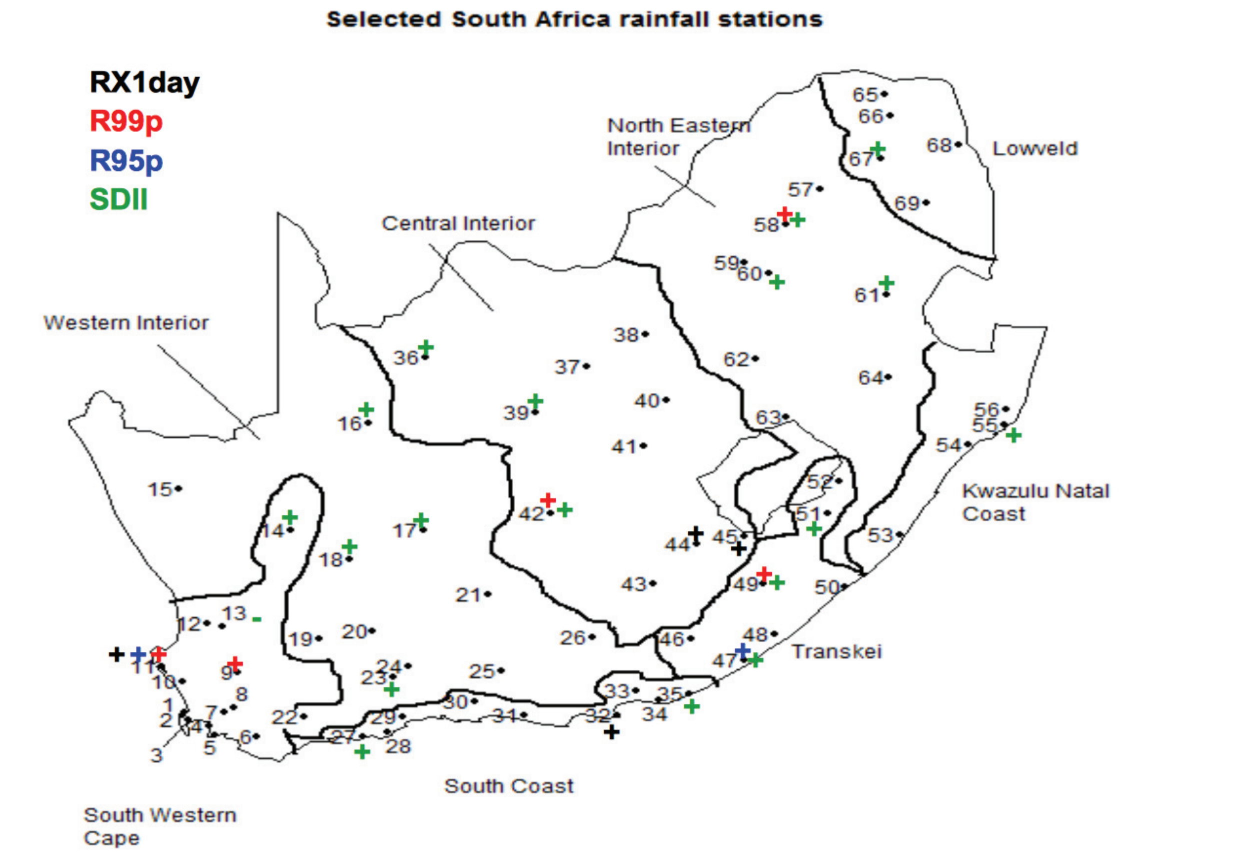


Figure 6.9. Stations with trends as indicated in the legend.

From the regional assessment of extreme rainfall indices we again suggest that the rainfall regions we used are not necessarily representative of extreme rainfall pattern regions. This was evident through the extreme rainfall profile for each of the stations in Table 5.1 earlier as well as in this section. For example station 14 displays very similar extreme rainfall indices to those stations in the northern regions of the Western Interior opposed to those of the South Western Cape region. It was also apparent that, as mentioned above, the 31 year period is not optimal for a study of trends in extreme rainfall.

However, as the extreme rainfall days were associated with particular synoptic circulation states in the 31 year period, which occur more frequently than the extreme rainfall days only, it is possible to identify trends in the frequency of occurrence in these states given. This would provide the means to relate the trends in the station data to the trends in synoptic states and quantify the likelihood of changes in the characteristics of extreme rainfall in the future. The next section relates the station data to the synoptic states as identified in the SOM and identifies changes in the frequency of occurrence of these.

6.3. Trends in synoptic arch-types related to extreme rainfall

Trends in the frequency of occurrence of synoptic states could only be run over the full 31 year time period as the degrees of freedom associated in the regions that had stations with significant trends were too few to make robust statements about statistical significance. For example, station 11 only had 74 and 16 95th and 99th percentile events respectively (see Table 10). Therefore, to gauge the trends in circulation changes associated with extreme rainfall, a trend analysis was performed on the frequency of occurrence of the synoptic types in the full 31 record as reported in Chapter 4 (Figure 4.2). In doing this, nodes with significant trends in their frequency of occurrence could be associated with stations that show significant trends in extreme rainfall.

Testing for statistical significance of trends in the frequency of occurrence of synoptic states was performed though bootstrapping annualized frequencies of occurrence over the 31 year period with the number of bootstrap replicates being set to 1000. Using the linear regression of each bootstrapped replicate a histogram of the slopes of the linear regressions was generated. This formed a normal distribution for regression slopes from which the 95th percentile could be determined. The slope of the regression of the actual data could then be placed within the normal histogram and if it fell above the 95th percentile the trend was considered significant.

6.3.1. Assessment of circulation trends over the full 31-year period

Nodes 36, 37 and 40 show significantly positive trends in frequency of occurrence throughout the 31 year time period at the 95th percentile level. These nodes were all associated with a sub-tropical low over the interior of the country and a higher pressure over the eastern parts of the country. Node 37 was the second highest mapped to node in the when extreme rainfall synoptics based on all 696 stations were passed through the trained SOM (see Figure 4.3) and node 36 the fourth highest mapped to node. Node 37 was also the most frequently mapped to node in summer followed by node 36. This would indicate that as these circulations have become more frequent the possibility that they may be associated with extreme rainfall could increase. Node 40 was the most frequently mapped to node in MAM and the second most frequently mapped to node in SON. This would suggest that characteristics extreme rainfall in these seasons may change.

Data from the five stations that indicated significant trends were used to assess whether the significant changes in the three circulation types were reflected in the extreme rainfall record. Trends in station data were compared to trends in the SOM mappings in order to see if changes in the synoptic drivers of extreme rainfall were reflected in the station record. These were evident in varying degrees. At station 11 extreme rain days mapped primarily to nodes 1(29), 9(16) however none of these nodes displayed a significant increase in the frequency of occurrence during the 31 year period and the same was true for station 9. However, stations 42, 49 and 58 each had a relatively high proportion of extreme rainfall associated with these nodes (Fig. 6.6). At station 42 the highest number of extreme rain days were associated with node 40(9) followed by node 21(8) then nodes 37(5) and 36(4). In station 49 node 37 ranked as the 4th most frequently mapped to node and at station 58 node 40(6) was the 5th most frequently mapped to node.

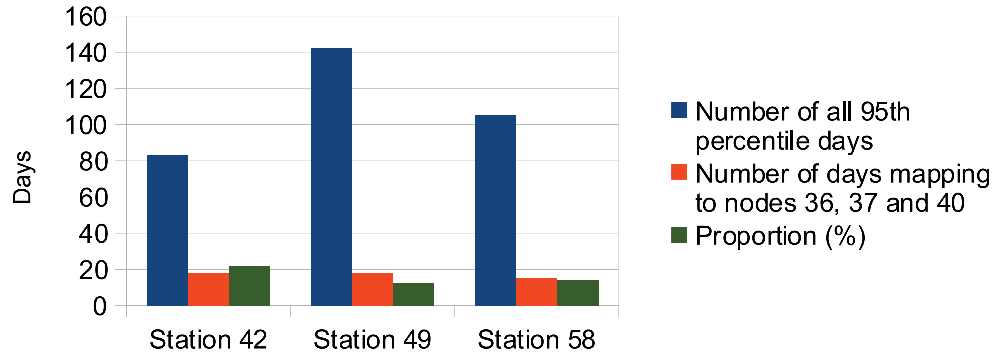


Figure 6.10. Proportion of extreme rain days mapping to nodes with significant changes.

Station 42 reflects most closely the trends in the synoptic states with these being apparent in all 3 states in of the circulation states node 40 appears prominently in all the 3 stations. Node 40 represented the most frequent synoptic type during the MAM season and the second most frequently mapped to node in SON.

6.3.2. Seasonal assessment of circulation trends

An assessment of trends in the seasonal mappings was performed to investigate changes in seasonal synoptics associated with extreme rainfall using the bootstrapping method described above. The results of this analysis are presented as a net diagram in Figure 6.7. In this figure the nodes are represented by the outer circle which forms the x-axis. The y-axis is the large 0, 1, 2 which show whether the seasonal trend of a node frequency mapping was statistically significant or not,. In the trend analysis if a particular node trend was significant it was given the value of 1 and if it was not it was assigned a 0. Therefore if a node showed a significant change in 2 seasons the ones are added and the chart y-axis reaches 2, the colours indicate the seasons. For example, in nodes 8-12 significant changes were detected in all these nodes during MAM but only in nodes 9-11 in JJA.

Significant trends are most evident in the shoulder seasons in which MAM has 21 nodes with significant positive trends and SON 18. In MAM nodes 1-16 all trend significantly but these nodes are generally infrequently mapped to (see Fig. 4.4). This would suggest a potential shift towards more winter like synoptic patterns during this season. However, there are also significant trends in nodes 22 and 40 which are frequently mapped to nodes in this season. During SON nodes 20, 30 and 40 were frequently mapped to nodes and these show significant positive trends. Although there are other significant trends these are at nodes are not frequently mapped to in the season (Fig. 4.4). During DJF a significant increase in circulations associated with nodes 34-38 was seen. All of these nodes were frequently mapped to in the season and were also associated with extreme rainfall (see Fig. 4.5). This would indicate that there has been an increase in the types of circulations that are associated with extreme rainfall. During JJA significant rends were found in nodes 9, 10, 11 and 22 which were not frequently mapped to modes of circulation.

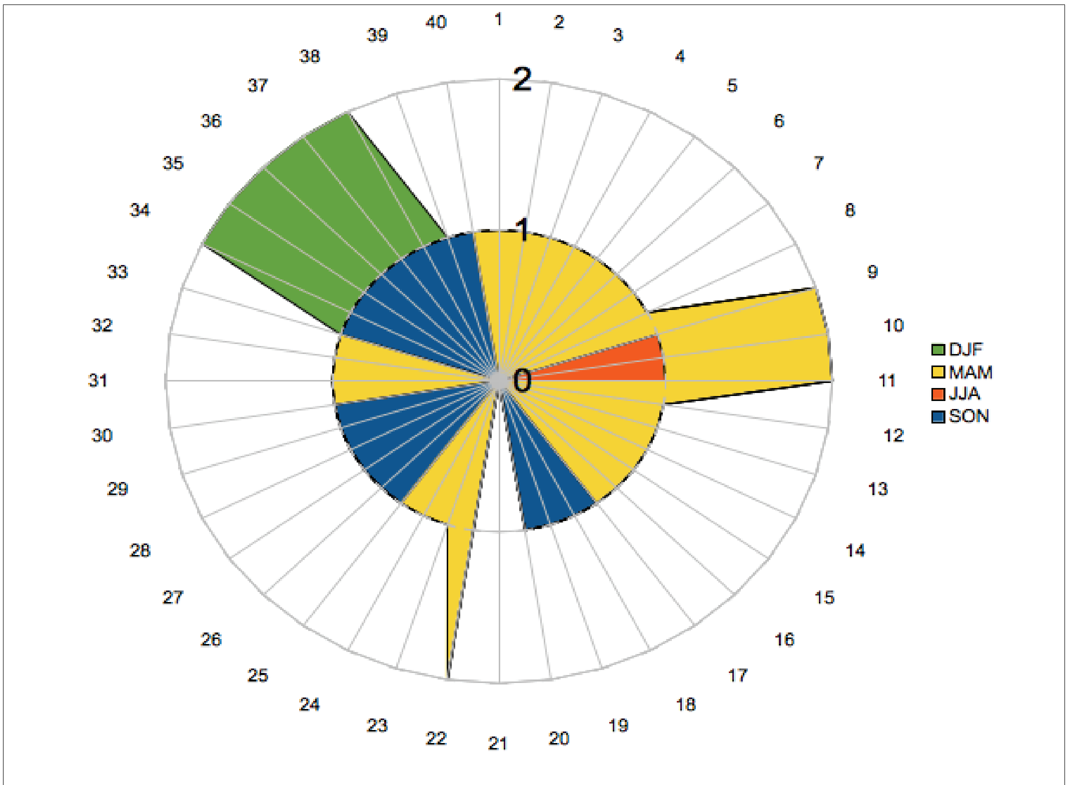


Figure 6.11. Trends in frequency of occurrence of seasonal modes of circulation.

It is unfortunately not possible to match the trends in the circulation modes with the extreme rainfall station data as there are too few degrees of freedom in the station data, especially when these data are disaggregated into seasons.

6.4. Summary and Discussion

As mentioned above positive trends in the station data were identified in the 95th and 99th percentile extreme rainfall indices, although, very few of these were statistically significant. Changes in the frequency of occurrence of circulation states in the 31 year period were examined and it was determined that significantly positive trends were found in circulations associated with winter rainfall as well as extreme summer rainfall.

The five stations that exhibited a significant increase in the occurrence of extreme rain had extreme rainfall days map to circulation states that showed significant trends. Station 42 in the Central Interior reflected the trend in the synoptic states most closely. Node 40 was the most common node mapped to in the three stations indicating changes in the frequency of occurrence of these types of circulation are likely to have influenced the significance of the trends at these stations.

Seasonal changes in the frequency of occurrence of circulation modes were very evident in the shoulder seasons and less so in summer and winter. The shoulder season trends were evident in highly mapped to nodes as well as less frequently mapped to nodes. In MAM this would suggest a small shift to more frequently occurring winter types of circulation patterns. Although the largest number of trending circulation modes occurred in autumn and spring, trends in DJF indicated more frequent summer types of circulations that were also associated with extreme rainfall. It is therefore likely that regions in South Africa under a summer rainfall regime would have experienced more extreme rainfall. Although this could not be verified in the station data through trends in the 95th and 99th percentile rainfall, trends in the Simple Daily Intensity Index (SDII) were identified in 12 of the stations falling into this rainfall regime. This index may therefore be a more sensitive index w.r.t. the examination of changes in extreme rainfall characteristics in this type of analysis.

Chapter Seven. Summary, conclusions and recommendations

7.1. Introduction

In Chapter One two main objectives for this project were stated. The first was to produce a rainfall station data set that had been quality controlled according to international standards so that these data could be confidently used in achieving the second objective. The second objective was to identify key synoptic process that resulted in extreme rainfall based on the clean station data and atmospheric circulation fields.

Within in these two main objectives were sub-objectives that aided the study.

Objective 1 – Produce a quality-controlled rainfall station data set

1.1 Update the station data set using data from a number of sources

1.2 Identify the attributes/characteristics of extreme rainfall (e.g. intensity, duration, seasonality, etc.) in the station record, and the historical trend of these attributes.

Objective 2 – Identify key synoptic process that resulted in extreme rainfall

2.1. Identify synoptic circulations associated with extreme rainfall within the context of all synoptic circulations that effect South Africa

2.2. Identify key synoptic circulations associated with extreme rainfall using only atmospheric data associated with extreme rainfall days in the station record.

2.3. Identify regionally specific extreme rainfall and the synoptic drivers of these and seasonal attributes of these.

2.4. Identify regions in South Africa that have experienced any changes in the frequency of occurrence of extreme rainfall as well as the driving synoptics.

These objectives were met in varying degrees and some were not met, they are summarized below.

7.2. Summary

Objective One – Produce a quality controlled station precipitation dataset

1.1. We have developed and executed an automated merging and quality control methodology on observed station data from multiple data providers. We identified many problems in the observational data but are satisfied that the quality control process produced data that is reliable for the other aspects of this project.

1.2. We examined trends of extreme rainfall in the station record as well as in the frequency of occurrence of synoptics associated with extreme rainfall. In the station record only five stations displayed significantly positive trends at the 95th and 99th percentile levels. Trends at other stations were either weakly positive or had no trend. The five stations were located in the South Western Cape, Eastern Cape, North East Interior and Central Interior. Three circulation states exhibited significant positive trends and all were generally associated with extreme summer rainfall. Extreme rain days in three of the stations that exhibited significantly positive trends mapped to these circulation modes, most especially those represented by node 40. Summer rainfall modes of circulation that were associated with extreme rainfall showed statistically significant positive trends.

Objective 2 – Identify key synoptic process that resulted in extreme rainfall

2.1. We identified seasonal circulation characteristics in the CFSR data for the study period. Winter exhibited frontal synoptics accompanied by a ridging high to the south of the country and interior high. Summer months exhibited a low pressure over the interior and high pressure systems to the south west of the country.

2.2. We identified synoptic circulations most associated with extreme rainfall in the context of all daily data. Extreme rainfall was associated with a low pressure trough over the interior interacting with ridging high – this pattern likely enhances onshore flow from east and south coast. Also identified were mid-latitude troughs to the south of the country.

2.3. We identified circulations associated with extreme rainfall recorded at 696 stations across South Africa ranging from deep surface low pressure troughs to cut-off lows in the upper air.

2.4. We identified dominant seasonal drivers of extreme rainfall across the whole country based on records from the above 696 stations:

Summer – Low pressure over centre of country interacting with onshore flow caused by a high pressure over the Agulhas current

Winter – Closed lows and frontal systems

Autumn – More winter-like circulations

Spring – Greater heterogeneity across synoptic types

2.5. We identified seasonally specific drivers of extreme rainfall in 8 rainfall regimes of South Africa. These are summarised in the table below (Table 7.1).

Table 7.1 Summary of synoptic states associated with regional extreme rainfall.

Region	**Peak Seasons**	**Pattern**
SW Cape	JJA	Surface low over the region and upper air trough to the south west; deeper upper air trough in 99th percentile
	SON/MAM	As for above but also a surface low over the subtropical interior which often linked with the mid-latitude surface low.
South Coast	SON/MAM	Passage of a cold front and a ridging high pressure, strong surface linkages between the sub-tropics and the mid-latitudes
	JJA	Deep upper air trough over region with strong ridging high; no inland low pressure
Eastern Cape	DJF	Surface low pressure trough over the western SA and weak high pressure over the SW coast
	SOM	Upper air trough in the mid-latitudes over the region and surface low over the central and east of the country.
	MAM	Like DJF but also weaker surface low in the west and stronger high in the SW.
KZN-Natal Coast	DJF	Deep surface low over the central interior and weak to moderate high to the S and SE
	SON	Deep upper air trough in the mid-latitudes with high pressure to the south and SE.
Lowveld	DJF	Deep surface low over central interior with moderate high pressure to the south and south east
	SON/MAM	Moderate to strong high pressure over the south and east coast
NE Interior	DJF	Deep surface low over the western and central interior of SA with a weak high pressure to the south
	SON/MAM	Deep upper air trough to the south west with a high pressure to the south and east in the case of the 95th percentile rainfall or deep surface trough for 99th percentile rainfall
Central Interior	DJF	Surface low over the west of SA and a weak high over the eastern regions
	SON	Upper air trough associated with a surface low in the west; surface high pressure to the east
Western Interior	DJF	Similar to Central Interior
	MAM	Surface high to the east is the most frequent mapping but extreme rainfall associated with most synoptic archetypes

7.3 . Conclusions

7.3.1. Conclusions reached about the station data

The station data used in this study had to be subjected to vigorous quality control despite the fact that many of the data had already been quality controlled in the now defunct CCWR, SAWS and ARC. We therefore suggest that station data obtained from these sources be subjected to similar quality control before being used in other projects as some results may be influenced by data quality. Once the data were quality controlled it could be used in for the rest of the project.

7.3.2. Conclusions reached about SOMs ability to identify key synoptic states associated with extreme rainfall

The SOM was able to identify characteristic circulation states that influence South African weather as well as the seasonal characteristics of these. Circulations associated with extreme rainfall were also identified using both country-wide and regionally specific data. The results showed extreme rainfall to be associated with primarily summer circulations through a linkage between the sub-tropics and the mid-latitudes at the surface and the passage of a trough in the mid-latitudes or just the sub-tropical low pressure. Winter extreme rainfall was associated with the passage of mid-latitude cyclones. However, some events known to produce extreme rainfall, specifically cut-off lows were not explicitly identified in the analysis. We suggest that an event-based SOM analysis would be more likely to capture these types of circulations.

7.3.3. Implications for regions where there are no observed records

It is difficult to generalize spatially concerning extreme rainfall as even in the 31 station record there were stations close to each other that did not have similar trends. For example station 11 showed a significant positive trend in the 99th percentile rainfall event but stations around it did not, the same could be seen at stations 47, 49 and 58. This is made more difficult in that the rainfall regimes used in the study are not necessarily representative of extreme rainfall regimes so extreme rain events resulting from a particular type of circulation could be split between different regions and the effect diluted in the analysis.

However, significant trends identified in the station data were associated with significant trends in synoptic circulations in summer rainfall cases. Additionally circulation modes associated with extreme rainfall showed positive trends which was reflected in the SDII index. It is therefore to suggest that extreme rainfall in the summer rainfall regions had increased over the past 31 years, a result that can be seen in the station data as well as the modes of circulation.

7.4. Recommendations and future work

The Intergovernmental Panel on Climate Change recently released a special report, "*Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation"* (Field *et al*., 2012). In short, it says that we can expect more of many kinds of extreme events. In it they state "*It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas of the globe*." Furthermore, many studies and assessments (Solomon et al., 2007) have found links between changes in global climate and changes in regional events such as heavy rainfall (Min *et al*., 2011), heat waves (Meehl and Tebaldi (2004), and flooding (Karl et al., 2009). Global climate change is also likely to influence local phenomena, including severe thunderstorms and tornadoes, but the nature and degree of the influence are uncertain, particularly for tornadoes (Karl *et al*., 2008). The trend toward more frequent extreme rainfall events only underscores how important it is that we enhance understanding of their synoptic drivers and their local expression so that we can more confidently predict and manage them.

To understand the potential changes of extreme rainfall characteristics in a South African context the following further work is proposed and recommended:

1. Establish extreme rainfall regions based on station and circulation data and investigate appropriate indices to use in establishing these regions such as the SDII.
2. Assess COL and TTT data to identify characteristic circulations associated with these and quantify changes in the characteristics and frequency of occurrence of these systems both historically as well as into the future.
3. Use downscaled climate change projections of the CMIP5 GCMs through the Co-Ordinated Regional Downscaling Experiment (CORDEX)-Africa initiative and other data to investigate changes in extreme rainfall characteristics and their synoptic drivers. These data will span from 1951-2100 and provide the opportunity to assess the historical and future changes.
4. Downscale the CMIP5 GCM data to the station scale and assess changes in the characteristics of extreme rainfall at a station scale and relate these changes to the synoptic circulations.
5. Assess how changes in the characteristics in extreme rainfall may affect society in a number of sectors such as e.g. agriculture, water supply and housing.

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Annexure1. Conference papers and Capacity Development

9.1 Conference papers (to be presented)

Lennard C. J. and D. Morison, 2012. *Changes in the synoptic drivers of extreme rainfall in South Africa,* European Geophysical Union Annual Meeting, Vienna, Austria.

Morison D., 2012. *Changes in the regional characteristics of extreme rainfall in South Africa,* SASAS, Cape Town, RSA

Lennard C. J. 2012. *Changes in the synoptic drivers of extreme rainfall in South Africa,* SASAS, Cape Town, RSA

Paper to be published in an international journal as well as WaterSA

9.2 Capacity Building

Degree	Name	Citizenship	Institution	Race / Gender	Status
M.Sc.	Morison, D	South Africa	UCT	F / W	Complete end 2012
Ph.D.	Grandin, R	South Africa	UCT	M / W	Complete end 2012
M.Sc.	Coop, L	South Africa	UCT	M / W	Complete