The synoptic drivers of extreme rainfall in South Africa

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Declaration

I know the meaning of Plagarism and declare that all of the work in the thesis, save for that which is properly acknowledged is my own.

Abstract

A number of studies have shown an increase in the intensity of extreme rainfall over many regions of South Africa during the last 50 to 100 years. However, the weather of a region at any given time is a direct function of the synoptic state of the atmosphere at that particular time. This thesis identifies synoptic states associated with extreme rainfall at a regional scale over South Africa and also investigates trends in extreme rainfall characteristics. Using 31 years of rainfall station data across South Africa, days which experienced extreme rainfall events, defined as the 95th and 99th percentile, were identified. These were then matched against mean sea-level pressure and 500hPa geopotential height circulation patterns obtained from the Climate Forecast System Reanalysis (CFSR) dataset to investigate the driving synoptics of extreme rainfall. Self-organizing maps (SOMs) were used to characterize the synoptic circulations on a general country-wide scale as well as for 8 different regional rainfall regimes at a seasonal scale. Synoptic circulations associated with extreme rainfall events often involved an interaction between more than one synoptic feature such as a linkage between a sub-tropical low pressure system and a mid-latitude cyclone or a ridging high pressure and a continental low pressure. Some features known for contributing towards a significant amount of extreme rainfall events such as cut-off lows in the south-western parts of the country were poorly characterized by the regional SOMs. This may be attributed to the spatial boundaries adopted in this study and suggests general rainfall regimes developed for South Africa are not appropriate for extreme rainfall analyses. Trends in extreme rainfall were assessed in the observed station data with the RClimDex software package and used ten extreme rainfall indices. Apart from the Simple Daily Intensity Index (SDII), which identified a number of significantly increasing trends amongst various stations throughout the country, very few significant trends were identified in the remaining indices. This may be attributed to the infrequent nature of extreme rainfall events and the relatively short 31 year study period. It was, however, discovered that 4 stations with significantly increasing trends in extreme rainfall were paired with synoptic circulations associated with extreme rainfall in the summer rainfall regime that had also experienced significantly increasing trends. Thus the characteristics of extreme rainfall identified in the station data have been associated with the driving synoptic scale circulations and their changing characteristics. However, the generalized regional rainfall regimes identified across South Africa are not appropriate for the study of extreme rainfall synoptic drivers. Here an event-based analysis would provide better insight to the attributes of specific extreme rainfall driving synoptics as well as providing an improved assessment of regional extreme rainfall.

Contents

Declaration 2

Abstract 3

List of Figures 7

List of Tables 10

Chapter one: Introduction **11**

1.1. Introduction…………………………………………………………………… 11

1.2. Rationale: Impacts of extreme rainfall in South Africa………………………… 12

1.3. Background information: South African climate and extreme rainfall………… 13

1.4. Literature review……………………………………………………………… 13

1.5. Objectives……………………………………………………………………... 19

Chapter Two: Data and methodology **20**

2.1. Introduction…………………………………………………………………… 20

2.2. Station rainfall data…………………………………………………………….. 20

2.2.1. Extreme rainfall thresholds……………………………………………… 21

2.3. Synoptic drivers of extreme rainfall…………………………………………….. 22

2.3.1. Synoptic assessment: Self-organizing maps………………………….. 22

2.3.2. Observed rainfall assessment and trends: RClimDex………………. 24

2.3.3. Synoptic circulation trends……………………………………………… 26

2.4. Summary………………………………………………………………………. 26

Chapter Three: Identifying synoptic circulations associated with extreme rainfall in South Africa **27**

3.1. Introduction………………………………………………………………….. 27

3.2. General circulation SOM……………………………………………………... 27

3.2.1. General synoptic assessment………………………………………….. 27

3.2.2. Seasonal assessment…………………………………………………… 30

3.3. Identification of synoptic states associated with extreme rainfall……………. 33

3.3.1. Extreme rainfall synoptics in the full 31 year period…………………. 33

3.3.2. Extreme rainfall synoptics SOM analysis………………………………… 35
3.4. Summary…………………………………………………………………………….. 41

Chapter Four: Analysis of the synoptic drivers of extreme rainfall at the regional scale **43**
4.1. South African rainfall patterns and regions……………………………………. 43
4.2. Regional selection of stations………………………………………………………… 44
4.2.1. Spatial representation………………………………………………………… 44
4.2.2. Data representativeness……………………………………………………... 46
4.3. Synoptic drivers of extreme rainfall in the 8 rainfall regions…………………. 50
4.3.1. South Western Cape…………………………………………………………. 50
4.3.2. Southern coast……………………………………………………………….... 53
4.3.3. Transkei………………………………………………………………………… 55
4.3.4. Kwazulu Natal coast………………………………………………………….. 58
4.3.5. Lowveld………………………………………………………………………… 60
4.3.6. North Eastern Interior……………………………………………………… 62
4.3.7. Central Interior…………………………………………………………….…. 65
4.3.8. Western Interior……………………………………………………………….. 67
4.4. Regional extreme rainfall discussion………………………………………………… 70
4.4.1. Seasonal synoptic distribution and assessment……………………… 70
4.4.2. Characterization of cut-off low pressure systems……………………. 74
4.5. Summary…………………………………………………………………………….. 78

Chapter Five: Trends in extreme rainfall **81**
5.1. Introduction………………………………………………………………………….. 81
5.2. Regional trends in the station data……………………………………………….. 81
5.2.1. South Western Cape…………………………………………………………. 82
5.2.2. Southern Coast……………………………………………………………….. 85
5.2.3. Transkei………………………………………………………………………… 87
5.2.4. Kwazulu Natal coast………………………………………………………….. 88
5.2.5. Lowveld………………………………………………………………………… 89
5.2.6. North Eastern Interior……………………………………………………… 89
5.2.7. Central Interior……………………………………………………………… 91
5.2.8. Western Interior……………………………………………………………….. 93

5.2.9. Summary and conclusions………………………………………………… 93

5.3. Relationship between trends in synoptic circulations and extreme rainfall…. 95

5.3.1. Assessment of synoptic circulation trends in the 31 year period and their relation to extreme rainfall in the station data…………………………………. 96

5.3.2. Seasonal analysis of synoptic trends………………………………….. 99

5.3.3. Summary………………………………………………………………. 103

5.3.4. Seasonal shift in synoptic circulations of extreme rainfall…………… 105

5.4. Summary and discussion………………………………………………………… 108

Chapter Six: Summary and conclusions **110**

References **115**

List of Figures

Figure 1: Spatial distribution of the sample of 698 stations from which a selection was made to assess extreme rainfall in this study.

Figure 2: The general circulation patterns identified by the 40 node SOM array in the domain from 1979 to 2009 at (A) MSLP and (B) z500 levels of the atmosphere with node 1 in the bottom left corner and node 40 in the top right corner.

Figure 3: Daily frequency map showing in percentages the proportion of days that mapped to each of the nodes throughout the 31 year period with node 1 in the bottom left corner and node 40 in the top right corner.

Figure 4: Daily frequency map displayed for each of the four seasons (DJF, MAM, JJA, SON) indicating the most dominant synoptic circulations of each season over South Africa.

Figure 5: Daily frequency map showing which nodes of the SOM with percentages the extreme rainfall days were associated with.

Figure 6: The synoptic circulations associated with extreme rainfall events throughout South Africa between 1979 and 2009 identified by the 40 node SOM at the MSLP level (A) and the z500 level (B).

Figure 7: Daily frequency map showing in percentages the amount of days mapped to each of the nodes of the extreme rainfall SOM throughout the 31 year period with node 1 in the bottom left corner and node 40 in the top right corner.

Figure 8: MSLP SOM on the left and z500 SOM on the right displaying the most frequently occurring nodes associated with extreme rainfall during the summer months of DJF from 1979 to 2009.

Figure 9: MSLP SOM on the left and z500 SOM on the right displaying the most frequently occurring nodes associated with extreme rainfall during the winter months of JJA from 1979 to 2009.

Figure 10: MSLP SOM on the left and z500 SOM on the right displaying the most frequently occurring nodes associated with extreme rainfall during the autumn months of MAM from 1979 to 2009.

Figure 11: MSLP SOM on the left and z500 SOM on the right displaying the most frequently occurring nodes associated with extreme rainfall during the spring months of SON from 1979 to 2009.

Figure 12: The 9 homogeneous rainfall regions identified by Landman et al. (2001). This study uses 8 of these regions excluding the Northern Namibia/Western Botswana region.

Figure 13: map showing the 69 selected rainfall stations throughout South Africa with a rough outline of the eight rainfall regions to identify in which region the stations occur.

Figure 14: 95^{th} percentile rainfall synoptic circulations for the South Western Cape region presented by a 20 node SOM map with MSLP and z500 mappings displayed in the top left and right respectively. The bottom left graph displays the seasonal distribution of extreme rainfall while to the right the frequency maps of each season are shown.

Figure 15: As for Figure 14 but for the Southern Coast region

Figure 16: As for Figure 14 but for the Transkei region

Figure 17: As for Figure 14 but for the KwaZulu Natal region

Figure 18: As for Figure 14 but for the Lowveld region

Figure 19: As for Figure 14 but for the North Eastern Interior region

Figure 20: As for Figure 14 but for the Central Interior region

Figure 21: As for Figure 14 but for the Western Interior region

Figure 22: 99^{th} percentile SOM for KZN coastal region displaying the upper air closed low pressure system identified by nodes 1 and 2 (circled) in the z500 layer.

Figure 23: 95^{th} and 99^{th} percentile z500 SOMs for the South Western Cape (A1 and A2 respectively), Southern Coast (B1 and B2 respectively) and Western Interior (C1 and C2 respectively) regions. The closest characterization of cut-off low synoptics is shown by the circled node 16 of the 99^{th} percentile z500 SOM of the Southern Coastal region.

Figure 24: (Same as Figure 13 from Chapter Four) Map showing the 69 selected rainfall stations throughout South Africa with a rough outline of the eight rainfall regions to identify in which region the stations occur.

Figure 24: Annual precipitation from 95^{th} percentile rainfall events (A1 and A2) and 99^{th} percentile rainfall events (B1 and B2) for Station 1 in the Cape Town area showing a steeper positive trend in the more extreme 99^{th} percentile rainfall compared to the 95^{th} percentile rainfall.

Figure 25: Annual precipitation from 99^{th} 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.

Figure 26: 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.

Figure 27: The change in extreme rainfall trends represented by the R95p index along the Transkei coastal stations from station 47 (A) further south with a positive trend to station 48 (B) in between with no trend to station 50 (C) further north with a negative trend.

Figure 28: Extreme rainfall indices R99mm (A) and R95p (B) representing the negative trends for the KZN Coast region.

Figure 29: 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.

Figure 30: 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 with the positive trend attributed largely to the years' post 1995.

Figure 31: 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 for both stations 44 (A2) and 45 (B2).

Figure 32: Relationship between the number of station observations for increasing and decreasing trends at the 5% significant level for each index.

Figure 33: Annual number of occurrences from 1979 to 2009 for each of the 40 synoptic circulation nodes of the general circulation SOM with the significantly positive trends identified with a red trend line in nodes 36, 37 and 40 (magnified at the bottom for clarity). Note, the nodes of the array are not laid out in the same sequence as those of the original SOM (in this case node 1 is in the top left-hand corner and node 40 in the bottom right-hand corner).

Figure 34: Relationship between days mapped to significantly increasing nodes and number of 95th percentile occurrences for each of the four stations.

Figure 35: A separate bootstrapping analysis similar to that used for the full 31 year period above was carried out in order to determine the significantly positive trending nodes for each season identified by the nodes with a red trend line.

Figure 36: Significant increasing trends for the number of occurrences of nodes 37, 36 and 34 for DJF with their frequency mapping displayed above each plot.

Figure 37: Nodes 32 and 22 identify significant increasing trends along with being the 4th and 5th most mapped to nodes respectively (frequency displayed above each plot) in the 31 years for MAM.

Figure 38: Node 40 and 30 of SON are the 2nd and 3rd most frequently mapped to nodes respectively of the season that also exhibit a significantly increasing trend over the 31 year period.

Figure 39: Summarizing the nodes that identified significantly positive trends in each of the four seasons.

Figure 40: Relationship between significantly increasing trends of MAM nodes and their respective mapping frequencies (displayed above the nodes) occurring in the winter months of JJA.

Figure 41: Relationship between significantly increasing trends of SON nodes and their respective mapping frequencies (displayed above the nodes) occurring in the summer months of DJF.

List of Tables

Table 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.

Table 2: Extreme rainfall profile for each of the selected stations used in this study with reference to the map in Figure 13.

Table 3: The average for each rainfall threshold for each of the rainfall regions, the 69 selected stations and the entire sample of 698 stations.

Table 4: List of the cut-off low pressure events assessed that resulted in extreme rainfall observed in the stations of the South Western Cape, Western Interior and Southern Coastal regions. The amount of rainfall on each date is provided and the node to which these dates were mapped to in their respective SOM. Each event occurring throughout the regions is also highlighted the same colour.

Table 5: Summary table of the synoptic drivers of extreme rainfall for each region and their peak seasons.

Table 6: Number of days mapped to the specific nodes (36, 37 and 40) and the relevant rank for each of the identified stations. Station 42 occurs in the Central Interior region, station 47 and 49 occur in the Transkei and station 58 occurs in the North Eastern Interior rainfall region.

Table 7: The 1^{st}, 2^{nd} and 3^{rd} most frequently mapped to nodes for each season. Bold print identifying nodes associated with a significantly positive trend in their frequency of occurrence over the 31 year period. The total amount of significantly positive trending nodes of each season is displayed in the last column.

Chapter one: Introduction

1.1. Introduction

Extreme rainfall events are usually infrequent and characterized by short periods of intense precipitation with potentially devastating consequences to society. The inconsistent nature of extreme rainfall events makes them challenging to study especially when it comes to analyzing long-term trends and changes in their attributes. Hence a long study period expanding multiple decades is necessary, however, obtaining adequate quality data over long-term periods without inhomogeneities possesses a problem in itself (Mason et al., 1999). In a global context the recent Intergovernmental Panel on Climate Change (IPCC) 2012, Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaption (SREX) has identified it as being “likely (66-100% probability) that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century” (IPCC, 2012). Additionally, it states that under higher emissions scenarios (A1B and A2) the southern African region will experience a decrease in the return period of extreme precipitation events (IPCC, 2012). Having said this a number of studies have shown an increase in the intensity of extreme rainfall over many regions of South Africa during the last 50 to 100 years [e.g. Frich et al., 2002; Groisman et al., 2005; Kruger, 2006; Mason et al., 1999; New et al., 2006]. While these studies have been based primarily on station data and derived indices, there has been very little effort to understand the synoptic drivers associated with extreme rainfall events and their observed long term changes.

Given that the weather experienced in a region at any given time is a direct function of the synoptic state of the atmosphere at that particular time, the relationship between the synoptic-scale atmospheric circulation and a local climate or environmental response can be investigated. Hewitson and Crane (2002) do this through presented self-organizing maps to the climatological community as a tool to link observed weather data with the driving synoptic circulations. The underlying question of this research addresses extreme rainfall events in South Africa and their synoptic drivers at a regional scale. The aim of this study involves linking observations of extreme rainfall events in station data with the accompanying synoptic circulation patterns and later use this relationship to investigate on a regional basis the changes of extreme rainfall from a synoptic perspective.

1.2. Rationale: Impacts of extreme rainfall in South Africa

Flooding caused by extreme rainfall can potentially result in fatalities, damage to or loss of property and infrastructure in which communities are either displaced or isolated from the rest of the country. Agriculture is affected by floods due to loss of produce and nutrient rich soils. Additionally, soil erosion places strain on the environment, natural habitats and hydrology of a region. During February and March 2000, tropical cyclones affecting the northern parts of the country attracted a large amount of global media attention due to the several hundred deaths and millions of dollars worth of damage to property, infrastructure and farm lands as a result of flooding (Reason and Keibel, 2004). These types of scenarios result in large insurance claims as well as place the vulnerable developing nature of the South African economy and its municipalities under pressure. Another example, this time imposed by a cut-off low system in 1981 resulted in many fatalities and damage in the arid Karoo region in which the town of Laingsburg was affected the most (Estie, 1981). Another cut-off low system in 2003 was again responsible for a large amount of infrastructural damage estimated to be about US$ 50 million in the rural region of the Klein Karoo near the towns of Montague and Ashton (Singleton and Reason, 2006). The passage of mid-latitude cyclones during the winter period have often resulted in flooding of the poor informal settlements on the Cape Flats of Cape Town, which leads to the displacement and temporary housing and food for thousands of people. One such example occurred during August 2004 in which direct losses incurred as a result of the event exceeded R6.5 million (DiMP, 2005). Water borne diseases such as cholera often become a major health problem for communities after flooding has either contaminated local drinking water sources and or resulted in large bodies of water becoming stagnant (Griffith et al., 2006).

Following some of these more recent extreme weather events the former Disaster Mitigation for Sustainable Livelihoods Programme (DiMP) at the University of Cape Town in collaboration with various other organizations conducted an applied research response titled Risk and Development Annual Review (RADAR) in 2009 for the Western Cape (DiMP, 2010). It was intended to be a resource for disaster risk management and risk-averse planning by evaluating from all aspects major disaster events that affected the Western Cape during the 6 year period from 2003 to 2008. The establishment of such reviews highlights the severity of these extreme rainfall events and resultant flooding and impacts to society.

It is therefore essential to gain a better understanding of the characteristics of extreme rainfall and the coupled driving synoptics in South Africa in order to identify vulnerable regions that do not have station data records and thus provide these regions with the characteristics of extreme rainfall. This information will also facilitate communities with the implementation of better adaptation and mitigation strategies. The investigation of the changes of extreme rainfall characteristics will also facilitate these strategies as well as provide information regarding intensity, frequency and spatially from a synoptic perspective.

1.3. Background information: South African climate and extreme rainfall

South Africa can be divided into geographic regions that experience different rainfall regimes across the country with clear seasonality. Tyson and Preston-Whyte (2000) describe in great detail the weather and climate regimes of southern Africa. Large parts of the Northern Cape and central interior are characterized by a dry arid climate with very low rates of precipitation. The south western region is characterized by winter frontal precipitation, while the eastern and interior plateau regions experience summer convective rainfall. The rainfall in these parts of the country can be easily linked to specific synoptic states while the Eastern Cape and parts of the south coast of the country experience rainfall from varying weather patterns with minimal seasonal distinction.

Extreme rainfall and consequentially flooding in South Africa usually occurs from specific synoptic states relative to these geographic regions of South Africa. These states include tropical and mid-latitude cyclones, tropical temperate troughs, cut-off lows and interactions between these conditions (Tyson and Preston-Whyte, 2000). As mentioned in section 1.2 above these weather patterns have been the cause of extreme rainfall and numerous flooding events resulting in wide spread damage in the past and continue to pose a major risk for the general society in South Africa.

1.4. Literature review

The topic of climate change has led to a significant amount of studies relating to trends in temperature and precipitation. Initially the focus of many of these studies was on the changes in the mean states of temperature and precipitation (New et al., 2006). The Intergovernmental Panel on Climate Change (IPCC) highlighted that there have been insufficient studies on observed historical trends in climate extremes (Nicholls et al., 1996). As a result a number of studies focusing on trends in climate extremes began to emerge towards the end of the 20th century and the beginning of the 21st century (New et al., 2006). It is generally known that climate change will influence the frequency and intensity of extreme events (Kruger, 2006). Mason et al. (1999) suggested that these changes may occur when there are only small changes in the climate. It is believed that changes in the characteristics of climate extremes will have greater, more direct impacts on society than the long-term changes in the average states (Mason et al., 1999).

Various issues augmented with the analysis of climate extremes and were identified along with evolving solutions throughout the literature of the past 10 years. Some of these issues pointed towards data inconsistencies and later concerns around derived indices necessary for objective analyses on climate extremes (New et al., 2006). As a result New et al. (2006) acknowledged that much of the studies concentrated on regions where the daily meteorological observations required for such analyses were already quality controlled and archived. However, extreme climatic events have significant impacts on environmentally vulnerable regions and thus the investigations of changes in the characteristics of extreme climatic events are of great importance for many regions especially developing countries. This issue was expressed by Mirza (2003) due to the poor adaptive capacity of developing countries when it comes to dealing with extreme climate events and thus argues that more focus is placed on dealing with post climate disasters instead of incorporating better vulnerability and adaptive assessments in development strategies. This is apparent throughout Africa, however, South Africa has begun to receive some more focus in the last decade with various studies relating to specific extreme climate events becoming more evident. For example, the extreme precipitation event of 11 to 16 February 1996 over the South African summer rainfall regions (Crimp and Mason, 1999), the severe storm and flood event that occurred over the southern coastal regions of South Africa on 14-15 December 1998 (Rouault and White, 2002) and numerous studies considering cut-off low pressure systems by Singleton and Reason (2006 and 2007).

The precise definition of extreme rainfall is an important concept for the analysis of severe rainfall events and a consistent universal definition of extreme rainfall and associated derived indices seemed to be lacking throughout the earlier studies. More recent studies began to address this issue and consequently incorporated greater emphasis on describing the indicators necessary for monitoring changes in climatic extremes in their analyses [e.g. Groisman et al., 2005, New et al., 2006 and Kruger, 2006]. This was made possible following a meeting of the World Meteorological Organisation (WMO) Commission for Climatology (CCI)/Climate Variability (CLIVAR) Working Group on Climate Change Detection in 1998 (Frich et al., 2002). In this study Frich et al. (2002) suggested 10 indicators to clarify whether the frequency and/or severity of global extreme weather and climate events changed during the second half of the 20th century. This was a very broad study on various regions around the globe and included temperature indices in addition to precipitation indices. Nonetheless, it was based on a set of clear extreme climatic indices. It was envisaged that these indicators would form the basis for future web-based and more coherent global information system on climate change monitoring. At the same time it was concluded that a significant proportion of the global land area was increasingly affected by a significant change in climatic extremes during the second half of the 20th century. More specifically, the study found that southern Africa showed a significant increase in most indicators of heavy precipitation events. However, it was again pointed out that large areas such as Africa remained unrepresented.

Another study in a global context was conducted by Groisman et al. (2005), however, this time focusing only on precipitation. In this study, observed changes in very heavy or intense precipitation were analyzed for over half of the land area of the globe. Instead of using specific indices like Frich et al. (2002), event frequency thresholds were used to define intense precipitation events. These thresholds were defined by three categories of daily precipitation events:

- Heavy: 90th and 95th percentiles
- Very heavy: 99th and 99.7th percentiles
- Extreme: 99.9th percentile

These thresholds provided a clear method for analyzing trends in intense precipitation on a regional scale. A useful application of these thresholds described in this study is to equate them into return periods. A similar application of return periods was used by Melice and Reason (2007) for extreme rainfall in George situated along the southern coast of South Africa. In so doing, very heavy precipitation occurring in the upper 0.3% of daily precipitation events for a 12 month period can be equated to a return period of approximately one daily event in 3 to 5 years and approximately 10 to 20 years when selected from a 3 month seasonal period of daily precipitation events. The regionally averaged very heavy precipitation threshold for the upper 0.3% of daily events for the eastern part of South Africa for an annual period was 85mm with a return period of 5 years and 90mm for a summer period (December-January-February) with a return period of 10 years. It was found that while annual and summer precipitation totals experienced no change over the study period from 1906 to 1997, there was an increase in the annual frequency of very heavy precipitation especially during the last three decades. This study contributes a different perspective of measuring extreme rainfall as well as to the implications of other studies that intense precipitation has increase over South Africa during the 20th century. Yet again it is based in a global context and only a very broad region covering the eastern part of South Africa is analyzed.

International coordination concerning a global cohesive set of indices necessary for analyzing extreme climate events was provided by the joint CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDMI). Additional issues addressed by the ETCCDMI included practical guidance and analysis toolkits (http://cccma.seos.uvic.ca/ETCCDMI/index.shtml). New et al. (2006) made use of ten of these precipitation indices in establishing trends in daily climate extremes over southern and west Africa during the period 1961 to 2000. It was found at the region-wide scale that there was a consistency between indices suggesting that average daily rainfall intensity had increased, along with the amount of rainfall on extreme rainfall days and periods, but the total rainfall and the number of days with heavy rainfall had decreased. In addition to this, most of the indices display no consistent spatial patterns of trends except for the consecutive dry days (CDD) index, which shows a consistent increasing trend over the region. This may be as a result of the large area covered by this study. Therefore more studies analyzing these precipitation indices for specific regions of South Africa may assist in defining changes in the characteristics of extreme precipitation.

A number of studies as mentioned have revealed that many regions of South Africa have experienced an increase in the intensity of extreme rainfall over the last 50 to 100 years. These observations are substantial even though most of the earlier studies highlighted the lack of consistent observational data necessary to analyze and make statistically defensible statements on long-term trends of extreme rainfall. This issue was expressed by Mason et al. (1999) in which the results of the study were based on 316 selected sites around South Africa over a 60 year period that were only tested for respective site relocations and not inhomogeneities resulting from changes in instrumentation due to the lack of metadata. Despite these inhomogeneities, significant increases in the intensity of extreme rainfall events over about 70%

of the country were identified during the periods 1931-1960 and 1961-1990. These increases are said to be the largest for the most extreme rainfall events.

Kruger (2006) conducted a follow-up study to Mason et al. (1999) and New et al. (2006) in which eight precipitation indices from the ETCCDMI were applied only to South Africa. The study period spanned from 1910 to 2004 and was chosen in order to obtain the longest period possible while still retaining a sufficient number of climate stations with rainfall records spanning the whole period. Thus the results are based on a smaller sample of stations (138) than that of Mason et al. (1999), however, the stations used are for the most part spatially well distributed throughout South Africa. This allowed for a more regional scale analysis of trends in the respective precipitation indices from the ETCCDMI for South Africa. Results obtained from some of the indices relating to less direct measures of heavy precipitation conclude:

- Inconsistent trends of increasing and decreasing annual total precipitation (PRCPTOT) throughout South Africa with statistical significant trends at only a few stations.
- With the exception of a very small region over the Free State and North-West provinces, the majority of South Africa indicates a decreasing trend in the annual maximum number of consecutive wet days (CWD), which is in conjunction with the regions indicating a decrease in PRCPTOT.

The indices relating to more direct measures of heavy precipitation showed on average significantly positive trends for stations of the same region covering the southern Free State and the majority of the Eastern Cape provinces, while the rest of the country showed inconsistent trends. These indices include:

- Annual total precipitation (mm) from RR > 95^{th} percentile for period 1961 to 1990 (R95p)
- Annual total precipitation (mm) from RR > 99^{th} percentile for period 1961 to 1990 (R99p)
- Annual maximum precipitation (mm) in 1 day (RX1day)
- Annual number of days when RR >= 30mm (R30 mm)
- Annual maximum precipitation (mm) in 5 consecutive days (RX5day)

The general conclusion of this study agrees with the results of New et al. (2006) suggesting that the largest part of South Africa showed no significant evidence of changes in precipitation over the past century. However, based on the trends for the indices relating more directly to heavy precipitation and those indicating no significant increase in annual precipitation for the southern Free State and the Eastern Cape provinces, Kruger (2006) subsequently concluded that daily rainfall had become more extreme over these regions during the study period. It is worth noting the correlation between the results of these two studies for the index representing the annual maximum number of consecutive dry days (CDD), which both showed positive trends for the eastern half of South Africa.

These studies have highlighted observed changes and trends in the characteristics of extreme precipitation along with clearer understanding of extreme rainfall measuring indices. However, all the results for South Africa are based on observations from station data alone and there has been little effort to understand the forcing dynamics of the observed trends at the synoptic scale by relating the attributes of extreme rainfall with the respective synoptic circulation patterns. Although there is a general awareness of the extreme rainfall causing synoptic states for the different regions of South Africa such as tropical and mid-latitude cyclones, tropical temperate troughs and cut-off low pressure systems mentioned above as well as numerous studies on certain events occurring in the past, further examination of the relationship between the station observations and these synoptic states will allow for the potential changes in the attributes of extreme rainfall and the forcing dynamics to be assessed over time. Some of the studies have suggested a few possible causes for these observed changes in intense precipitation such as increased atmospheric moisture (Mason et al., 1999) and sea surface temperature anomalies (Williams et al., 2007), while none have gone into much detail from a synoptic perspective.

Hope et al. (2006) have, however, examined shifts in the synoptic systems influencing rainfall variability over the southwestern region of Western Australia for the period 1948 to 2003 using self-organizing maps (SOMs) and NCEP/NCAR reanalysis data. This method proved to be very useful in relating the synoptic patterns with changes in rainfall over the region. Hewitson and Crane (2002) also expressed the effectiveness of SOMs in describing the changes in synoptic circulation patterns over time as well as in relating these changes to observed station precipitation data for a region in North America. Therefore it would be useful to apply a similar method in a South African extreme rainfall context.

Most of the studies regarding changes in precipitation imply a link between increasing greenhouse gas levels in the atmosphere and the observed changes in precipitation (Groisman et al., 2005; Hope et al., 2006; Mason and Joubert, 1997). Very few studies have focused on how these observed changes will possibly prevail into the future with increased greenhouse gasses forcing. Mason and Joubert (1997) used a general circulation model simulation to investigate the possible changes in extreme rainfall over South Africa as a result of doubling atmospheric carbon dioxide. The results suggested an increase in the frequency and intensity of extreme daily rainfall events throughout most of southern Africa and implicate the sensitivity of atmospheric convection to temperature as a possible cause for such changes in precipitation. Again this study focused only on the future trends without the associated synoptic forcing's driving these future changes and therefore the assessment of the future synoptic conditions responsible for such changes through the use of self-organizing maps may build on this study.

1.5. Objectives

The primary aim of this work is to identify synoptic circulations associated with extreme rainfall in the observational record. This can later be used to investigate on a regional basis the past and future changes of extreme rainfall from a synoptic perspective.
In order to address this question a number of objectives were compiled. These include:

- Identify the attributes of extreme rainfall events in the station data records.
- Identify synoptic circulations associated with extreme rainfall across the entire region of South Africa.
- Identify extreme rainfall specific synoptic circulations using only data from extreme rainfall events.
- Identify the synoptic drivers of extreme rainfall at the regional scale.
- Identify trends in the characteristics of extreme rainfall.
- Identify regions in South Africa that have experienced any changes in the frequency of occurrence of extreme rainfall and the associated synoptic circulations.

To achieve these objectives this study is structured in the following manner. Chapter Two provides a brief overview of the methodology use throughout the process of relating synoptic circulations to extreme rainfall events. Chapter Three presents the results of the SOM in which the association of extreme rainfall with the synoptic circulations is established over the whole of South Africa. Chapter Four presents the results of the SOM for the synoptic drivers of extreme rainfall at the regional scale. Chapter Five describes the trends associated with extreme rainfall in the station data records and the trends in the synoptic circulations associated with extreme rainfall relating to the trends in the station data. Chapter Six provides a summary and conclusion.

Chapter Two: Data and methodology

2.1. Introduction

In order to assess the synoptic circulation patterns of extreme rainfall events in South Africa a number of data sets and methods are required. Data sets used in this study include observed daily rainfall station data records and reanalysis data for atmospheric variables during a 31 year period from 1979 to 2009. The methods used for relating extreme rainfall events with their associated synoptic circulations include various selection procedures for obtaining the highest quality data, setting extreme rainfall thresholds for extracting appropriate days for analysis, clustering of synoptic circulations using self-organizing maps (SOMs), relating these to the observed extreme rainfall events in the station records, the use of RClimDex and trend analyses. This chapter presents the data and the methodologies used as well as some of the constraints experienced. Further details of each are also provided in the respective chapters.

2.2. Station rainfall data

Analysis of extreme indices requires daily data from rainfall stations. Obtaining such data with a high degree of quality is difficult for most areas of the globe (New et al., 2006). Spatial coverage is still poor for most regions and other inequalities hinder the use of large amounts of the available data in the form of missing values and inhomogeneity within the datasets (Mason et al., 1999). This study uses station data housed at the Climate Systems Analysis Group of the University of Cape Town for South Africa which have been updated with station data from the South African Weather Service. These station data have been subjected to stringent quality control procedures at CSAG that were based on quality assurance checks of the Global Historical Climatology Network (GHCN) tests (http://www.ncdc.noaa.gov/oa/climate/ghcn-daily). Some of these checks included assessing the length of record and amounts of missing data, errors in magnitude and search for outliers as well as the merging of many stations for which there were multiple data sources into one source.

South Africa has a rather wide spatial coverage of rainfall stations throughout the country consisting of 4011 available stations to select from. In order to select stations to be used in this study the amount of missing data within each of the individual 4011 stations during the 31 year study period (1979 to 2009) was assessed. Stations having the least amount of missing data during the study period in order to produce statistically defensible statements regarding extreme rainfall patterns and trends were retained. Firstly, the stations needed to have records that included observations expanding the entire duration of this 31 year period. This reduced the sample of stations adequate for the study from the initial 4011 stations down to 1034 stations. The amount of missing data occurring during the study period was then checked for each station and stations with more than 5% of data missing were excluded. This reduced the number of stations further to 698 stations covering South Africa (Figure 1) from which to make a final selection. The criteria for final selection of the stations are detailed in Chapter Four section 4.2.

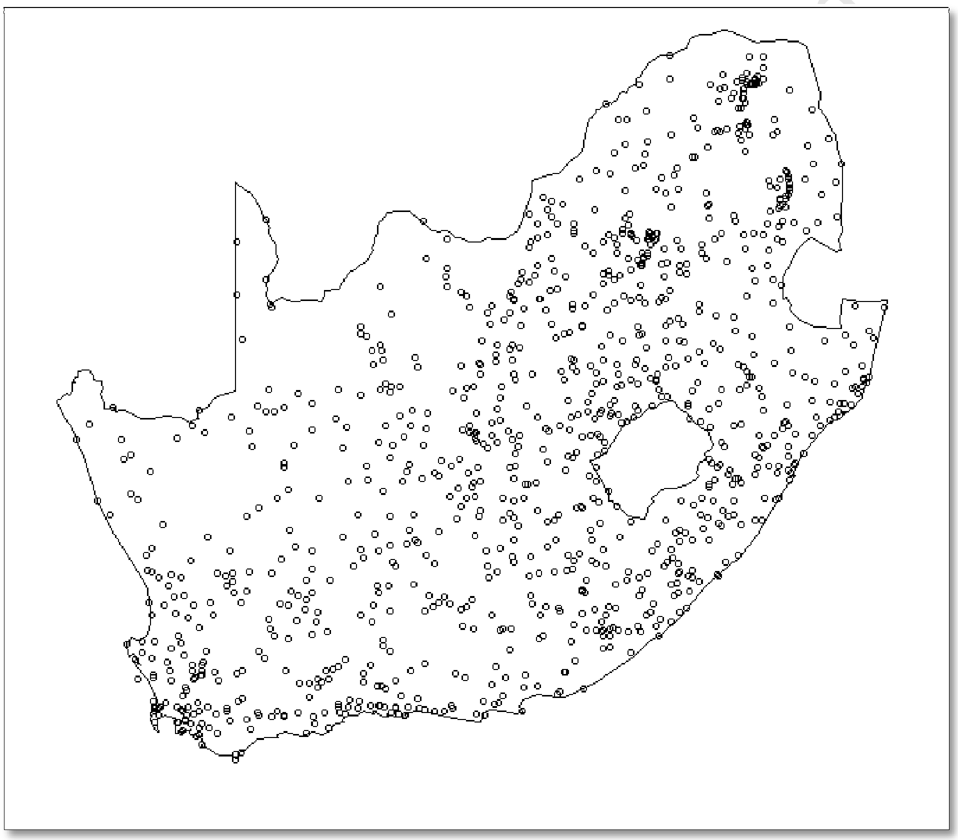

Figure 1: Spatial distribution of the sample of 698 stations from which a selection was made to assess extreme rainfall in this study.

2.2.1. Extreme rainfall thresholds

The definition of extreme rainfall varies but is usually expressed as a percentile or a threshold exceedence (Frich et. al. 2002; Groisman et. al., 2005; Kruger 2006; New et. al., 2006).

Consequently the definition of extreme rainfall used in this study adopts a similar method in which extreme rainfall is expressed based on rainfall values greater than the 95th percentile and in some cases the 99th percentile from the stations with reliable results. These percentiles were calculated excluding days in which 0mm of rainfall occurred as this study focuses on extreme rainfall and not a general climatology. It was discovered that after calculating these percentile thresholds that the inclusion of days with 0mm of rainfall resulted in the thresholds not being representative of extreme rainfall events within each region. These values, their frequency of occurrence and maximum precipitation recordings within the 31 year period produce an extreme rainfall profile for each of the selected stations (see Table 3, Chapter Four). The 95th percentile is also used in the extreme rainfall SOM analysis as well as the RClimDex indices analysis described below.

2.3. Synoptic drivers of extreme rainfall

2.3.1. Synoptic assessment: Self-organizing maps

Large scale synoptic circulation patterns establish the environment from which regional daily weather responses occur (Tyson and Preston-Whyte, 2000). For this reason a methodology capable of quantifying the large scale circulation-regional response relationship will assist in identifying synoptic states associated with extreme rainfall. Self-organizing maps (Kohonen, 1997) was adopted as the method for identifying and clustering the synoptic states of the atmosphere. Self-organizing maps (SOMs) have been used numerous studies of the climate system (Cavazos, 2000; Hope, 2006; Lui and Weisberg, 2011; Sheridan and Lee, 2011), while Hewitson and Crane (2002) provide a detailed study for the application of SOMs in synoptic climatology. SOMs are a form of artificial neural net (ANN) that reduce high dimensional data into lower dimensionality (such as two-dimensions) while representing the input data in the form of producing a map of data archetypes. 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 (such as Principal Component Analysis (PCA)). For this reason they provide a useful mechanism for visualizing complex distributions of synoptic states given that precipitation is a function of more than one atmospheric variable interacting at any given time (Hewitson and Crane, 2002). In this way the dimensions of the data being analyzed are reduced while still representing the original data and preserving their relationships. As a result generalized modes of synoptic circulation patterns are established over South Africa. By using this technique daily atmospheric data spanning the full 31 year study period is categorized into a number of characteristic synoptic circulations from which it is possible to infer local weather responses. This information therefore makes it possible to relate extreme precipitation events from station records to their associated synoptic states and examine these events in this context.

The SOM software used in this study is part of SOM_PAK version 3.1 (http://www.cis.hut.fi/research/som_lvq_pak.shtml). There are three distinct stages in the data mapping routine in which firstly the type and size of the SOM is set followed by the training procedure and thirdly the evaluation of error and results are visualized. These stages are briefly described below to provide an understanding of the SOM procedure.

The type and size of the SOM may be described as the SOM architecture (Kohonen, 1997). The size of the SOM map represented by the number of nodes in the two-dimensional array is chosen subjectively by the user based on the degree of generalization. Each node in this case defines a particular synoptic state thus the range of synoptic states represented by the resulting SOM is heavily influenced by the number of nodes making up the SOM array. As a result fewer nodes in the SOM array would produce more generalized circulation archetypes, while a greater number of nodes would represent a wider range of circulation patterns. Although South African synoptic systems have been categorized into six to eight main types of circulation (Tyson and Preston-Whyte, 2000) a relatively large SOM array consisting of 40 nodes was chosen in order to assist in identifying synoptic circulations responsible for extreme rainfall. A smaller SOM array would fail to identify specific synoptic circulations across the spatial domain due to the wide range in rainfall causing synoptic circulations throughout South Africa, while a larger SOM array did not contribute any further information in this regard. It was therefore envisaged that the selected 40-node SOM would adequately represent all the expected synoptic types.

The second stage of the SOM is the map training process. This stage forms the initial clustering process of the data and ensures that the variance structure of the data is covered by the resultant nodes of the SOM array. This part of the SOM procedure also introduces the relevant atmospheric variables used in this study obtained from climate reanalysis data. Two atmospheric variables, mean sea-level pressure (MSLP) and 500 hPa geopotential height (z500), were used in this study as they are able to provide a good indication of the processes associated with the regional atmospheric circulations (Hewitson and Crane, 2002; Hope et al., 2006). Hewitson and Crane (2002) present a range of analytical approaches that can be accomplished simply by applying a SOM to SLP data in the context of synoptic circulation changes over time relating to precipitation data. It is further stated that such an analysis is easily extended to multivariate circulation data, for example coupling SLP with 500 hPa geopotential heights. The MSLP provides an understanding of the circulation occurring in the lower atmosphere and identifying synoptic circulations such as cold fronts, low pressure troughs, tropical temperate troughs and sub-tropical systems. The z500 variable provides information regarding the upper air flow, which is important for identifying deep convection, which has show to have a significant impact on previous extreme rainfall events, especially in terms of identifying cut-off low pressure systems (Singleton and Reason, 2006). Cavazos (2000) identified the 500-1000 hPa thickness to be one of the most important controls of daily precipitation in a study using SOMs to investigate extreme climate events applied to wintertime precipitation in the Balkans. It was also identified that moisture transport at the 700 hPa level was a significant control. Crimp and Mason (1999) have also identified the importance of moisture transport at the 650 hPa level in a study on an extreme precipitation event in February 1996 over South Africa. However, the inclusion of this variable would go beyond the scope of this study.

Extreme rainfall events are often localized and therefore by analyzing extreme rainfall at a regional scale adopted by this study, a high resolution reanalysis data set was necessary in order to identify the synoptic characteristics of these features in relation to extreme rainfall. For this the newer Climate Forecast System Reanalysis (CFSR) data produced at the National Centre for Environmental Prediction (NCEP) was used. The resolution of this reanalysis data set was the highest at 50km compared to the other available reanalysis data sets such as NCEP Reanalysis 1 and 2 (2.5 degrees) (Cavazos and Hewitson, 2005; Tennant, 2004), ERA 40 (2.5 degrees) and ERA Interim data (0.75 degrees). Daily data of the CFSR was extracted for the 31 year study period from 1979 to 2009 and covered a spatial domain for Southern Africa. The extent of this spatial domain was chosen in order to adequately assess the major rainfall causing synoptic circulations over South Africa with a latitudinal range from the sub-tropics to the mid-latitudes and a longitudinal range that captures the evolution of mid-latitude cyclones from west to east. Consequently a domain extending from 20°S to 40°S and 15°E to 35°E was established and consisted of 61x45 grid cells.

Assessing the similarity between the adjacent nodes of the SOM assists with visualizing the results and forms the third stage of the SOM procedure. The measure of similarity is obtained by computing the Euclidean distance between nodes in the original measurement space (Hewitson and Crane, 2002). Hewitson and Crane (2002) describe how this may be monitored through the use of a Sammon mapping scheme (Sammon, 1969). A Sammon map therefore allows for the similarity between nodes of the SOM to be displayed as a distance such that the SOM would be displayed as a distorted surface. Ultimately the SOM map displays an array of nodes for which each day of the 31 year period is associated with subsequently providing a visual understanding of the synoptic state of any particular day from 1979 to 2009. The resulting SOMs of this procedure relevant to this study including a full analysis are presented in Chapter Three.

2.3.2. Observed rainfall assessment and trends: RClimDex

The RClimDex package (http://cccma.seos.uvic.ca/ETCCDMI) was used for analyzing trends in the observed station data and extreme indices. ClimDex was the initial package developed for calculating extreme climate indices using Microsoft Excel as a platform from which RClimDex was the enhancement based on the statistical analysis software package R (New et. al., 2006). RClimDex computes all 27 core indices recommended and used in the regional workshops coordinated by the World Meteorological Organization/Climate Variability and Predictability (WMO/CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) (New et al., 2006). This study utilizes 10 of the extreme climate indices specific to rainfall. A list of these indices and their description is displayed in Table 1.

Table 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

It is important to note that in the case of this study the RClimDex indices for heavy precipitation days (R10mm) and very heavy precipitation days (R20mm) pose a constraint in the context of regional rainfall analysis in South African due to the wide range in precipitation experienced across the country. For example the average 95^{th} percentile rainfall amount for the stations selected in the Lowveld region is 53mm while the average 95^{th} percentile rainfall amount for the stations of the Western Interior region is 30mm. An even greater difference occurs between the average amounts of the 99^{th} percentile rainfall amounts between the rainfall regions. The R10mm and R20mm indices describe the annual count of days when the daily rainfall rate exceeded 10 and 20 millimeters respectively. These amounts may be considered either to be high or low amounts in various regions of South Africa and are therefore better applied when using averaged rainfall amounts over larger areas such as in a global context for summarizing the wet part of the year (Frich et. al. 2002). For this reason a more accurate representation is created in this study by substituting these two indices with the Rnn index, which is calculated based on a user defined rainfall amount. The 95^{th} and 99^{th} percentile rainfall amounts were obtained for each station and thus used as the user defined daily precipitation threshold in this index (R95mm and R99mm) for each region instead of the fixed 10 and 20 millimeter amounts.

2.3.3. Synoptic circulation trends

It is possible to perform trend analyses for the synoptic circulations identified by the SOM analysis based on the frequency of occurrences of the nodes. While the extreme rainfall trends in the observed station data were analyzed using RClimDex, the synoptic circulation trends were analyzed using a bootstrapping procedure within R. This provided a more robust method for identifying nodes of the SOM that experienced significant trends throughout the 31 year period. From this stations that experienced significant trends in their observed extreme rainfall indices could then be matched to the significantly trending nodes. This provided an understanding of the changes that may have occurred in the driving synoptic circulations of extreme rainfall for various regions in South Africa during the 31 year study period as well as shifts in the seasonal characteristics of extreme rainfall synoptics.

2.4. Summary

The synoptic circulation patterns of extreme rainfall events in South Africa are assessed in this study based on the data and methodology described in this chapter. In so doing the initial step involves examining the station data in which a comprehensive selection procedure ensures that stations consisting of the best quality data are selected for use in this study from the 4011 available stations. The use of Self-organizing maps (SOMs) facilitates the synoptic data assessment as well as to link the extreme rainfall events identified in the observed station data to their associated synoptic circulations. Subsequently two SOM analyses are carried out, firstly to characterize the general synoptic circulations experienced throughout the entire 31 year period over South Africa to which observed extreme rainfall events may be associated with and secondly to assess the synoptic drivers of extreme rainfall at a more specific regional scale. The latter requires further station selection procedures, which are described in greater detail in the relevant Chapter Four (section 4.2). These stations also provide the observed daily rainfall data from which extreme rainfall thresholds are defined as well as facilitate the assessment of trends and indices using the RClimDex package. Together with the synoptic circulation trends identified by the SOM assessments it was possible to assess the changing characteristics of the synoptic circulations associated with extreme rainfall.

Chapter Three: Identifying synoptic circulations associated with extreme rainfall in South Africa

3.1. Introduction

Regional weather conditions throughout South Africa are driven by the dominant larger-scale circulation patterns on a daily basis. Tyson and Preston-Whyte (2000) describe six to eight main circulation types over South Africa. These include the subtropical South Atlantic anticyclone, subtropical South Indian anticyclone, ridging high pressures, easterly wave disturbances with subtropical lows, west coast troughs, continental high pressures, westerly wave lows with cold fronts and composite synoptic types such as cloud bands and tropical temperate troughs. The large-scale dominant circulations often have smaller-scale circulations associated with them ultimately influencing the local weather response (such as coastal lows, convective systems, land and sea breezes etc.). As described in Chapter Two section 2.3, these large-scale circulations are represented through the use of Self-organizing maps (SOMs).

Generalized modes of daily synoptic circulations are established for South Africa in a 40 node SOM map representing the entire 31 year study period from 1979 to 2009. This is presented in the first SOM analysis (Section 3.2). It is important to note at this stage that the SOMs in this study are structured with node one occurring in the bottom left corner of the array and count upwards from left to right such that the last node occurs in the top right corner of the array (this is the same for the smaller regional SOMs in Chapter 4). Each day in the study period is associated with one of the nodes of the SOM and its synoptic characteristics from which local weather causing events may be deduced. Therefore the relationship between the synoptic circulations and the local scale responses can be investigated using the daily rainfall data from stations. Extreme rainfall days can also be associated with nodes of this SOM thus providing the general synoptic characteristics of these specific days. A second SOM analysis (Section 3.3) was carried out using data consisting of only the days in selected station data records that experienced extreme rainfall during the 31 year period. This facilitated a comprehensive assessment of extreme rainfall synoptic circulations and characteristics.

3.2. General circulation SOM

3.2.1. General synoptic assessment

The daily MSLP and z500 synoptic circulations experienced throughout the 31 year study period are characterized by the 40 individual nodes of the SOM array shown in Figure 2 (A and B respectively). A general feature of the SOM as seen in this figure is to arrange the most opposite synoptic states in the opposite sides and corners of the array.

The bottom left corner of the MSLP SOM map (Figure 2A) identifies a presence of low pressure mid-latitude cyclones in the lower latitudes of the domain. The transition in the synoptic circulations across the SOM array then unfolds in such a way that the top left corner of the array is dominated by nodes representing circulations associated with tropical-extratropical interactions (Hart et. al., 2010), the bottom right of the array identifies circulations associated with ridging high pressure systems and the middle of the SOM array identifies synoptics associated with a southward extending low pressure from the northern latitudes accompanied by high pressures in the southern regions of the domain (Tyson and Preston-Whyte, 2000). These nodes situated in the centre of the SOM array represent transitional circulations between the synoptic circulations identified by the outer nodes of the SOM array.

The z500 SOM (Figure 2B) characterizes the 500 hPa layer of the atmosphere over South Africa in such a way that the bottom nodes of the SOM sees the domain being dominated by deep mid-latitude low pressures typical of winter circulation patterns (Tyson and Preston-Whyte, 2000). While these circulations are also identified at the surface level in the MSLP SOM, they have a greater presence in the z500 SOM indicating the depth of these circulations and the meridional flow in the mid-troposphere associated with them. These deep mid-latitude low pressures have moved southward in the domain shown by the nodes towards the top of the z500 SOM as high pressure zonal air flow dominates the upper layers of the atmosphere, which is typical of summer circulation patterns (Tyson and Preston-Whyte, 2000). The seasonal variation of the synoptic circulations over South Africa is therefore characterized by the z500 SOM as well as the MSLP SOM. The frequencies of days within each of the four seasons are later in this chapter mapped to specific nodes of this SOM.

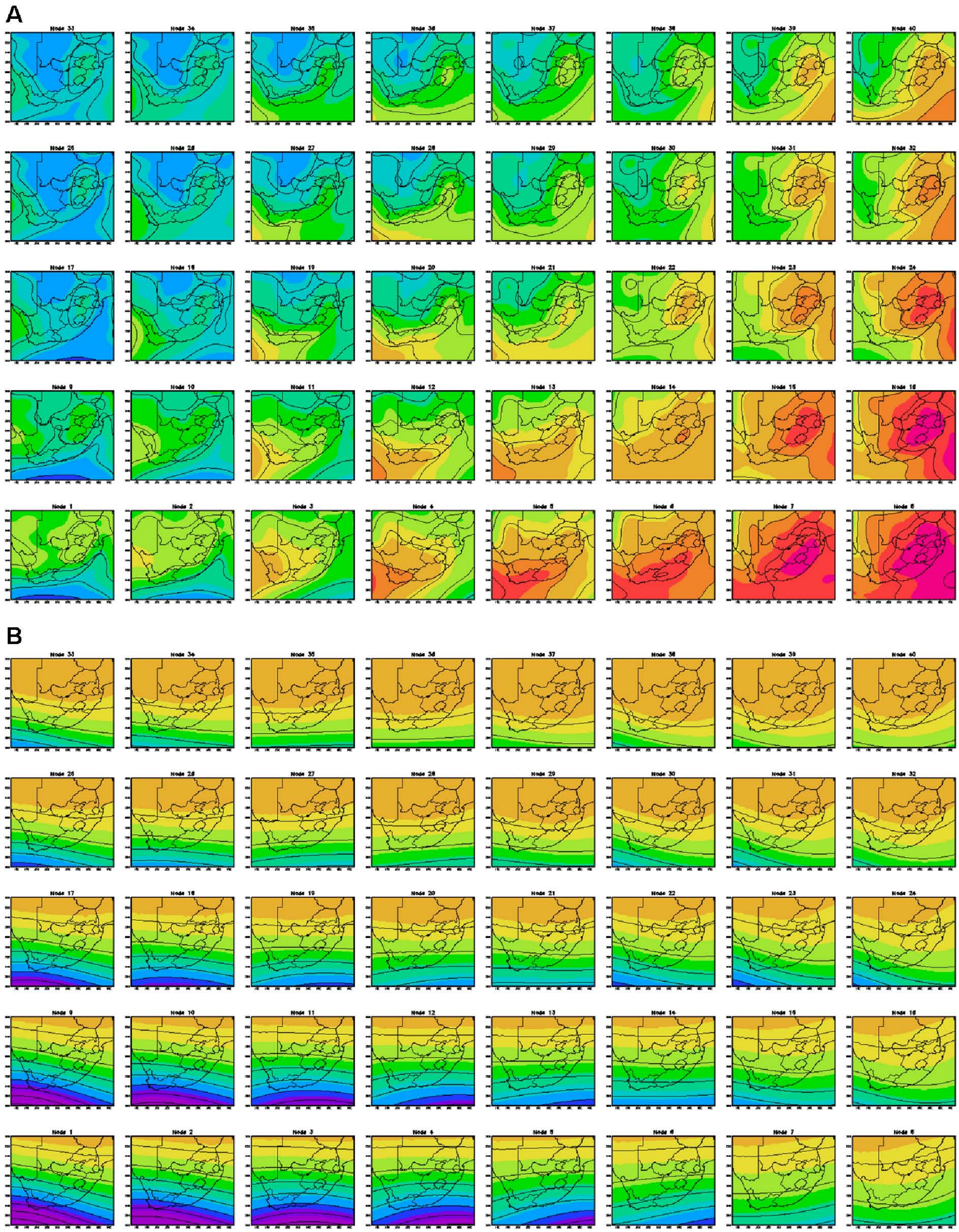

Figure 2: The general circulation patterns identified by the 40 node SOM array in the domain from 1979 to 2009 at (A) MSLP and (B) z500 levels of the atmosphere with node 1 in the bottom left corner and node 40 in the top right corner.

As each day in the 31 year period is mapped to a specific node it is possible to determine the daily frequency for each of the nodes in the SOM. This provides an understanding of the most dominant synoptic circulations that occurred throughout the 31 year period. Typical of the SOM procedure, the highest frequencies occurred at the corners of the SOM shown in Figure 3. In this case all four of the corner nodes (1, 8, 33 and 40) experienced a daily frequency mapping of over 3%. The most frequently mapped to node was node 40 with 4.38% of the days in the 31 year period being associated with the synoptics of this particular node. The second highest frequency was obtained by node 37 with 3.60%.

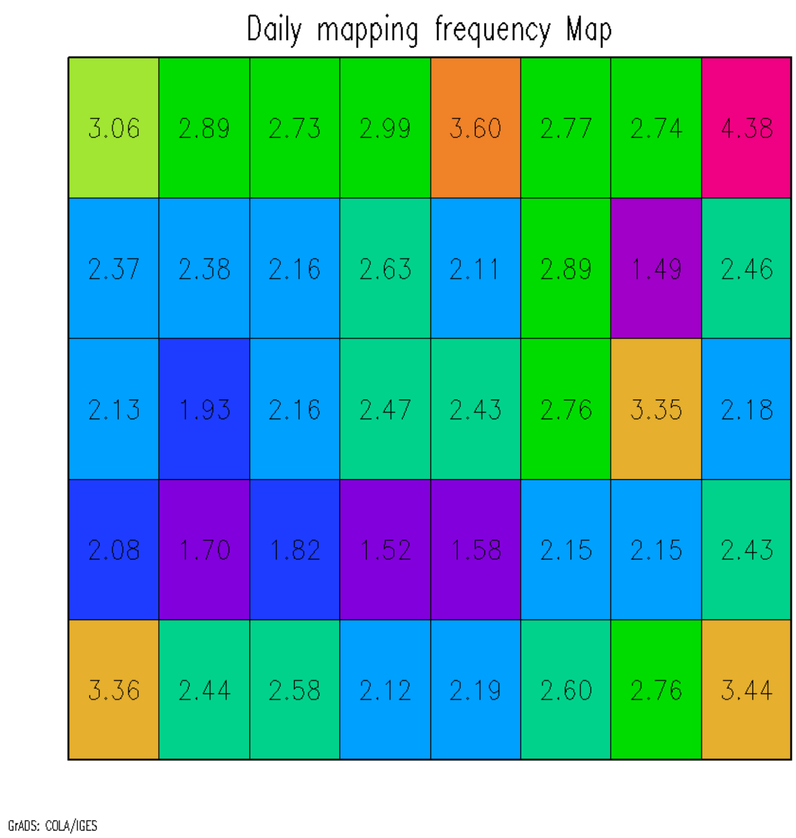

Figure 3: Daily frequency map showing in percentages the proportion of days that mapped to each of the nodes throughout the 31 year period with node 1 in the bottom left corner and node 40 in the top right corner. As with all the frequency maps in the rest of this study, nodes with darker purple and blue shading are the lower frequencies mostly occurring less than 2%.

3.2.2. *Seasonal assessment*

The seasonal frequency mapping of the SOM is also achievable by dividing the daily data into the four seasons and passing them through the trained SOM. The seasons of South Africa are divided such that summer is defined by the months of December, January and February (DJF), autumn by March, April and May (MAM), winter by June, July and August (JJA) and spring by September, October and November (SON). This established a seasonal distribution of synoptic circulations associated with each season displayed in Figure 4.

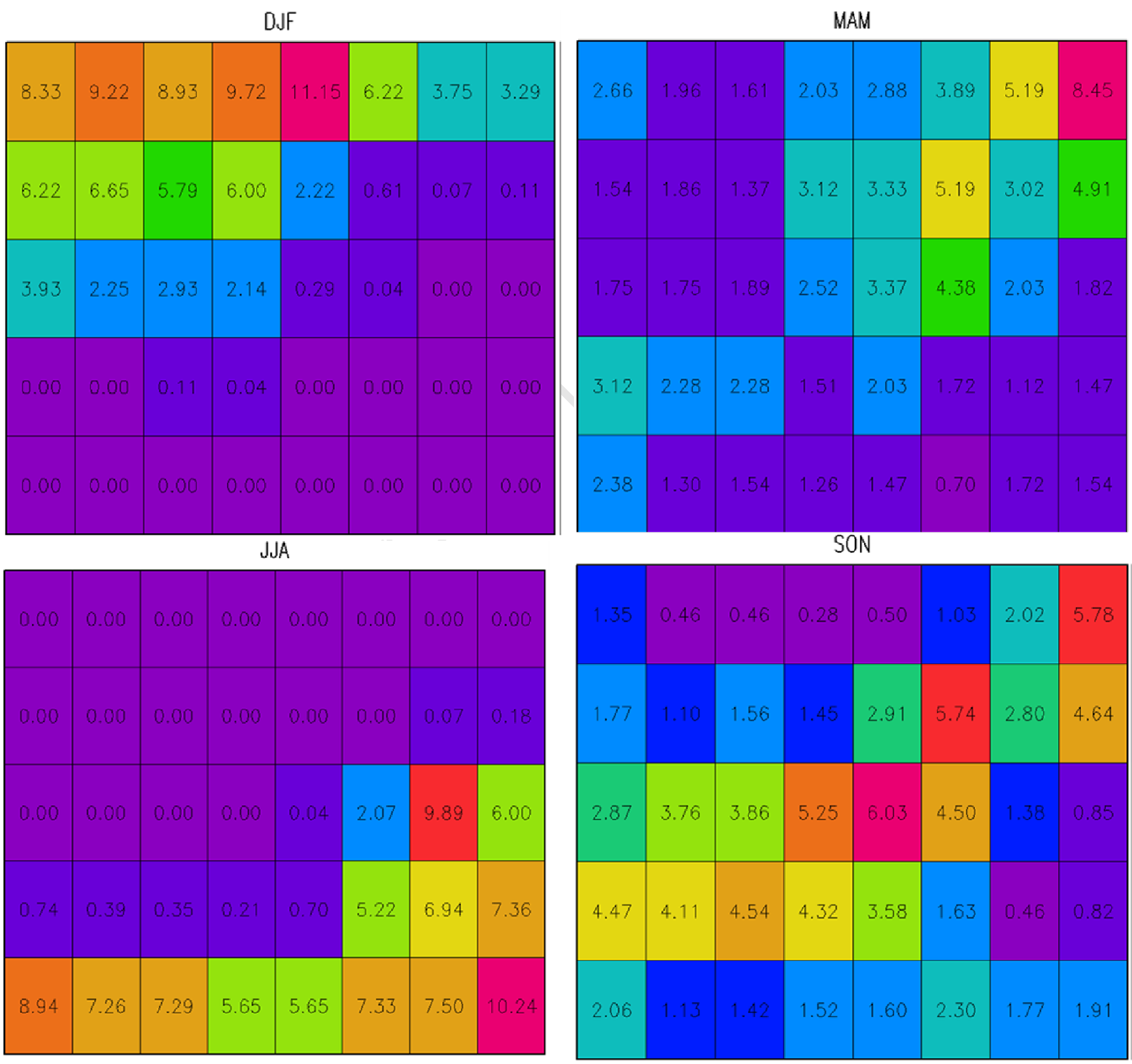

Figure 4: Daily frequency map displayed for each of the four seasons (DJF, MAM, JJA, SON) indicating the most dominant synoptic circulations of each season over South Africa.

The summer and winter months map to definite regions of the SOM array and as such are associated with characteristic synoptic circulations. This is evident in the summer months that map to the top and left of the SOM while the winter months map to the bottom and right of the SOM. The most frequently mapped to node for DJF is node 37 with 11.15% followed by nodes 36, 34, 35 and 33. These nodes all have very similar synoptic characteristics with a well defined sub-tropical low pressure system extending from the northern latitudes of the domain covering the majority of the interior of the country at the surface level. These synoptic states are generally associated with rainfall over the interior parts of the country characteristic of the summer rainfall regime of South Africa (Tyson and Preston-Whyte, 2000). The presence of a high pressure towards the southern and eastern parts of the domain off the coast of South Africa facilitates the advection of moisture into the interior providing another mechanism for greater rainfall (Crimp and Mason, 1999). In the winter months of JJA the most frequently mapped to node was node 8 with 10.24%. The synoptics of this node identify a strong high pressure system at the surface covering most of the country along with an upper air ridge over the interior which is typical during winter. The second highest mapped to node during JJA was node 23 with 9.89%. The synoptics of node 23 are somewhat different to node 8 while still typical of winter-like circulations with an approaching upper air trough in the mid-latitudes and a surface low pressure to the south-west of the country signifying an approaching cold front, which are largely responsible for rainfall to the south-western parts of the country (Reason and Rouault, 2005; Hewitson and Crane, 2006). A surface high pressure system is still evident over the north eastern parts of the country. The next most frequently mapped to nodes for JJA occur towards the bottom left of the SOM (nodes 1, 2 and 3), which identify a strong upper air trough in the mid-latitudes accompanied by a surface low pressure system to the south of the country and an initiating ridging high pressure in the case of node 3 all associated with frontal conditions bringing rainfall to the south western and southern coastal regions of South Africa (Reason and Rouault, 2005; Hewitson and Crane, 2006).

The daily frequency mappings for the autumn and spring months (MAM and SON respectively) are more heterogeneous across the SOM than the mappings of DJF and JJA. Most MAM mappings were to the top right nodes of the SOM with the most frequently mapped to node being node 40 followed by nodes 39, 30 and 32. The synoptics of these nodes identify a surface trough over the western parts of the country and a high pressure over the eastern parts. The upper air ridge over the country along with the small indication of a trough in the mid-latitudes notable in nodes 39, 30 and 32 indicate a change in the seasons from summer-like conditions towards winter-like conditions as the Inter-Tropical Convergence Zone (ITCZ) activity begins to weaken (Hart et. al., 2010). Spring (SON) mappings are more widely dispersed across the SOM, however, the higher frequency nodes generally identify a sub-tropical low pressure at the surface level over the interior and a high pressure system at the surface to the south of the country. This is most evident in node 21, which is the highest mapped to node of the season with 6.03%. Some of the other more frequently mapped to nodes (9 to 12) show signs of the passage of mid-latitude cyclones and ridging high pressure systems at the surface to the south of the country. This variation displays the transition between the winter and summer season synoptic circulations.

3.3. Identification of synoptic states associated with extreme rainfall

The general circulation SOM above was produced using every day in the 31 year period and each day mapped to a particular node so that the synoptic conditions of each day could be interpreted. It is therefore also possible to match days from the observational station data to corresponding nodes of the SOM (Hewitson and Crane, 2002). This facilitated a synoptic assessment of extreme rainfall as days that experienced extreme rainfall in the observed station data could be assigned to a SOM node and the particular synoptic archetype associated with extreme rainfall identified. This assessment is carried out in two parts below. The first investigates the synoptic circulations associated with extreme rainfall days using the trained general circulation SOM above and the second involves assessing extreme rainfall synoptic circulations based on a new SOM that was produced using reanalysis data from only extreme rainfall days as found in the station record during the 31 year period.

3.3.1. Extreme rainfall synoptics in the full 31 year period

In order to extract extreme rainfall days from the observed station data records it was necessary to obtain a sample of stations with an adequate quality of data. The data of 698 stations were used in this section for extracting extreme rainfall days (Chapter Two) and these extreme rain days were mapped to the trained general circulation SOM. The extreme rainfall threshold was set as the 95th percentile level in each individual station and all the days that either matched or exceeded this threshold were extracted. The corresponding synoptic circulation data for each of these days was then extracted from the reanalysis and passed through the trained SOM to associated extreme rainfall days with general synoptic circulations. This process generated a daily frequency map of the extreme rainfall days shown in Figure 5.

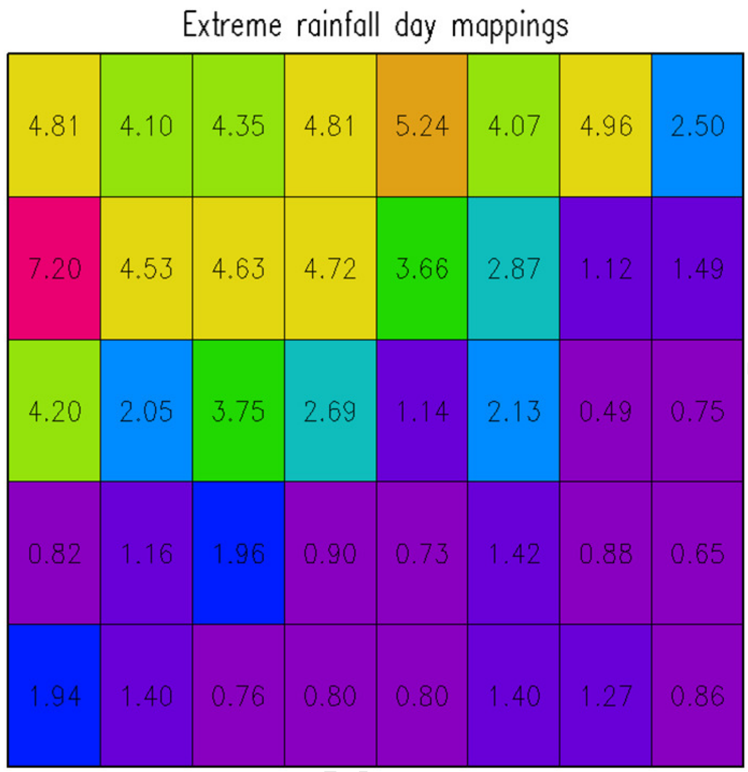

Figure 5: Daily frequency map showing which nodes of the SOM with percentages the extreme rainfall days were associated with.

The results indicate that one node in particular (node 25) was highly mapped to by extreme rainfall days compared to the rest of the nodes (7.20%). The synoptics associated with node 25 identify an approaching mid-latitude trough to the south west of the country at the 500 hPa level and widespread low pressure conditions at the surface across most of the domain from the sub-tropics and mid-latitudes foremost over the central interior and the south east coast. The rest of the most frequently mapped to nodes of the SOM occur towards the top and left of the array around node 25. From the seasonal assessment these nodes are associated predominantly with summer-like synoptic conditions in which a deep sub-tropical low pressure system covers the majority of the interior of the country at the surface level. Therefore a large amount of extreme rainfall from the 698 stations is associated with summer circulations (Tyson and Preston-Whyte, 2000). In order to reach a more defined spatial analysis of extreme rainfall causing synoptics, reanalysis data from extreme rainfall days identified above were extracted and used to produce a second SOM that is based only on circulations associated with extreme rainfall.

3.3.2. Extreme rainfall synoptics SOM analysis

To further assess the synoptic circulations associated with extreme rainfall throughout South Africa a new SOM was generated using only circulations associated with the days that experienced extreme rainfall in the station records. The corresponding synoptic circulation data for each of the days that matched or exceeded the 95^{th} percentile threshold from the 698 stations were extracted from the CFSR reanalysis data and used to produce a 40 node SOM array shown in Figure 6.

A general synoptic assessment of the SOM identifies circulation patterns associated with mid-latitude cyclones, southward extending tropical lows, tropical-extratropical interactions and ridging high pressure systems all at the surface level (Figure 6A). The z500 level (Figure 6B) identifies deep mid-latitude troughs extending into the northern regions of the domain associated with significant meridional flow. There is also evidence of cut-off low pressure systems in the upper atmosphere identified by nodes 1 and 2. These synoptics are found to be consistent with other extreme rainfall producing circulations identified by various studies (Crimp and Mason, 1999; Hart et. al., 2010; Singleton and Reason, 2006; Singleton and Reason, 2007). The z500 level of this extreme rainfall synoptics SOM displays a wider range of activity in the upper atmosphere in comparison to the general circulation SOM from above in which zonal air flow dominated the majority of the nodes. This provides an understanding of the role the upper air layers of the atmosphere have in driving extreme rainfall.

The frequency map shown by Figure 7 identifies nodes 17 and 40 with the highest percentage frequencies (4.53% and 4.31% respectively). The synoptics at the surface level of node 17 are characterized by a sub-tropical trough over a large region of the central interior of the country and a ridging high pressure system to the south of the country. These circulations trail an upper air mid-latitude trough that has passed by the south of the country and situated off the south-eastern coast.

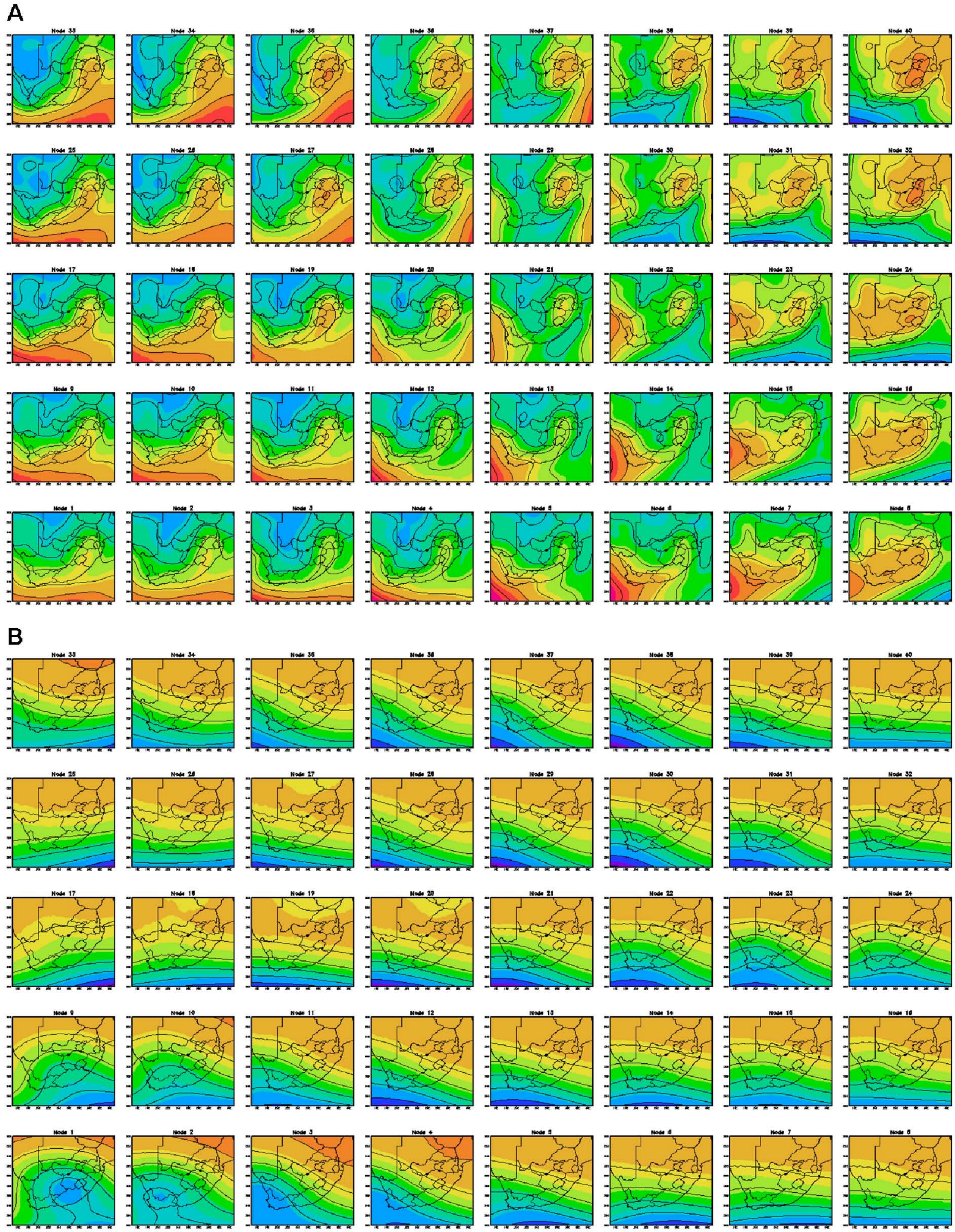

Figure 6: The synoptic circulations associated with extreme rainfall events throughout South Africa between 1979 and 2009 identified by the 40 node SOM at the MSLP level (A) and the z500 level (B).

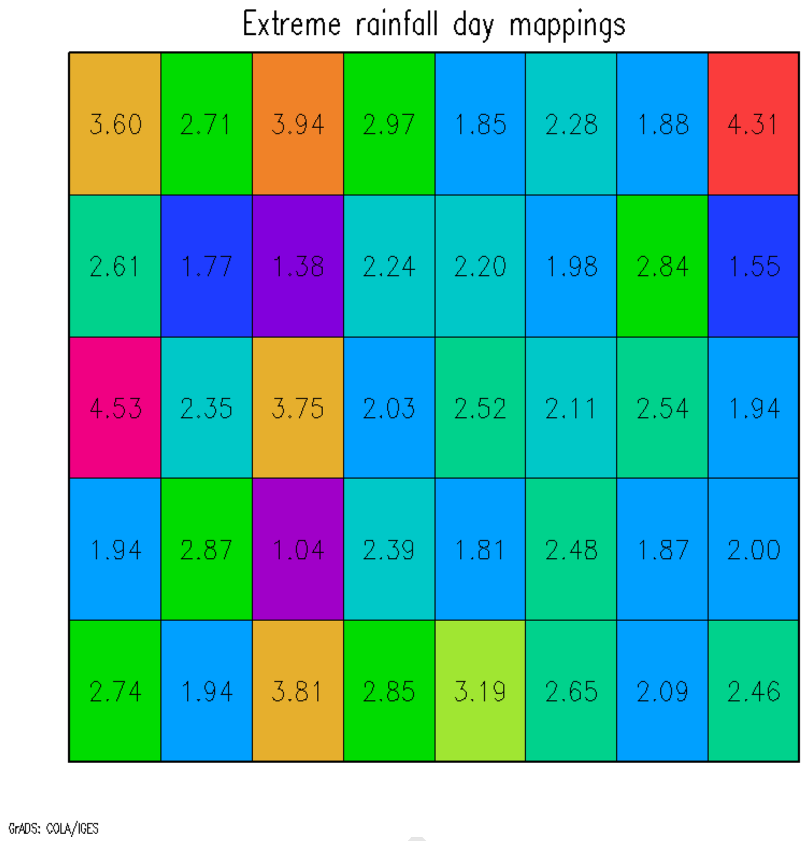

Figure 7: Daily frequency map showing in percentages the amount of days mapped to each of the nodes of the extreme rainfall SOM throughout the 31 year period with node 1 in the bottom left corner and node 40 in the top right corner.

Node 40 is characterized by an approaching surface low pressure to the south west of the country and a high pressure system over the eastern interior. Other frequently mapped to nodes include nodes 3, 19, 33 and 35. The synoptic circulations of these nodes all suggest the passage of mid-latitude cyclones to the south of the country followed by a ridging high pressure system and a sub-tropical trough at the surface level.

The characteristics of the synoptic circulations associated with each season were assessed using the daily frequency mapping similar to that carried out above for the general circulation SOM. This identified the characteristics of synoptic circulations associated with extreme rainfall for each season. The individual frequency maps are not displayed here and instead the most frequently occurring nodes of each season are labeled on the relevant nodes of the SOM such that these nodes in both the MSLP and z500 layers can be directly analyzed.

The most frequently mapped to nodes of summer (DJF) were nodes 40 (8.05%), 19 (7.13%) and 17 (6.17%) shown by Figure 8. Node 40 is characterized by a high pressure system over the north eastern interior parts of the country and an approaching mid-latitude low pressure to the south west at the surface level. The significant contrasts of these pressure systems within close proximity to each other will result in strong pressure gradient forces bringing high winds speeds and the ability to transport moisture into the central parts of the country resulting in unstable air masses over large parts of the interior (Crimp and Mason, 1999; Tyson and Preston-Whyte, 2000). This synoptic state is not truly characteristic of summer circulations thus indicating the significance of its occurrence at this time of year and the probable association with extreme rainfall. Nodes 17 and 19 display a greater resemblance of summer-like synoptic circulations according to the above general circulation SOM seasonal analysis. These nodes are characterized by a southward extending low pressure covering most of the western and central interior of the country as well as a ridging high pressure system (node 17) to the south at the surface level. This surface level high pressure system appears to be ridging behind a passing mid-latitude trough towards the southern region of the domain in the upper air layer, in which southeasterly onshore flow advects cold air from relatively high latitudes onto the Eastern Cape coast (Singleton and Reason, 2006).

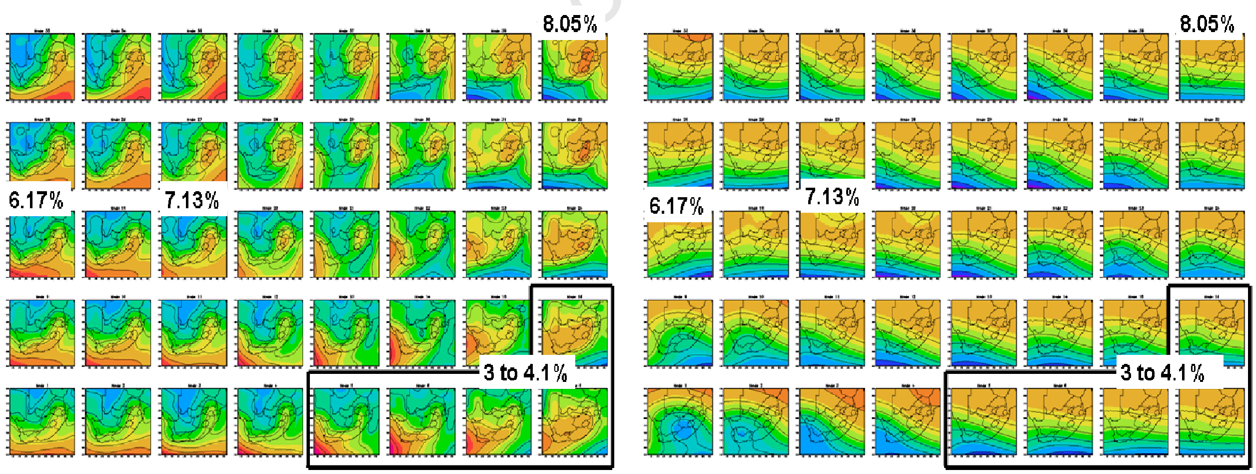

Figure 8: MSLP SOM on the left and z500 SOM on the right displaying the most frequently occurring nodes associated with extreme rainfall during the summer months of DJF from 1979 to 2009.

The winter months of JJA identified nodes 1 and 2 as having the highest frequency mappings (15% and 12.9% respectively). Figure 9 shows the synoptics of these nodes are both very similar with a surface high pressure extending the full length of the domain to the south of the country and a low pressure covering parts of the interior. These synoptic are not characteristic of the predominant rainfall driving synoptic associated with winter (Tyson and Preston-Whyte, 2000), however, as mentioned in the synoptic assessment of this extreme rainfall SOM these are the only two nodes that show evidence of a cut-off low-like pressure system in the upper air layers. These circulations are capable of stratosphere-troposphere exchange and deep moist convection that are often the cause of intense localized rainfall (Singleton and Reason, 2007). Other highly mapped to nodes of JJA include nodes 23, 31, 38 and 39. These nodes all identify synoptics characteristic of winter-like circulations in which a mid-latitude surface low pressure system is accompanied by an upper air layer mid-latitude trough forming a deep mid-latitude cyclone associated with frontal conditions to the south and south west of the country (Tyson and Preston-Whyte, 2000).

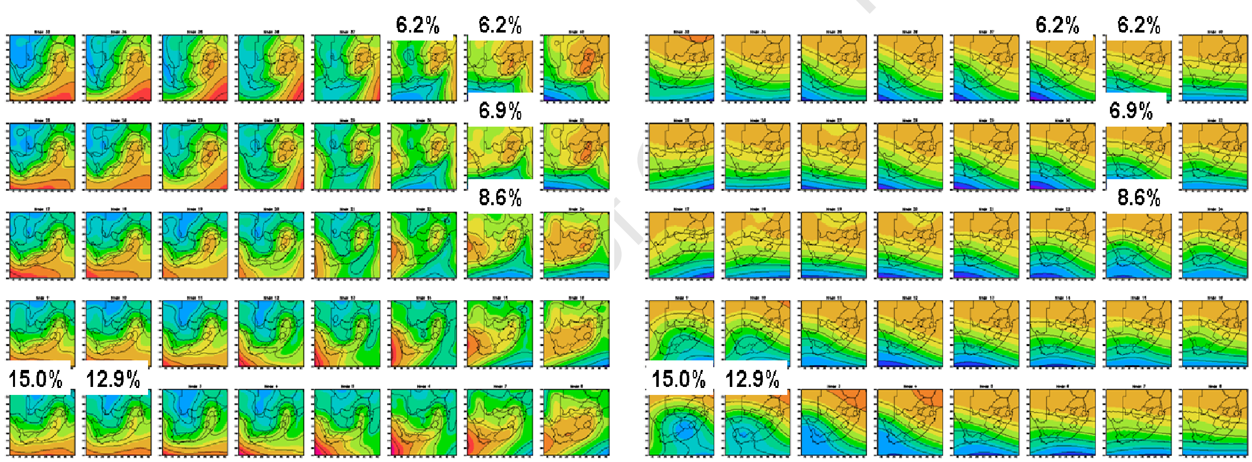

Figure 9: MSLP SOM on the left and z500 SOM on the right displaying the most frequently occurring nodes associated with extreme rainfall during the winter months of JJA from 1979 to 2009.

The synoptic circulations associated with the most frequently mapped to nodes of MAM (Figure 10) are similar to those of JJA with nodes 23, 24 and 31 together making up 18.4% of the frequency. Nodes 17 and 34 are also frequently mapped to (5.7% and 5.2% respectively) identifying a ridging high pressure system to the south of the country and a low pressure covering most of the interior at the surface level. In the case of node 34, the high pressure system is situated further towards the south east of the domain and the low pressure system has resemblances of a west coast trough, which is conductive to widespread rain over the western parts of South Africa (Tyson and Preston-Whyte, 2000). Node 17 was also one of the more frequent nodes occurring during summer. However, nodes 1 and 2, associated with the cut-off low-like pressure systems, which were significantly mapped to during winter do not feature in this case for MAM. This is surprising knowing that the peak season for cut-off low pressure systems is MAM (Singleton and Reason, 2007) suggesting that these circulations are not associated with cut-off lows. This is investigated further in Chapter 5.

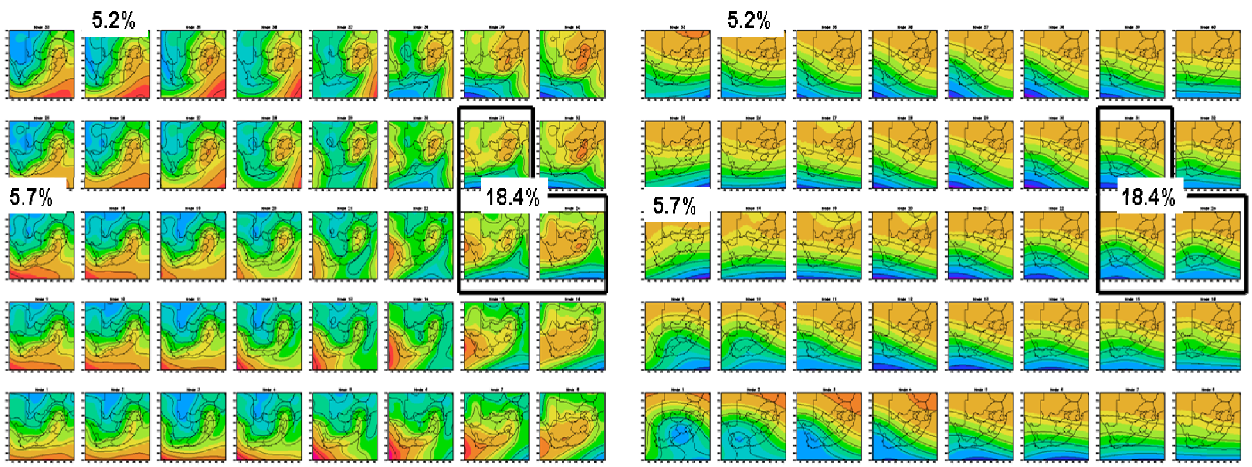

Figure 10: MSLP SOM on the left and z500 SOM on the right displaying the most frequently occurring nodes associated with extreme rainfall during the autumn months of MAM from 1979 to 2009.

The most frequently mapped to node of SON shown in Figure 11 was node 33 with 9.0%. Node 35 also experienced a high frequency with 5.6%. Both these nodes are characterized by synoptic circulations similar to node 34, which experienced a high frequency during the MAM season. These include a low pressure extending down from the sub-tropics covering most of the western parts of the country and a strong high pressure system in the south and south east of the country at the surface level. This provides an understanding that extreme rainfall often results from these synoptic circulation patterns (Singleton and Reason, 2006) during the shoulder seasons similar to the synoptic identified and described in nodes 17 and 19 of the DJF SOM. Nodes 3 and 4 are also frequently mapped to nodes for SON together making up 17.9%. These nodes are characterized by a sub-tropical trough over the majority of the interior of the country at the surface level and a deep mid-latitude trough in the upper air layers responsible for meridional flow. Together these synoptics provide conditions appropriate for uplifting of unstable air over large parts of the country (Tyson and Preston-Whyte, 2000).

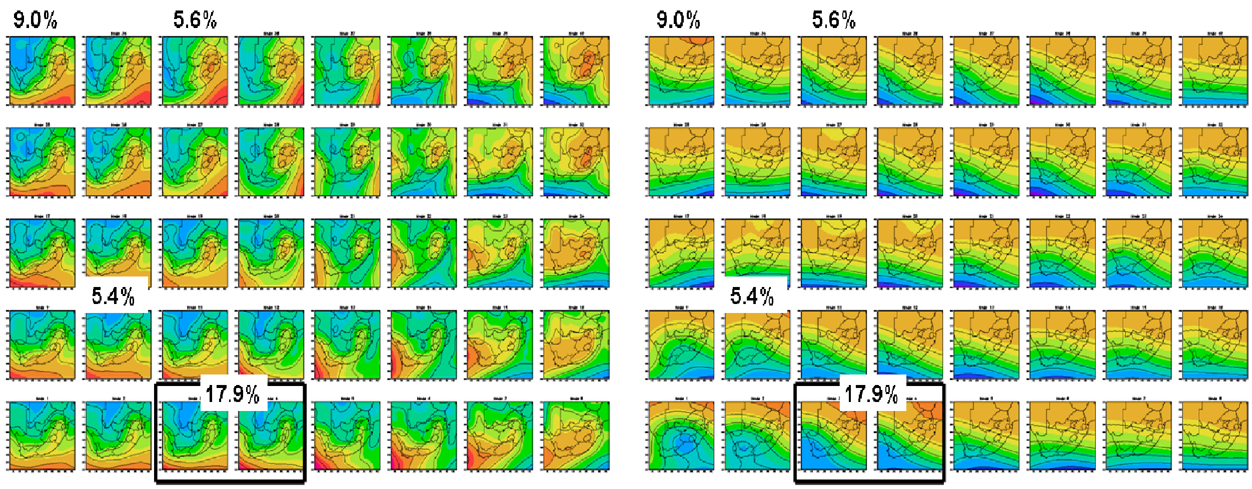

Figure 11: MSLP SOM on the left and z500 SOM on the right displaying the most frequently occurring nodes associated with extreme rainfall during the spring months of SON from 1979 to 2009.

3.4. Summary

A general circulation SOM was created consisting of every day in the 31 year period from 1979 to 2009. This SOM identified correctly the dominant synoptic circulations over the domain for South Africa described largely by Tyson and Preston-Whyte (2000). The seasonal synoptic characteristics were also distinguished and clearly defined by the daily frequency mapping for the core seasons of summer and winter. The summer months identified a predominant sub-tropical low covering most of the country and a high pressure to the south at the surface level while the winter months are associated with mid-latitude cyclones and a surface high pressure over the interior of the country. Shoulder season circulations were spread more widely across the SOM. Extreme rainfall days were then mapped to the synoptic circulations identified by this SOM and node 25 was mapped to most frequently. In general most of the extreme rainfall was associated with summer-like synoptic circulations. A second SOM which was generated using synoptic data only associated with extreme rainfall days provided a more detailed analysis of the extreme rainfall driving synoptics over South Africa in which the role of the upper air could be clearly seen. Synoptic circulations identified by this SOM to be associated with extreme rainfall included mid-latitude cyclones, sub-tropical troughs, ridging high pressure systems and tropical-mid-latitude linkages.

This chapter has provided an understanding of the general synoptic circulations over South Africa as well as those associated with extreme rainfall. The SOM methodology used in this chapter is validated by the consistency of the resultant synoptic circulations over South Africa with the literature and their accurate seasonal characteristics. However, the specific regions in which extreme rainfall occurred as a result of these synoptic circulations has not been assessed at this stage of the study. Therefore it is difficult to infer extreme rainfall driving synoptics at a regional scale in South Africa especially due to the variation in rainfall regimes across the country described above. This will be examined in greater detail in the following chapter.

Chapter Four: Analysis of the synoptic drivers of extreme rainfall at the regional scale

4.1. South African rainfall patterns and regions

The spatial extent of South Africa is characterized by a number of different rainfall regimes driven by different synoptic circulations. These synoptic circulations have a noticeable regional distribution throughout the various geographic regions of the country along with a seasonality factor. In general it is widely accepted that the South Western region is characterized by winter frontal precipitation, while the eastern and interior plateau regions experience summer convective rainfall. Also 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 various synoptic patterns with minimal seasonal distinction. Consequently any attributes of the synoptic drivers of extreme rainfall would be lost when examining extreme rainfall data across all the different rainfall regimes generally affecting the country as a whole. Although Chapter Three identified synoptic circulations associated with extreme rainfall, the degree of generalization is too great to assess the synoptic drivers at a regional scale. In order to address this and examine this extreme rainfall, the station data was spatially divided into specific rainfall regimes across the country and a seasonal assessment was also pursued.

Landman et al. (2001) identified nine homogeneous rainfall regions (Figure 12) throughout the general climate regimes of Southern Africa. These rainfall regions capture the large variability and types of rainfall received from various synoptic patterns throughout South Africa and therefore provide the basis of spatial criteria necessary for analyzing regionally specific extreme rainfall for this study. Eight of the nine regions identified by Landman et al. (2001) are considered for this study. These include the South Western Cape, South Coast, Transkei, KwaZulu Natal Coast, Lowveld, North Eastern Interior, Central Interior and the Western Interior. The Northern Namibia/Western Botswana region was excluded from this study as it falls outside the boarders of South Africa.

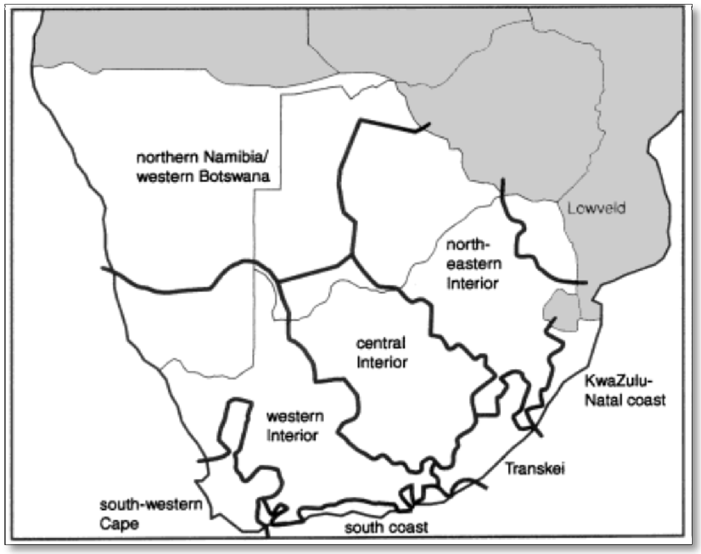

Figure 12: The 9 homogeneous rainfall regions identified by Landman et al. (2001). This study uses 8 of these regions excluding the Northern Namibia/Western Botswana region.

4.2. Regional selection of stations

As described in Chapter Two the wide spatial extent of stations available throughout South Africa was filtered to obtain a sample of stations with a degree of data quality eligible for the extreme rainfall analysis. For this assessment, of the synoptic drivers of regionally specific extreme rainfall, the stations were selected from the sample of 698 stations described above. Once the data quality was assured the criteria on which the stations were selected included factors such as spatial representativeness, topographical effects, data representativeness and the number of extreme rainfall day's experiences. These criteria are described in detail below.

4.2.1. Spatial representation

There are many variables apart from the dominant large-scale circulations that ultimately are responsible for the regional synoptic circulations of rainfall, such as the distinct ocean currents surrounding the country and their associated sea surface temperatures (SST's), the topographical relief ranging from mountainous regions to flat lands. These factors are evident throughout South Africa and therefore have to be taken into consideration when selecting stations to maintain a representative sample that throughout each of the eight rainfall regions. Each station has a set of metadata variables that assists in considering the above factors for selecting stations. These metadata variables provide geographic information in terms of 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 (with the exception of Kwazulu Natal (KZN) Coast region with 4 selected stations) were initially selected per region, 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 Transkei consist of a lower altitude coastal plain as well as high mountain areas. The coastal plains and mountains usually occur within the same rainfall region and are within relatively close proximity to each other. Stations from both high and low-lying areas within the regions were selected so that the rainfall of those particular regions is well represented. Often the consequences resulting from extreme rainfall in the high mountain catchment areas are experienced further down rivers around the more populated coastal plains.

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 include the South Western Cape, South Coast, Western Interior (mostly the southern parts) and the Transkei. The Transkei as well as the eastern parts of the South Coast region form a spatial transition zone between the mid-latitude driven winter rainfall from the west and the thermally moisture driven summer rainfall regime in the eastern parts of the country.

The eastern parts of South Africa inland from the Kwazulu Natal coast are characterized by very high mountains that lead to an inland 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.

Applying the spatial and synoptic criteria described above yielded a selection of 69 representative stations (Figure 13) from the sample of 698 stations upon which the assessment of regional extreme rainfall characteristics within South Africa may be based. Further representativeness of these stations was assessed according to their individual observed rainfall characteristics in relation to their rainfall regimes (described in section 4.2.2).

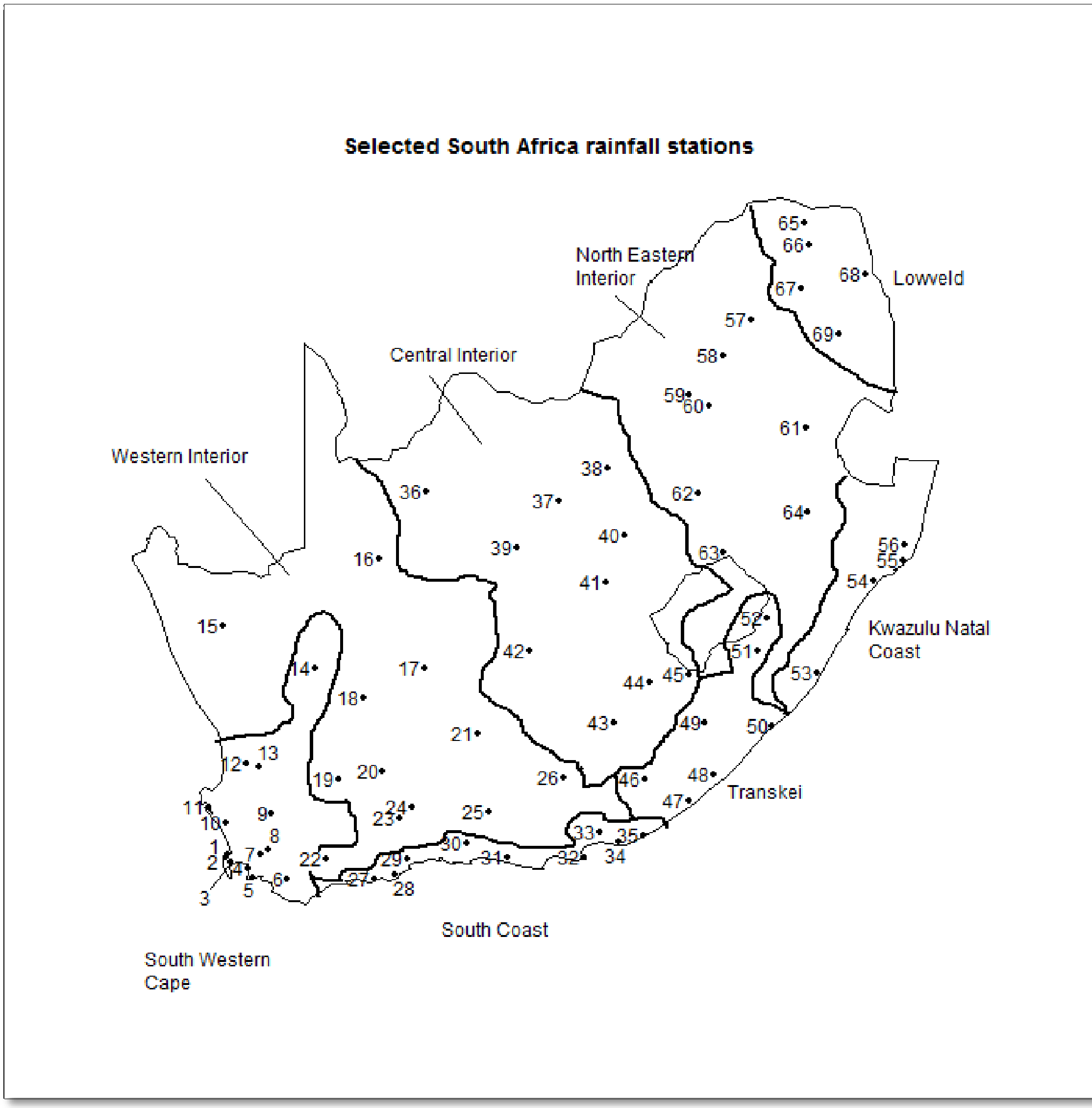

Figure 13: map showing the 69 selected rainfall stations throughout South Africa with a rough outline of the eight rainfall regions to identify in which region the stations occur.

4.2.2. 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. In order to achieve this, percentile thresholds and averages are used to compare the characteristics of the 69 selected stations data sets against all 698 stations. As this study focuses on extreme rainfall scenarios the upper rainfall thresholds are calculated for each stations data set. 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 was also identified (Table 2).

Table 2: Extreme rainfall profile for each of the selected stations used in this study with reference to the map in Figure 13.

Regions	Labels	Name	Latitude	Longitude	Altitude (m)	95th percentile (mm)	95th percentile events	99th percentile (mm)	99th percentile events	Maximum recording (mm)
South Western Cape	1	MOLTEN	-33.93	18.42	93	30	156	50.23	31	95
	2	WOODHEAD_DA	-33.98	18.41	733	48.9	176	79.952	36	152
	3	RONDEVLE	-34.06	18.5	8	26.985	146	48.791	30	115.4
	4	STEENBRAS	-34.18	18.85	380	32.63	174	59.165	35	176
	5	BETTYS_BAY_HEROLD_PORTE	-34.35	18.93	34	36	171	62.7	34	221.8
	6	BOSKLOO	-34.39	19.65	128	28	81	46.255	16	100
	7	FRANSCHHOEK_ROBERTSVLE	-33.93	19.08	256	74	136	126.958	27	277.8
	8	STETTYNSKLOO	-33.84	19.26	451	46.4	132	94.55	27	190.5
	9	BOKVELDSKLOO	-33.19	19.33	1035	45	82	67.93	17	115
	10	DARLIN	-33.37	18.38	120	21.2	106	33.135	21	66
	11	LANGEBAA	-33.09	18.03	14	20.21	74	31.5	16	59.2
	12	ELANDSFONTEI	-32.3	18.82	457	29.5	90	44	20	96
	13	ALGERIA_-_BO	-32.37	19.06	517	43	86	69	18	106
	14	BRANDVLEI_KAN	-30.6	20.22	953	26.675	23	46.641	5	96
Western Interior	15	SPRINGBOK_DABEE	-29.82	18.32	856	16.5	42	36.87	9	66
	16	THORNLE	-28.63	21.52	884	28.585	35	46.068	7	58
	17	OORLOGSHOE	-30.58	22.43	1204	34.275	41	55	12	170
	18	GROOTFONTEIN_WILLISTO	-31.12	21.19	1188	29	27	50	7	66
	19	SUTHERLAND_GUNSFONTEI	-32.57	20.68	1529	30	47	46.115	9	100
	20	GROOTFONTEIN_MERWEVILL	-32.44	21.59	808	41.175	25	82.175	5	131.5
	21	LOSKO	-31.78	23.52	1219	28.97	37	45.126	8	86.2
	22	MARLOT	-34.01	20.44	247	37.5	138	67.622	28	149.2
	23	DAMASKU	-33.27	21.94	666	27.45	36	53.94	8	63
	24	ZACHARIASFONTEI	-33.09	22.17	823	28	29	46.405	6	112
	25	MOOREDAL	-33.17	23.75	630	31.325	63	52	14	94
	26	STRUISHOE	-32.55	25.28	914	27.05	82	49.15	17	127
South Coast	27	STILBAAI_SAP	-34.38	21.41	20	26	102	46.095	20	97.5
	28	DIE_EILAN	-34.28	21.84	49	21.32	113	50.836	23	94.5
	29	MOSSELBAAI_KWEPERTUI	-34.01	22.08	220	35	87	67.8	17	212
	30	WELGELEGE	-33.73	23.29	853	32	88	62.86	18	238
	31	WITELSBOS_-_BO	-33.99	24.12	227	48.5	116	93.5	24	191
	32	HUMEWOOD_-_GOLF_CLU	-33.98	25.67	15	23.69	127	47.312	26	139
	33	TYGERHOE	-33.55	25.99	457	32.565	56	66.325	12	146
	34	ALEXANDRIA_-_BO	-33.7	26.37	198	35	119	70.2	24	212.5
	35	PORT_ALFRE	-33.6	26.88	61	36.56	94	68.744	19	160.6
Central Interior	36	WHYENBA	-27.41	22.48	1372	34.5	44	67.76	9	100
	37	WELKO	-27.6	25.17	1310	35.8	61	65.8	13	116
	38	LEEUKO	-27.01	26.15	1219	34	85	53.965	17	89
	39	DELPORTSHOOP_-_PO	-28.42	24.3	1030	36.55	50	76.53	10	140.5
	40	GROOTKUI	-28.22	26.5	1280	35	75	55.885	15	132
	41	BAINSVLEI-MU	-29.06	26.13	1372	40	69	70.015	12	135
	42	GROOT_-_ARENDSKRAA	-30.28	24.57	1295	25.5	83	50.175	16	93
	43	WILDEPERDEHOE	-31.57	26.3	1707	27.5	108	45.52	21	115
	44	HELVELLY	-30.85	27.02	2034	38.9	117	64.12	24	101.5
	45	FUNNYSTON	-30.7	27.82	2286	29	144	44.43	29	86
Transkei	46	HOGSBACK_-_BO	-32.59	26.93	1375	40.97	141	66.982	29	228.2
	47	UMZONIAN	-32.98	27.82	168	37.775	183	79.255	37	261.5
	48	KENTANI_-_BO	-32.5	28.32	488	45	114	90.5	23	268
	49	ENGOBO_MANINA_PLANTATIO	-31.58	28.15	1067	49.17	107	82.37	22	181.5
	50	SILAKA_NATURE_RESERV	-31.62	29.52	256	56.16	102	100.628	21	330.5
	51	THE_MEADOWS_FAR	-30.27	29.22	1460	28.235	142	48.238	29	95
	52	COBHAM_-_BO	-29.68	29.42	1675	33	201	55	43	180.5
Kwazulu-Natal Coast	53	THE_VALLEY	-30.67	30.42	183	46.9	156	97.96	32	244.5
	54	GINGINDHLOV	-29.03	31.57	100	37	160	85	32	296
	55	KWAMBONAMBI-BO	-28.66	32.17	30	56.485	130	111.585	26	337
	56	KANGEL	-28.37	32.2	76	35	153	79.905	31	305
North Eastern Interior	57	DOORNFONTEI	-24.33	29.08	1219	38	80	60.94	16	107
	58	ILLAWARR	-24.97	28.51	1062	33	105	53.799	21	116
	59	DE_KROON_-_IR	-25.67	27.83	1152	40.08	60	76.04	12	110
	60	IREN	-25.87	28.22	1448	30.82	135	55.336	27	111.1
	61	CHRISSIESMEER_-_PO	-26.28	30.21	1675	40.325	73	70	16	166.2
	62	DRIEFONTEI	-27.44	28	1626	37.5	85	58.77	17	100
	63	KOEBER	-28.51	28.53	1767	26	155	48	29	105
	64	WATERVAL_-_TN	-27.79	30.25	1190	38	93	64.8	19	111.2
Lowveld	65	TSHIPIS	-22.6	30.17	579	43.92	38	73.588	8	100
	66	ENTABENI_BO	-23	30.27	1376	66	136	137.614	27	360
	67	ZOMERKOMST-BO	-23.78	30.12	792	54.9	108	120.54	22	340
	68	LETABA_MOOIPLAA	-23.52	31.4	305	45.75	65	83.55	13	173.5
	69	MARIEPSKOP_-_BO	-24.58	30.87	914	55.85	111	130	24	386.5

Table 3: The average for each rainfall threshold 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	36.3	117	61.5	24	133.3
Western interior	30.0	50	52.5	11	101.9
South coast	32.3	100	63.7	20	165.7
Central interior	33.7	84	59.4	17	110.8
Transkei	41.5	141	74.7	29	220.7
Kwazulu Natal coast	43.8	150	93.6	30	295.6
North Eastern interior	35.5	98	61.0	20	115.8
Lowveld	53.3	92	109.1	19	272.0
South Africa (69 selected stations)	**36.4**	**99**	**66.5**	**20**	**155.1**
South Africa (698 stations)	**35.5**	**80**	**62.0**	**16**	**144.4**

Table 3 describes the average for each rainfall threshold calculated for each region based on the stations described in Table 2. It is then possible to compare the data represented by the stations from each region with the sample of 69 selected stations and the entire sample of 698 stations. This comparison provides an indication as to whether the stations chosen for each region are not subject to any bias selection decisions that could skew the results based on the rainfall data of this analysis. It is important to note that the objective in selecting stations for the study was to include stations that provided both a spatial representation and a representative rainfall profile particular to the region in which they occur.

Apart from the variation in these thresholds from the wetter South African climates in the eastern regions to the drier climates towards the western and interior, it is apparent from these calculated thresholds in Table 3 for each region that there are no obvious discrepancies amongst the selected stations rainfall data when compared to the sample from which they were selected. The end column of Table 3 identifies the maximum rainfall recorded based on the stations selected within each region. Because these figures are based on the data of the sample of stations (69 and 698) used in this study, this does not represent the maximum rainfall ever recorded within South Africa. Stations that may have recorded higher rainfall amounts may have been excluded from this study based on their data quality as described in Chapter 2. The higher number of occurrences of the 95th and 99th percentile rainfall events was anticipated for this study due to the known scarcity of extreme events. Thus the selection process sought to optimize this number by acquiring stations with a greater number of extreme events providing a higher degree of significance in the study, while the actual 95th and 99th percentile rainfall amounts remain very similar to that of the whole sample of 698 stations.

The 69 selected stations therefore portrayed extreme rainfall characteristics that were representative of the entire country of South Africa and more specifically of the 8 rainfall regions. These stations were then used to assess the synoptic drivers of extreme rainfall at a regional scale. In so doing extreme rainfall days were identified from each of the 69 stations and the corresponding synoptic data was extracted from the reanalysis data. This data was passed through the trained extreme rainfall SOM from Chapter Three (section 3.3.2) based on the driving synoptics of all 698 stations. Using the extreme rainfall records of the stations within each region a SOM map was then produced for each of the 8 regions in order to identify the regionally specific synoptic states associated with extreme rainfall.

4.3. Synoptic drivers of extreme rainfall in the 8 rainfall regions

The 95th and 99th percentile rainfall data were used to generate SOMs for each region such that the synoptic drivers of each percentile's rainfall in each region could be identified and contrasted. The analysis also includes a seasonal assessment for each region given the seasonal distribution of rainfall across South Africa. The section is structured such that there is a general description of the synoptic circulations presented by the SOM results for each of the eight regions as well as a description and brief discussion of the seasonal frequency mappings. Thereafter a summary of the results and a general discussion follows.

4.3.1. South Western Cape

The synoptic circulations associated with extreme rainfall identified by the 95th percentile SOM include mostly upper air mid-latitude troughs associated with meridional air flow (Figure 14). The surface level pressure SOM identified a number of synoptic states in which all nodes included a low pressure to the south of the country accompanied by nodes, towards the upper right of the array characterized by a strong high pressure system over the interior and eastern parts of the country while the nodes on the left side of the array are accompanied with signs of a linkage between low pressure troughs over the interior and mid-latitude troughs in the south.

The winter months of June, July and August (JJA) recorded the highest number of extreme rainfall occurrences with just fewer than 900 95^{th} percentile rainfall days within the 31 year study period followed by the autumn months of March, April and May (MAM) with just under 500 occurrences. 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 resulting in 56% of extreme rainfall days being associated with these 5 nodes. The synoptics of these nodes are very similar as they are all situated towards the upper right of the SOM array and thus characterized by the passage of mid-latitude cyclones to the south of the country with a strong high pressure system over the eastern half and interior of the country.

Although the least occurrence of extreme rainfall is attributed to the summer months of December, January and February (DJF), only 4 nodes on the left of the SOM characterize the majority of 95^{th} percentile rainfall (nodes 5, 9, 13, 17). The synoptics of these nodes consist of a low pressure over the interior of the country and a mid-latitude cyclone to the south. The mid-latitude cyclone is also evident in the upper atmosphere with meridional flow. The surface synoptic circulations of these nodes show evidence of a linkage between the sub-tropical regions and the mid-latitudes indicating the potential existence of tropical temperate troughs (TTTs). Tropical temperate troughs are a major contributor towards mean annual rainfall in South Africa and are more frequent during the warmer months from October to January (Jury and Pathack, 1993).

The extreme rainfall for the shoulder seasons is different to the winter months in which the majority of extreme rainfall is attributed to nodes mostly on the left side of the SOM array. While nodes 1, 5 and 9 are common in each season, nodes 5 and 2 account for 22% of extreme rainfall in the autumn months of MAM, which as mentioned above has the second highest season of extreme rainfall occurrences annually. Nodes 6 and 13 account for 27.7% of extreme rainfall during the spring months of September, October and November (SON). These nodes (with the exception of nodes 2 and 5) are characterized by a linkage between the mid-latitude low pressure systems and the sub-tropics over the interior of the country similar to the summer type extreme rainfall synoptics. These frequencies indicate a clear seasonal distinction between the synoptic patterns of extreme rainfall between the wetter winter months and the shoulder seasons together with the summer months for the South Western Cape region.

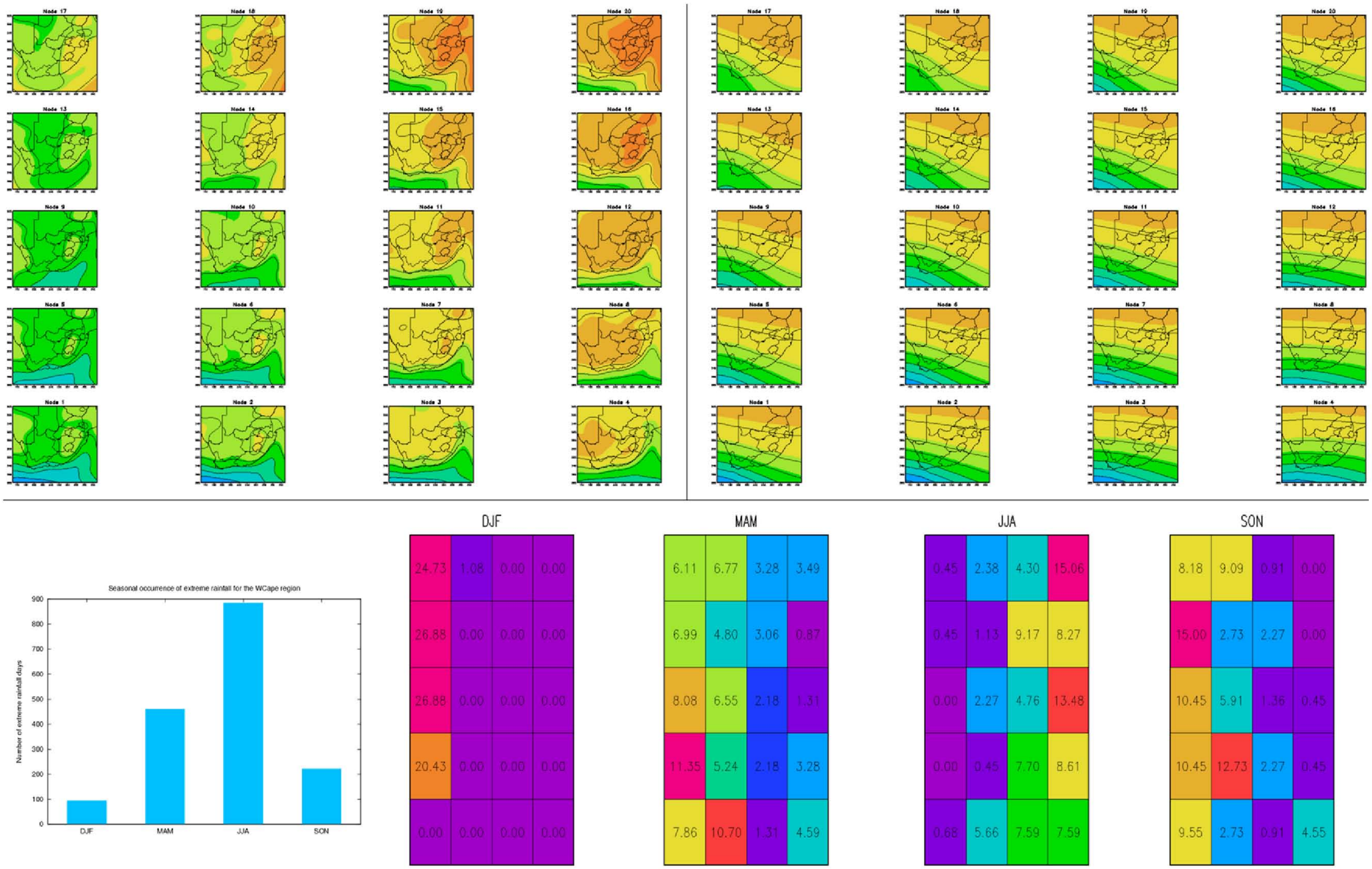

Figure 14: 95th percentile rainfall synoptic circulations for the South Western Cape region presented by a 20 node SOM map with MSLP and z500 mappings displayed in the top left and right respectively. The bottom left graph displays the seasonal distribution of extreme rainfall while to the right the frequency maps of each season are shown.

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 such that deeper troughs together with a more northerly extent occur in the upper air flow implying stronger mid-latitude cyclones as well as stronger high pressure systems and more pronounced linkages between the mid-latitudes and the sub-tropics are evident.

4.3.2. Southern Coast

The 95th and 99th percentile SOMs of the Southern coast region have characterized at the surface level synoptic circulations including ridging high pressure systems, clear linkages between low pressure troughs over the majority of the country and mid-latitude cyclones possibly forming tropical temperate troughs (Figure 15). Deep mid-latitude cyclones are identified in the upper air flow with some weak evidence of cut-off low pressure systems in the 99th percentile map.

The 95th percentile SOM has a relatively even seasonal distribution of the occurrences of extreme rainfall days between MAM, JJA and SON. SON seems to have only slightly more extreme rainfall days than MAM with both experiencing 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 four nodes account for 52% of extreme rainfall. Node 6 is characterized by a wide spread surface low pressure linkage across the majority of the country with signs of a surface high pressure system moving in behind from 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. These 4 nodes are accompanied with a mid-latitude trough in the upper air flow. 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.

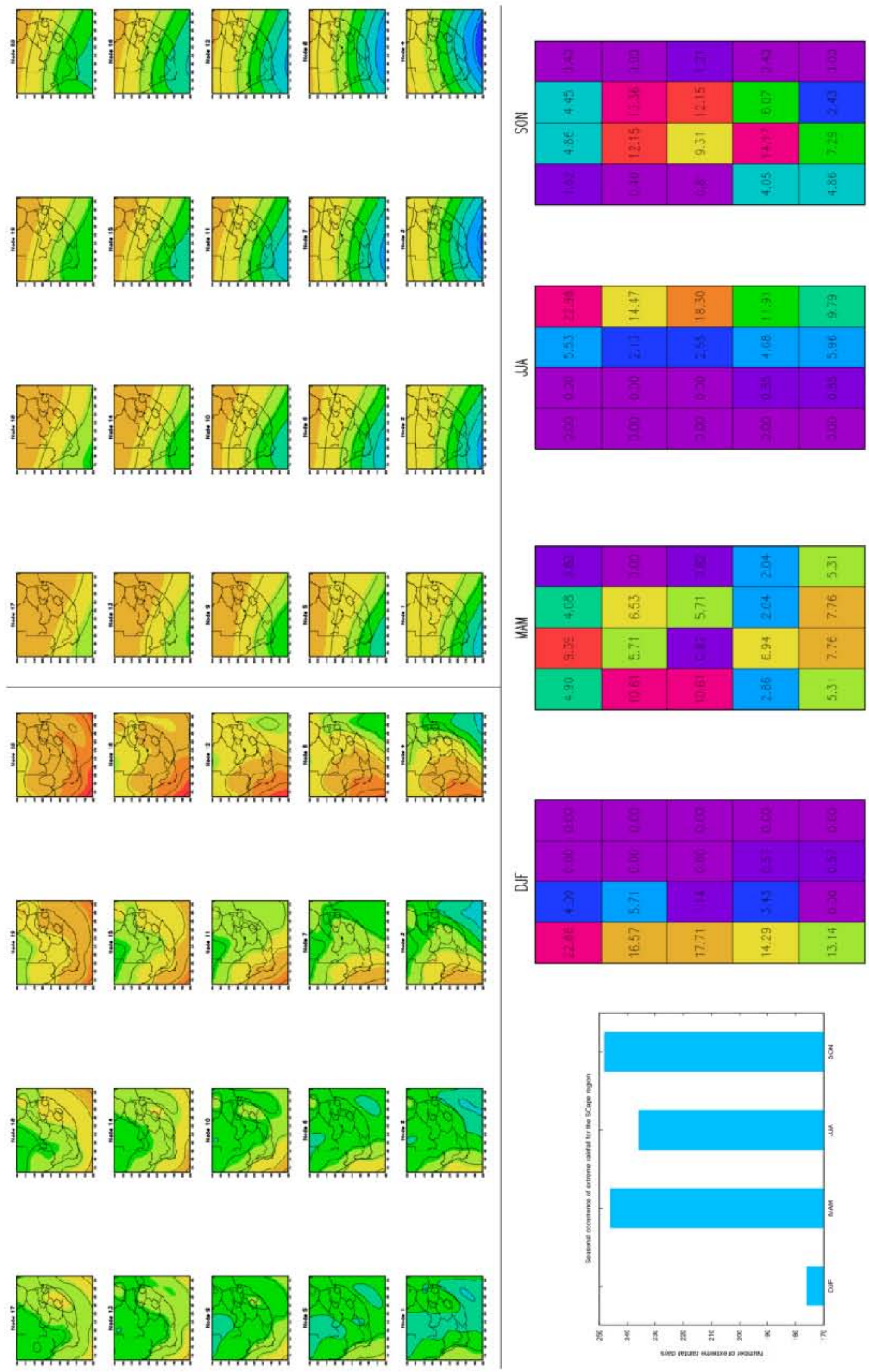

Figure 15: As for Figure 14 but for the Southern Coast region.

The majority of extreme rainfall during JJA is attributed to the nodes down the right side of the SOM array with node 20 experiencing 23% of extreme rainfall alone. These nodes are mostly characterized by strong surface ridging high pressure systems moving in behind upper air mid-latitude troughs. The differing synoptic circulations responsible for extreme rainfall in each season are evident by the frequency distribution of node mappings between the seasons. The summer months are predominantly mapped to the left of the SOM array and the winter months mapped to the right while the months of SON are mapped to the centre of the SOM. Similar to the South Western Cape region this SOM mapping pattern indicates the seasonal distinction between the circulations associated with extreme rainfall in the Southern coast region with the exception of MAM which is evenly mapped throughout the SOM array.

The 99th percentile SOM has a slightly different seasonal make-up of extreme rainfall with a greater 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 rainfall 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.

4.3.3. Transkei

The 95th and 99th percentile SOMs for the Transkei have identified nodes with surface troughs over the interior of the country and towards the top of the array nodes with strong high pressure systems to the south of the country (Figure 16). The upper air flow is characterized primarily by zonal air flow with the exception of the nodes on the left of the SOM array that provide evidence of mid-latitude troughs.

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 extreme rainfall during DJF is largely represented by 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 with weak signs of a high pressure system off the east coast. These synoptic circulations would result in the onshore flow of moisture from the warm sea surface temperatures (SSTs) of the Agulhas current into the region through which the interaction of the topography would provide a means for greater uplift ultimately driving rainfall in the region. 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. Having said this it is apparent the Transkei region experiences an obvious change in the seasonal rainfall distribution from the winter rainfall driven regions to the west described above (South-western Cape and Southern coast) towards a summer rainfall regime characteristic of the eastern and interior parts of the country.

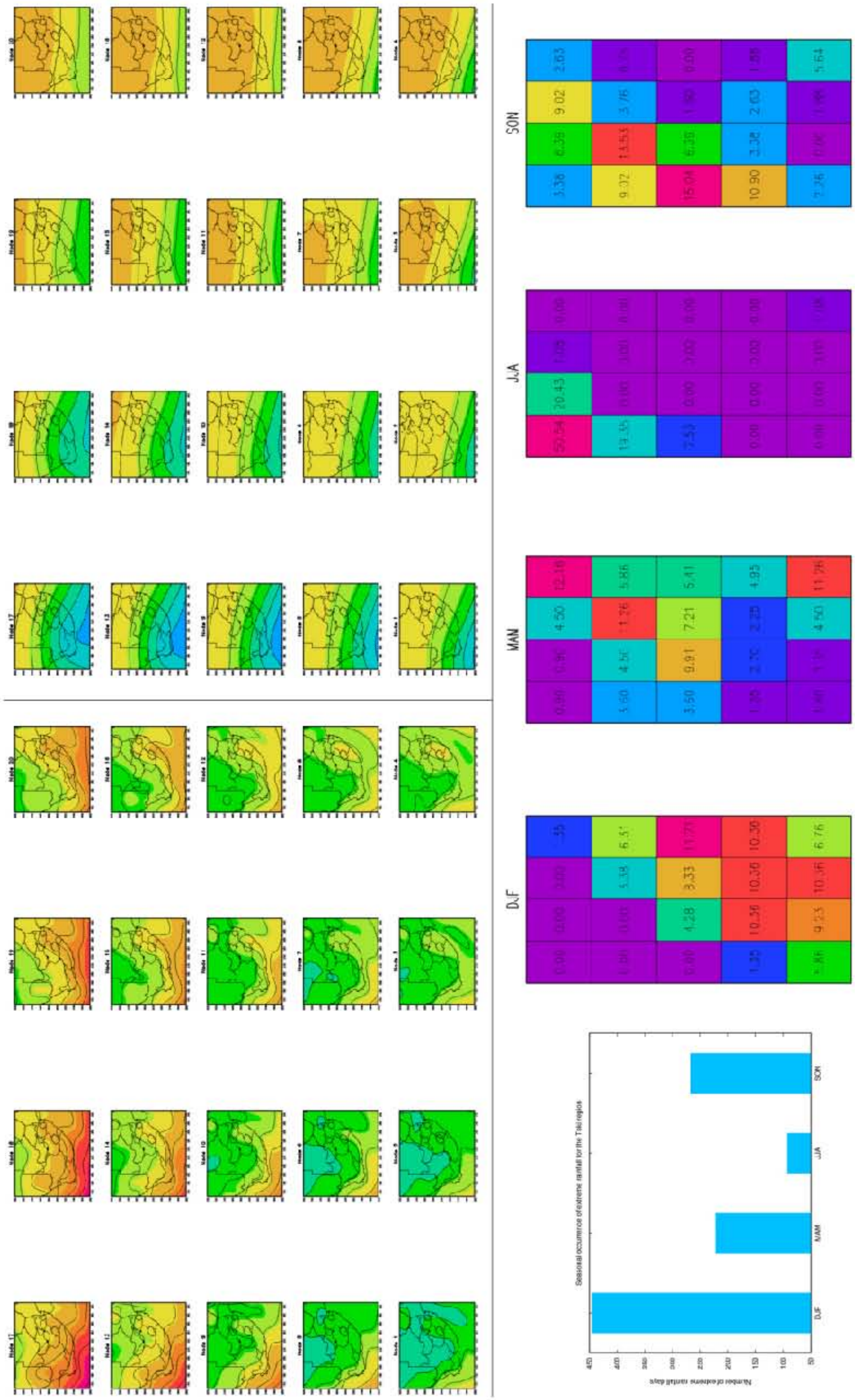

Figure 16: As for Figure 14 but for the Transkei region.

4.3.4. Kwazulu Natal 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 with a significant northward extent occurring in the nodes of the top left corner of the array (nodes 13, 17, 18) covering most of the country (Figure 17). Surface troughs over the interior and a variety of upper air circulations are also evident throughout the SOM. These upper air circulations range from meridional flow with relatively deep mid-latitude cyclones (nodes on the left) and some evidence of cut-off low pressure systems in the 99th percentile SOM to weak zonal upper air flow.

The KZN Coastal region has a similar seasonal distribution of extreme rainfall occurrences as the Transkei with the largest being attributed to the summer months of DJF followed by SON. The extreme rainfall for DJF is mostly represented by nodes 4, 7, 8 and 12 (56%) with node 4 acquiring the largest frequency of 16.74% in the 95th percentile SOM. These nodes are characterized by a surface trough extending from the sub-tropics covering the interior as well as most of the country. The zonal upper air flow indicates that the extreme rainfall is mostly driven by the surface synoptics. The SON month's extreme rainfall synoptics are represented largely by nodes 5, 9 and 10 (together accounting for 34%). These nodes have different characteristics from DJF with evidence of a stronger ridging high pressure system at the surface and a weak mid-latitude trough in the upper layers.

MAM and JJA experience the fewest number of extreme rainfall event annually. MAM has a very widespread mapping across the SOM indicating little significant synoptic circulations responsible for extreme rainfall in the season. Alternatively while JJA experienced less than 100 occurrences, these mapped mostly to the four nodes (7, 13, 17, 18) in the top left corner of the SOM that are characterized by the strong surface high pressure system over the south and south-east of the domain accompanied by a deep mid-latitude cyclone in the upper air.

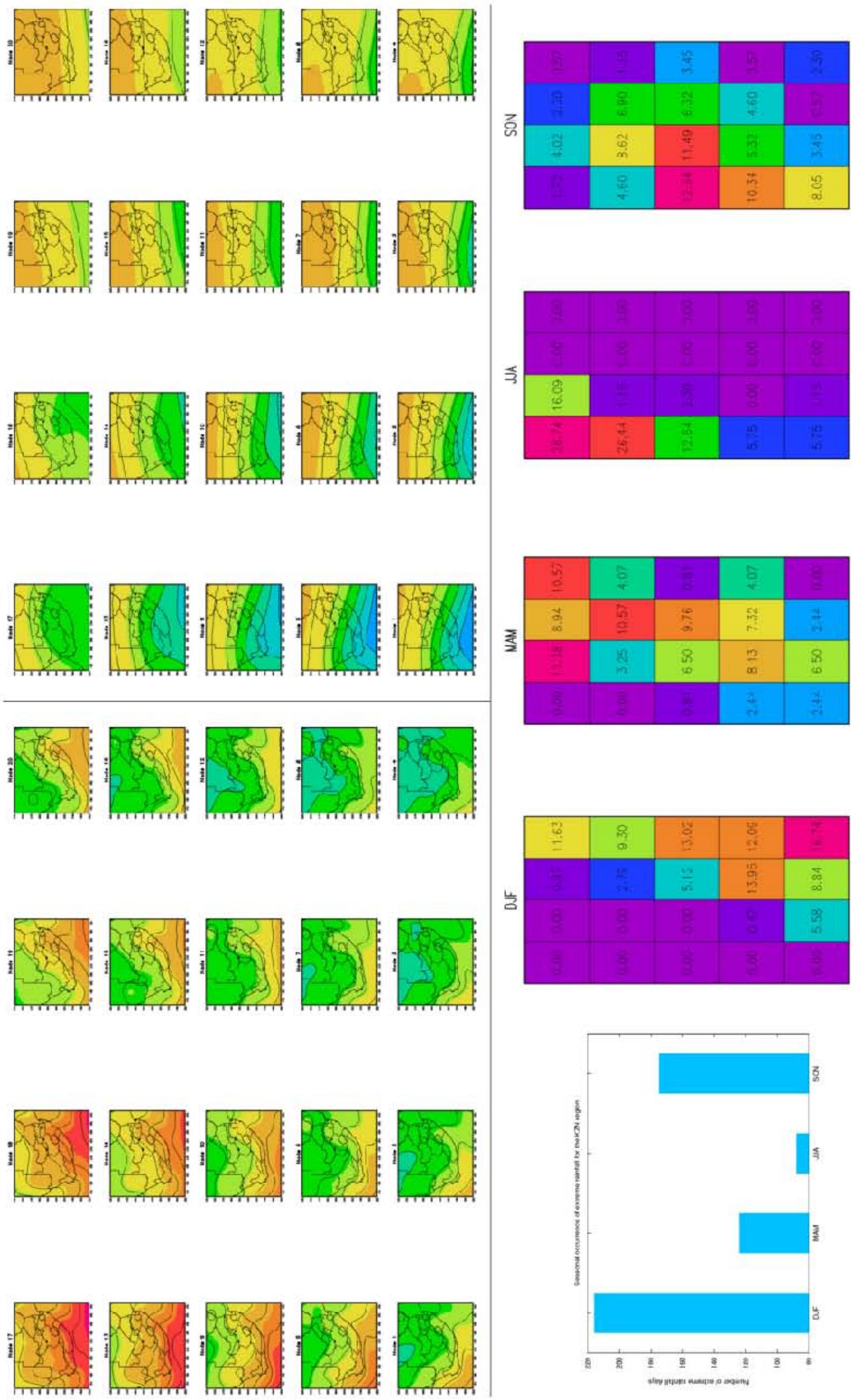

Figure 17: As for Figure 14 but for the KwaZulu Natal coast region.

The SOM representing rainfall from the 99th percentile events also expresses a difference in the synoptic drivers of extreme rainfall between DJF and SON. The summer months are mapped to the right of the array (including node 10) while SON experiences a widespread mapping throughout the array of nodes 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 layers. Node 17 has characteristics similar to the extreme rainfall of the winter months of the Transkei and Southern Coastal regions with a ridging high pressure system at the surface and a low pressure trough over the interior accompanied by a very deep mid-latitude cyclone in the upper air flow.

4.3.5. Lowveld

The extreme rainfall synoptics represented by the 95th and 99th percentile SOMs for the Lowveld are generally driven by the surface synoptics. These circulations are characterized by high pressure systems to the south of the country that often tend to extend northward along the east coast of South Africa as well as low pressure troughs over the central interior parts of the country (Figure 18).

The seasonal distribution of the extreme rainfall events follows the summer rainfall regime characteristic 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 low pressure trough over the interior and a high pressure system at the surface over the east coast of South Africa. Node 18 is characterized by a weaker surface low pressure and a stronger high pressure to the east. The positioning of this high pressure system towards the east of the country provides on-shore air flow from the warm ocean current resulting in a large influx of moisture inland that may interact with the surface low pressure providing the necessary uplift for precipitation.

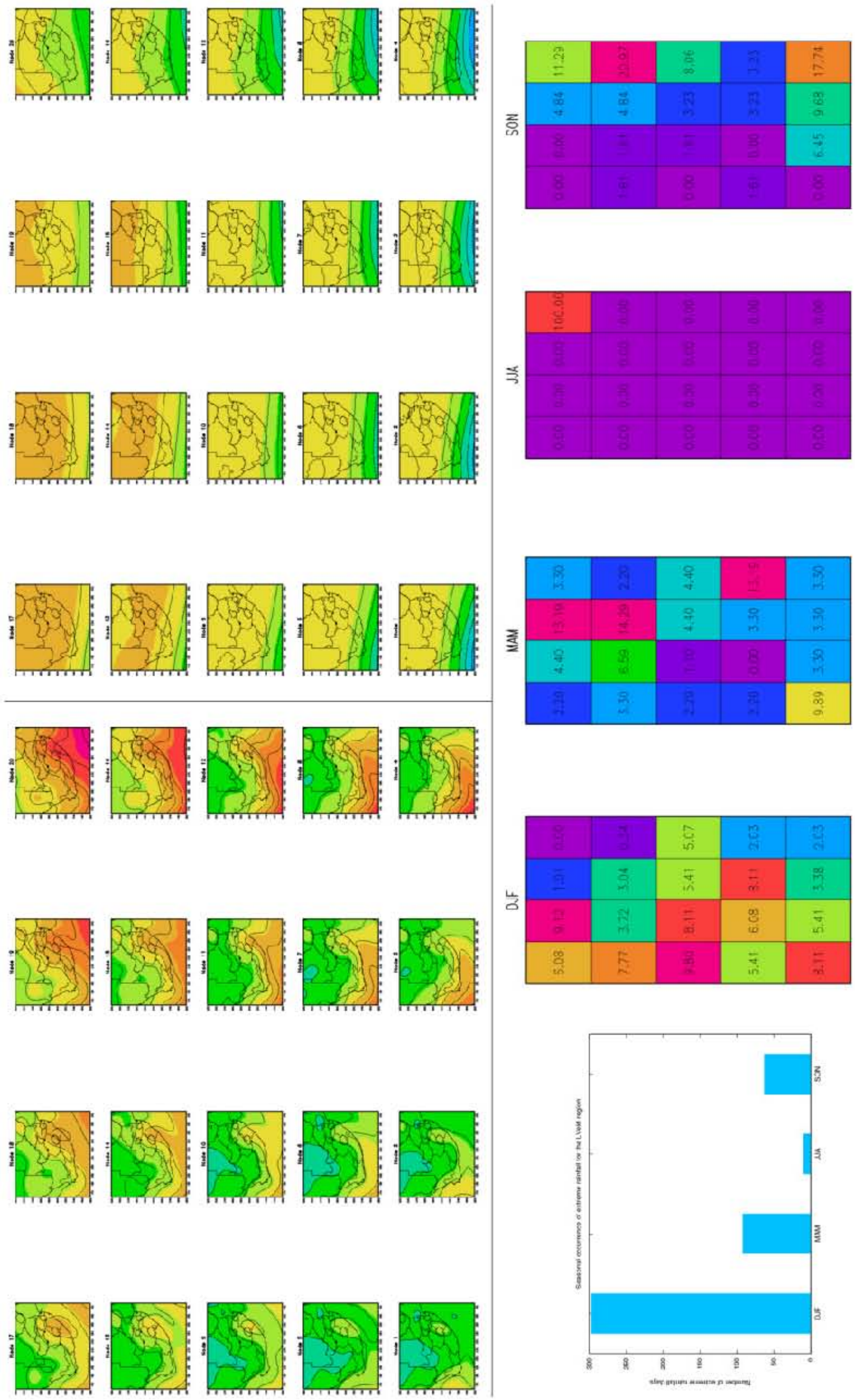

Figure 18: As for Figure 14 but for the Lowveld region.

With very few extreme rainfall occurrences during the winter months of JJA (less than 20), these are all be attributed to node 20. The synoptics of this node identify the strongest surface low pressure to the east of the country with a weak trough in the upper air. The shoulder seasons also experienced very few extreme rainfall events (compared to DJF) with MAM having a widespread distribution across the SOM map while SON mapped mostly to the nodes on the right of the array. These nodes are characterized by the surface high pressure system to the south and south-east of the country with a weak upper air trough.

The 99th percentile rainfall events has a different seasonal distribution to the 95th percentile in which SON experienced the highest number of extreme rainfall days (120) followed by DJF with 90 days. 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 a weaker high pressure over the east coast. Node 19, unlike nodes 1 and 9 does not exhibit a strong ridging high pressure, however, a southward extending low pressure exists over the interior and western half of the country with an upper air trough to the south west of the country. What is referred to here as a southward extending low pressure appears to be similar to that described by Tyson and Preston-Whyte (2000) as a subtropical low and a continental tropical low by Dyson and Van Heerden (2002). The summer month's nodes of the 99th percentile SOM are associated with an even further southward extending low pressure system and generally weaker high pressure systems over the east coast of the country at the surface. The high pressure systems featuring in the nodes of the SOM are important with regards to extreme rainfall in the Lowveld through the advection of moisture into the region from the Indian Ocean (Crimp and Mason, 1999).

4.3.6. North Eastern 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 are mostly characterized by high pressure systems at the surface level to the south and east of the country with southward extending low pressure troughs from the north covering the interior (Figure 19).

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 and the least number of occurrences attributed to JJA. The synoptic circulations associated with the 95th percentile DJF rainfall events are represented by the top part of the SOM array with nodes 19 and 20 accounting for 21% of events. These synoptic circulations are characterized by the MSLP SOM identifying a southward extending low pressure trough over the interior and a weak high pressure system over the eastern parts of the country. invading tropical weather systems have previously been associated with heavy rainfall events over the northeastern interior of South Africa such as February 2000 (Dyson and Van Heerden, 2001) Node 20 has slight evidence of a linkage between the sub-tropical low and the mid-latitudes. The combination of these continental tropical lows and intense overland heating in the summer months result in thermal convection in which together with moisture contribute towards a large amount of rainfall to this region (Tyson and Preston-Whyte, 2000). The frequency distribution of SON is distinctly different to DJF with most of the mapping attributed to nodes towards the bottom of the SOM. These nodes are characterized by a strong high pressure system across the south of the country and extending northward along the east coast at the surface. A weak mid-latitude trough is evident in the upper air of these nodes. MAM has a wide-spread distribution pattern across the SOM while 95% of the few extreme rainfall occurrences of JJA are attributed to nodes 1 and 2, which have a similar synoptic pattern described for SON.

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). Low pressure systems at the surface level over the interior become more pronounced during the summer months as a result of intense over land heating resulting in thermal convection (Tyson and Preston-Whyte, 2000). The second highest occurrence of extreme rainfall events in the 99th percentile SOM also is attributed to SON (40 days) followed by MAM with 20 days. In SON the mappings are to the left of the SOM array which feature a low pressure at the surface and a high pressure over the east coast similar to the nodes mapped to for DJF, however, an upper air mid-latitude trough is apparent in these nodes (especially nodes 13, 17 and 18). This may suggest that during the months of SON the upper air circulation is important in driving the extreme rainfall into the 99th percentile.

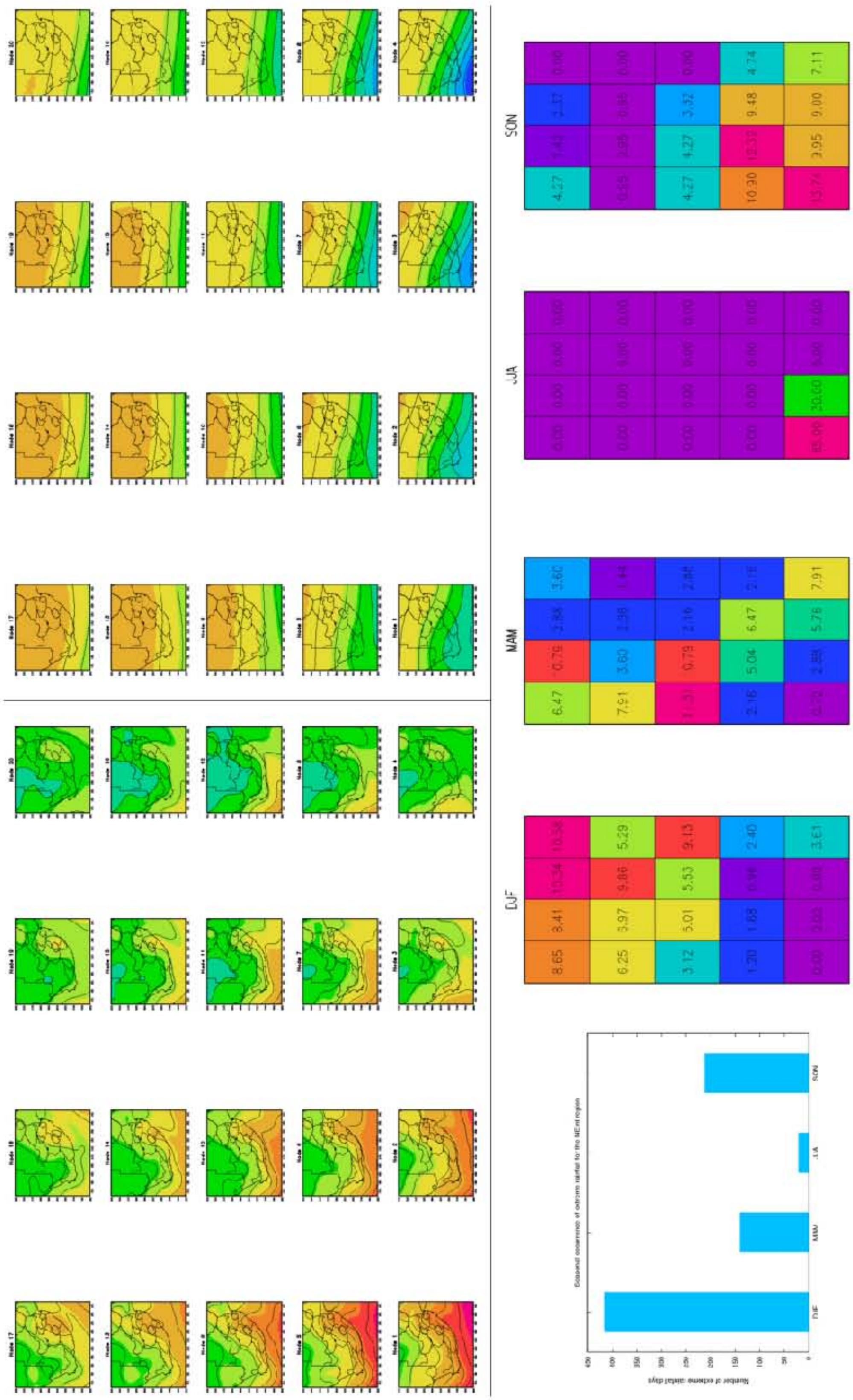

Figure 19: As for Figure 14 but for the North Eastern Interior region.

4.3.7. Central Interior

Over the Central Interior synoptic circulations identified by the SOM for the 95th and 99th percentile extreme rainfall events are similar to those identified for the North Eastern Interior in terms of a southward extending low over the interior and high pressure systems towards the eastern half of the country (Figure 20). A number of nodes for the Central Interior SOM have identified a linkage between the sub-tropics and the mid-latitudes indicative of tropical temperate troughs (Hart et. al., 2010). 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 experiencing the highest number of days (370) followed by the shoulder seasons each with a similar number (about 200) of extreme rainfall days. Nodes 1, 6 and 7 are the most significant nodes representing 34% of 95th percentile extreme rainfall events during DJF. The synoptic circulations of these nodes are characterized by a surface trough over the interior with node 1 showing signs of a linkage to the mid-latitudes, while nodes 6 and 7 do not show this linkage but have a stronger high pressure system over the eastern parts of the country. Similar to the North-eastern Interior, this high pressure together with the trough over the interior during the warmer summer months are responsible for driving the extreme rainfall to the region.

MAM shows a wide-spread mapping across the 95th percentile SOM array with node 12 experiencing the highest frequency (15.5%) in which a low pressure at the surface exists over the western parts of the country together with a relatively strong high pressure to the east. SON is mapped mostly to the top nodes of the SOM while JJA is mapped only to the top row of the SOM (nodes 17-20). These nodes are generally associated with synoptic circulations characterized by a strong surface high pressure over the eastern parts of the country together with deep mid-latitude troughs in the upper air. More specifically, node 17 shows subtle evidence of a surface low pressure linkage between the sub-tropics and the mid-latitudes situated over the Central Interior region, while node 20 shows a closed low pressure system in the upper atmosphere in the south western parts of the country.

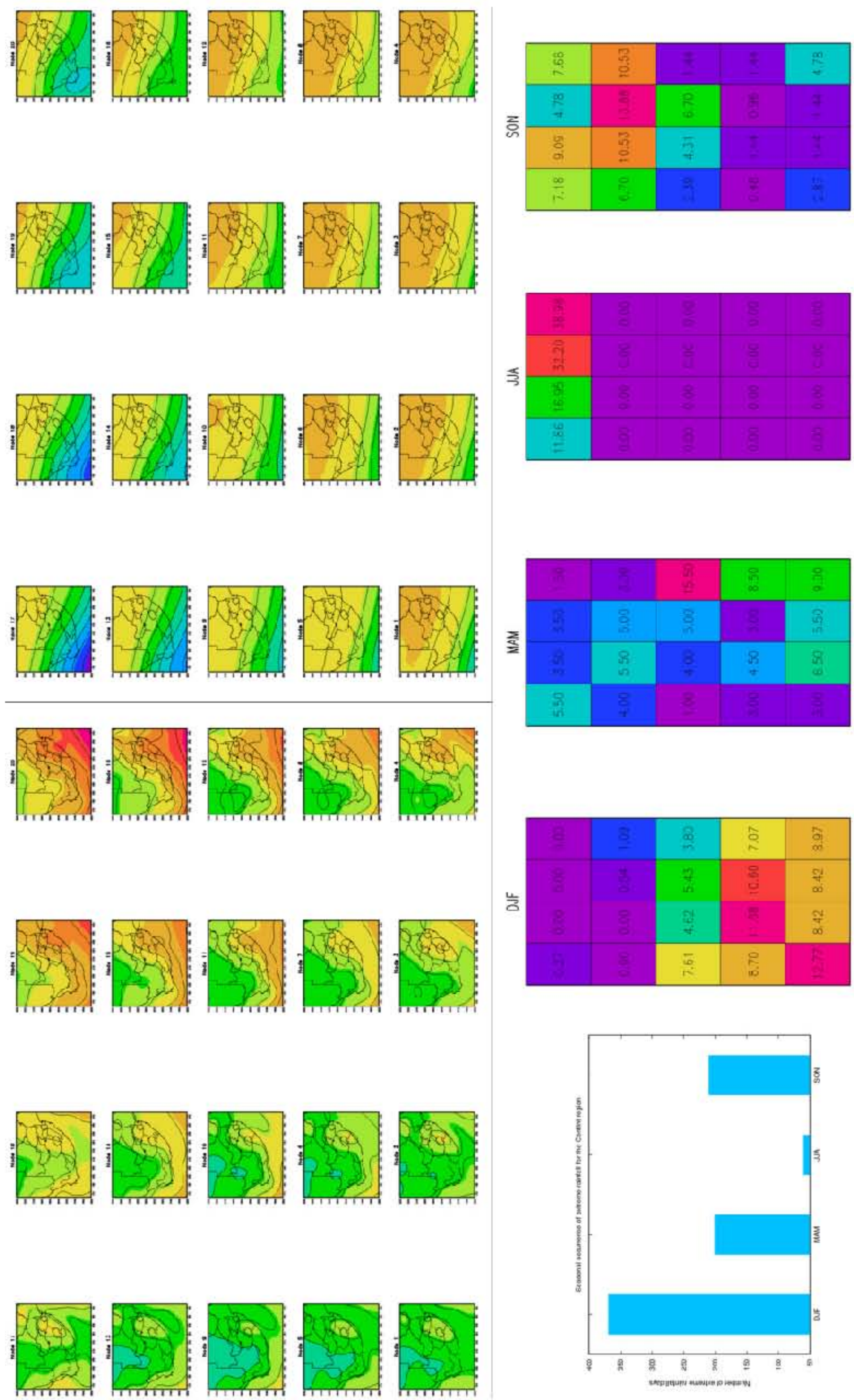

Figure 20: As in figure 14 but for the Central Interior region.

The 99th percentile extreme rainfall events are more common during DJF (66 days) followed by SON (34 days) and MAM (25 days). DJF mapped predominantly to the left of the SOM array with nodes 5 and 10 experiencing the highest frequency of 17% and 14% respectively. The synoptics of these nodes are characterized by a strong southward extending low 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. The 99th percentile rain days of SON were mapped to the right of the SOM where 17.65% were attributed to node 8. This extreme rainfall is associated with a surface low pressure trough extending over the Central Interior region and a possible linkage to a deep upper air mid-latitude cyclone.

4.3.8. 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 adjacent Central Interior, however, it is also situated west enough for its rainfall to be influenced by deep passing mid-latitude cyclones (Figure 21). 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), deep low pressure systems to the south of the country existing at the surface and upper air layers (nodes 13, 17 and 18 of the 99th percentile SOM) and linkages between the sub-tropics and 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 extreme rainfall 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 accounting for 39% of events and a further 33% contribution from nodes 5-7. These nodes are characterized by a surface low pressure trough over the interior with a linkage to the mid-latitudes (nodes 1 and 5) and a weak high pressure system towards the eastern parts of the country (nodes 2, 3, 7) without a link to the mid-latitudes. The upper atmosphere of these nodes is characterized by widely spaced isobars without much evidence of deep mid-latitude troughs.

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. With inspection of the other nodes at the bottom half of the SOM array it is evident that the upper atmosphere of these nodes provides little forcing towards the extreme rainfall in the region and therefore the surface synoptics would suggest a greater influence on driving extreme rainfall during DJF and MAM.

During SON, highest mapping frequencies occur around the middle of the SOM array (nodes 9-12, 14 and 15). Nodes 9 and 14 are characterized by a sub-tropical trough over the interior with a linkage to the mid-latitudes at the surface while nodes 10-12 and 15 show this sub-tropical low and a high pressure to the south and east of the country at varying intensities without the linkage. The upper atmosphere of all these nodes is characterized by a mid-latitude cyclone that is shown to be stronger in the nodes towards the left of the map and weaker towards the right. There is an obvious seasonal distinction that exists between winter and summer months of JJA and DJF respectively such that winter months of JJA are mapped to the top few nodes of the SOM where the deeper mid-latitude troughs and surface high pressures are evident throughout the domain.

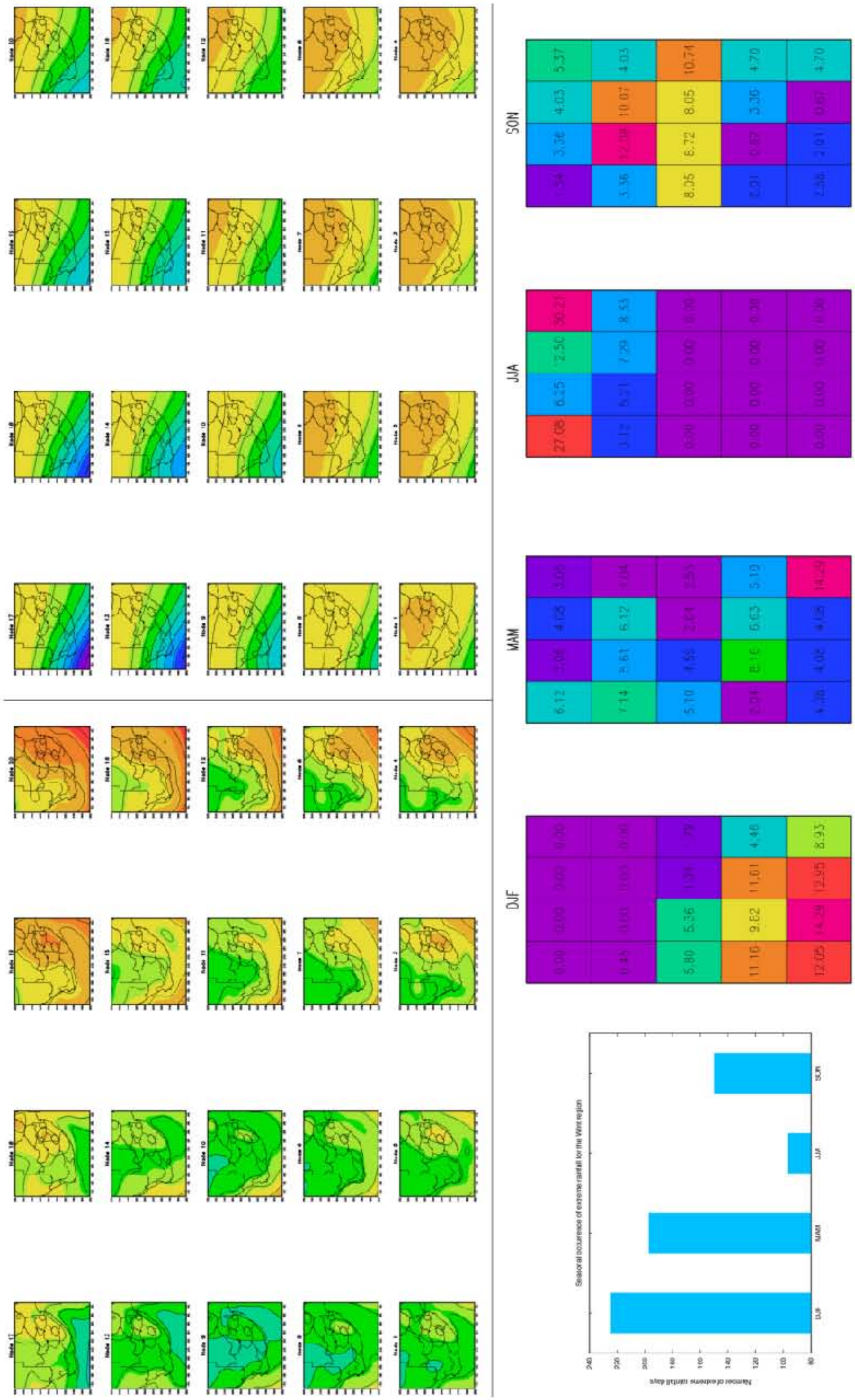

Figure 21: As in Figure 14 but for the Western Interior region.

The extreme rainfall events of the 99^{th} percentile SOM for DJF are largely attributed to node 20 with 27.5%. 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. This linkage will bring a large amount of moisture and unstable air into the region ultimately driving extreme rainfall. Interestingly the frequency distribution of MAM is also largely attributed to one node (node 4), which has a surface low pressure over the western interior and surface high pressure over the eastern parts of the country. The rest of the extreme rainfall occurrences in MAM are 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. With only 17 99^{th} percentile rainfall events occurring during JJA, only two nodes were the most significantly mapped to (node 1 and 17). The synoptic circulations of these two nodes are very different in which node 1 is characterized by a strong surface high pressure to the south of the country and very weak low pressure over the interior while node 17 has distinct frontal characteristics with the presence of a deep mid-latitude cyclone at the surface and upper air layers.

4.4. Regional extreme rainfall discussion

The SOMs identified the synoptic circulations of the regional rainfall patterns across the country highlighting the synoptics associated with extreme rainfall within each region. The seasonal distribution of extreme rainfall events was also identified through the seasonal SOM mappings and agrees with the seasonal rainfall patterns for each region. Summer rainfall regions experienced the highest number of extreme events and mapped to typical summer circulation patterns while winter rainfall regions mapped to winter synoptics. The most notable synoptic circulations associated with extreme rainfall events identified by the SOMs often involve an interaction between the more dominant circulation patterns.

4.4.1. Seasonal synoptic distribution and assessment

The synoptic circulations responsible for extreme rainfall during the summer months to the eastern parts of South Africa are often the driving force of moisture influxes. There are a number of sources for this moisture and each may vary in significance between extreme rainfall events. This was identified by Crimp and Mason (1999) in the analysis of an extreme rainfall event in

February 1996 in which the main source of moisture was identified to be the Indian Ocean to the east and southeast of South Africa and not the equatorial Indian Ocean. Landman *et. al.* (2005) also identified the south-western Indian Ocean as an important moisture source for summer rainfall over the eastern interior for assessing the predictability of extreme rainfall seasons over South Africa.

The sub-tropics have also been identified as a major contributing source of moisture from the north into the central parts of the country as the Inter Tropical Convergence Zone (ITCZ) shifts further southwards during the summer months (Tyson and Preston-Whyte, 2000). The synoptics described by the results obtained in this study for the summer rainfall regions appear to be consistent with these scenarios in which the southward extending low pressure from the tropics over the continent exists as well as a ridging high pressure extending across the oceans to the southeast of South Africa, thus contributing towards the influx of moisture from various sources.

These synoptic features are described in the MSLP SOM, while the z500 SOM shows very little evidence of clear extreme rainfall driving synoptics. Therefore the synoptic circulations characterizing the extreme rainfall for the summer rainfall regions appear to be dominated by the surface level SOM. However, Dyson and Van Heerden (2002) described that a 200 hPa high exists over southern Africa virtually every day, which seems to be evident in the z500 SOM, while tropical weather systems may exist. Therefore having this study based only on atmospheric pressure SOMs these tropical rainfall synoptics described by Dyson and Van Heerden (2002) may not be characterized. Hence Dyson and Van Heerden (2002) describe a method for identifying tropical weather systems in which the use of several other components such as the vertical profile of total static energy (TSE) and conditional stability are accounted for. This is similar for the central and interior regions of the country, however, in these scenarios evidence of a linkage between the sub-tropical low pressure troughs and the mid-latitudes is more pronounced. These synoptics coupled with a deep mid-latitude trough in the upper air flow are similar to those that form tropical temperate troughs (TTTs) described in detail by Hart et. al. (2010).

Synoptic circulations identified to have similar characteristics to TTTs have been described for a number of nodes in five regions (Central Interior, North Eastern Interior, Western Interior, South Western Cape and Southern Coastal regions). These nodes are mapped to most frequently during DJF followed by the shoulder seasons. TTTs are synoptic features that contribute between 30-60% towards mean annual rainfall depending on the location throughout the country (Hart et al., 2012). They are, however, difficult to identify in this study as they rely on a number of other factors such as cloud data to accurately quantify them. Having said this, 821 cloud band systems were identified by Hart et al. (2012) for the period 1979-2011 of which dates were supplied for the period 1979-1999 to assist with associating extreme rainfall days identified in this study with these TTT events. Therefore, dates that mapped to the SOM nodes with TTT characteristics were matched to the dates of the TTT days in order to associate the extreme rainfall from the nodes resembling TTTs for the five regions mentioned above with authentic TTTs. Very few TTTs result in extreme rainfall as described by Hart et al. (2012). A peak of 3-4 cloud bands occur per month during November-March and days of heavy rainfall (>50mm) contributed by TTT systems have a mean value below 0.5 days per month (Hart et al., 2012).

Nodes 1, 5 and 17 of the Central Interior region display TTT characteristics (Figure 20). During DJF 22% of the 95th percentile rainfall events were attributed to these three nodes. MAM and SON experienced less 95th percentile rainfall from these nodes with only 11.5% and 10.5% respectively. The 21 year period from 1979 to 1999 yielded 76 days that mapped to these three nodes from which only 11 were associated with TTT days. Node 1 matched to six days, node 5 to three days and node 17 matched to two days. The North Eastern Interior identified only two nodes in the SOM (nodes 4 and 20, Figure 19) with TTT synoptics. During DJF 14% of the 95th percentile rainfall events were attributed to these two nodes, while 11.5% and 7% was attributed to these nodes during MAM and SON respectively. There were 63 extreme rainfall days mapped to these two nodes during the 21 year period from which 14 were associated with TTT days. Eleven of these 14 days were associated with node 4 while only three were associated with node 20. Four nodes of the Western Interior SOM (nodes 1, 5, 9 and 13, Figure 21) identified TTT characteristics. During DJF, 29% of the 95th percentile rainfall events mapped to these nodes, 18% during MAM and 16% during SON. A total of 82 extreme rainfall days were associated with these four nodes from which 21 days matched up to TTT days with node 9 recording the highest portion of nine days. The South Western Cape identified 74% of DJF 95th percentile rainfall events to be associated with nodes 5, 9 and 13 (Figure 14), which display TTT synoptics. MAM identified 34% and SON identified 45% of 95th percentile rainfall events from these three nodes. Confirming this relatively high mapping frequency to these three nodes is a large total of 199 days that mapped to them throughout the 21 year period. Of these 199 days, 50 were associated with TTT days. Node 5 experienced the largest portion with 24 days followed by node 9 with 20 days, while node 13 was only associated with 6 TTT days. Nodes 1, 2, 5 and 6 of the Southern Coast region display a strong low pressure linkage between the sub-tropics and the mid-latitudes resembling TTT synoptics (Figure 15). Although there were very few 95th percentile rainfall events during DJF compared to the other three seasons shown by the table in the bottom left corner of Figure 15, 31% of the events were mapped to these 4 nodes. MAM identified 23% to be associated with these nodes, while SON identified 30%. There was a total of 127 days associated with these four nodes from which 30 matched up to TTT days. Node 1 experienced 50% of these days with a total number of 15 days being associated with TTT days.

The seasonal pattern of TTTs were characterized by the mapping frequencies of the nodes that resembled synoptic circulations similar to TTTs for the respective regions above with DJF experiencing the highest proportion followed by either MAM or SON. However, a small proportion of the days that mapped to these nodes were associated with known TTT days. Apart from the Central Interior an average of 75% of the days that mapped to the respective TTT-like nodes for the North Eastern Interior, Western Interior, South Western Cape and Southern Coastal regions were not associated with known TTT days. Therefore it is difficult to infer that the extreme rainfall associated with these synoptic linkages between the sub-tropics and mid-latitudes identified by various nodes of the SOMs in each of the 5 regions described above are as a result of TTTs. Subsequently it was noted that on many occasions extreme rainfall was recorded the day before a TTT day occurred.

During the winter months (JJA) extreme rainfall occurred predominantly in the South Western Cape in which the driving synoptics were identified as the passage of low pressure systems across the mid-latitudes bringing frontal rainfall to the region. It is also noted that the synoptic conditions associated with extreme rainfall during the winter months are very similar for the coastal regions from the Southern Coast, Transkei and KZN Coast and are characterized by ridging high pressure systems and sub-tropical troughs at the surface level with deep mid-latitude cyclones in the upper air flow. Again the interaction between these synoptic states is responsible for the extreme rainfall in which the surface high pressure encourages convergence and advection of moisture inland from the Agulhas Current. The topography of these regions also facilitates further uplift feeding this moist air into the unstable upper air layers resulting in the observed extreme rainfall. There is also evidence of synoptic circulations resembling cut-off low pressure systems in nodes 1 and 2 over the KZN coastal regions in the 99th percentile SOM (Figure 22). These systems are however, according to Singleton and Reason (2007), not associated with true cut-off low pressure systems that are known to bring extreme rainfall to the southern coastal and interior regions of the country.

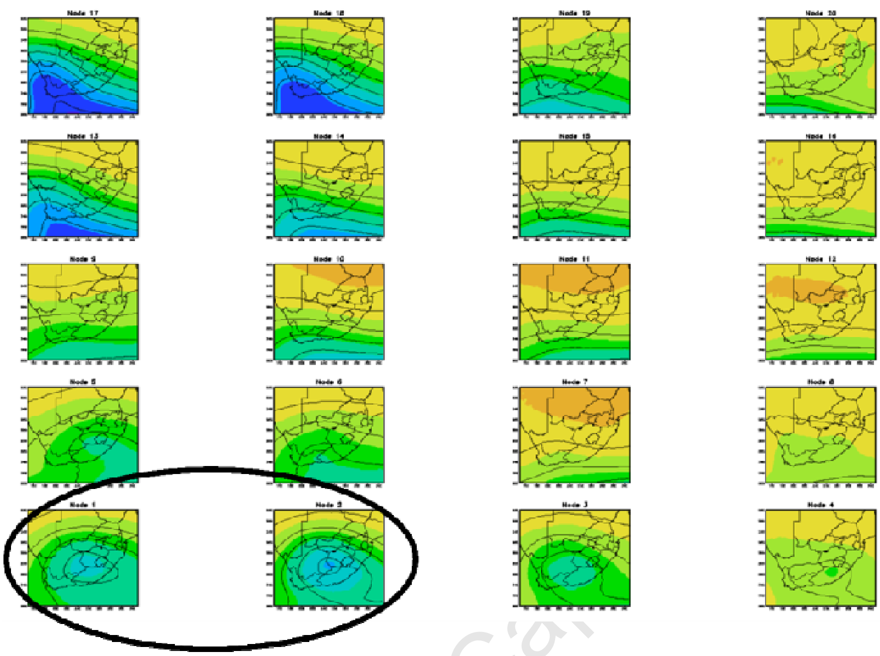

Figure 22: 99th percentile SOM for KZN coastal region displaying the upper air closed low pressure system identified by nodes 1 and 2 (circled) in the z500 layer.

There are a significant number of extreme rainfall events evident during the shoulder seasons of MAM and SON throughout all the regions. The frequency of extreme rainfall events of these months show that the summer rainfall driven eastern half of the country as well as the Southern Coastal region experiences a higher number of extreme rainfall events during SON compared to 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. This higher frequency of extreme rainfall events during MAM over the South Western Cape and Western Interior may be attributed to the peak in the number of cut-off low pressure systems observed over these regions during this time of year (Singleton and Reason, 2007). However, these cut-off lows have not been identified by the SOMs in these regions.

4.4.2. Characterization of cut-off low pressure systems

Although the SOMs have identified the rainfall regions and the synoptics associated with extreme rainfall events, there has been limitations in characterizing some extreme rainfall features, for example the tropical weathers systems impacting the northeastern parts of South Africa identified by Dyson and Van Heerden (2002). However, this is as a result of other components in addition to the MSLP and 500 hPa levels adopted in this study, while cut-off low's are also a known extreme rainfall causing feature impacting the South Western Cape, Southern Coast region and southern parts of the Western Interior region that was poorly characterized by the z500 SOM (Figure 23). The closest synoptic pattern resembling that of a cut-off low for the Southern Coastal region is identified in node 16 of the z500 99th percentile SOM (Figure 23, B2) and similarly in nodes 1 and 2 of the z500 99th percentile SOM of the KZN Coastal region (Figure 22). As mentioned above nodes 1 and 2 of the KZN Coastal region SOM cannot be associated with cut-off low causing extreme rainfall.

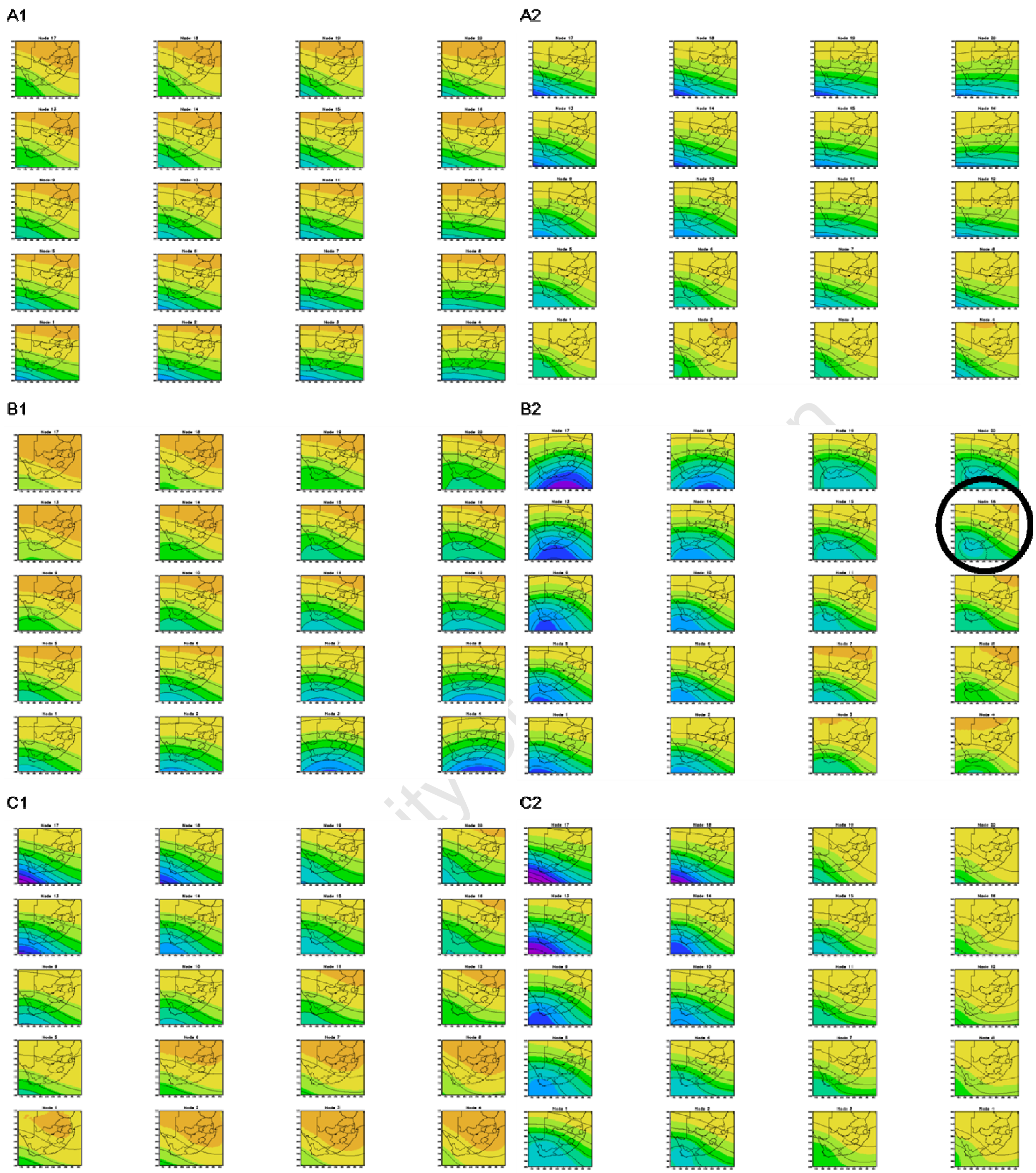

Figure 23: 95th and 99th percentile z500 SOMs for the South Western Cape (A1 and A2 respectively), Southern Coast (B1 and B2 respectively) and Western Interior (C1 and C2 respectively) regions. The closest characterization of cut-off low synoptics is shown by the circled node 16 of the 99th percentile z500 SOM of the Southern Coastal region.

An assessment of cut-off low events was carried out based on the literature of known occurrences. These cut-off low events included 5 separate occasions (with the exception of the event that occurred on 22-24 August 2006, which was only observed as a 95th/99th percentile event by station 22 in the Western Interior). The dates of these events include:

- 23-25 January 1981
- 23-25 March 2003
- 31 July-3 August 2006
- 21-23 November 2007
- 11-13 November 2008

The dates of these events were matched to the rainfall observations recorded at various stations throughout the 3 rainfall regions (South Western Cape; Southern Coast and Western Interior) known to have been affected by these particular events. Table 4 lists these events (including the event of 22-24 August 2006) and the amount of rainfall observed at the particular stations on each day with the associated node of the respective SOM (Figure 23). Although the events are shown to occur over the period of a few days, most of the scenarios only experienced 95th/99th percentile rainfall on either one, two and seldom all three days. However, the relationship between the cut-off low pressure systems assessed and the observed extreme rainfall that occurred at the various stations throughout these regions was consistent. Unfortunately, the dates on which the extreme rainfall associated with these events was observed mapped to nodes of the SOMs for the respective regions that do not exhibit cut-off low synoptic circulations (i.e. node 16 for the Southern Coastal region 99th percentile SOM).

Over the Western Interior region nodes associated with the cut-off low events were nodes 1-3, 5-7, 10 and 14, while the South Western Cape region identified nodes 1, 2 and 5 to be associated with cut-off low events. The Southern coastal region experienced cut-off low events that were mapped to nodes 2, 3, 6, 7, 9, 12 and 13. Therefore none of the cut-off low events assessed mapped to node 16 that exhibits synoptic circulations most similar to that of a cut-off low mentioned above for the Southern Coastal region.

Table 4: List of the cut-off low pressure events assessed that resulted in extreme rainfall observed in the stations of the South Western Cape, Western Interior and Southern Coastal regions. The amount of rainfall on each date is provided and the node to which these dates were mapped to in their respective SOM. Each event occurring throughout the regions is also highlighted the same colour.

Region	Year	Month	Day	rainfall (mm)	95th %ile SOM node	99th %ile SOM node	rainfall (mm)	95th %ile SOM node	99th %ile SOM node	rainfall (mm)	95th %ile SOM node	99th %ile SOM node	rainfall (mm)	95th %ile SOM node	99th %ile SOM node	rainfall (mm)	95th %ile SOM node	99th %ile SOM node	rainfall (mm)	95th %ile SOM node	99th %ile SOM node
Western Interior	Station Lable:				22			23			24										
	1981	1	23							29	9	NA									
	1981	1	24	91.8	10	10															
	1981	1	25	68.3	12	3	45.2	12	NA												
	2003	3	23	68.7	9	14	54	9	14												
	2006	7	31	71	15	5															
	2006	8	22	76.2	16	1															
	2006	8	23	86.5	16	2															
	2006	8	24	64.8	15	5															
	2007	11	21	99.5	10	10															
	2008	11	11	127	10	10															
	2008	11	12	149.2	11	6															
	2008	11	13	116	11	7															
Southern Coast	Station Lable:				27			28			29			30			31				
	1981	1	24	52	9	7	53	9	7	82	9	7									
	1981	1	25													115	18	7			
	2003	3	23	70	6	2															
	2003	3	24										120	9	3	110	9	3			
	2003	3	25													114.6	9	3			
	2006	8	1	66.5	11	9	88.6	11	9	85	11	9									
	2006	8	2										163	3	13	166.6	3	13			
	2007	11	21				64.5	10	6	212	10	6									
	2007	11	22	46.5	10	6				71	10	6	238	10	6						
	2007	11	23													132	10	7			
	2008	11	12	51	14	12	69.5	14	12												
	2008	11	13	97.5	14	12	69	14	12												
South Western Cape	Station Lable:				3			4			6			7			8			10	
	1981	1	24							40	13	NA									
	1981	1	25	35.5	17		82	17	2				121.5	17	NA	96.5	17	2	26	17	NA
	2003	3	23				40.1	13	NA	100	13	5				96.5	13	5			
	2006	8	3				34.5	4	NA												
	2007	11	21				67	13	1	61	13	1	160.1	13	1						
	2008	11	11				48	13	NA	55	13	1				71	13	NA	40	13	NA
	2008	11	12							35	17	NA	86.5	17	NA	160	17	2			

The regional SOM analysis was carried out in order to assess the extreme rainfall driving synoptic circulations of each rainfall regime in South Africa in order to reduce the degree of generalization of synoptic circulations that would have occurred in the country-wide SOM analysis of Chapter Three. Therefore it was envisaged that the regional SOM analysis would assist in identifying synoptic circulations such as cut-off low pressure systems due to their significance in driving extreme rainfall in specific regions of South Africa. However, it is apparent that this was not achieved in the assessment and may be due to a number of reasons. Firstly, the extreme rainfall regimes are possibly different to the general rainfall regimes that were used to define the rainfall regions of the country used in this study. This is evident by observing the occurrence of specific cut-off low events that are spatially divided between the three regions of the South Western Cape, Western interior and the Southern coastal region (Table 4). In particular, it is obvious that station 22, which is situated in the Western Interior region provides evidence of observing the events similar to those observed in the 2 other regions suggesting that this station ought to occur within these regions in assessing extreme rainfall from cut-off low pressure systems. This is reiterated by the geographic position of station 22 in relation to these 3 regions (Figure 13). This proposes that extreme rainfall circulation patterns may be better defined using a spatial division based on observed extreme rainfall events themselves instead of the events being split up amongst different regions. It may then be possible to map out extreme rainfall specific regions of South Africa ultimately providing a more precise description of the extreme rainfall driving synoptics for a particular region. Secondly, extreme rainfall may occur and thus only be observed in the station data records the day before or the day after the most clearly visible cut-off low pressure synoptics form. This SOM analysis would therefore miss these events due to the synoptic circulations identified by the SOM being derived from the reanalysis data based on the observed extreme rainfall events in the station data.

4.5. Summary

The regional assessment of extreme rainfall was presented in this chapter in which specific synoptic circulations were associated with extreme rainfall in particular seasons. A selection of 69 stations was selected according to criteria including data quality, spatial representation and data representativeness. Observed rainfall data from these stations were spatially divided between 8 homogeneous rainfall regimes for South Africa derived by Landman et al. (2001) in order to represent the extreme rainfall within each region from which the synoptic drivers were identified using SOMs. Table 5 provides a summary of the synoptic circulations driving extreme rainfall in the peak seasons of each region.

Table 5: Summary table of the synoptic drivers of extreme rainfall for each region and their peak seasons.

REGION	PEAK SEASON	SYNOPTIC DESCRIPTION
South Western Cape	JJA	Low pressure systems to the SW of country at the surface with deep mid-latitude trough in upper air characterizing the passage of mid-latitude cyclones. Strong high pressure system over interior and eastern half of country at surface
	MAM	Linkage between mid-latitude low pressure and sub-tropics at the surface with a deep mid-latitude trough in the upper air
Southern coast	SON/MAM	Surface sub-tropical troughs with a ridging high pressure to the SW of country and some evidence of low pressure linkage between the sub-tropics and the mid-latitudes. Deep mid-latitude trough in the upper air
	JJA	Strong surface ridging high pressure system to the SW following a mid-latitude cyclone
Transkei	DJF	Surface sub-tropical trough over interior of country and weak high pressure off east coast interacting with warm Agulhas current adverting warm moist air onshore into the region
	SON	Strong ridging high pressure at the surface following a mid-latitude trough in the upper air
KZN coast	DJF	Widespread surface sub-tropical low pressure over majority of country with weak high pressure to the south
	SON	Strong ridging high pressure system at the surface with a mid-latitude trough to the south of country in the upper air
Lowveld	DJF	Driven mainly by a southward extending low pressure trough over the interior of country with high pressure system over east coast
North Eastern Interior	DJF	Driven mainly by a southward extending low pressure trough over the interior of country with thermal lows and a high pressure system over the east coast
	SON	Weaker surface low pressure over the interior with strong high pressure across the south of the country extending northward along east coast with mid-latitude trough in upper air indicating an interaction between the upper and lower atmosphere in driving extreme rainfall
Central Interior	DJF	Driven mainly by a southward extending low pressure trough covering majority of interior regions with signs of a linkage to the mid-latitudes and a high pressure over the east coast
	SON	Greater interaction between the upper and lower atmosphere with strong high pressure over the south eastern regions at the surface and deep mid-latitude trough in the upper layers
	MAM	Synoptic circulations spread between those representing DJF and MAM for the region
Western Interior	DJF	Very similar to Central Interior synoptic circulations characterized by a low pressure sub-tropical trough covering majority of the region with signs of a linkage to the mid-latitudes and a weak high pressure over the east coast, however, 99^{th} percentile rainfall shows signs of interactions with upper air mid-latitude troughs
	MAM	Mixture of synoptic patterns largely similar to DJF in some scenarios, however, to a lesser extent coupled with a stronger high pressure over east coast

With the exception of the South Western Cape and Southern Coast regions it is apparent that summer (DJF) recorded the highest number of extreme rainfall events in the remaining 6 regions. It is generally observed that the interior regions (Lowveld, North Eastern Interior, Central Interior, and Western Interior) as well as the KZN coastal region are predominantly influenced by southward extending tropical low pressure systems and high pressure systems over the Indian Ocean during the core summer rainfall months.

The South Western Cape experienced the highest number of extreme rainfall events during winter (JJA) and was associated with the passage of mid-latitude cyclones evident at the surface and upper atmosphere with the 99th percentile rainfall experiencing more intense deeper systems. The frontal dynamics of these mid-latitude cyclones are often the cause of extreme rainfall to the South Western Cape region. The Southern Coast region also experienced a high number of extreme rainfall during winter as it is also affected by the passage of mid-latitude cyclones and the associated cold fronts, however, it also experiences a high number of extreme rainfall events in the shoulder seasons of MAM and SON in which a surface ridging high pressure is a prominent feature. The interacting of this ridging high pressure with the topography of the region drives extreme rainfall similar to the Transkei region.

The extreme rainfall experience during the shoulder seasons of South Western Cape and Southern Coast regions is often associated with a linkage between the sub-tropics and the mid-latitudes. This linkage is also observed to be associated with extreme rainfall in the Western and Central Interior regions, though during their core summer rainfall season. The scope of this study does not include factors necessary for attributing these low pressure linkages to tropical temperate troughs, however, a number of TTT events that resulted in extreme rainfall were mapped to some of these nodes in the respective regions. Circulations characteristic of cut-off low pressure systems were not identified for the regions that are known to experience extreme rainfall as a result of these systems. The spatial boundaries to which this study was based is believed to be the limiting factor to this issue as cut-off low's are likely to impact upon a region that may extend across the regional boundaries in this study and therefore these specific synoptic patterns would be filtered out by the more general circulation patterns, hence an event based assessment would be more likely to identify these features.

Chapter Five: Trends in extreme rainfall

5.1. Introduction

The destructive nature extreme rainfall events inflict upon society emphasizes the importance of understanding their characteristics and trends to assist in formulating adaption and coping strategies. With an understanding of the driving synoptics of extreme rainfall events established in previous chapters this chapter addresses the trends associated with extreme precipitation. The inconsistent nature of extreme rainfall events does, however, require a longer study period in order to thoroughly assess trends and surmise statistically defensible future projections. Hence the 31 year period of 1979 to 2009 used in this study is limiting in this regard due to the availability of adequate quality reanalysis data necessary for the SOM analysis. Reanalysis data prior to 1979 (the advent of the satellite observation era) has been shown to be problematic (Kistler et al., 2001; Tennant, 2004), which unfortunately restricts the synoptic analysis to this period. Trends in the station data records were related to trends in the frequency of occurrence of synoptic circulations identified by the SOM from Chapter Three in order to determine whether the trends in the extreme rainfall events identified in the station records were reflected in the synoptic circulation trends. Additionally a seasonal assessment of regional changes was carried out to identify any shifts in the synoptic drivers of extreme rainfall.

5.2. Regional trends in the station data

The regional trends in extreme rainfall are investigated using 10 of the RClimDex extreme climate indices specific to rainfall (Chapter Two, Table 1). These indices are calculated from daily station data in which each of the 69 stations within each rainfall region of South Africa were individually assessed and their resulting trends analyzed. The resulting trends are presented for each of the 8 South African rainfall regions addressed in this study. Stations are referred to using their numbered labels with reference to Table 2 and Figure 13 of Chapter Four (reproduced below for convenience). Identified trends were analyzed in conjunction with neighboring stations in order to assess whether they may reflect a change for particular areas.

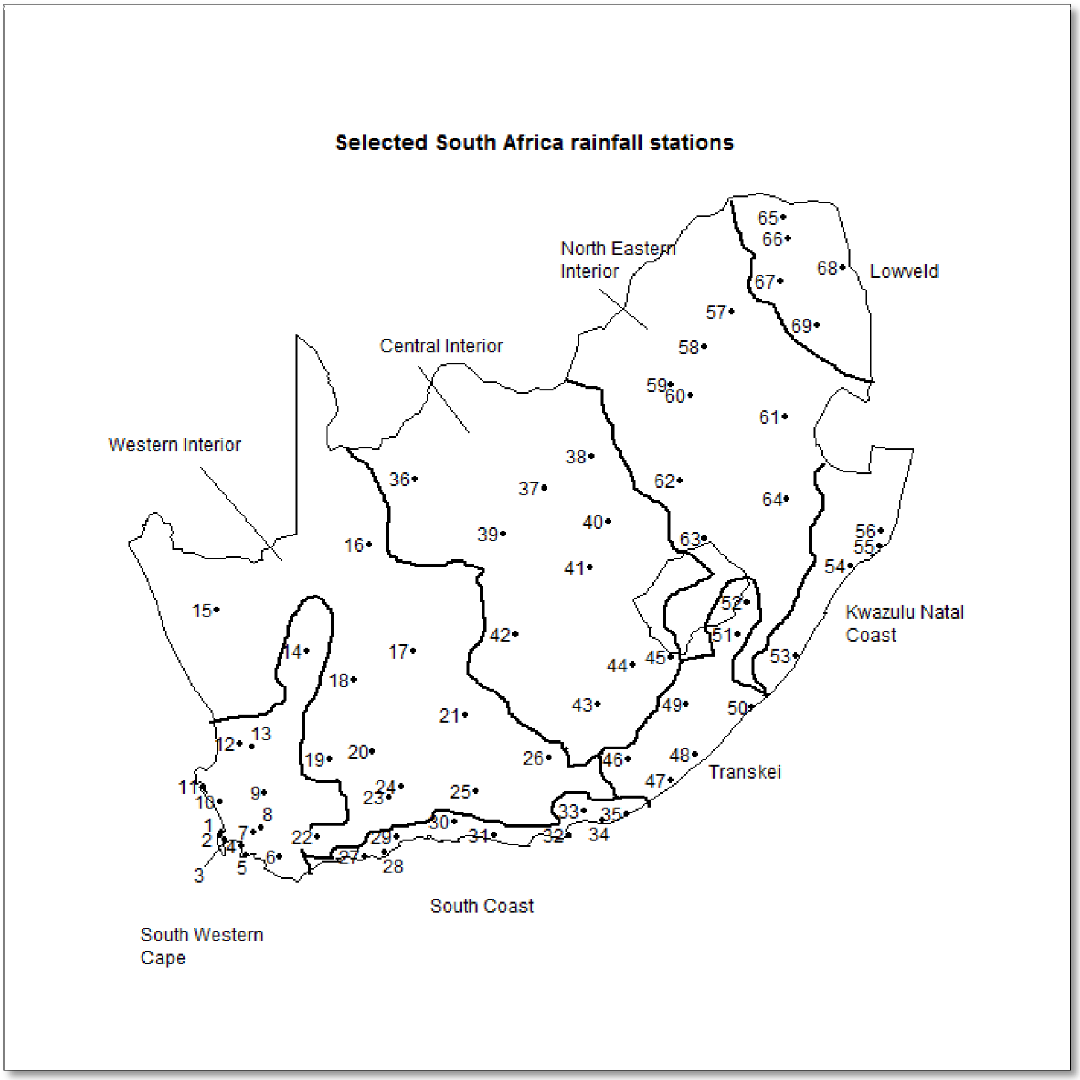

Figure 13: (From Chapter Four) Map showing the 69 selected rainfall stations throughout South Africa with a rough outline of the eight rainfall regions to identify in which region the stations occur.

5.2.1. South Western Cape

Of the 14 stations in the South Western Cape region, 6 stations (1, 6, 8, 11, 12 and 14) identified predominantly positive trends in the extreme rainfall indices (R95mm, R99mm, R95p, R99p, RX1day, RX5day and SDII). However, most of these trends were not significant at the 5% level. The stations that clustered around the Cape Town area at lower altitudes (1 and 3) identify a steeper positive trend for the very extreme 99th percentile rainfall indices compared to the 95th percentile rainfall indices (Figure 24). 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.

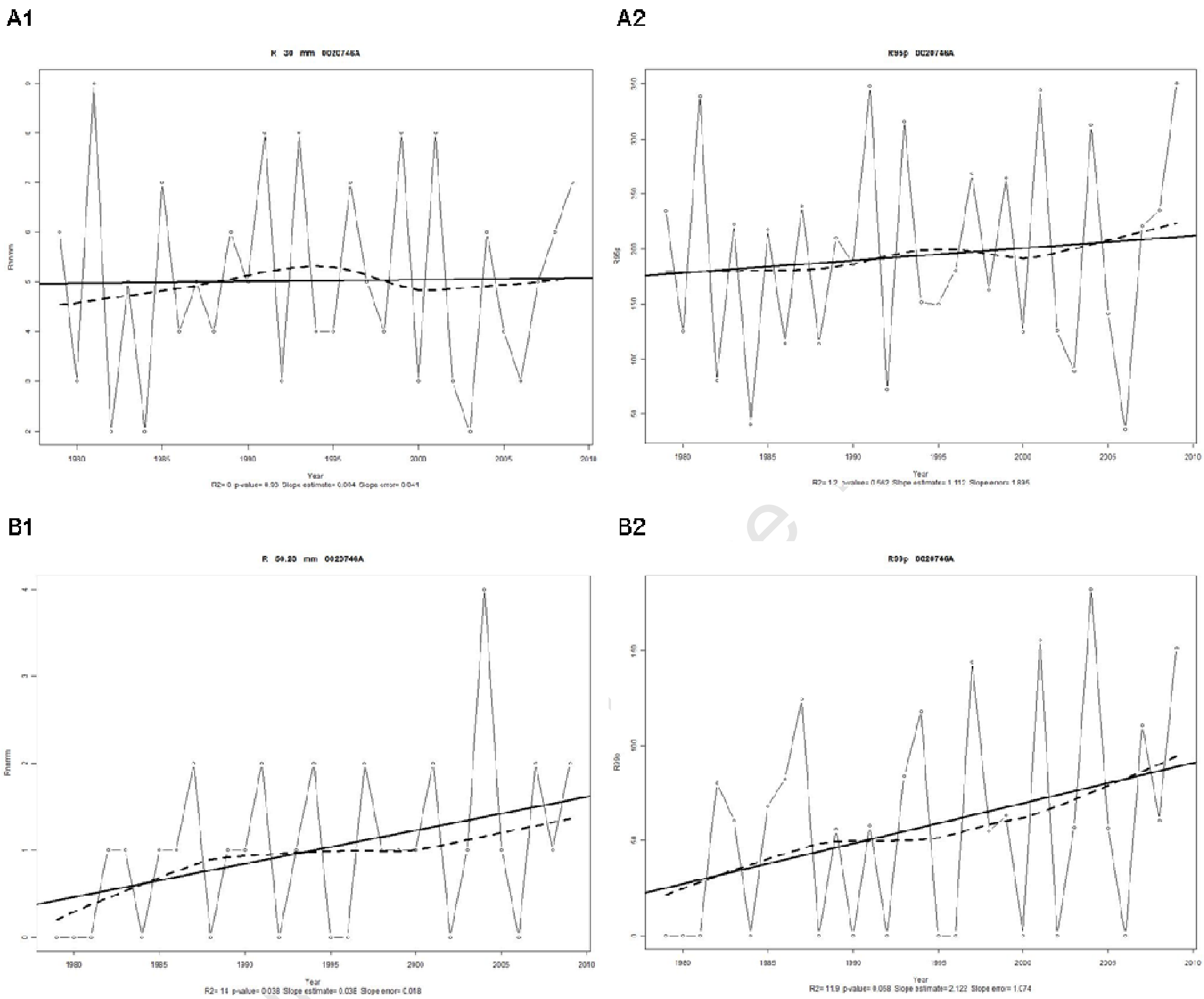

Figure 24: Annual precipitation from 95th percentile rainfall events (A1 and A2) and 99th percentile rainfall events (B1 and B2) for Station 1 in the Cape Town area showing a steeper positive trend in the more extreme 99th percentile rainfall compared to the 95th percentile rainfall.

Further up the west coast station 11 was the only station in the region to have experienced positive trends throughout all the extreme rainfall indices that were also significant at the 5% level. This is primarily due to an increase in these indices since the year 2000 (Figure 25). 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.

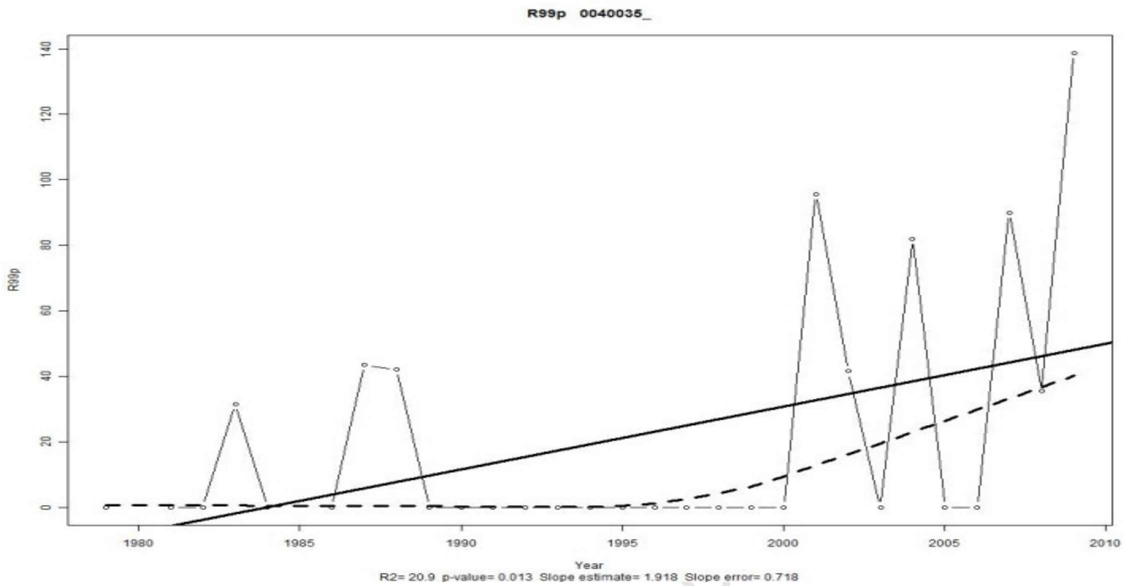

Figure 25: Annual precipitation from 99th percentile rainfall events for Station 11 on the West Coast showing the significantly (p-value = 0.013) increasing trend influenced by the extreme rainfall years post 2000.

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.

In general there are mixed trends very little significance among the stations of the South Western Cape region. It can be 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. 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 at higher altitudes within this region. Some stations that produced significant trends are not corroborated by stations very close to and similar in profile to them. The topography of the region may cause these differences and more stations within a specific region would need to be sampled to confirm the identified trends. The short 31 year period causes the resulting trend to be heavily influenced by 1 to 4 years of extreme rainfall years clustered together in the time period as shown by station 11.

5.2.2. Southern 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. These stations are located closer to the South Western Cape region along the Southern Coast and also occur at lower coastal altitudes. Station 27 and 35 both experience significantly positive trends in the SDII (Figure. 26). Their profile throughout the indices are very similar and this significant trend in the SDII index may be attributed to the positive trends in the extreme rainfall indices along with the positive CDD 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 Southern Coast region and 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 (30 to 35) further eastwards along the Southern Coast region apart from a significantly positive trend in the RX1day index for station 32.

The Southern Coast region thus 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 apparent 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.

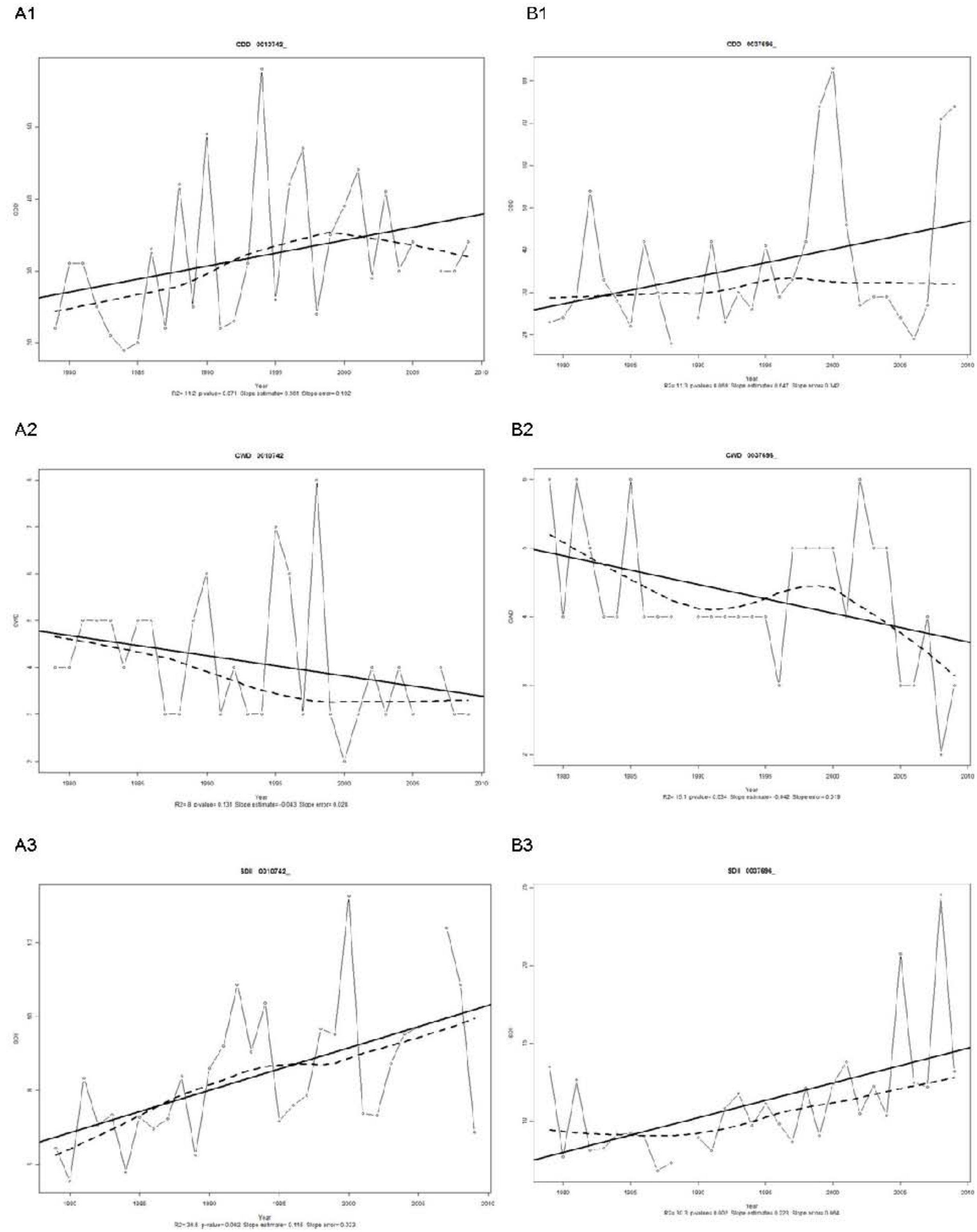

Figure 26: Relationship between the CDD index (A1 and B1), CWD index (A2 and B2) and the SDII index (A3 and B3) for stations 27 (A) and 35 (B). The SDII is significant for both stations at the 5% level.

5.2.3. Transkei

The 4 stations (46, 49, 51 and 52) further inland and at higher altitudes identify a mix of trends that appears similar to the mountainous region of the South Western Cape. Of these 4 stations 46 and 52 both identify negative (non-significant) trends in their 95th and 99th percentile rainfall indices and no clear trends in the other indices, while 2 stations (49 and 51) identified mostly positive extreme rainfall indices. These trends are significantly positive for the 99th percentile indices for station 49. While the trend at station 51 was not significant at the 5% level, the SDII index did, however, identify a significantly positive trend at the 5% level along with station 49 for this index. Station 47 on the coast has a similar pattern of trends to station 49 except the positive trends are significant for the 95th percentile indices instead of the 99th percentile indices, while the SDII index for station 47 is also significantly positive. Along the coast, stations 47, 48 and 50 follow an interesting pattern in their trends for the extreme rainfall indices (Figure 27). Station 47, which is situated the furthest south and closer to the Southern Coast region displayed trends similar to some of the stations of the Southern Coast region with positive 95th and 99th percentile indices trends. Further up the coast station 48 had few trends throughout all its indices, while even further up the coast and nearer to the KZN Coast region station 50 had a pattern of trends similar to the KZN Coast region (described in 5.2.4) in which the 95th and 99th percentile extreme rainfall indices are all negative.

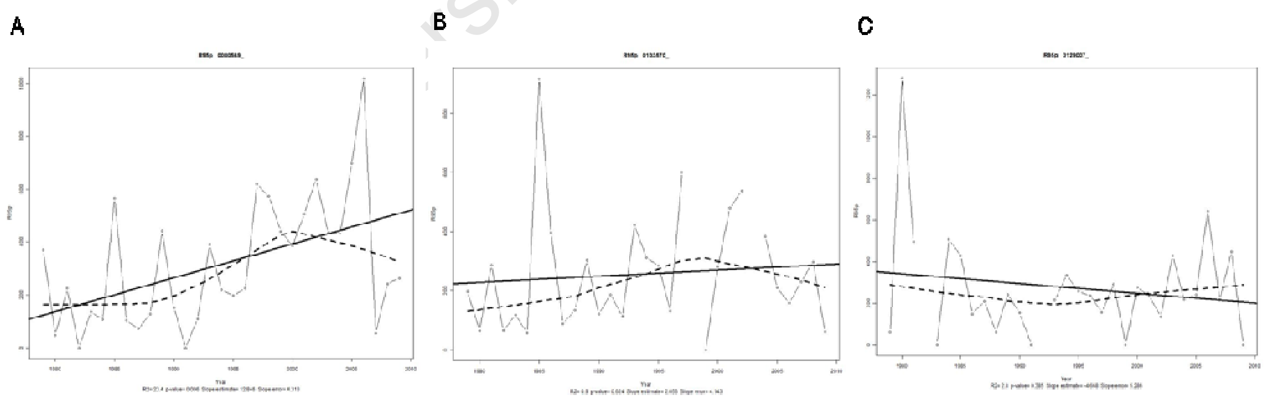

Figure 27: The change in extreme rainfall trends represented by the R95p index along the Transkei coastal stations from station 47 (A) further south with a positive trend to station 48 (B) in between with no trend to station 50 (C) further north with a negative trend.

A spatial transition appears to exist among 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 KZN Region. This is evident with station 48 identifying no obvious trends and situated roughly between station 47 and station 50, which have very different patterns of trends in their indices with similarity to their respective neighboring regions. The 4 stations situated inland from the coast and at higher altitudes are evidently different to those stations on the coast.

5.2.4. Kwazulu Natal Coast

Most of the 95th and 99th percentile extreme rainfall indices trends are negative throughout all the stations in the KZN Coastal region (Figure 28). Station 55 is the only station to identify a significantly positive trend at the 5% level associated with the SDII index. This occurs as a result similar to the relationship described above for the Southern Coast region (section 5.2.2) between a strong negative trend (at the 5% level of significance) for the CWD index coupled with a positive (non-significant) trend for the CDD index. This, however, does not agree with the negative trends identified for the extreme rainfall indices, the RX1day and RX5days for this station.

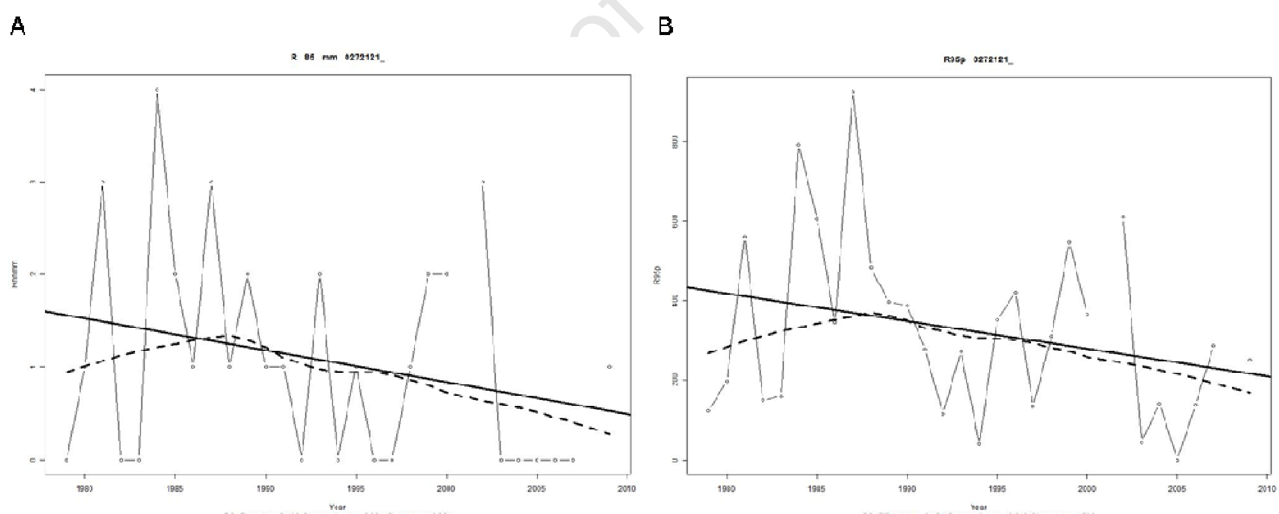

Figure 28: Extreme rainfall indices R99mm (A) and R95p (B) representing the negative trends for the KZN Coast region.

The stations in the KZN Coast region generally show no trends or non-significant negative trends throughout the stations, while more specifically identifying negative trends in the CWD and positive trends in the CDD indices. These are generally not accompanied with a significant trend in the SDII index (apart from station 55) 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 thus identified throughout the region.

5.2.5. 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. While these are slightly positive, none are significant. The other trends are mixed between either positive, 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 identify either 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 no trends or a mix of trends without any significance for this index.

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 trend 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 described below.

5.2.6. North Eastern Interior

There is a general mix between positive and no trends among the 95th and 99th percentile extreme rainfall indices for the 8 stations in the North Eastern Interior region. Station 58 experienced positive trends throughout the four 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 (Figure 29).

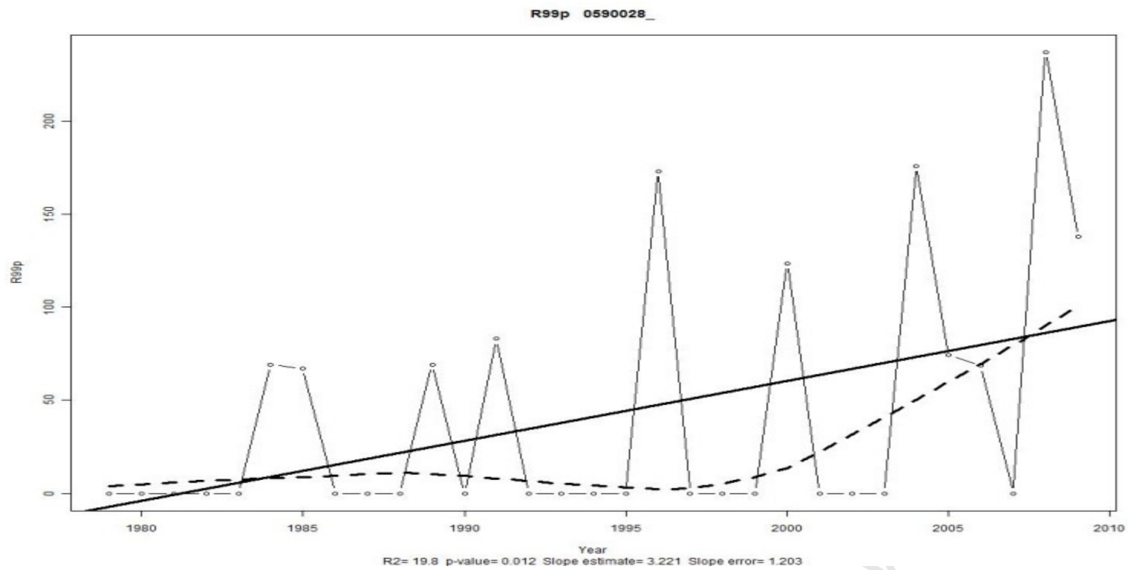

Figure 29: Contribution of rainfall in mm from extreme events greater than the 99th percentile with a clear increase in extreme years from 1995 for station 58.

Apart from station 64, all the other stations identified positive trends for the CDD index (stations 59 and 61 significant at the 5% level) together with positive trends in the SDII index in which stations 58, 60 and 61 were significant at the 5% level. Although these stations have a mixed representation of trends for the CWD index, the relationship between these three indices remains similar to that of various other regions described above. The stations situated further south in the North Eastern Interior region identified fewer trends with some tending slightly towards being negative in the extreme rainfall indices without any significance. 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. Station 64 identified no real trends at all apart from slightly negative SDII index (p-value: 0.057), which in this scenario is opposite to all the other stations in this region (Figure 30).

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.

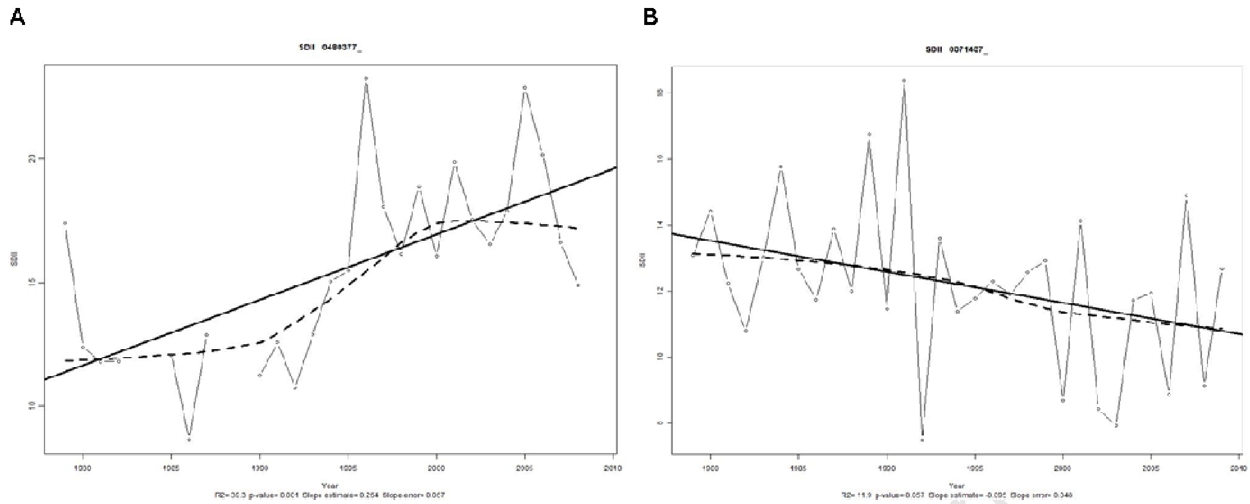

Figure 30: The negative trend for the SDII index for station 64 (B) compared to the positive trend for station 61 (A), which is more representative of the stations spread throughout the North Eastern Interior region with the positive trend attributed largely to the years' post 1995.

5.2.7. Central Interior

The Central Interior region identified generally positive trends in all indices apart from the CWD index. Five of the 10 stations (36, 39, 42, 44 and 45) representing the region identified positive trends throughout all the 95th and 99th percentile extreme rainfall indices, though only the two indices describing the number of days in which rainfall exceeded the 95th (R95mm) and 99th (R99mm) percentile thresholds were significant at the 5% level for station 42. All 10 stations identified an increase in the total annual precipitation (PRCPTOT) with stations 36 and 42 being significant. Stations 36, 39 and 42 all showed significantly positive trends for the SDII index, while stations 44 and 45 showed significantly positive trends for the RX1day index. These significant trends for the RX1day for these two stations (44 and 45) were not carried through to the RX5day index in which station 44's RX5day in fact identifies a non-significant negative trend (Figure 31).The extreme rainfall trends of the 4 stations (37, 38, 40 and 41) in the central and eastern parts of the region become flatter with less significance identifying a mix between positive and negative trends.

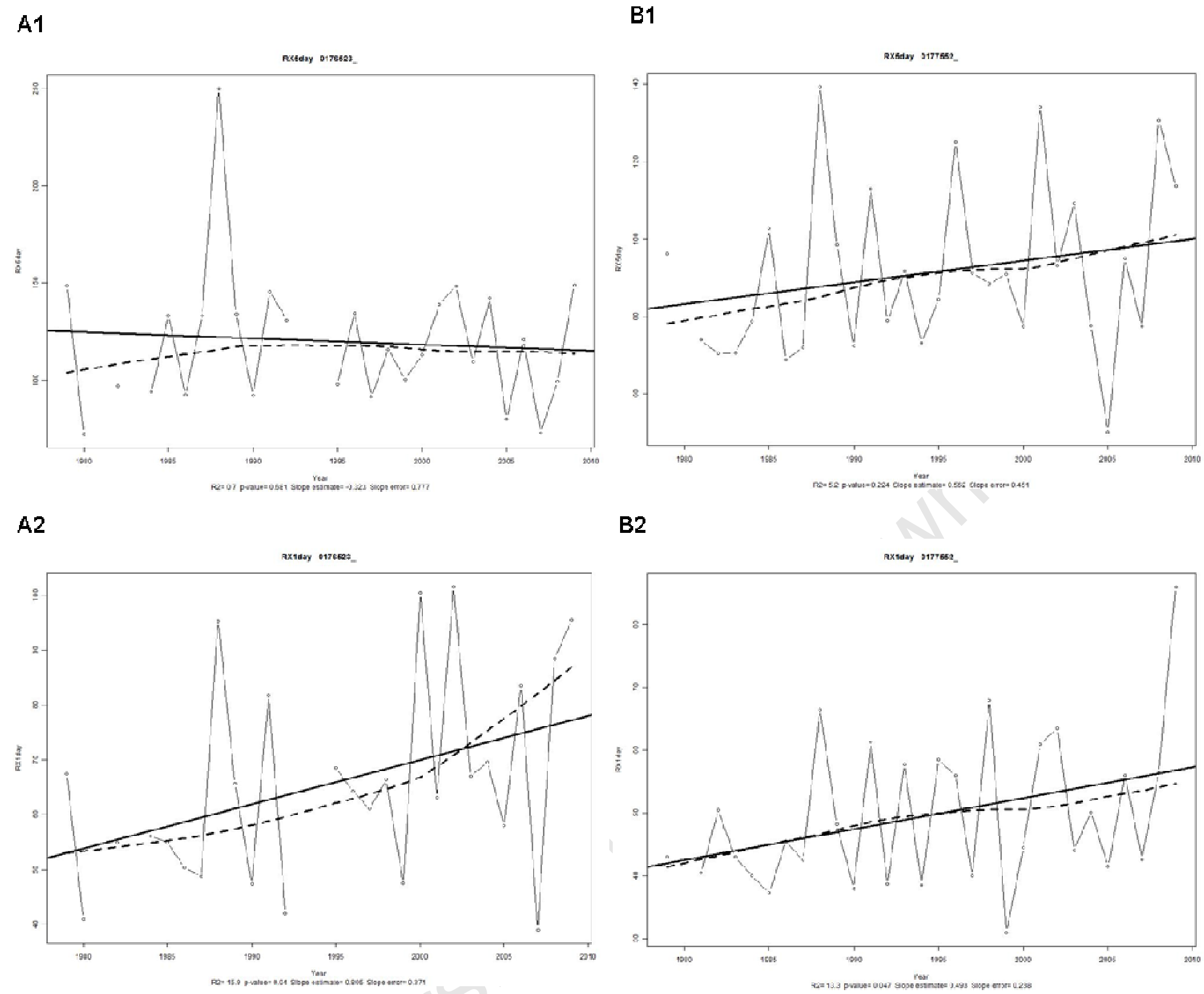

Figure 31: The difference between the extreme rainfall trends for the RX5day (A1 and B1) and the RX1day (A2 and B2) for stations 44 (A) and 45 (B). The RX1day index identifies a significantly positive trend at the 5% level for both stations 44 (A2) and 45 (B2).

It is difficult to identify a pattern between the extreme rainfall trends for stations 37, 38, 40 and 41 when there is disparity in the trends between the 95th and 99th percentile indices, while stations 36, 39 and 42 identify positive trends throughout the 95th and 99th indices hence a higher level of significance. Stations 44 and 45 occur above 2000 meters in altitude and further towards the south of the Central Interior region. Both stations identify significantly positive trends for the RX1day index and less clear trends in the RX5day index, which may suggest a trend in the rainfall becoming more extreme over a shorter period of time (such as 24 hours) in the higher altitudes of this region.

5.2.8. Western Interior

The stations in the northern half of the region (15 to 18) identified slightly positive trends that are not significant for the extreme rainfall indices. In the case of the Western Interior, as opposed to the South Western Cape (Figure 24), the 95th percentile rainfall indices show a steeper positive trend compared to the very extreme 99th percentile indices. Stations 15 to 18 have a significantly positive trend for the SDII index (apart from station 15 which is not significant at the 5% level) accompanied with the positive CDD index and negative CWD index similar to the relationship described above for many of the regions (Figure 26 of the Southern Coast region). The stations in the southern parts of the region (19 to 26) display a general mix of trends without any significance or consistency between neighboring stations. These stations are, however, situated throughout a part of the region where the rainfall is influenced heavily by the topography in which mountain ranges provide a spatial barrier between the wetter coastal region to the south and the arid Karoo region hence a large variability.

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). The northern stations identify more clear trends in the extreme rainfall indices including significantly positive trends for the SDII index and are characterized by similar trend patterns to stations 36, 39 and 42 of the Central Interior region described above, while the stations further to the south display mixed trends similar to the patterns described in the bordering Southern Coast region.

5.2.9. Summary and conclusions

The 31 year study period poses difficulties with analyzing and identifying significant trends due to the small number of extreme events occurring per station during this period. Due to the nature of extreme rainfall events, they should ideally have a much longer time series when analyzing trends such as in Kruger (2006). As a result many stations with close proximity within regions often display mixed signals. The trends are also heavily influenced by a few extreme rainfall years and therefore do not provide an accurate representation of a trend.

However, some general observations were identified. Throughout all the stations across the country, apart from the KZN Coastal region, positive trends exist in the 95th and 99th percentile extreme rainfall indices, though very few of these are significant at the 5% level. There was also a general feature with many of the stations having experienced 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 (Figure 32). This significance was closely linked to the trends identified to be significantly positive for the CDD index and negative for the CWD index together with a general agreement of positive trends (though mostly non-significant) in all the 95th and 99th percentile extreme rainfall indices. The southern parts of the Central Interior and the inland parts of the Transkei 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.

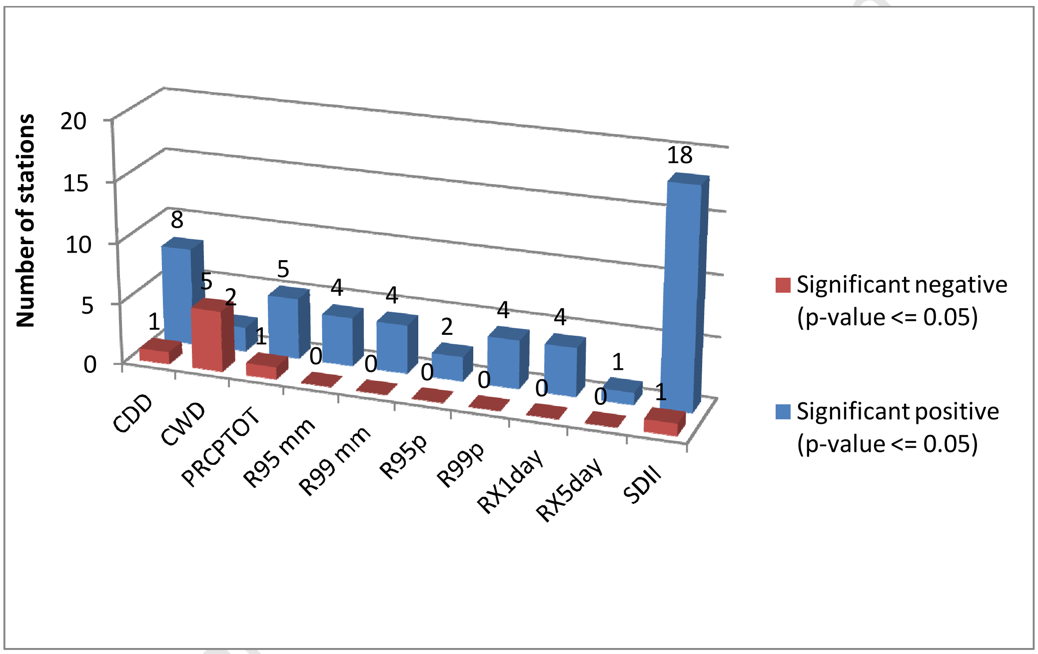

Figure 32: Relationship between the number of station observations for increasing and decreasing trends at the 5% significant level for each index.

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 the RX1day events opposed to the RX5day events. This, together with the many positive SDII index trends may indicated that extreme rainfall has begun to occur over a shorter time period.

A spatial difference is apparent within the coastal rainfall regions of the South Western Cape, Southern Coast and the Transkei between the higher altitude stations situated inland and the lower altitude coastal stations. Stations situated closely together at different altitudes can have very different patterns of trends, which are usually very mixed with no agreement. It may be beneficial for this type of assessment to assess these trends between neighboring stations at similar altitudes. The coastal regions also experience a spatial 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 KZN Coastal region.

The regional assessment of extreme rainfall indices presented in this section once again suggests that the rainfall regions used in this study are not necessarily representative of extreme rainfall pattern regions throughout South Africa. This was initially evident through the extreme rainfall profile for each of the stations represented in Table 2 (Chapter Four). For example station 14 displays very similar extreme rainfall indices to those stations in the northern regions of the Western Interior as opposed to those of the South Western Cape region. However, it is evident, as mentioned previously, that the 31 year study period is not optimal in terms of studying trends in extreme rainfall events. Though, it is possible to assess the trends in the synoptic circulations identified by the SOM from Chapter Three that are associated with extreme rainfall events and occur more frequently throughout the 31 year period. This provides a means of relating the extreme rainfall events trends evident in the station data to those that are more robust in the synoptic circulation data. Hence any changes in the frequency of occurrence of synoptic circulations associated with extreme rainfall could be identified. The procedure and results of which are presented in the section 5.3.

5.3. Relationship between trends in synoptic circulations and extreme rainfall

The number of 95th and 99th percentile rainfall observations per station ranges from 23 to 201 for the former and from 5 to 43 for the latter (Table 2, Chapter Four). The numbers of observations are too few throughout the 31 year study period to make robust statements regarding the statistical significance of their trends. For example station 11 that identified significant trends in the RClimDex indices analysis only has 74 and 16 occurrences of 95th and 99th percentile rainfall events respectively. However, the SOM analysis is based on every day of the 31 year study period therefore each node will have a much higher frequency of occurrence and provide a larger sample size to carry out trend analyses and detect statistical significance. Nodes with significant trends in their frequency of occurrence throughout the 31 year study period can then be associated with stations that map mostly to these particular nodes, thus describing a more robust method for identifying significant trends in extreme rainfall synoptics associated with the respective stations and regions compared to those trends identified by RClimDex that are based on only a few observations from the station data.

Testing for statistical significance in trends of the frequency of occurrences of each synoptic circulation over the 31 year study period was performed using a Monte Carlo bootstrapping technique. This involved bootstrapping analyzed frequencies of occurrences over the 31 year study period with the number of bootstrap replicates set to 1000. A linear regression was generated for each of the bootstrap replicates from which a histogram of the slopes of the linear regressions was created. The 95th percentile of these slopes was then calculated and compared to the slope of the actual data. If the slope of the actual data was above the 95th percentile the trend was considered significant.

5.3.1. Assessment of synoptic circulation trends in the 31 year period and their relation to extreme rainfall in station data

Nodes 36, 37 and 40 were the only nodes of the general circulation SOM that identified significantly positive trends from the bootstrap testing (Figure 33). The synoptics associated with these nodes are all similar with a sub-tropical low over most of the country and a high pressure over the eastern parts of the country. Nodes 36 and 37 have a more pronounced sub-tropical low pressure with a week high pressure, while node 40 has a weaker sub-tropical low situated further westwards and a stronger high pressure system covering most of the eastern parts of the country extending inland from the Indian Ocean. All these nodes are associated with very similar widely spaced isobars and zonal air flow in the upper atmosphere (z500) implying greater importance of the surface synoptics.

The frequency of extreme rainfall days based on the 698 stations mapped to the general circulation SOM indicate that node 37 was the second highest mapped to node with 5.24% (Figure 5, Chapter Three). Node 36 was the 4th highest mapped to node. Hence, the synoptic circulations of these two nodes may be considered to be associated with a large proportion of extreme rainfall events experienced in the 31 year study period. As these nodes have shown a significant increase in the number of occurrences over the 31 year study period, extreme rainfall resulting from these synoptic circulations has therefore shown an increase over the 31 year period.

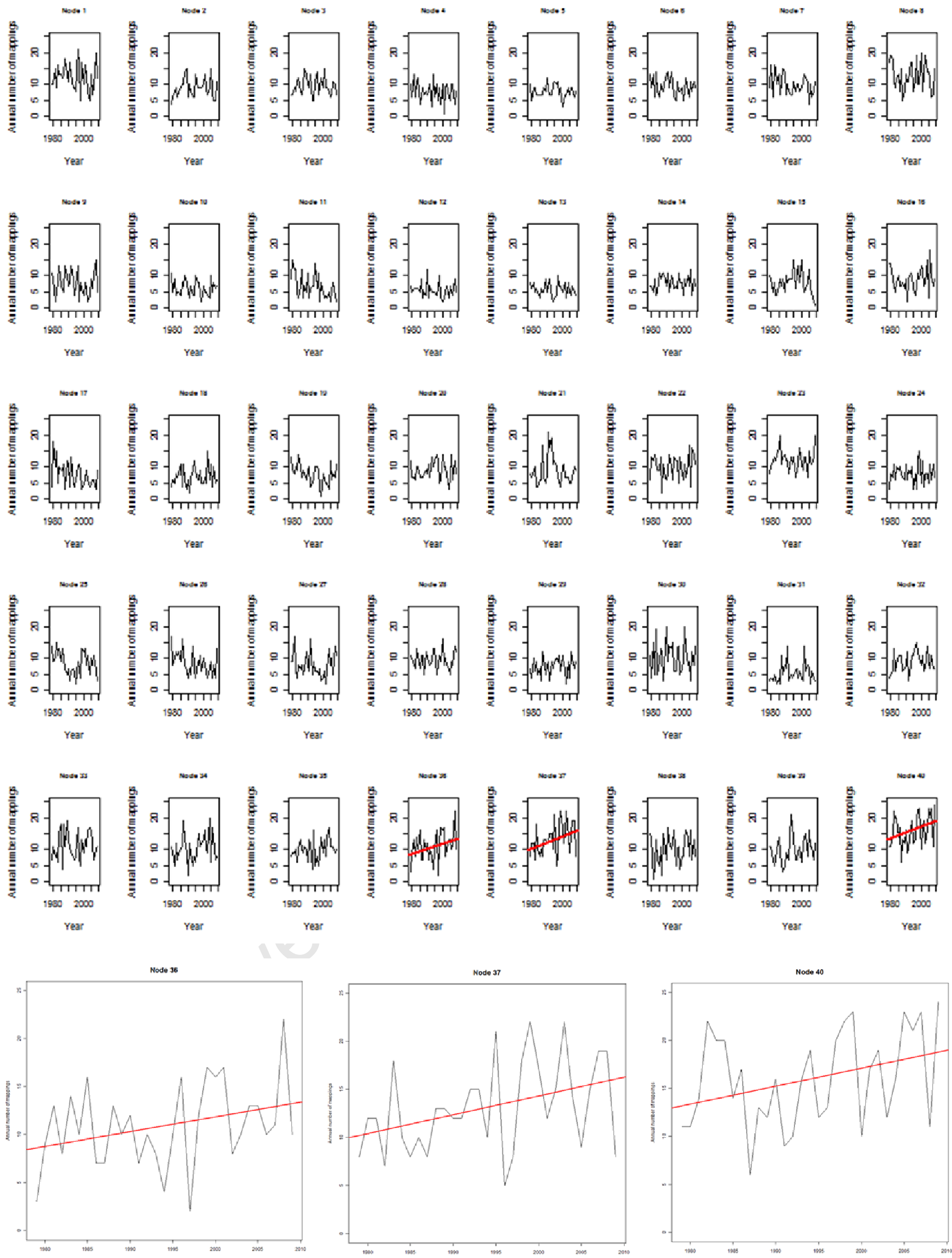

Figure 33: Annual number of occurrences from 1979 to 2009 for each of the 40 synoptic circulation nodes of the general circulation SOM with the significantly positive trends identified with a red trend line in nodes 36, 37 and 40 (magnified at the bottom for clarity). Note, the nodes of the array are not laid out in the same sequence as those of the original SOM (in this case node 1 is in the top left-hand corner and node 40 in the bottom right-hand corner).

The trends of these synoptic circulations are assessed in comparison to the extreme rainfall trends identified in the station data. Data from the stations that identified significantly positive trends in the RClimDex extreme rainfall indices were used in order to determine whether these trends were reflected in the station records.

The node frequency mappings for the 95th percentile extreme rainfall days of the 18 stations that identified a significantly positive trend in the SDII index (Figure 32) revealed that the highest number of days mapped to node 28 (6.5%). Node 40 was the second highest (6.3%), while nodes 36 and 37 that are associated with increasing trends of extreme rainfall synoptics were the 4th (5.6%) and 6th (5.0%) most frequently mapped to nodes respectively. Stations 1, 6, 8, 11, 42, 47, 49 and 58 identified significantly positive trends in the 95th and 99th percentile extreme rainfall indices. However, not all of these stations mapped to the nodes displaying significantly positive trends in the frequency of occurrence during the 31 year period. For example the most frequently mapped to node for station 1 was node 1 (59 times); station 11, which showed clear significantly positive trends for most of the extreme rainfall indices, also mapped most frequently to node 1 (29 times) and second highest to node 9 (16 times). Therefore the extreme rainfall trends experienced at these stations are not reflected in the synoptic circulation trends of extreme rainfall.

Stations 42 (Central Interior region), 47, 49 (both of the Transkei region) and 58 (North Eastern Interior region) frequently mapped to the three significantly positive trending nodes (36, 37 and 40 - Table 6). Node 40 was the highest mapped to node for station 42 (9 times) and node 36 was the highest mapped to node for station 47 (15 times). Although station 47 had node 36 as its most frequently mapped to node it also had a high number of 95th percentile extreme rainfall occurrences and therefore mapped to a wide range of nodes at the same time (Figure 34). Stations 42, 49 and 58 had a lesser number of 95th percentile rainfall occurrences in proportion to the number of days mapped to nodes 36, 37 and 40, especially in stations 42 and 49.

A relationship therefore exists between nodes 36, 37 and 40 and stations 42, 47, 49 and 58 in which an increasing trend is associated with these extreme rainfall synoptic nodes and the increasing trend in extreme rainfall indices associated with the stations that frequently map to these same nodes. This suggests that extreme rainfall associated with these synoptic circulations in the respective station regions have increased during the 31 year period. This would indicate that as these circulations have become more frequent the possibility that they may be associated with extreme rainfall could increase.

Table 6: Number of days mapped to the specific nodes (36, 37 and 40) and the relevant rank for each of the identified stations. Station 42 occurs in the Central Interior region, station 47 and 49 occur in the Transkei and station 58 occurs in the North Eastern Interior rainfall region.

			Node 36		Node 37		Node 40	
Label	StationID	Name	Occurrence	Rank	Occurrence	Rank	Occurrence	Rank
42	0199107_	GROOT_-_ARENDSKRAA	4	8	5	7	**9**	**1**
47	0080569_	UMZONIAN	**15**	**1**	-	-	-	-
49	0126245_	ENGOBO_MANINA_PLANTATIO	-	-	7	6	-	-
58	0590028_	ILLAWARR	5	9	-	-	6	6

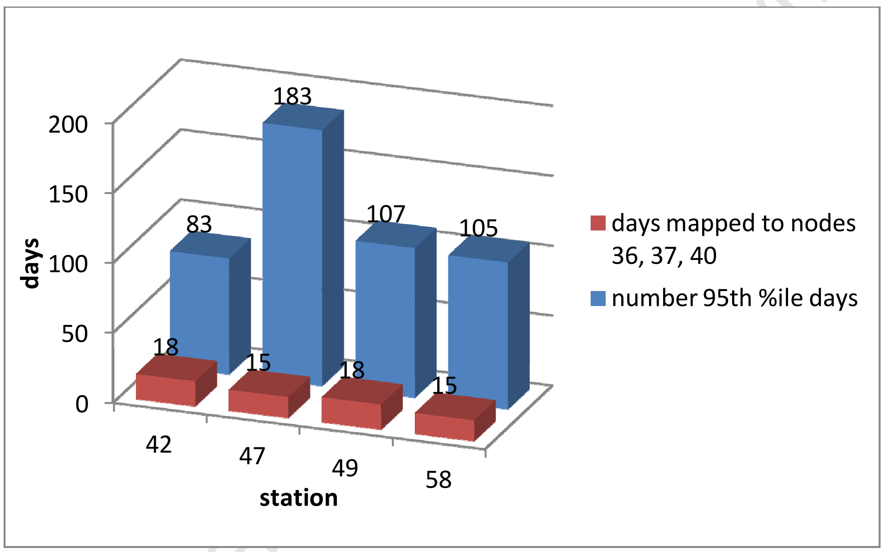

Figure 34: Relationship between days mapped to significantly increasing nodes and number of 95th percentile occurrences for each of the four stations.

5.3.2. Seasonal analysis of synoptic trends

The synoptic circulation patterns of nodes 36, 37 and 40 are representative of general summer conditions over Southern Africa. This is confirmed with the higher frequency of days mapped to these nodes in summer months (Figure 4, Chapter Three). Node 37 was the most frequently mapped to node in DJF with 11.15%, followed by node 36 with 9.72%. This may indicate that during the summer months extreme rainfall associated with the synoptics of these nodes had increased over the 31 year period. Node 40 was more frequently mapped to in the shoulder seasons of MAM (highest mapped to node with 8.45%) and SON (second highest mapped to node with 5.78%). Therefore the increased number of occurrences of node 40 suggests a possible increase in the number of extreme rainfall events during these months. Each season was analyzed in more detail as to which nodes were the most important in terms of frequency mapping and significantly positive trends (Figure 35).

Figure 35: A separate bootstrapping analysis similar to that used for the full 31 year period above was carried out in order to determine the significantly positive trending nodes for each season identified by the nodes with a red trend line.

DJF has the fewest number of significantly positive trending nodes out of the four seasons with only 5 nodes identifying significantly positive trends. However, 4 of the 5 nodes are the 4 most frequently mapped to nodes of the season thus identifying a clear relationship between the most frequently mapped to nodes and their increasing number of occurrences throughout the 31 year period. These nodes include 37 (11.15%), 36 (9.72%), 34 (9.22%) and 35 (8.93%) displayed in Figures 35 and 36. Nodes 37 and 36 were also amongst the most frequently mapped to nodes of the extreme rainfall SOM that also identified significantly positive trends mentioned above. This suggests the most significant changes in extreme rainfall to be occurring in the summer months of DJF. However, the larger sample of stations over the summer rainfall regions of South Africa is noted in this regard.

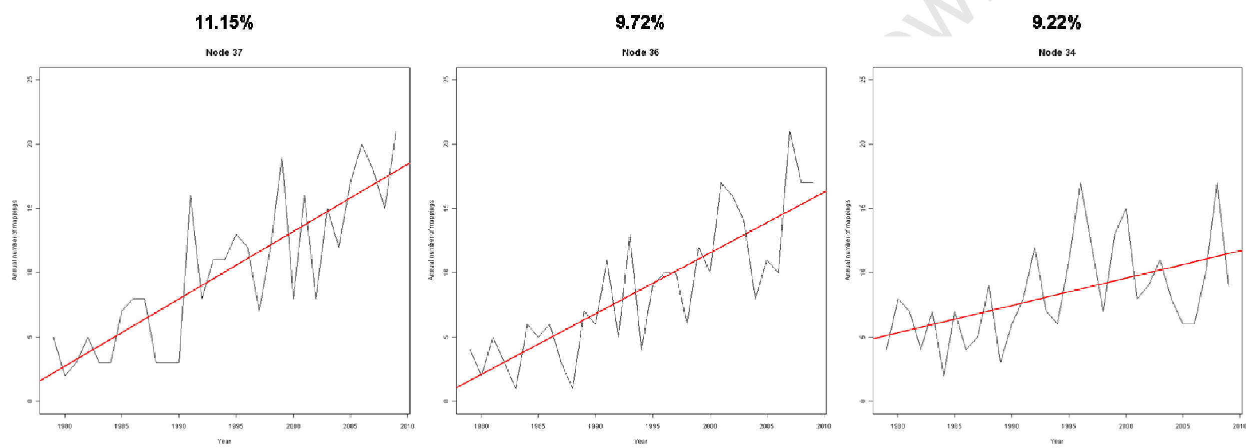

Figure 36: Significant increasing trends for the number of occurrences of nodes 37, 36 and 34 for DJF with their frequency mapping displayed above each plot.

MAM has the highest number of significantly positive trending nodes out of the four seasons with 21 in total (Figure 35). The 3 most frequently mapped to nodes of MAM are nodes 40, 39 and 30, which do not display any significant trends. However, the 4^{th} and 5^{th} most mapped to nodes (32 and 22 respectively) do identify significantly positive trends for the number of occurrences over the 31 year period highlighted in Figure 37. Although there are a large number of significantly increasing trends in certain synoptic circulations, they are either not frequently mapped to or associated with extreme rainfall.

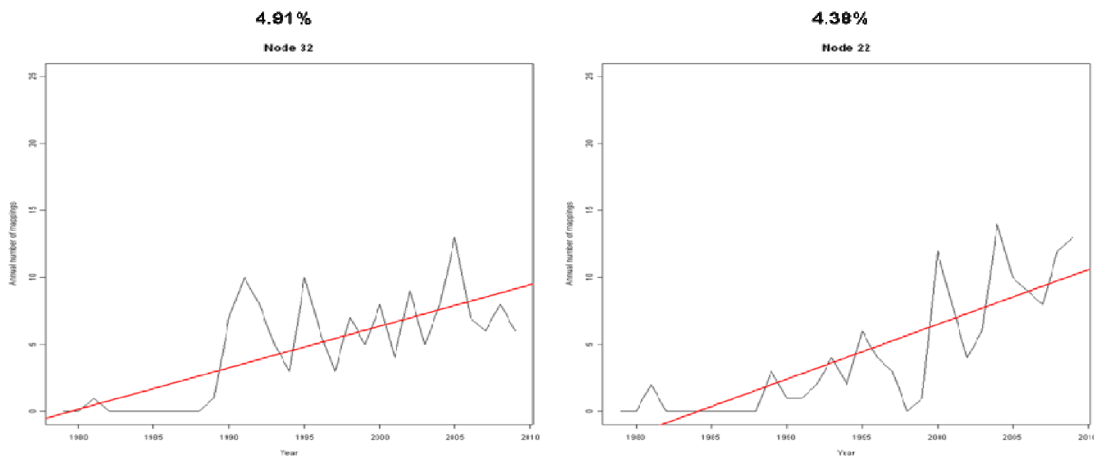

Figure 37: Nodes 32 and 22 identify significant increasing trends along with being the 4th and 5th most mapped to nodes respectively (frequency displayed above each plot) in the 31 years for MAM.

SON had the second highest number of significantly positive trending nodes (after MAM) with 18 in total (Figure 35). The most frequently mapped to node of SON was node 21 (6.03%) followed closely by node 40 (5.78%) and node 30 (5.74%). There is no significant trend associated with node 21, while node 40 and 30 both identified a significantly positive trend (Figure 38). Node 40 possesses summer-like rainfall synoptics and thus suggests an increase towards more frequent summer rainfall synoptic circulations earlier in the year.

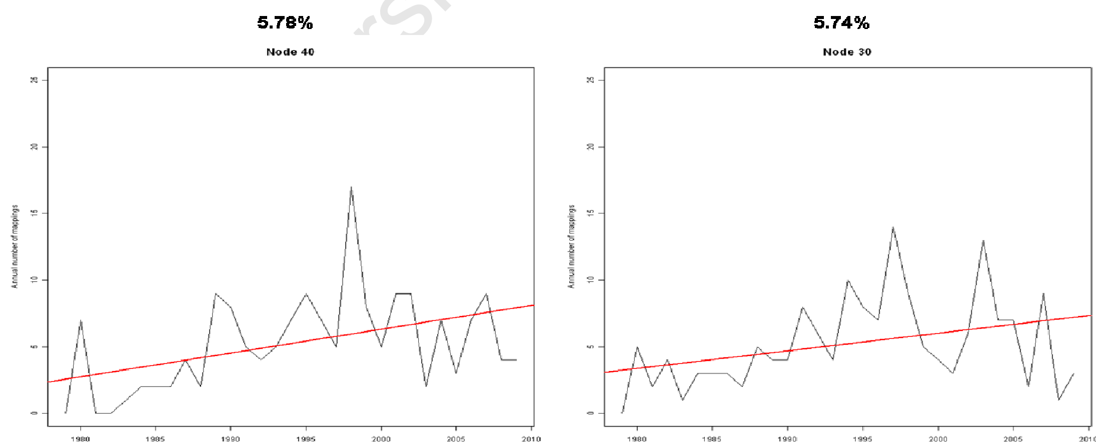

Figure 38: Node 40 and 30 of SON are the 2nd and 3rd most frequently mapped to nodes respectively of the season that also exhibit a significantly increasing trend over the 31 year period.

JJA identified 7 nodes with significantly positive trends (Figure 35) of which none of them were frequently mapped to during the season. This would indicate that there are no trends associated with the nodes responsible for extreme rainfall during the winter months.

5.3.3. Summary

Trends in the frequency of occurrence of synoptic circulations in the first SOM were tested for statistical significance. Stations that identified increasing extreme rainfall trends in their observed records were then matched to the nodes which identified significant trends through their frequency mappings to the respective nodes. Nodes 36, 37 and 40 identified a significant increase in their number of occurrences over the 31 year period and were also associated with extreme rainfall synoptic circulations. Stations 42, 47, 49 and 58, which most frequently mapped to these nodes and experienced an increase in observed extreme rainfall indices, were identified as having an increase in the number of occurrence of synoptic circulations associated with extreme rainfall.

The shoulder seasons of MAM and SON both displayed a larger number of significantly positive trending nodes (21 and 18 respectively) compared to the smaller number identified in the summer months of DJF (5) and winter months of JJA (7) (Figure 39, Table 7). Winter months had the least amount of significance with regards to the relationship between the most frequently mapped to nodes of the season and their trends. The most important nodes regarding significant trends for MAM would be nodes 32 and 22, which were the 4th and 5th most frequently mapped to nodes that also identified significantly increasing trends. The months of SON and DJF are the most significant months with regards to the most frequently mapped to nodes of the respective seasons experiencing significantly positive trends. This is most evident in DJF in which all 3 of the most frequently mapped to nodes (37, 36 and 34) experienced significantly positive trends. SON had the second and third most frequently mapped to nodes (40 and 30) experiencing significantly positive trends. DJF is the only season in which the most frequently mapped to nodes correspond with a significant increase as well as with extreme rainfall identified synoptic circulations. This would indicate that there has been an increase in the occurrence of synoptic circulations that are associated with extreme rainfall in the summer rainfall regions.

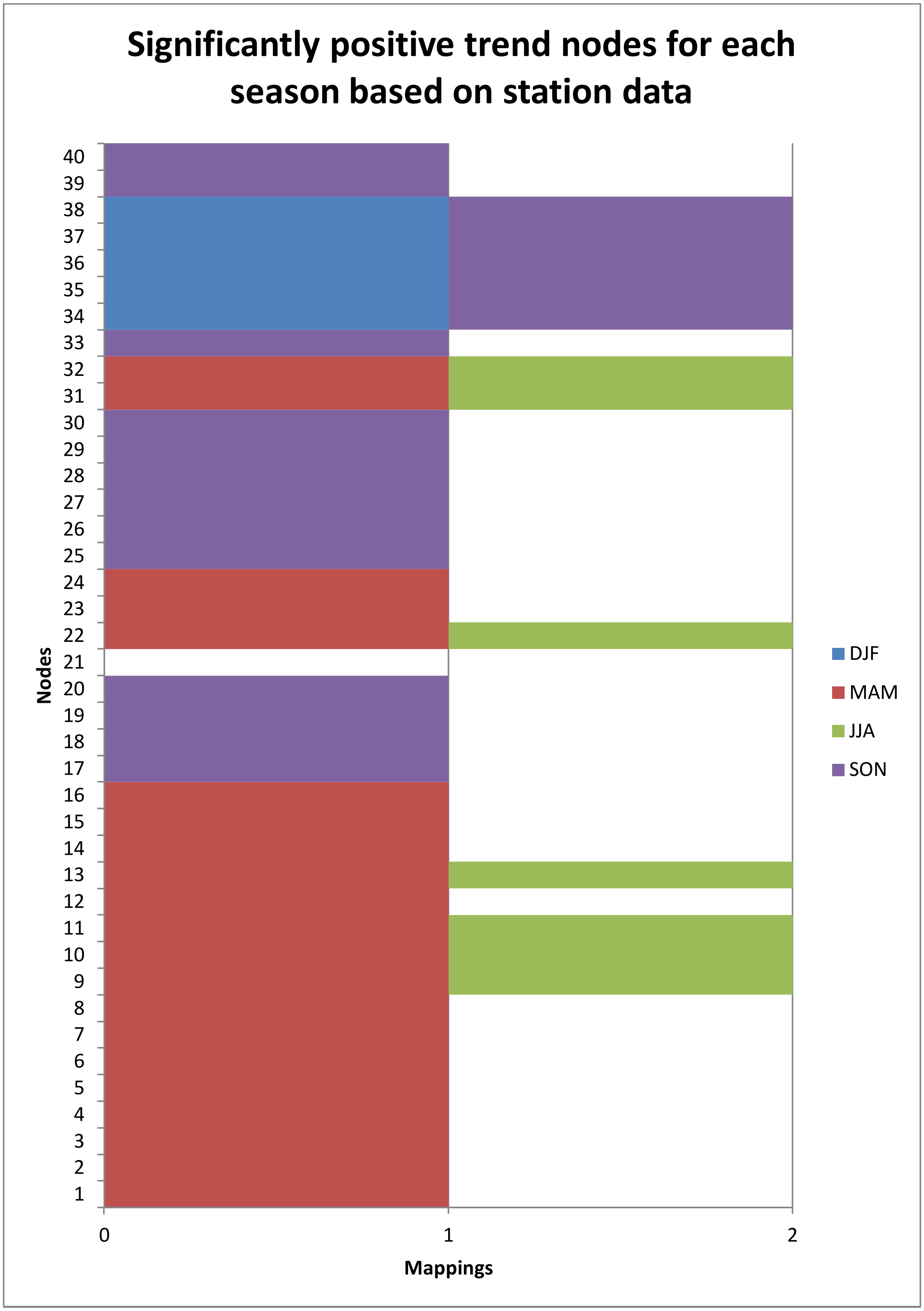

Figure 39: Summarizing the nodes that identified significantly positive trends in each of the four seasons.

Table 7: The 1st, 2nd and 3rd most frequently mapped to nodes for each season. Bold print identifying nodes associated with a significantly positive trend in their frequency of occurrence over the 31 year period. The total amount of significantly positive trending nodes of each season is displayed in the last column.

season	1st		2nd		3rd		total
	node	frequency	node	frequency	node	frequency	
DJF	**37**	**11.15**	**36**	**9.72**	**34**	**9.22**	5
MAM	40	8.45	39	5.19	30	5.19	21
JJA	8	10.24	23	9.89	1	8.94	7
SON	21	6.03	**40**	**5.78**	**30**	**5.74**	18

5.3.4. Seasonal shift in synoptic circulations

A general impression suggests there is a shift in the synoptic circulations between certain adjacent seasons. This was identified by the relationship occurring between the nodes identifying significantly positive trends in the one season that were related to the most frequently mapped to nodes of an adjacent season.

In the 31 year study period, nodes 40, 39, 30, 32 and 22 were the most frequently mapped to nodes of the MAM season, however, the nodes associated with most of the significantly positive trends for MAM are nodes that characterize the synoptic conditions for the winter months of JJA (Figure 40). These nodes include 1 to 8, 14 to 16 and 22 to 24. This would suggest that more winter-like synoptic circulations are becoming more evident earlier in the year towards the autumn months of MAM. It is, however, difficult to associate these nodes with extreme rainfall due to their low frequency mappings in this regard shown in Figure 5 of Chapter Three. Although this may be as a result of the generalization of this SOM assessment, closer inspection of the synoptic circulations of these nodes suggest characteristics associated with extreme rainfall during winter months described in Chapter Four.

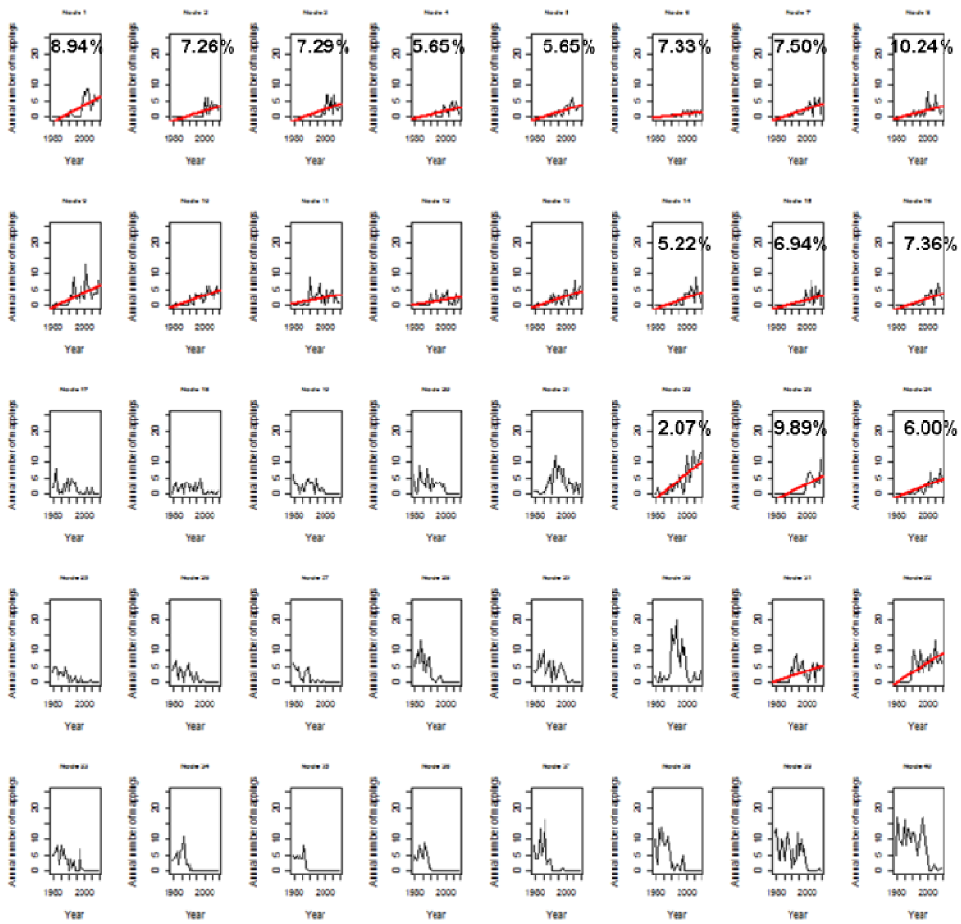

Figure 40: Relationship between significantly increasing trends of MAM nodes and their respective mapping frequencies (displayed above the nodes) occurring in the winter months of JJA.

A similar pattern is evident for SON in which the nodes associated with most of the significantly positive trends are the nodes that characterize the synoptic conditions for the summer months of DJF (Figure 41). These nodes include 17 to 20, 25 to 29 and 33 to 40. This would again suggest a possible shift in the synoptics characterizing the summer months of DJF earlier into spring. Nodes 36 and 37 were identified to be associated with extreme rainfall (Figure 5, Chapter Three). Although the trend for these two nodes is significant, the slope in the trend of the number of occurrences with time was very gradual and could be attributed to the latter years of the study period. Additionally node 25, which experienced the highest attribution of extreme rainfall and was not frequently mapped to for SON (1.77%), while it had a frequency of 6.22% for DJF identified a significantly increasing trend in SON. Therefore an increase in the occurrence of extreme rainfall driving synoptic circulations is evident in the spring months of SON.

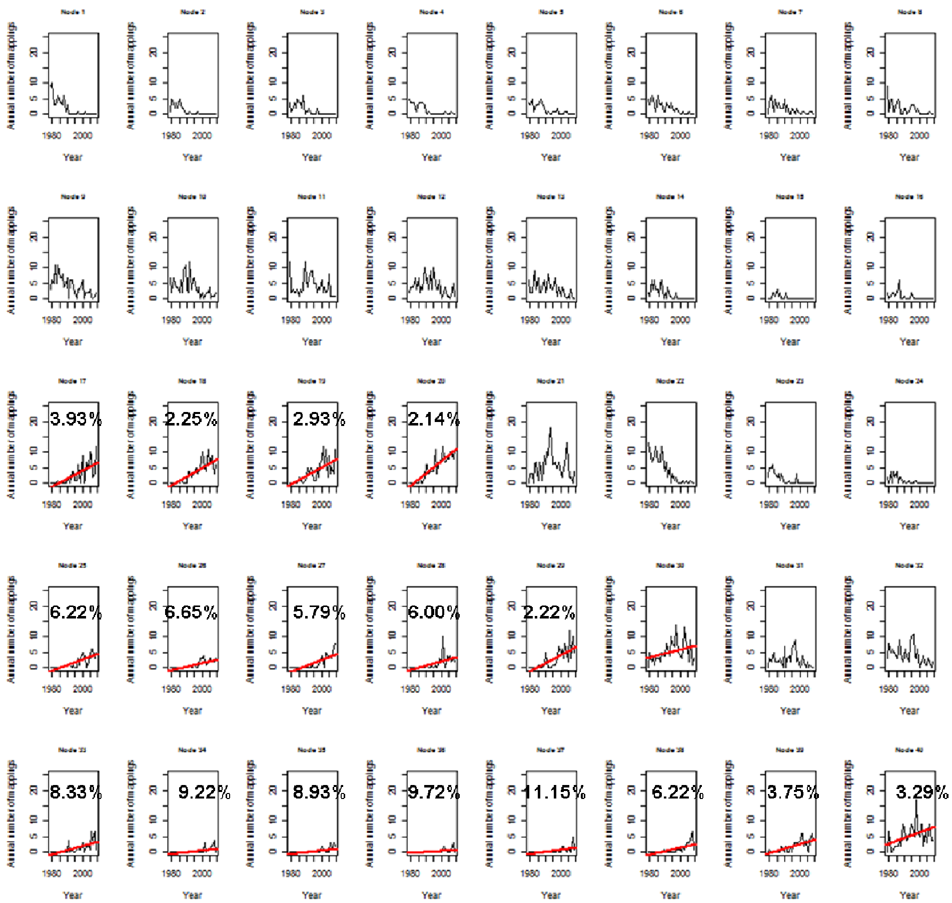

Figure 41: Relationship between significantly increasing trends of SON nodes and their respective mapping frequencies (displayed above the nodes) occurring in the summer months of DJF.

This relationship also exists between JJA and SON in which 6 out of the 7 significantly positive trending nodes of JJA (9 to 11, 13, 22 and 32) are also some of the most frequently mapped to nodes of SON. However, the slop of these trends are very gradual over the study period for JJA and while the nodes are most frequently mapped to for SON, SON experienced a very widespread mapping distribution resulting in low frequencies for these nodes (4.5%, 4.1%, 4.5%, 3.6%, 4.5% and 4.6% respectively).

Seasonal shifts in the synoptic circulations identified above are difficult to associate with extreme rainfall patterns in the station data. Though, these shifts in the synoptic circulations towards occurring earlier in the year relative to the following seasons are to some extent contrasting to the findings of Tadross et al. (2005) that describe general seasonal rainfall onset for the period 1979-1997 has been tending to occur later in the seasons, in particular over the coastal regions and the Limpopo Valley. This again might suggest that the general rainfall regimes used in this study may be different to extreme rainfall regimes that may exist throughout the country. The relationship that exists particularly between the months of SON and DJF indicates a possibility of summer extreme rainfall shifting earlier in the year into the months of SON.

5.4. Summary and discussion

Trends associated with extreme rainfall were assessed in this chapter for both the observed station data and the synoptic circulation patterns identified by the SOM analysis. RClimDex software was used for calculating trends in extreme rainfall indices based on the observed station records and a bootstrapping procedure was used for calculating the trends associated with the synoptic circulations identified in the nodes of the SOMs.

The predominantly limiting factor noted in this assessment was the 31 year study period evidently being too short for identifying extreme rainfall trends with significance. Apart from the SDII index, this was mostly apparent in the remaining 9 RClimDex indices for the observed station records. Though, a general observation revealed that a positive trend existed among the extreme rainfall indices (predominantly the 95^{th} and 99^{th} percentile threshold indices) throughout all the rainfall regimes except for the KZN coastal region. The SDII index, however, presented a strong signal of positive trends in which 18 of the 69 stations showed trends that were significant at the 5% level. Most of the positive extreme rainfall trends with significance were identified in the region around the southern parts of the Central Interior and the inland/northern parts of the Transkei, which agrees with the results obtained by Kruger (2006) for the same region.

Significantly positive trends in the synoptic circulations were identified in nodes 36, 37 and 40 of the SOM indicating these nodes have experienced an increase in their frequency of occurrence over the 31 year period. They are predominantly associated with summer rainfall type synoptics. Stations 42, 47, 49 and 58 were frequently mapped to these nodes, while at the same time also experienced positive trends in their extreme rainfall indices with significance at the 5% level in the SDII index for all four stations. The significance of the SDII index evident throughout this chapter suggests that it may be a sensitive indicator of changes in extreme rainfall patterns. Therefore the SDII index may be a more robust measure of extreme rainfall trends when using observed station data.

Spring (SON) and summer (DJF) experienced the highest number of nodes that were identified to have significantly increasing frequencies that were also associated with extreme rainfall synoptics. While a general observed relationship exists between shifts in the seasonal synoptic circulations characteristic of a season towards a preceding season, it is difficult to associate these shifts along with shifts in extreme rainfall. This was only evident in the relationship existing between SON and DJF in which synoptics associated with summer extreme rainfall are becoming more evident in SON.

Chapter Six: Summary and conclusion

The consequences of extreme rainfall events on society highlight the importance of research around this topic in order to gain a better understanding of their driving processes. Research associated with the effect of climate change on extreme weather events was highlighted by the Intergovernmental Panel on Climate Change (Nicholls et al., 1996) and as a result a number of studies involving this field of research arose over the following decade. One of these in particular is the latest release of the IPCC 2012, Summary for Policymakers SREX, which builds on the previous IPCC reports and highlights the importance of assessing extreme scenarios. As mentioned previously one of the conclusions to emerge from this report relative to this study was the "likely" (66-100% probability) increase in the frequency of heavy precipitation or the proportion of total rainfall from heavy falls during the 21st century (IPCC, 2012). Additionally, studies that involved South Africa showed an increase in the intensity of extreme rainfall over many regions of the country during the last 50 to 100 years. In this study we also assess changes in the characteristics of extreme rainfall over South Africa seen in the station record but furthermore relate these changes to the driving synoptic circulations. In addressing this a number of objectives were set which involved: (1) obtaining a sample of quality controlled observational station data for a 31 year study period from which extreme rainfall events could be identified based on various thresholds and (2) linking these observed extreme events to the associated synoptic circulation patterns obtained from the CFSR reanalysis data both on a country-wide and regional scale using SOM analysis. Finally trends in the frequency of occurrence of the extreme events were assessed and matched with trends in the driving synoptics.

The country-wide general circulation SOM analysis correctly identified the large-scale weather influencing synoptic circulations over South Africa along with the seasonal characteristics. The extreme rainfall analysis of this SOM indicated that the z500 level played a significant role in driving extreme rainfall due to the more clearly visible synoptic features and also that extreme rainfall was mostly associated with predominantly summer-like synoptic patterns. These synoptic circulations included a clear linkage between the sub-tropics and the mid-latitudes at the surface level in which the large majority of the country is over-shadowed by a low pressure system and in the upper layers the passing of a deep mid-latitude trough is present. Winter extreme rainfall was mostly associated with the passage of mid-latitude cyclones.

Synoptic circulations associated with extreme rainfall were assessed at the regional scale based on 8 rainfall regimes identified by Landman et al. (2001). The highest number of extreme rainfall events in the summer regions mapped to nodes resembling summer rainfall synoptic patterns while for the winter regions were associated with those resembling winter rainfall synoptic patterns. Extreme rainfall was identified to be predominantly associated with an interaction between synoptic features instead of one particular circulation in the summer rainfall region. As mentioned above this included a low pressure linkage between the sub-tropics and the mid-latitudes at the surface level. It was discovered that the synoptic drivers of winter extreme rainfall for the coastal regions of the Southern Coast, Transkei and KZN Coast were all very similar and involved interactions between a ridging high pressure and a sub-tropical trough at the surface level with a deep mid-latitude cyclone passing to the south in the upper air level. The South Western Cape experiences most of its extreme rainfall from synoptic circulations dominated by the passage of deep mid-latitude cyclones evident in the upper and lower atmospheric levels. With the presence of a surface high pressure over the rest of the country there is no evidence of interactions between synoptic circulations influencing the extreme rainfall over the South Western Cape.

Although the majority of extreme rainfall events were identified to occur within the respective rainfall season of each region, the seasonal assessment identified a high occurrence in the shoulder seasons. Summer rainfall regions experienced a higher occurrence of extreme events in the spring months of SON compared to the autumn months of MAM while the western winter driven rainfall region of the country experienced a greater occurrence in MAM as opposed to SON.

It was evident in the regional SOM assessment of extreme rainfall events that cut-off low pressure systems were not identified despite their significant association with extreme rainfall events in the Southern regions of the country. These events were reflected in the observed station data and linked to the associated synoptics. However, the spatial divisions between the 8 rainfall regimes used in this study were not representative of extreme rainfall synoptics which resulted in specific extreme events like cut-off lows being divided amongst often three regions and this prevented the regional SOMs from identifying them. It is therefore suggested that an event-based analysis would provide better insight to the attributes of specific extreme rainfall driving synoptics as well as providing an improved regional classification and assessment of extreme rainfall.

Most of the challenges in the study arose when analyzing the trends associated with extreme rainfall events, the most important being the 31 year study period being too short to yield any form of significance due to the low frequency of extreme rainfall events. This was evident in the observed station data records as various stations within a given rainfall region with close proximity to each other displayed different signals and few significant trends were identified altogether. The few significant trends that were identified in the station data were associated with summer rainfall regions and were mostly reflected in the SDII extreme rainfall index. An assessment of trends in the synoptic circulations associated with extreme rainfall identified significantly increasing trends for specific summer extreme rainfall driving synoptics characterized by a sub-tropical low over most of the country and a high pressure over the eastern parts of the country. These significantly increasing synoptic circulations were matched to those stations that had exhibited a significantly increasing trend in their observed records of extreme rainfall. This relationship between the significantly increasing trends in the extreme rainfall associated synoptics and the significantly increasing trends in the observed station data therefore indicates that extreme rainfall has increased in the summer rainfall regions of South Africa over the 31 year study period. The SDII index may also be a robust tool for assessing the trends of extreme rainfall in observed station data.

An assessment into the inter-seasonal shift of extreme rainfall driving synoptics was also carried out. This was achieved by analyzing the relationship between nodes associated with extreme rainfall synoptics in each season and those that displayed significantly increasing trends in the adjacent seasons. It was evident that 3 out of the 4 inter-seasonal relationships (JJA-MAM, DJF-SON and SON-JJA) yielded a shift towards an earlier onset of extreme rainfall. This is opposed to the general understanding that seasonal rainfall in South Africa is more likely to be shifting towards later onsets within the respective regimes. This again highlights the difference between the characteristics of extreme rainfall and general rainfall patterns in South Africa.

To address the main aim of this study, which was to identify synoptic circulations associated with extreme rainfall in South Africa, a number of objectives were set out in the introductory chapter:

- Identify the attributes of extreme rainfall events in the station data records

- Identify synoptic circulations associated with extreme rainfall across the entire region of South Africa
- Identify extreme rainfall specific synoptic circulations using only data from extreme rainfall events
- Identify the synoptic drivers of extreme rainfall at the regional scale
- Identify trends in the characteristics of extreme rainfall
- Identify regions in South Africa that have experienced any changes in the frequency of occurrence of extreme rainfall and the associated synoptic circulations

Each of these objectives were met and in so doing various findings were made, in particular those regarding the regional and seasonal distribution of the specific synoptic circulations associated with extreme rainfall events. However, the research methods fell short of being able to achieve certain outcomes like identifying cut-off lows. This provided insight into the spatial difference between the general rainfall regimes of South Africa compared to the extreme rainfall regimes as well as investigating the use of the SDII extreme rainfall index as a tool for assessing trends in observed station data.

The increased awareness of the impacts associated with extreme weather events around the globe coupled with climate change research presents the question of how these extreme events may be influenced by a changing climate in future years. As previously mentioned this topic is highlighted by the latest IPCC special report on extreme scenarios in which we can expect a “likely” (66-100% probability) increase in the frequency of heavy precipitation or the proportion of total rainfall from heavy falls during the 21st century. This question has also been addressed in the past and Mason and Joubert (1997) found that an increase in heavy rainfall events over southern Africa may be expected under a doubled CO^2 climate. More recently studies have found links between changes in global climate and regional extreme weather events (IPCC, 2012). In terms of the findings presented in this study in order to comprehend the potential changes in extreme rainfall at a regional scale in South Africa further work may be carried out. This includes:

1. Establishing extreme rainfall specific regions based on station and circulation data.
2. Investigate the use of appropriate extreme indices for assessing trends in extreme rainfall characteristics such as the SDII.

3. Assess cut-off low and TTT data to identify the specific synoptic circulations associated with these systems.
4. Using the latest GCM output data to assess the future changes in the characteristics of extreme rainfall events over South Africa.
5. Assess how the potential changes in the characteristics of extreme rainfall may affect society in a number of sectors such as agriculture, water supply and housing.

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