OBSERVED TRENDS IN DAILY EXTREME TEMPERATURE INDICES (PERCENTILES) OVER THE WESTERN AND EASTERN CAPE OF SOUTH AFRICA FOR THE PERIOD 1960 TO 2005.

By

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Abstract

This thesis has investigated changes in the frequency of extreme cold and hot tails in the probability distributions (percentile indices) of minimum and maximum temperature events over the Western Cape and Eastern Cape for the period 1960-2005. The focus was to determine whether the changes in hot and cold tails (extreme tails) showed any trends or variability. The data used in this thesis are from 12 high quality observing weather stations over the two regions. The findings of this study suggest a statistically significant decreasing trend in the frequency of cold days and cold nights over the Western Cape. A statistically significant increasing trend for hot days and hot nights was also found for the same area. No clear evidence exists to suggest any trend over the Eastern Cape, except for relative changes in the extreme tails associated with seasonal and monthly variations.

The possible relationships and the influence of the present atmospheric circulation anomalies on temperature extremes were sought from NCEP re-analyses by means of comparisons on the seasonal scale between the first and last decades of the study period. It is suggested that more extreme temperatures have occurred towards the recent decades, in particular during the 1995-2005 decade. These patterns appear to be associated with a tendency to more intense anticyclonic conditions in spring and autumn and occasionally in winter seasons. However, the results also suggest that further investigation of the relationship between any trend in surface air temperature and the changes in regional circulation to ascertain if local mechanisms might modulate any large scale trend arising from anthropogenic induced global warming remains a challenge.

Acknowledgements

The author would like to express appreciation to my supervisor Prof Chris Reason for the invaluable guidance and advice during this study. Thanks are due to the management of the South African Weather Service (SAWS) for the financial support and time to study. The databank division at SAWS supplied the data. Last but not least all my colleagues at SAWS who helped with comments and suggestions.

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Chapter 1: Introduction

1.1. Background on extreme temperatures

Over recent years, extreme events such as heat waves, cold snaps and droughts have received increased interest from climatologists and researchers worldwide. Since changes in climatic extremes continue to take place due to natural or human induced processes (Bonsal et al., 2001; Tank et al., 2005), the need for continuous investigations on these changes, especially on extreme temperature events is inevitable. Impacts of changes in temperature could be felt through manifestations in changes in the hot and cold tails [i.e. the upper (lower) 90th (10th) percentile indices denoted by TX90P, TN90P (TX10P, TN10P)] of minimum and maximum temperatures (Tank et al., 2005).

Studies accomplished on extreme temperature events over Southern Africa include those of (New et al., 2006; Kruger and Shongwe, 2004; Muhlenbruch-Tegen, 1992; King'UYU et al., 1999; Unganai, 1997; Hughes and Balling, 1996) and in other parts of the globe (Alexander et al., 2006; Tank et al., 2005; Easterling et al., 2000, 2003; Vincent et al., 2005; Bonsal et al., 2001; DeGaetano, 1996; DeGaetano and Allen, 2002; Zhai and Pan, 2003). The general consensus among these studies is that, many parts of the globe appear to depict a significant decrease in the number of cool days and nights, as opposed to positive trend in hot days and nights that showed no significance.

Further analysis of changes in the extremes at a global scale is well documented in Frich et al. (2002).

In South Africa, the assessment of past and recent changes in the hot and cold tails (hereafter extreme tails) of temperature events, with the knowledge of paucity and/or more often spatially sparse observational network, elicits the necessity and importance for continual investigations of these climatic characteristics. Vincent et al. (2005) indicated that subtle verification on the possible changes in daily extremes is crucial especially because they affect many aspects of human life.

Kruger and Shongwe (2004) for instance, investigated the temporal and spatial trends of minimum and maximum temperatures over South Africa during the period 1960-2003. Their study consisted of 26 climatic stations across the country, looking into the extreme maximum and minimum temperatures at various time scales (annual, seasonal and monthly). They further discussed the role of urban, non-urban and El Nino Southern Oscillation (ENSO) effects on such extremes.

Their study found that the mean annual maximum temperature has shown significant positive trends over the inland stations as opposed to the coastal stations. These trends were shown to be dependent to a certain degree on the season (Kruger and Shongwe, 2004). A temporal monthly variation was also evident for some individual stations in the latter study. The study also reported a decrease in extreme days and nights with relatively low temperatures, but an increase in trend over the country of days and nights with relatively high temperatures.

These findings are backed up by the results of the study of King'UYU et al. (1999) encompassing Eastern Africa and parts of Southern Africa. They found that the northern part of the study area was characterized by warming nighttime and cooling daytime temperatures for the period 1939-1992. The study, like that of Kruger and Shongwe (2004), also found significant correlations between temperature and the ENSO phenomenon relative to certain seasons. Hughes and Balling (1996) investigated various results constructed from urban and non-urban stations for the period 1960-1990. Their findings were similar to those of Kruger and Shongwe (2004).

In another study, Muhlenbruch-Tegen (1992) showed some evidence of monthly mean temperature trends over a 49-year period (1940-1989) in South Africa. Despite the fact that this study found in some cases little significant temperature changes over land, the main findings were consistent with the increasing trend showed by Kruger and Shongwe (2004). Using data from a limited number of stations in South Africa, New et al. (2006) observed similar trends in maximum and minimum temperatures. They further suggested that the distribution of hot ends of extremes appears to have undergone more changes (particularly in the

North West of the region) than the cold extremes (especially in the South East and East) for minimum temperatures.

1.2. Atmospheric circulation and rainfall over the region and the study area.

Numerous previous studies demonstrated that atmospheric circulations have important bearings on the cloud cover and rainfall over the African subcontinent (Hastenrath et al., 1995; Preton-Whyte and Tyson, 1988; Tyson 1986; Kabanda and Jury, 1999; Van Heerden et al., 1988; Lindesay, 1988; Matarira and Jury, 1992; Mulenga et al., 2003; Jury and Levy, 1993; Mason 1995). In this thesis, the focus is placed on the Western Cape (WC) and the Eastern Cape (EC) provinces of South Africa.

The WC is a mainly austral winter rainfall area (Reason et al., 2002), and receives its rainfall mainly from cold fronts (Reason et al., 2002; Reason and Jagadheesha, 2005), and to lesser extent, cut-off lows (Singleton and Reason, 2007a). Winter rainfall totals are influenced by the sea surface temperature (SST) anomalies in the South Atlantic ocean as well as by sea-ice variations in the Weddell Sea and Drake Passage region (Reason et al., 2002; Reason and Jagadheesha, 2005; Blamey and Reason, 2007). On the other hand, the EC is a year round rainfall area, receiving rainfall from cold fronts, cut-off lows (Singleton and Reason, 2006), ridging anticyclones and tropical temperate trough associated cloud bands (Preston-Whyte and Tyson, 1988; Williams et al., 2007).

1.3. Historical changes in extreme temperature and the projected changes on Southern Africa climate.

Historical observations of the mean global surface air temperature showed a high rate of warming associated with individual seasons in the recent decades, especially from 1990 to 2005 (Lugina et al., 2006). The finding supported is over Southern Africa by Kgatuke et al. (2003), who simulated an increase in maximum temperatures for the present climate from 1991 to 2000, using the nested climate model DARLAM (Division of Atmospheric Research Limited Area Model). Future projections for the periods from 2021 to 2030 and 2051 to 2060 suggest warmer summer conditions and increased warming in response to green-house gas forcing (Kgatuke et al., 2003).

The instrumental records of the mean annual maximum temperature have already showed a rapid increase over the central interior of the subcontinent in the recent years, and these changes are projected to strengthen in future (Kgatuke et al., 2003). The eastern and central parts are argued to indicate a tendency of drying out, while the cloud bands are likely to be shifted to the west (Engelbrecht, 2005; Kgatuke et al., 2003). Presently, drier and warmer winters have been simulated (Kgatuke et al., 2003). This possibility is likely to increase, with subtropical high pressure belt projected to intensify and mid-latitude cyclones moving further south (Kgatuke et al., 2003).

Jones et al. (2004) also support these climate change projections over southern Africa. Their findings suggest that the average surface warming will be 3.8°C (4.1°C) in summer (winter) by the 2080s, with rainfall projected to decrease over much of the western and the subtropical subcontinent and increase over eastern and tropical Southern Africa during summer (Jones et al., 2004). These projections were based on the PRECIS (Providing Regional Climates for Impacts Studies) model.

With Southern Africa characterized by pronounced intrinsic rainfall variability (Mulenga et al., 2003), and given the present pressure patterns, and the projected changes in future climate in the southern Africa (Kgatuke et al., 2003; Engelbrecht, 2005), it is possible that changes in the past and present atmospheric circulation patterns could have already had adverse effects on the distribution of temperature extremes over the WC and EC region.

1.4. Motivation of the study

This thesis builds greatly on previous studies of extreme temperature events. Investigations of extreme temperature events over the country were focused mainly on annual, seasonal to monthly trends, with little attention on the frequency (hereafter occurrence) of extreme tails (ends) and the associated atmospheric circulation patterns. This study attempts to fill the gap that exists in other previous studies on the possible relationships between trends in extreme surface air temperature and changes in the regional atmospheric circulation patterns. The main objective of this study is not to investigate the impacts of climate change on extreme temperature. However, the study is partly motivated by the climate model projections of changes that are projected to happen over the Southern Africa region for temperature, rainfall and Sea Level Pressure (SLP). Therefore this investigation considers how the current changes in high pressure system over the subcontinent and the displacement of mid-latitude cyclones further south (Engelbrecht, 2005; Kgatuke et al., 2003) might influence the occurrence of extreme percentile indices of maximum and minimum temperature over the WC and EC regions of South Africa.

Here, we endeavoured to achieve this by mainly using and focusing on percentile indices. Additional indices such as the absolute indices, i.e. the monthly highest maximum and minimum temperature (TXx, TNx) and the monthly lowest maximum and minimum temperature (TXn, TNn) were also used to verify the extreme temperature events. Similarly the annual maximum temperature (SU or warm days) and the annual minimum temperature (TR20 or warm nights) were further considered for supportive analysis in this study.

Therefore, this thesis compares and examines the existence of any significant changes in the occurrence of extreme ends of temperature between the WC and EC of South Africa. The main objective is to assess if the observed changes in the occurrence of the extreme tails of minimum and maximum temperature can explain any form of trend and or variability. We further explore if the observed extreme changes are a function of anomalous atmospheric circulation patterns over the recent century or just a result of general warming in the distribution of the minimum and maximum temperature.

1.5. Conclusion

The purpose of this chapter was to present the existing evidence on the investigation of daily and extreme temperature events globally. This was done to provide the foundation upon which the daily extreme temperature indices over the Western Cape and the Eastern Cape Provinces of South Africa are analyzed. The available literature on the investigation of extreme temperature both in the region and globally demonstrated that there is a significant decrease in the number of cool days and nights, as opposed to positive trend in hot days and nights that showed no significance. There is also some evidence that other variable such as cloud cover; rainfall and atmospheric pressure circulation patterns have bearing on extreme temperature.

Based on the above evidence, it was necessary for this study to investigate extreme temperature indices at the two provinces. The study is divided into four chapters. Literature review is presented in chapter 1, data and methods in chapter 2, the analysis and discussions of the results in chapter 3, with chapter 4 summarizing and concluding this study.

Chapter 2: Data and Methods

2.1. Introduction

The data used for analysis in this study is derived from 12 high quality observing stations covering the WC (7 stations) and EC (5 stations) of South Africa. These data were also used in other studies that investigated temperature trends over the region. The variables investigated and the quality control measures and methods used are defined below.

2.2. Data and Quality control

2.2.1. Observed station data

Daily minimum and maximum temperature data were obtained from the climate data bank of the South African Weather Service (SAWS). This data set, which covers a 45 year period, was used to calculate selected temperature indices (Table 2.1). This then provided us with the possibility to examine the significant changes in the occurrence of cold and hot (extreme) tails of the minimum and maximum temperature for the WC and EC areas of South Africa over the period 1960-2005.

The quality of daily observations is crucial for studies of daily extremes, especially that of temperature. This thesis adopted extra measures used in other studies to supplement the quality control methods employed by the South African Weather Service (SAWS). The quality control methods adopted here are similar to the ones used in other regional and global studies (e.g. Kruger and Shongwe, 2004; New et al., 2006; Alexander et al., 2006; Easterling et al., 2003).

Table 2.1: Indices used in the study and their description.

Index	**Description**	**Definition**	Units
TX90p	Hot day frequency	Percentage of days when TX>90th percentile of 1960-2005	%
TX10p	Cool day frequency	Percentage of days when TX<10th percentile of 1960-2005	%
TN90p	Hot night frequency	Percentage of days when TX>90th percentile of 1960-2005	%
TN10p	Cool night frequency	Percentage of days when TX<10th percentile of 1960-2005	%
TXx	Maximum daily maximum (hottest day)	Monthly highest maximum (TX)	°C
TXn	Minimum daily maximum (Coolest day)	Monthly lowest maximum (TX)	°C
TNx	Maximum daily minimum (hottest night)	Monthly highest minimum (TN)	°C
TNn	Minimum daily minimum (coolest night)	Monthly lowest minimum (TN)	°C
SU	Warm days	Annual count when TX>25°C	Days
TR20	Warm nights	Annual count when TN>20°C	Days

Time consuming but rigorous processes were carried out before the indices could be calculated and analyzed. Firstly, the methods adopted by New et al. (2006) were opted for this study. The data was then manually checked for apparent errors (e.g. minimum temperature greater than maximum temperature). A standard deviation of 3 was defined in this study as a threshold or limit to assert if there were any outliers in the data. Note that other studies resulting from regional workshops used standard deviations of 3.5 and 4 respectively (e.g. New et al., 2006; Alexander et al., 2006).

Where irregularities were suspected in the data set, or if any misgivings about extremely high values in the data set arose, we verified the results by comparing the station with the neighbouring ones before the station could be used for analysis. Issues of homogeneity remained an important element of this study, hence in addition to the homogeneity test done by a written statistical language called RClimDex (herein after "R"), it was necessary for this study to verify if the station had relocated or undergone major changes, and that was done using the metadata files. The data used in this study was derived from 12 high quality observing stations (see Figure 2.1) covering the WC and EC of South Africa. Kruger and Shongwe (2004) employed more or less the same stations for their study.

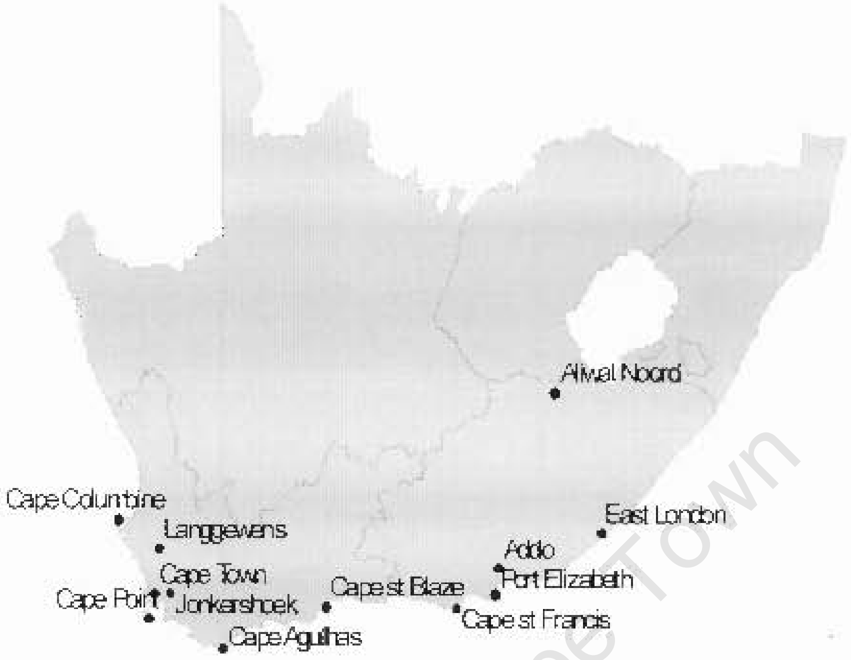

Figure 2.1: Names of stations investigated and the provinces they are located in.

A slightly modified selection criterion to that of New et al. (2006) was applied to determine which stations were to be used in this study. Therefore as a prerequisite, the station data was regarded to be as complete as possible if no more than five percent of the data over the period is missing (e.g. a station that has more than two and half years of missing data for the period 1960 to 2005 could not be used for analysis), or if more than one month data was missing within a year. Other previous studies (e.g. Alexander et al., 2006; and Kruger and Shongwe, 2003) have respectively adopted 80% and 90% of available data for each station as a qualifying condition for a station to be used.

2.2.2. NCEP re-analysis data

The National Centre for Environmental Prediction (NCEP) re-analyses data set, provided by the NOAA-CIRES Climate Diagnostic Centre, was used to study associated circulation anomalies that might aid in the explanation of the trends or inter-annual variability of observed extreme tails of temperature. The data is a global model assimilation of observational data from a number of sources including rawinsonde, satellite, land stations, and ship data (Kalnay et al., 1996).

These data have been used in many scientific studies, including studies of trends in temperature (e.g. King'UYU et al., 1999; Vincent et al., 2005; Dai et al., 2005; Hasanean, 2004). The reliability (or lack thereof) of the NCEP re-analyses data prior to 1979 is pointed out in other previous studies (e.g. Mulenga et al., 2003). The impact that may result from the inconsistency and limitations of this data on the results of this study over the said period was noted. However, the data from 1979 – onwards has been demonstrated to be of higher quality (Tennant, 2004). Therefore, the NCEP re-analyses geopotential height and wind data were analyzed for the Southern African domain from 0° – 50°S and 0° – 60°E from 1960 to 2005.

2.3. Definitions and Methods

2.3.1. Daily observations

Daily observed temperature data were analyzed utilizing the "R" software package, which is a user friendly statistical package available for download from (http://cccma.seos.uvic.ca/ETCCDMI). The indices (see Table 2.1) selected for analysis in this study were from the 16 temperature indices of daily maximum and minimum temperature. They were calculated in the manner consistent with the formulations and internationally coordinated standards by the Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI). The validity of the approach is discussed in other regional and global studies, for example, Peterson et al.,1999; Tank et al., 2005; New et al., 2006; Vincent et al., 2005.

The definitions used in this study are consistent with the manipulations and calculations of the indices as arranged and embedded in "R" software, and were not in anyway altered (see Table 2.1). These methods were widely used in other studies throughout regional workshops, for example New et al. (2006), Bonsal et al. (2001), Kruger (2007) and Vincent et al. (2005). More details of the methods are contained in Zhang and Yang (2004). The extreme hot day and night indices, i.e. the 90th percentiles of maximum and minimum temperature (TX90p and TN90p), were defined as the probability of hot days and hot nights frequency (occurrence) when the percentage of days and nights are greater than the 90th percentile of 1960 to 2005. Similarly cold days and nights temperature extremes (TX10p and TN10p) were defined as the probability of cold days and cold nights frequency (occurrence) when the percentage of cold days and cold nights is less than the 10th percentile of 1960 to 2005.

The absolute indices TXx and TNx (TXn and TNn), which indicate the hottest day (night) and the coolest day (night) were defined as the highest monthly maximum (minimum), and the lowest monthly maximum (minimum). The warm days (SU) and warm nights (TR20) were defined as the annual count when maximum (TX) temperature is greater than 25°C and the annual count when minimum temperature (TN) is greater than 20°C but less than 25°C respectively.

It is worth mentioning that the latter definition of warm days and warm nights do not represent very hot days and hot nights respectively. Rather they were used in this thesis to assess if the maximum and minimum temperatures indicate and support warming trends in the extreme cold and hot tails. Hence the definition used in "R" for these indices was acceptable in this study as it was only used for supportive analysis, and was found not to have altered the results of the extreme percentile indices.

This study used an improved methodology developed in "R" to obtain percentile indices (Vincent et al., 2005). This improved version was developed by Zhang and Yang (2004). A bootstrapping procedure was developed to better estimate the percentiles during the reference period (1961 to 1990), Zhang and Yang (2004), Vincent et al. (2005). Further details of the methods and procedures on how to manipulate the data and results could be found in Zhang and Yang (2004), Vincent et al. (2005).

The trends analyzed were computed using linear least squares, and locally weighted linear regression. The significance of the linear trend was tested by a two-sided test statistic at the 5% level (Zhang and Yang, 2004; Kruger, 2006). Using this approach, this study had confidence in the qualitative procedures and the reliability of the methods and the results produced by the “R” software. This study further relied on the evidence provided by other studies using almost the same approach (e.g. Vincent et al, 2005; Peterson et al, 1999; New et al, 2006), to provide the underlying explanation behind changes in the extreme tails of the minimum and maximum temperature over the two southern coastal regions of South Africa.

The study therefore maintained the test statistics employed in “R”. The indices were used for their straightforward and easy to understand nature although this approach may reduce the number of possible statistical characteristics of the extremes (Tank et al, 2005). The application of a more robust statistical approach was beyond the scope of this study. However, this is the area that may require further investigation to improve understanding of the distribution and the trends of extreme temperature events.

In addition to the trends calculated using "R" software, we calculated or averaged each of the four percentile indices from the stations in the WC and EC and plotted the time series with a five year moving average to smooth the local linear trends. Trends were tested at the 5% level using a two sided t-test statistic for significance. These plots were used to visualize and assess as to whether there was evidence of consistent spatial trends or temporal variations between the WC and the EC in the extremes percentile indices where the maximum and minimum temperature extremes were above (below) the 90th (10th) percentile respectively.

2.3.2. Atmospheric variables

The NCEP/NCAR re-analyses data (Kalnay et al., 1996) were used to assess regional atmospheric circulation. Although the 2.5° horizontal resolution of the NCEP re-analyses is inadequate to fully capture regional topographic and SST gradients, it is sufficient to assess the influence of the regional atmospheric circulation on the distributions of temperature extremes.

To determine if there is any evidence of circulation influences, we contrasted the seasonal circulation patterns at 850 mb level to examine differences in mean circulation between the first decade and the last decade (i.e. 1995 to 2005 minus 1960 to 1970) of the study. The associated seasonal mean zonal winds at 850 mb are analyzed to determine the strength and direction of the circulation.

However, it is worth noting that small scale features, such as the changes in the land use and topography could also possibly affect the temperature extremes. Thus further studies using downscaling may be necessary to achieve a better understanding of the effects of topography on extreme temperatures.

The seasons were categorized according to the definition used by Muhlenbruch-Tegen (1992), Kruger and Shongwe (2004) in their studies of extreme temperature. They are defined as December-February (DJF) for summer, March-May (MAM) as autumn, June-August (JJA) as winter, and September-November (SON) as spring, and were produced for the periods investigated in this study.

2.4. Conclusion

The data and methods adopted for analysis in this thesis were in line with other previous investigations on extreme temperature analysis throughout the world. Additional steps were also taken to ensure high quality and the reliability of the data. The NCEP data was also used to investigate circulation associated with the results derived from station observations data. It should be noted that this study focused on temperature in isolation to other station observed variables. However, it is noted in this study that further statistical analysis amenable to incorporating climate change observations would be required in future.

Chapter 3: Results and Discussions

3.1. Introduction

In this chapter, the analysis of trends for the percentile indices, absolute indices and threshold indices derived from the data analysis and methodologies in Chapter 2 are sought. Trends in the occurrence of extreme cold and hot tails (ends) of the minimum and maximum temperature were investigated with focus based on trends and variability, and whether the observed changes could be explained by the changes in the regional circulation patterns or just the accompanied warming in the maximum and minimum temperature events.

For a simple indication of whether the results (hot and cold tails) are significant or not, Tables 3.1 & 3.2 below summarize the number of stations with statistically significant positive, negative and no significant extreme tails. Where results are statistically significant, these are highlighted in bold for significant positive, and underlined for significant negative for the period 1960 to 2005. For the purposes of this thesis, those results that are statistically significant will be reported as significantly increase or decrease, unless stated otherwise. Results that are not statistically significant are also stated.

Table 3.1: Stations in the Western Cape showing results for the frequency of hot and cold (extreme) tails of temperature indices for 1960 to 2005. The values indicate the number of

stations with statistically significant increase in the frequency of extreme tails (bold), statistically significant decrease (underlined) at the 5% level. Non-significant increase (+) and non-significant decrease (-), with (±) showing a mixture of stations with positive and negative extreme tails.

Extreme Indicator	No. of stations with positive (increase) extreme tails	No. of stations with negative (decrease) extreme tails	Statistically significant at the 5% level	Non-significant
Cold days	0	7	4	(-) 3
Cold Nights	0	7	5	(-) 2
Hot Days	3	4	**3**	(-) 4
Hot Nights	7	0	**4**	(+) 3
Coolest Day	6	1	**1**	(±) 6
Coolest Night	7	0	**3**	(+) 4
Hottest Day	3	4	0	(±) 7
Hottest Night	6	1	**1**	(±) 6
Warm Days	7	0	**3**	(+) 4
Warm Nights	6	1	0	(±) 7

Table 3.2: Same as Table 3.1, but for the Eastern Cape.

Extreme Indicator	No. of stations with positive trends	No. of stations with negative trends	Significant	Non-significant
Cold days	2	3	2	(±) 3
Cold Nights	2	3	**1** & 2	(+) 2
Hot Days	1	4	**1** & 1	(-) 3
Hot Nights	4	1	**1**	(±) 4
Coolest Day	4	1	0	(±) 5
Coolest Night	3	2	0	(±) 5
Hottest Day	4	1	0	(±) 5
Hottest Night	3	2	0	(±) 5
Warm Days	4	1	**2**	(±) 3
Warm Nights	4	1	**1**	(±) 4

3.2. The occurrence of cold and warm extreme tails (Percentile Indices)

The probability distribution or the frequency of the four indices of the upper (90th) and lower (10th) percentile indices of the minimum and maximum temperature are presented in Figure 3.1, and analyzed for a total of 12 stations in the WC (7 stations) and EC (5 stations). It could be seen from the plots (Figure 3.1), and the summaries in Table 3.1, that all the 7 stations in the WC show a decrease in the occurrence of extreme cold day and cold night tails, with 4 and 5 of the 7 stations showing significant results for cold days and nights respectively (Table 3.1).

The occurrence of extreme hot days over the WC indicates a mixture of stations with opposite (increased and decreased) extreme tails distribution. It could also be seen from Table 3.1 that of the seven stations illustrated in Figure 3.1 over the WC, four stations mainly over the interior (i.e. Langgewens, Jonkershoek, Cape Town and Cape St Blaze at the coast) showed a decrease in the occurrence of hot days although this was not significant. The occurrence of hot night extremes illustrates an increase at almost all the stations. However, the significant increase was observed at the stations along the coast for hot night extremes, except for the Cape St Blaze station that showed a decrease that was not significant.

On the other hand, the EC province showed mainly contrasting results in the extreme tails distribution of maximum and minimum temperature among all the five stations investigated (Figure 3.1). These opposite results among the stations are more noticeable for almost all the four percentile indices, except for the occurrence of hot night extremes, which indicates four stations (i.e. Aliwal Noord and Addo inland, and Port Elizabeth along the coast, with East London also along the coast being the only station that showed significant increase) with consistent positive or increased extreme tails (Table 3.2).

It can be seen from Figure 3.1 and Table 3.2 that out of the total number of five stations, the coastal station of Cape St Francis and the inland station of Addo (Figure 3.1) are the only two that showed a significant decrease in the occurrence of cold night extremes. Similarly significant decreases in the cold day tails were observed at the Addo and East London stations. The overall results in the EC (Figure 3.1) show a few stations (1 at most) with significant increase or decrease in the occurrence of the extreme events at places, but were mainly dominated by spatially mixed or opposite results with decreasing or increasing extreme events that did not show any significance in almost all the indices studied.

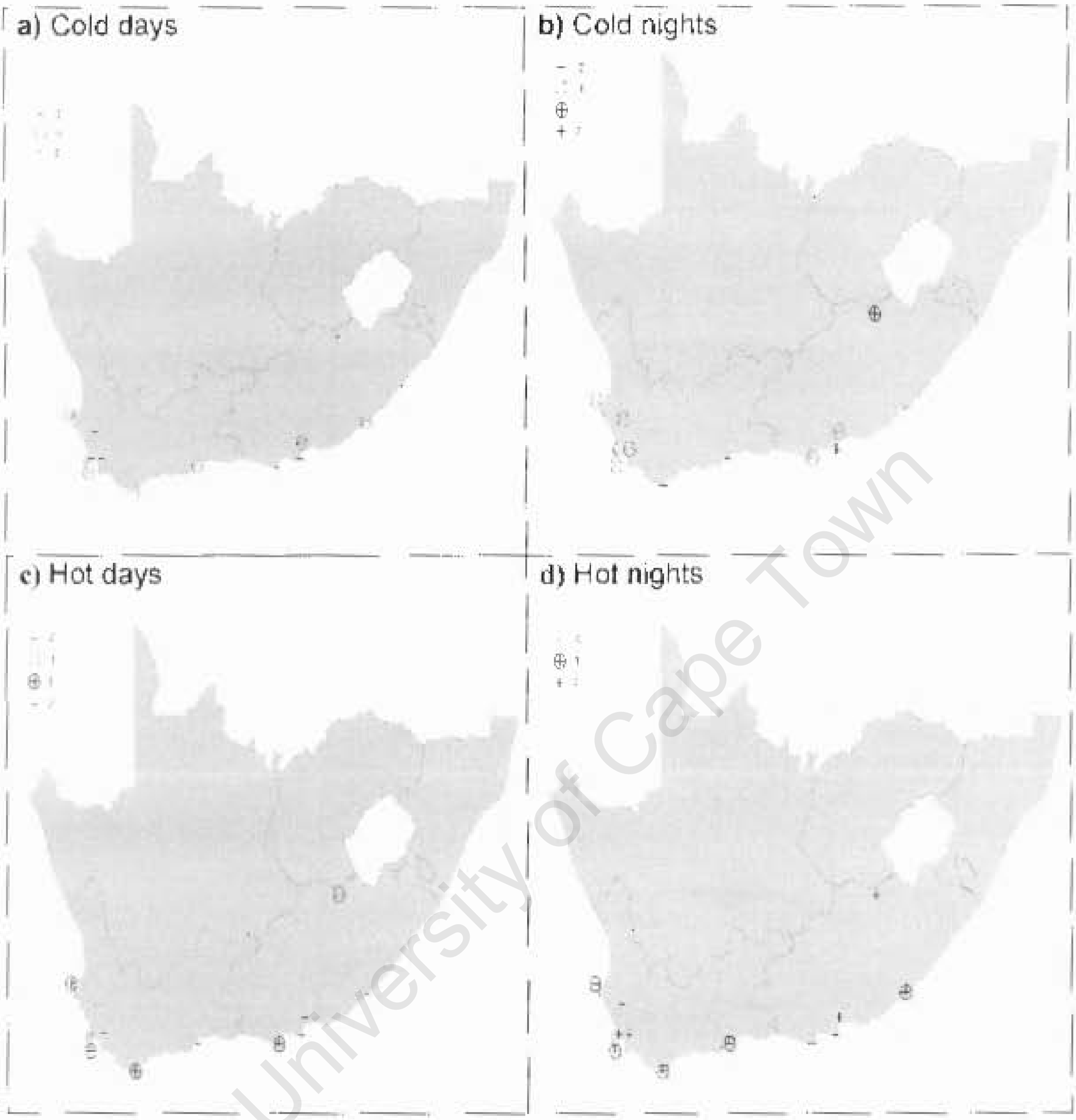

Figure 3.1: The station probability distribution trends for the four indices (the 10th and 90th percentiles) of daily minimum and maximum temperature for the period 1960 to 2005. The symbols are explained as follows; 1 with a positive sign in a circle denotes a significant increasing trend at the 5% level. -1 with a negative sign in a circle denotes a significant decreasing trend at the 5% level. Minus sign with a -2 shows no significant negative trend, and positive sign with a 2 shows no significant positive trend

3.3. Comparison of the station averaged time series for cold and hot tail extremes between the WC and the EC

It may not be possible to suggest, on the basis of the similarities or variations in the distribution of extreme tails shown by the individual stations over the same area (Figure 3.1), that the results show any spatial or temporal consistency. Therefore, in addition it was important to combine these stations together in order to compare and assess whether there was any consistent spatial and temporal trends that are significant for cold days (hot days) and cold nights (hot nights) extremes between the WC and EC, or if these trends were simply the reflection of the distribution and the magnitude of the changes at individual stations associated with regional atmospheric circulation patterns.

The results presented in Figures 3.2 & 3.3 were derived from the same data as those in Figure 3.1, but the only difference is that Figures 3.2 & 3.3 represent the time series for the 7 stations (5 stations) averaged or combined together for the WC (EC), while those discussed in Figure 3.1 in the previous section discriminated extreme tails at individual stations.

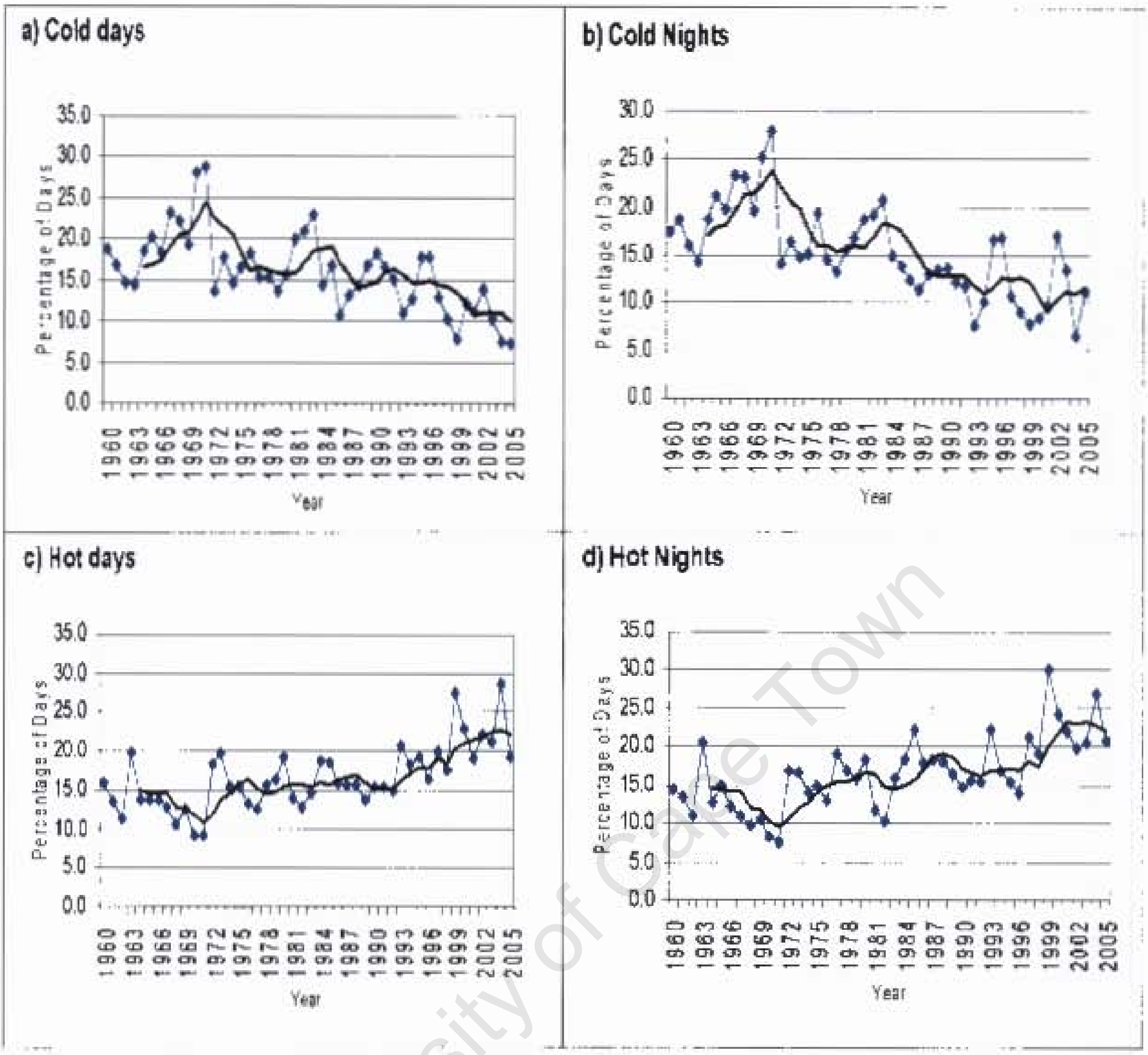

Figure 3.2: Trends in averaged stations time series for Western Cape, showing the occurrence of (a) cold days, (b) cold nights, (c) hot days, and (d) hot nights based on daily minimum and maximum indices. The bold line is the 5 year running mean.

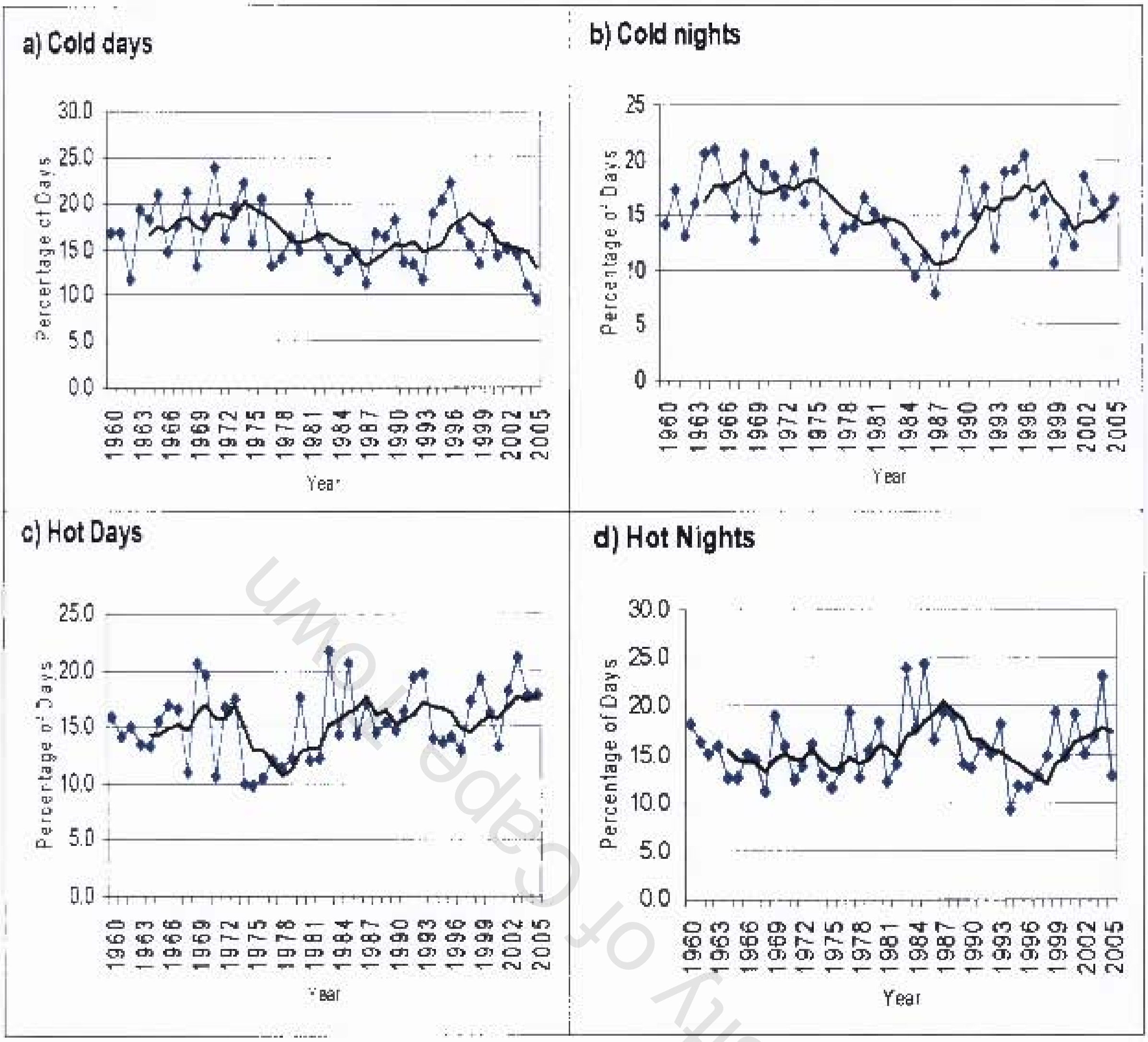

Figure 3.3: Same as Figure 3.2, except for the Eastern Cape region.

These results were constructed by averaging all the stations for each of the four percentile indices, and the results were tested by two sided t-test statistic for significance and plotted as one time series for each of the regions (WC and EC). Figure 3.2 suggests that, taken together, the stations over the WC illustrate a cohesive spatially decreasing temporal trend that is statistically significant for cold days and cold nights. In addition, a coherent increasing trend that is statistically significant in the extreme hot days and hot nights was found for the WC for all the stations combined together.

On the other hand, the EC illustrated a lack of any coherent spatial trends in the extremes. However, the results shown in Figure 3.3 demonstrate that this province might have been dominated by temporal variations associated with greater sparsely spatial distribution of stations, or as a result of the magnitude of changes in the occurrence of extreme events at those individual stations. These results are in line with the findings of King'UYU et al. (1999), who found that the warming trends have not been geographical uniform. It is also possible that these results might be associated with seasonal changes in temperature trends explained by Lugina et al. 2006; Kruger and Shongwe (2004). It should be stated that the stations in the WC are however located closer together than those in the EC. This difference may have led to the calculated station averages being biased to those areas where the distribution of stations' density is highest (e.g. over the WC).

These results are more intriguing despite the fact that the two areas border the southern coast of the country. Interestingly, the spatially consistent trend observed in the WC and the temporal variations over the EC are more pronounced especially towards the second half of the last two decades. This period coincides with the 1980's and the 1990's, and the first several years of the twenty-first century, which were observed to be much warmer (Lugina et al., 2006). Hence, it was important to investigate the regional atmospheric circulation anomalies in the first and last decades of the study for comparative analysis as is done in sub-section 3.6 of this Chapter.

3.4. Absolute indices

Figure 3.4 demonstrates trends in the hottest days (hottest nights) and coolest days (coolest nights). These indices were respectively defined as the highest daily maximum and the lowest daily minimum, and were averaged over a month to give the lowest and highest monthly minimum and maximum temperature.

Increasing trends in coolest days (monthly highest minimum) and coolest nights (monthly lowest minimum) were found at most stations in the WC and the EC, though most of these were not significant. A statistically significant increasing trend in the coolest nights was observed only at the Cape Columbine station along the WC coast. It is quite evident from these results that the influence of the changes or the increase in coolest days (Figure 3.4) might be seen in the associated cold days that have become less frequent or have decreased significantly both at the individual stations (Figure 3.1) and from averaged station time series (Figure 3.2). This is especially well defined over the WC due to increasing trends in the coolest days (monthly lowest maximum) (Figure 3.4). The same results are also true for the cold nights. Similarly, the increased occurrence of the extreme hot days and hot nights seem to be supported by the increased trends in hottest days and hottest nights at some stations over the WC (Figure 3.4).

The results in the EC once again showed contrasting trends among the stations in the area. From these results, it was not obvious that the relative changes in the occurrence of extreme tails of temperatures over the EC with the changes or increasing trends in highest daily maximum or lowest daily minimum could be related, unlike the case for the WC. This result was especially difficult to attain in the areas where stations are relatively sparsely distributed such as in the EC.

However, it could be suggested that the increases (decreases) in the monthly maximum or minimum temperature might have positively (negatively) influenced the trends in extreme temperature tails over the EC (WC). Therefore the absolute indices presented here, while providing some explanation for certain properties in the distribution of the extreme temperature (percentile) indices, do not essentially suggest, in particular in the case of EC, that the extreme tails are solely influenced largely by changes or any consistent warming in the mean monthly minimum and maximum. They also do not however rule out this possibility either.

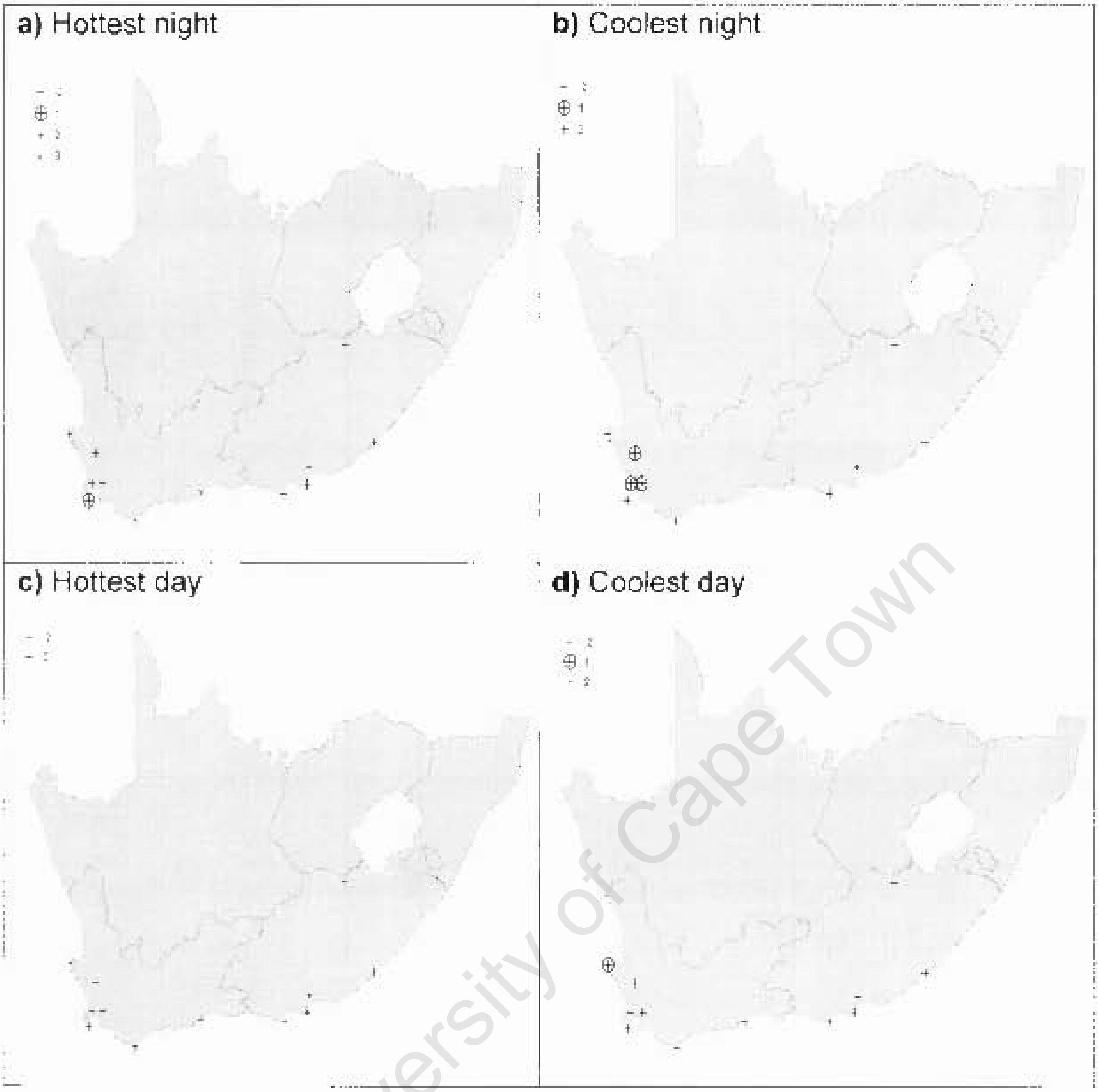

Figure 3.4: Station trends in the highest and lowest mean monthly maximum and minimum temperature for the period 1960 to 2005. The symbols are explained as follows; 1 with a positive sign in a circle denotes a significant increasing trend at the 5% level. Minus sign with a −2 shows no significant negative trend, and positive sign with a 2 shows no significant positive trend. X with a 3 denotes no trend.

3.5. Threshold indices

Figure 3.5 represents the trends in annual warm days and warm nights (that is the annual count when the maximum temperature is greater than 25°C and the minimum temperature is greater than 20°C but less than 25°C). The results presented here agree to a larger extent with the increase in the mean annual maximum and minimum trends analysis of Kruger and Shongwe (2004), and also with the observations of Muhlenbruch-Tegen (1992) along the coastal region of South Africa.

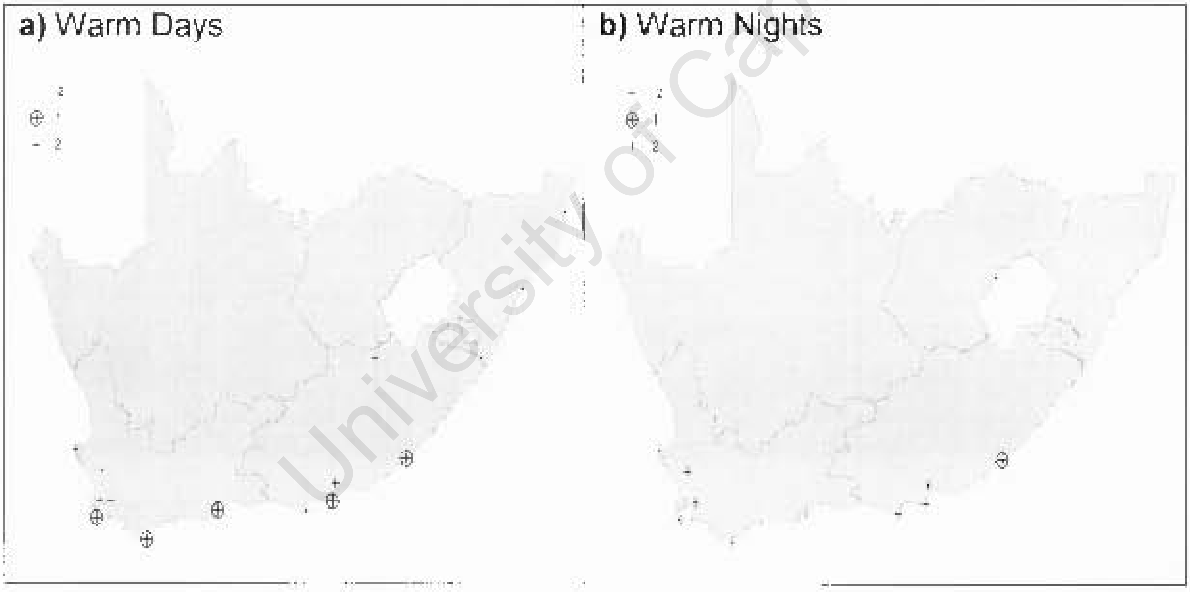

Figure 3.5: Station trends in annual temperature thresholds (maximum and minimum) from 1960 to 2005. The symbols are explained as follows; 1 with a positive sign in a circle denotes a significant increasing trend at the 5% level. Minus sign with a –2 shows no significant negative trend, and positive sign with a 2 shows no significant positive trend.

It is apparent from the results that the stations along the WC coast, and to lesser extent the EC show significantly increasing trends in the annual temperature thresholds (i.e. warm days and warm nights). This is in agreement with the increasing trends in hot days and hot nights extreme tails over the WC (Figure 3.1). It could also be shown that the results support changes in the trends in the mean monthly maximum and monthly minimum temperature (Figure 3.4), where significant trends were also observed for some of the stations in the WC. It is also evident that these results give an indication that the occurrence of hot days and nights extremes were partly as the result of the increase in the hottest days and nights over both the EC and especially the WC regions.

It could be suggested that the increase in the occurrence of extreme tails of minimum and maximum temperature, especially over the WC was partly due to the combination of the changes in mean monthly trends (highest and lowest minimum and maximum) (Figure 3.4), and the increased warming in the annual temperature thresholds. Moreover, these results are consistent with the global analysis of the changes and the occurrence of the daily extreme temperature (hot and cold tails) indices (Figure 3.1) (e.g. DeGaetano, 1996). In this context, it is not conclusive, but it might be illustrated that the representation of the increased number of days in which temperature value lies below or above a threshold may be a useful tool in determining the extent to which extremes occur, and this might further help the understanding of the changes in the extreme indices.

3.6. Regional atmospheric circulation and the comparison between the 1960 to 1970 and 1995 to 2005 decades on the seasonal scale

Kgatuke et al. (2003), Engelbrecht (2005) suggested that an increase (decrease) in the maximum temperature could be associated with a decrease (increase) in cloud cover and associated rainfall. These authors pointed out that if the maximum temperature decreases due to cloud cover and more precipitation, then the minimum temperature is most likely to increase due to less rapid cooling at night. This result could even be more apparent over the semi-arid areas of South Africa (Kgatuke et al., 2003). Other studies of climate change (e.g. Jones et al., 2004) have already suggested changes over Southern Africa in extreme rainfall patterns and increasing temperatures due to global warming.

In this section, atmospheric circulation anomalies, and the available literature on evidence of extreme precipitation patterns during the recent century are explored in relation to the temperature extremes. Over Southern Africa, a number of studies have investigated the changes in and the occurrence of extreme precipitation (droughts and flooding) in the twentieth-century (e.g. Fauchereau et al., 2003; New et al., 2006; Singleton and Reason (2007a); Singleton and Reason (2007b); Rouault and Richard, 2005; Kruger, 2006). The latter study analyzed trends in daily precipitation indices over South Africa for the period of 1910 to 2004.

Kruger (2006) showed that the annual total precipitation has decreased significantly over areas such as Limpopo, Mpumalanga, north eastern Free State and the western KwaZulu-Natal including the southeastern EC, as well as the south coast of South Africa. Significant increases in annual precipitation were found in areas of the northern part of North-West Province, and parts of the WC, Northern Cape and parts of the EC.

It should be mentioned that explaining the influence of atmospheric circulation on the trends and variability or changes in the extreme maximum and minimum temperatures is challenging, especially with little work having been done on the possible relationships between trends in surface air temperature and changes in the regional atmospheric circulation or rainfall.

Previous studies on extreme temperature (e.g. Muhlenbruch-Tegen (1992) found the influence of SST on extreme temperatures over coastal regions of South Africa. Other studies include those of (Kruger and Shongwe, 2004; King'UYU et al., 1999), who also focused on extreme temperature events, and who found a correlation between temperature and ENSO phenomenon for certain seasons. Although it is not obvious that any trend in surface air temperature should be accompanied by a regional change in circulation, it is important to investigate any relationships to try to ascertain whether local mechanisms or circulation patterns might modulate any large scale trend arising from global warming.

The results presented in Figures 3.6 – 3.7 are not conclusive but may provide some indications of the possible influence of regional atmospheric circulation patterns on extreme temperature events over the WC and EC regions for the period 1960 to 2005. The plots show the difference between the most recent decade (1995 to 2005) from the 1960 to 1970 decade. Although this approach does not discriminate between multidecadal variability and a long term trend, it does provide a simple way to assess changes during the period studied in this thesis.

The plots in Figure 3.6 suggest a reduced tendency of cyclonic conditions over Southern Africa during the summer season (DJF) as a result of a small difference in height changes between the last decade and the first decade. This tendency of weaker cyclonic (lower pressure) patterns during this period may be attributed to changes in the intensity of the continental heat lows and the location of the Inter-Tropical Convergence Zone (ITCZ) (Rautenbach, 1998), which influence the location and intensity of northwest-southeast (NW-SE) cloud bands over the subcontinent during summer (Williams et al., 2007). These results furthermore show that the tendency of a persistent deep surface continental cyclonic system during summer that is usually associated with strong convergence over Botswana region (Rautenbach, 1998) and other parts of the subcontinent appears to be weakening as the intensity of the anticyclonic conditions becomes stronger during the 1995 to 2005 decade.

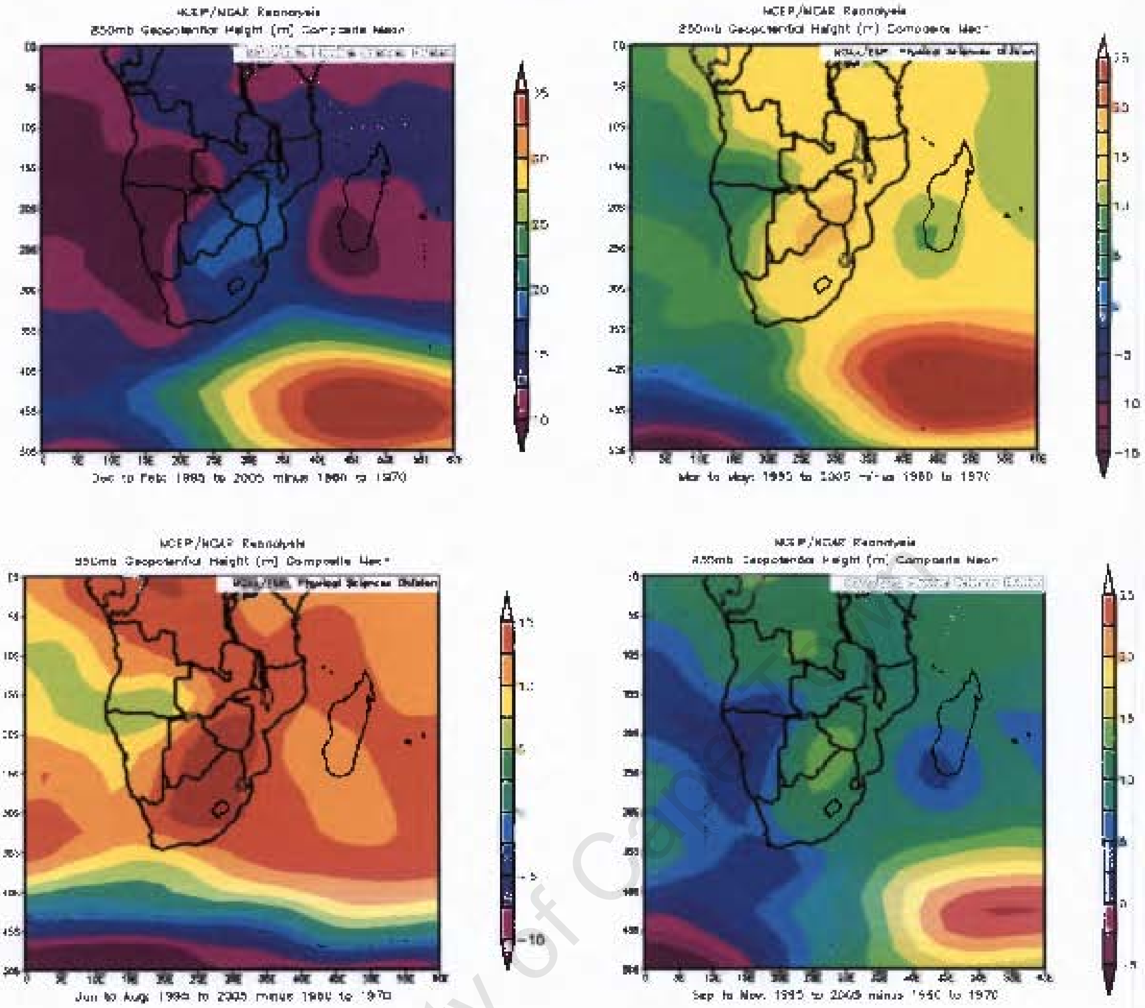

Figure 3.6: The mean geopotential height composites at the 850 hPa level averaged for the DJF, MAM, JJA, and SON seasons for the period 1995 to 2005 minus 1960 to 1970 in the interval of 5m. Negative values indicate tendency for low pressure (trough), and positive values for high pressure (ridge) conditions.

However, it could be argued that, during the summer season (i.e. the warmest season), the increased occurrence in hot days and hot nights as observed over the WC might be related to a tendency of more easterly winds (Figure 3.7) south of the country and not really over the continent in the 1960 to 1970 decade relative to 1995 to 2005 decade. It is suggested that this flow could have been driven by the stronger high pressure system over the mid-latitude South Indian Ocean (Figure 3.6), and the location of a surface trough down the west coast, which could lead to more offshore flow off the interior to the South WC. For the EC, the wind and pressure patterns during this season appear to be weaker and the tendency to more easterly flow might not make much difference in terms of the occurrence of hot days and nights as this flow is more or less directed parallel to the coast rather than on- or offshore relative to the EC landmass.

For the autumn season (MAM), the circulation patterns show relatively weaker anticyclonic conditions than JJA over the continent but stronger anticyclonic conditions over the South Indian ocean that appear to be associated with the warmer conditions in the 1995 to 2005 decade compared to the 1960 to 1970 decade (Figure 3.6). These patterns suggest more favourable conditions for an increased occurrence of hot days over the region. This dominance of subtropical high pressure in the recent decade and the implied southward shift of the midlatitude westerly systems, suggest a change in wind patterns over the WC that is relatively weak with stronger easterly anomalies (i.e. weaker westerlies given the direction of the mean flow) southeast of South Africa (Figure 3.7).

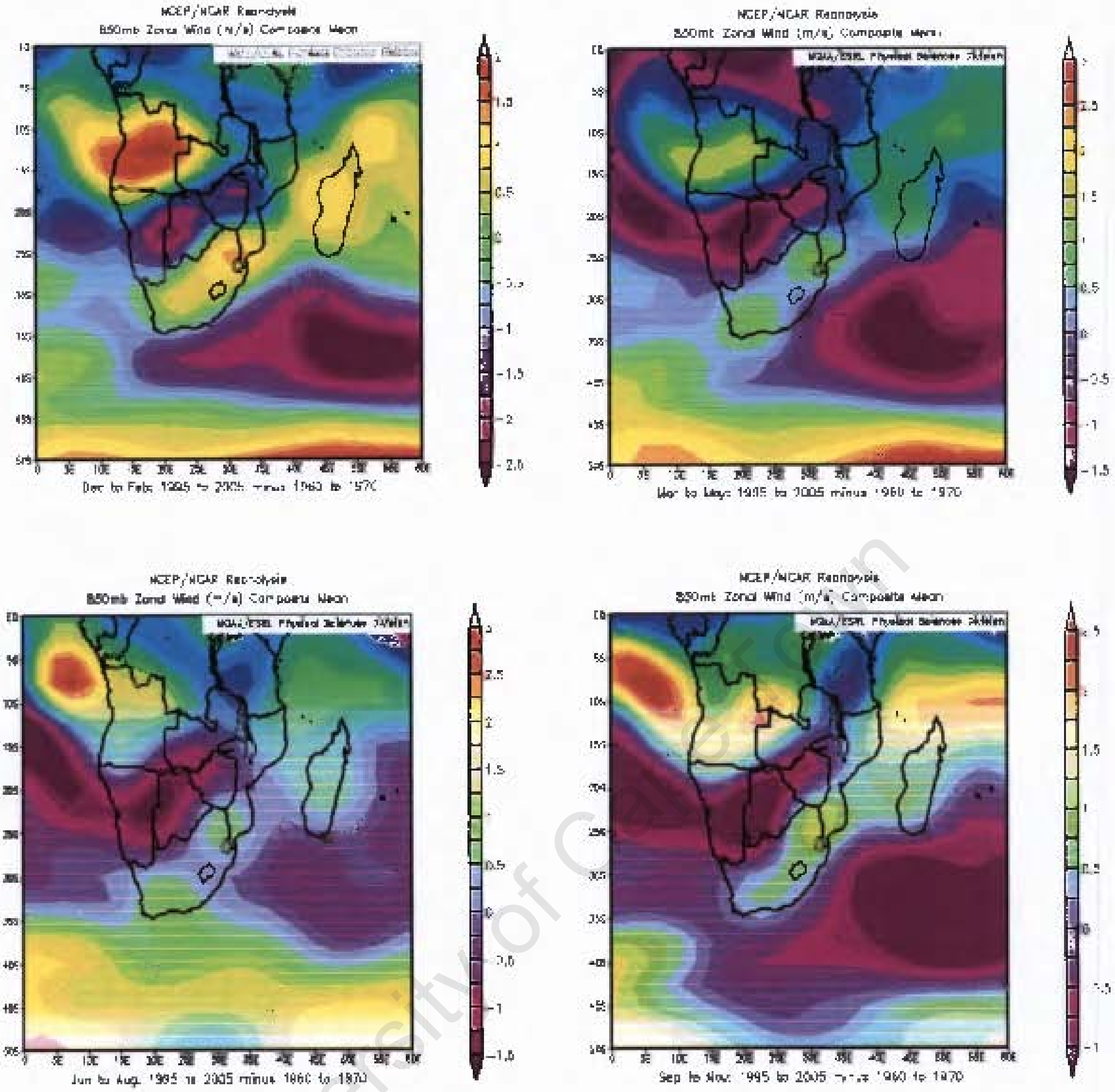

Figure 3.7: Near surface mean zonal winds (East-West) component contoured at an interval of 0.5 m/s. Winds are averaged for the DJF, MAM, JJA, and SON seasons for the period 1995 to 2005 minus 1960 to 1970. Negative values indicate easterlies and positive anomalies indicate westerlies.

The results suggest a greater possibility of northerly to north-westerlies that may be more favourable for hot and dry offshore conditions over the larger landmass of the central and eastern parts of the country, including the EC. These results agree to a large extent with the high autumn temperature conditions suggested by Kruger and Shongwe (2004), and consistent with the findings of Muhlenbruch-Tegen (1992) of significant increase in temperatures along coastal areas and the adjacent southern interior during MAM.

On the other hand, the decreasing trend in the occurrence of cold days and cold nights observed over the WC may be related to the tendency for higher pressure or more anticyclonic conditions during the core winter months (JJA) in the last decade relative to the first decade (Figure 3.6) and a slight tendency for more southwesterly flow over the southwestern South Africa (Figure 3.7). The latter implies a greater inflow of humid mid-latitude South Atlantic air to the southern WC and the possibility of increased low level stratus clouds and hence less very cold nights over the WC.

The occurrence of more anticyclonic conditions over Southern Africa during the last decade (1995 to 2005) relative to the first decade (1960 to 1970) during the main rainfall season over the WC (i.e. JJA) implies a greater possibility of more offshore flow over the EC region. This tendency for anticyclonic conditions during winter season (JJA) suggests that approaching fronts would be more likely to be steered south of the landmass as they approach the country, thereby reducing frontal rainfall and cold air advection over the EC and other parts of the central and eastern parts. As a result, warmer and clearer sky conditions might be expected to be more likely over the EC during the last decade relative to the first decade, leading to berg wind conditions and increased temperatures and warmer winters over the region.

During spring (SON), there is also an eastward shift and a tendency for more or stronger anticyclonic conditions (higher pressure) over the South East Atlantic to the west coast during the 1995 to 2005 decade relative to 1960 to 1970 decade (Figure 3.6), but the difference between the decades is smaller than of JJA. Consistent with these height changes is a tendency for more easterlies (Figure 3.7) along the south coast, again favouring warming over the WC. These results seem to be in contrast to Muhlenbruch-Tegen (1992) who found a downward trend in mean temperature during winter (JJA) and spring (SON).

3.7. Conclusion

The results presented in this chapter suggested a statistically significant decreasing trend in the frequency of cold days and cold nights over the Western Cape. A statistically significant increasing trend for hot days and hot nights was also found for the same area. No clear evidence existed to suggest any trend over the Eastern Cape. The effects of small scale features such as land changes and local topography might be considered for future work to delineate clearly the distribution of extreme temperature trends.

The potential association of anticyclonic conditions and temperature extremes was observed over the oceanic regions south of South Africa mainly during winter. The relative changes in the extreme temperature events over the Eastern Cape were most likely associated with seasonal changes and the increase in pressure over the subcontinent. It is suggested that the increase of high pressure over the recent decades and the associated frequency of extreme temperature events should be further investigated to determine the link to both natural variability and the effects of anthropogenic induced climate change.

Chapter 4: Conclusions

4.1. Summary and Remarks

This study looked at the recent instrumental record for any trends. The study was not focusing on future climate change effects on temperature extremes, but was partly motivated by the projected climatic changes that are likely to happen over the South African region for temperature, rainfall and sea level pressure (SLP). The emphasis or focus of this thesis was on the behaviour and the occurrence of the upper (90th) and the lower (10th) percentiles of maximum and minimum temperatures for the period 1960 to 2005.

The analysis of trends for the percentile indices, absolute indices and threshold indices (shown in Table 2.1) was performed for the WC and EC regions of South Africa. The absolute and threshold indices were considered for qualitative and synthetic analysis of the extreme tails of maximum and minimum temperatures. The possible relationships and the influence of atmospheric circulation anomalies on temperature extremes were also explored by means of comparisons on the seasonal scale between the first and last decades of this period.

For the most part, the WC showed evidence of cohesive spatial and temporal trends in the extreme indices, whereas the EC showed mostly contrasting results from one station to another and no consistent trend was observed. As stated elsewhere in this thesis, these differences in the results over the WC and EC could be a result of the calculated station averages, which could be biased to areas where the stations are densely distributed, or result from the dissimilarities in geographical or physical properties of the location of stations, such as the effects of small scale features (e.g. land changes and local topography). Investigation of possible local effects was beyond the scope of this study; however, it is a factor that could be of importance for the distribution of temperature extremes and should therefore be investigated in future work.

The results presented in this thesis showed a significant change or shift in the extremes, with some relationship with atmospheric circulation patterns. It was however, not possible for this thesis to conclude if a tendency or the trend towards fewer cold days and nights was well defined. On the other hand, the increased hot night extremes analyzed suggested that further investigation is needed to determine whether the WC or the EC is getting warmer overall. However, it was clearer that extreme cold tails are less frequent or decreasing with time and space whereas hot tails are increasing, especially over the WC.

Explaining the underlying causes of the changes and the variations in the occurrence of extreme tails of temperature over the two regions, especially over the EC was rather difficult for this study to attain. However, the examination of the regional atmospheric circulation anomalies suggested a relationship between extreme tails of minimum and maximum temperature and the increased height changes in the atmospheric circulation patterns during the 1995 to 2005 decade relative to 1960 to 1970. This condition seems to be consistent with the generally increasing trend in annual warm days (maximum) and warm nights (minimum) temperatures over both the WC and EC. Moreover, the relatively warmer period of 1995-2005 decade compared to 1960-1970 suggested a linkage of warmer temperatures with mainly high pressure patterns in spring and autumn and occasionally in winter seasons.

On the other hand, a decrease in geopotential heights further south was argued to be influential on the recorded daily minimum temperatures over the WC during winter and spring as a result of mid-latitude cyclones and cold fronts approaching the west coast. At the same time, increasing pressure patterns were evident over the mid-latitude south Indian Ocean during summer and autumn. This pressure increase was suggested to lead to a likelihood of more easterly flow over the WC causing offshore conditions and the increase in surface temperatures in the WC.

The results presented in this thesis agree in general with the global warming trends in the recent decades (e.g. Lugina et al., 2006). They also agree to a large extent with the intensified high pressure system and significant changes in extreme temperature over the last few decades over the subcontinent and the displacement of mid-latitude cyclones further south. This inference was not fully explored in this thesis, but could also be argued that these present conditions may accelerate in accordance to future climate change projections (e.g. Kgatuke et al., 2003). However, improved understanding is required of the mechanisms that may contribute to the changes in the atmospheric circulation over the region in the past few decades and in particular to the warming in the last decade, and how these might affect temperature changes in future.

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