

**The impact of climate change and variability on tomato  
(*Lycopersicon esculentum*) production in the Limpopo Province,  
South Africa**

By

**Tshiala Milambo Freddy**

*Submitted in partial fulfilment for the degree*

*Philosophiae Doctor (Environment & Society)*

at

**University of Pretoria, South Africa**

Department of Geography, Geoinformatics & Meteorology

Faculty of Natural & Agricultural Sciences

Supervisor: Dr Jane Mukarugwiza Olwoch

Co-supervisor: Dr Botai Ondego Joel

July 2014



UNIVERSITEIT VAN PRETORIA  
UNIVERSITY OF PRETORIA  
YUNIBESITHI YA PRETORIA

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Student: Tshiala Milambo Freddy

Supervisor: Dr Jane Mukarugwiza Olwoch

Co-supervisor: Dr Joel Botai Ondego

Department of Geography, Geoinformatics & Meteorology,

University of Pretoria, South Africa

Degree: Doctor of Philosophy (Environment and Society)

**Abstract**

The Limpopo Province is a major tomato growing region in South Africa, producing 66% of the total annual tonnage of tomatoes. The Limpopo Province is particularly vulnerable to the impact of climate change, partly because it is exposed to extreme weather events. According to the Intergovernmental Panel on Climate Change (IPCC) Africa will be hit hardest by climate change as larger areas could be stricken by yield decreases of over 50% by the year 2020 because of an increasingly hotter and drier climate. This will threaten food security and the livelihoods of people in most parts of Africa. First and foremost in this research study, a detailed analysis of annual seasonal trends in minimum and maximum temperatures was investigated, as well as the diurnal temperature range over the Limpopo Province for the period 1950-1999. In particular, using daily data from 30 catchment areas, three temperature variables were calculated: the average, maximum and minimum temperature. The analysis demonstrated that there was an increase of 0.12°C every decade in the mean annual

temperature for the 30 catchments over the 50-year period. Furthermore, the present study analysed the correlation of tomato records for the Limpopo Province with climatic variables in order to assess the climate change effects on tomato production and food security in South Africa. The trend analysis of tomato production in the Limpopo, tomato yield showed increased by a factor of 2 from 1971-2006. Thus the response of tomato production during that period of 35 years was more favourable. This shows that the largest values in tomato yield were in the last decades when temperatures were high. From our analysis, the trend of tomato production in the Limpopo, tomato yield increased by a factor of 2 during the period of 1971-2006 was not significant. In particular, during the spring, summer, autumn and winter seasons, tomato yield increased by a factor of 2 respectively. With the exception of February and June, most months registered positive trends in tomato production. The study reported in this thesis investigated the frequency of occurrence of heat waves (HWs) over Limpopo. The analysis of the occurrences of HWs over this region is important due to their impact on agricultural production as well as human health. Overall, our results indicate that during the period 1950-1999, the Limpopo Province experienced HW events. The results from the present study demonstrated that during the four seasons (spring, summer, autumn and winter) the HW trends were not monotonic over the five decades (1950-1999). Furthermore, the research reported in this thesis analysed the distribution of leafminer agromyzid pest over the Limpopo Province in a changing climate. The analysis of tomato pest distribution is vital because the leafminer agromyzid pest has a major impact on tomato production. In general, the aim of analysing the leafminer agromyzid pest was to determine how climate change influences the distribution of the leafminer agromyzid pest and hence impacts on tomato production in the Limpopo Province, South Africa. The present analysis

illustrates that the leafminer agromyzid pest and climatic factors exhibit a non-linear relationship, which could be best described by a polynomial function of order two while in general, the influence of climate change on the spatial distribution of the leafminer agromyzid pest over the Limpopo Province is apparent.

**Key words:** climate change, the Limpopo Province, heat waves, leafminers agromyzid, tomato production

## **Acknowledgements**

I would like to thank God for life and blessings throughout my studies. “Glory be to thy name”. I would also like to acknowledge the participation and support of many people, especially Dr Jane Olwoch for her supervision throughout my studies. Additionally, I would like to extend my appreciation to Dr Botai Joel Ondego for taking over the co-supervision of my research towards completion. I was very privileged to work with him. His support feedback was valuable in shaping the contents of this study. I would also like to thank Dr Francois Engelbrecht for contributing to the present research. To Professor Hannes Rautenbach for the good working environment which made my stay enjoyable at the Department of Geography, Geoinformatics and Meteorology. To Phylemon and Yvette for their assistance with the Geoinformatics System (GIS) tool, your contributions made the success of this thesis as well.

I also acknowledge the financial support of the Cannon Collins Trust and the Agricultural Research Council (ARC) as well as the Water Research Commissioner (WRC). My sincere thanks also go to Professor Sivakumar Venkataraman for providing a generous bursary opportunity through the National Research Foundation (NRF) to sustain my study and Dr Hassan Abubeker for providing me with a bursary through my involvement in the European Union AnimalChange Project.

There are no words to express my profound gratitude to my parents, my late father Jean Tshiala Milambo and my mother Henriette Nzombo Nkembe. I also wish to extend my sincere gratitude to my uncle Nyengelele Christian Muleba and his family for their guidance and support throughout my studies at the University of Pretoria. My sincere thanks also go to the Faculty of Agricultural and Natural Science, the

Department of Geography and Geoinformatics and Meteorology, staff and fellow graduates at the University for their support and friendship.

Lastly, I would like especially to thank my wife Tshiala Ngalo Valerie and my children Shanelle Nkembe and John Tshiala who have always been there for me.

## Declaration

I, the undersigned, hereby declare that this thesis is entirely my own work, that I am the owner of the copyright thereof unless to the extent explicitly otherwise stated and that I have not previously submitted it in its entirety or in part for to obtain any qualification elsewhere. All sources used or quoted have been properly indicated and acknowledged by means of complete references.

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Tshiala Milambo Freddy

Signature:.....

Date:.....

## **Biosketches**

Milambo Freddy Tshiala is a PhD student at the University of Pretoria on a Cannon Collins Studentship. His main interests are in the area of climate change and its impact on agriculture, specifically tomato production.

Dr Jane Mukarugwiza Olwoch is the Managing Director (Earth Observation) at the South Africa National Space Agency (SANSA).

Dr Joel Botai Ondego is a senior lecturer in the Department of Geography, Geoinformatics and Meteorology at the University of Pretoria specialising in Remote Sensing and Space Geodesy.



## Table of Contents

<b>Abstract</b> .....	<b>2</b>
<b>Acknowledgements</b> .....	<b>4</b>
<b>Declaration</b> .....	<b>6</b>
<b>Biosketches</b> .....	<b>7</b>
<b>List of Figures</b> .....	<b>12</b>
<b>List of Tables</b> .....	<b>15</b>
<b>Chapter 1: Introduction</b> .....	<b>16</b>
1.1. General introduction .....	16
1.2. Significance of the study.....	24
1.3. Aim and objectives .....	25
1.4. Research questions.....	26
1.5. Hypothesis.....	26
1.6. Thesis outline.....	26
1.7. References.....	26
<b>Chapter 2: Study area, data and methodology</b> .....	<b>34</b>
2.1. Study area.....	34
2.2. Data and methodology .....	34
2.3. References.....	38
<b>Chapter 3: Analysis of Temperature Trends Over the Limpopo Province, South Africa</b> .....	<b>43</b>
3.1. Abstract .....	44
3.2. Introduction.....	43
3.3. Regional setting .....	45
3.4. Data and methodology .....	46
3.5. Results and discussion .....	49
3.5.1. Mean monthly temperature over the Limpopo .....	49
3.5.2. Trends in mean annual maximum, minimum and mean temperature.....	52
3.5.3. Seasonal trends.....	54
3.5.4. Trends in diurnal temperature range (DRT) .....	56
3.6. Discussion and conclusions .....	58
3.7. Acknowledgement .....	62
3.8. References.....	63
<b>Chapter 4: Five decade analysis of heat waves in the Limpopo Province, South Africa</b> .....	<b>65</b>

4.1. Abstract .....	66
4.2. Introduction.....	67
4.3. Study area.....	72
4.4. Data and methodology .....	73
4.5. Results and discussion .....	72
4.5.1. Extremes temperature and temperature events over the Limpopo.....	73
4.5.2. Trends in heat waves frequencies .....	75
4.5.2.1. Trends in the annual frequency of occurrence of hws over the Limpopo Province during 1950-999. ....	75
4.5.2.2. Trends in the seasonal frequency of occurrence of HWs over the Limpopo Province during 1950-1999. ....	76
4.5.2.2.1 Trends in autumn frequency of occurrence of HWs over the Limpopo Province during 1950-1999. ....	77
4.5.2.2.2. Trends in the occurrence of HWs in winter over the Limpopo Province during 1950-1999 .....	78
4.5.2.2.3. Trends in the occurrence of HWs in spring over the Limpopo Province during 1950-1999. ....	79
4.5.2.2.4. Trends in the occurrence of HWs in summer over the Limpopo Province during 1950-1999. ....	82
4.6. Conclusions and implications .....	82
4.7. Acknowledgements.....	83
4.8. References.....	84

## **Chapter 5: Impact of climate variability on tomato production over the Limpopo Province, South Africa.....**

5.1. Abstract .....	87
5.2. Introduction.....	88
5.3. Study area.....	92
5.4. Data and methodology .....	93
5.5. Results and analysis .....	92
5.5.1. Trend in tomato production in the Limpopo Province (1971-2006).....	92
5.5.2. Relationship between tomato production and average temperatures during 1971 to 2006 .....	94
5.5.3. Seasonal tomato production as related to temperature average in °C (1971-2006) .....	95
5.5.3.1. Seasonal production of tomato in relation with temperature in °C during autumn (1971-2006) .....	95
5.5.3.2. Seasonal production of tomato in relation with temperature in °C during spring (1971-2006) .....	96

5.5.3.3.	Seasonal production of tomato in relation with temperature in °C during summer (1971-2006)	97
5.5.3.4.	Seasonal production of tomato in relation with temperature in °C during winter (1971-2006)	98
5.5.3.5.	Relationship between tomato production and average rainfall during 1971-2006	99
5.5.4.	Seasonal tomato production as related to rainfall average in °C (1971-2006)	100
5.5.4.1.	Seasonal production of tomatoes in relation to rainfall in mm during autumn (1971-2006)	100
5.5.4.2.	Seasonal production of tomatoes in relation to rainfall in mm during spring (1971-2006)	101
5.5.4.3.	Seasonal production of tomatoes in relation to rainfall in mm during summer (1971-2006)	101
5.5.4.4.	Seasonal production of tomatoes in relation to rainfall in mm during winter (1971-2006)	102
5.5.5.	Monthly tomato production	105
5.6.	Discussion	107
5.7.	Conclusions	108
5.8.	Acknowledgements	109
5.9.	References	110

<b>Chapter 6: Leafminer agromyzid pest distribution over the Limpopo Province in a changing climate</b>	112
6.1. Abstract	113
6.2. Introduction	114
6.3. Study area	117
6.4. Materials and methods	119
6.4.1. Data	119
6.4.2 Pest model development	122
6.5. Results	124
6.5.1. Normalised $r_m$ index in the distant future 2071-2100	126
6.5.2. Net reproduction rate of leafminer under present, near- and distant future climate change scenarios	127
6.5.3. Mean generation time of leafminer under present, near- and distant future climate change scenarios	130
6.5.4. Differences between the future and present-day parameters	131
6.6. Discussion and conclusion	133
6.7. Acknowledgement	136
6.8. References	136

<b>Chapter 7: Conclusions and recommendations</b> .....	141
7.1. Summary .....	141
7.2. Scientific contributions .....	142
7.3. Conclusion .....	145
7.4. Challenges .....	146
7.5. Recommendations for future research .....	147

## List of Figures

Figure 1.1. Percentage of tomato production per province in South Africa .....	19
Figure 2.1. Map of the study area: the Limpopo Province .....	35
Figure 3.1. Monthly mean temperature in Degree Celsius (°C) from 1950-1999 over the Limpopo Province.....	49
Figure 3.2. Temperature trend (°C/decade) in mean annual temperature for the period 1950-1999 .....	53
Figure 3.3. Trend (°C/decade) in mean maximum annual temperature for the period 1950-1999.....	54
Figure 3.4. Trend (°C/decade) in mean minimum annual temperature for the period 1950-1999.....	55
Figure 3.5. Trend (°C/decade) in mean winter and summer annual temperature for the period 1950-1999 .....	55
Figure 3.6. Trends in diurnal temperature range (°C/decade) for the period 1950-1999..	57
Figure 4.1. Observed moving average: $T_{\text{mx}} \geq 30^{\circ}\text{C}$ from 1950-1999 .....	74
Figure 4.2. Observed moving average: $T_x \geq 35^{\circ}\text{C}$ from 1950-1999 .....	74
Figure 4.3. Trends in the annual frequency of occurrence of HWs over the Limpopo Province during 1950-1999.....	76
Figure 4.4. Trends in autumn frequency of occurrence of HWs over the Limpopo Province during 1950-1999.....	77
Figure 4.5. Trends in the occurrence of HWs in winter over the Limpopo Province during 1950-1999. ....	78
Figure 4.6. Trends in the occurrence of HWs in spring over the Limpopo Province during 1950-1999. ....	79
Figure 4.7. Trends in the occurrence of HWs in summer over the Limpopo Province during 1950-1999.....	80
Figure 5.1. Trend of tomato production per tonnage in the Limpopo Province (1971-2006) .....	93
Figure 5.2. Trend of average annual maximum temperature and tomato production in the Limpopo Province (1971-2006).....	94

Figure 5.3. Seasonal production of tomato in relation with temperature average in °C during autumn (1971-2006) .....	95
Figure 5.4. Seasonal production of tomato in relation with temperature average in °C during spring (1971-2006) .....	96
Figure 5.5. Seasonal production of tomato in relation with the temperature in °C during summer (1971-2006).....	97
Figure 5.6. Seasonal production of tomato in relation with temperature in °C during winter (1971-2006) .....	98
Figure 5.7. Trend of average annual rainfall and tomato production in the Limpopo Province (1971-2006).....	99
Figure 5.8. Seasonal production of tomatoes in relation to rainfall average in mm during autumn (1971-2006).....	100
Figure 5.9. Seasonal production of tomatoes in relation to rainfall average in mm during spring (1971-2006).....	101
Figure 5.10. Seasonal production of tomatoes in relation to the rainfall in mm during summer (1971-2006).....	102
Figure 5.11. Seasonal production of tomatoes in relation to rainfall in mm during winter (1971-2006).....	103
Figure 5.12. Monthly trend production.....	104
Figure 6.1. Location of northern province of South Africa (shaded area).....	118
Figure 6.2. Differences between maximum actual temperature value and CCAM temperature values in degree Celcius (°C).....	121
Figure 6.3. Intrinsic rate of increase ( $r_m$ ) of leafminer agromyzid under present climate change scenarios (1981-2010). .....	124
Figure 6.4. Intrinsic rate of increase ( $r_m$ ) of leafminer under near future climate change scenarios (2041-2070).....	125
Figure 6.5. Intrinsic rate of increase ( $r_m$ ) of leafminer under distant future climate change scenario (2071-2100) .....	126
Figure 6.6. Net reproduction rate ( $r_o$ ) of leafminer under present climate change scenarios (1981-2010).....	127
Figure 6.7. Net reproduction rate ( $r_o$ ) of leafminer under near future climate change scenarios (2041-2070).....	128

Figure 6.8. Net reproduction rate ( $r_0$ ) of leafminer under distant future climate change scenarios (2071-2100)..... 129

Figure 6.9. Mean generation time (tg) of leafminer under present climate change scenarios (1981-2010)..... 130

Figure 6.10. Mean generation time (tg) of leafminer under near future climate change scenarios (2041-2070)..... 131

Figure 6.11. Mean generation time (tg) of leafminer according to distant future climate change scenarios (2071-2100) ..... 132

Figure 6.12. Differences between the future and present-day parameters.....132

## List of Tables

Table 4.1. The Maximum temperature extreme indices .....	75
Table 5.1. Correlation and Significance between Tomato production and Rainfall as well as Temperature.....	107
Table 6.1. Statistics of the CCAM simulation and the observations .....	121
Table 6.2. Population parameters of leafminer in five temperature treatments (Zhang <i>et al.</i> , 2000). .....	123
Table 6.3. Empirical relationship between temperature (T) and population parameters based on the laboratory experiment depicted in Table 6.2. ....	123



## Chapter 1: Introduction

### 1.1. General introduction

The last assessment report from the Intergovernmental Panel on Climate Change (IPCC) predicts an increment in mean temperature from 1.1°C to 5.4°C toward the year 2100 (Ebi and Meehl 2007). An increment of this magnitude is expected to affect global agriculture significantly (Cannon 1998). In addition, such changes in climatic conditions could profoundly affect the population dynamics and the distribution of crop pests as reported in Woiwod (1997). These effects could either be a) direct, through the influence that weather may have on the insects' physiology and behaviour (Harrington, Fleming and Woiwod 2001; Huey and Berrigan 2001; Bale, Masters, Hodkinson, Awmack, Bezemer, Brown, Butterfield, Buse, Coulson and Farrar 2002; Samways 2005; Parmesan 2007; Merrill, Gutierrez, Lewis, Gutierrez, Diez and Wilson 2008), or may be mediated by host plants, competitors or b) natural enemies (Harrington, Fleming and Woiwod 2001; Bale *et al.* 2002). In temperate regions, most insects have their growth period during the warmer part of the year (Bale *et al.*, 2002). Because of this, species whose niche space is defined by climatic regime will respond more predictably to climate change while those in which the niche is limited by other abiotic or biotic factors will be less predictable (Bale *et al.*, 2002). In the first case, the general prediction is that if global temperatures increase, the species will shift their geographical ranges closer to the poles or to higher elevations, and increase their population size (Sutherst 2000; Harrington *et al.* 2001; Bale *et al.* 2002; Samways 2005). In agreement with this prediction, many examples may be found in the literature (Gordo and Sanz 2006; Olfert and Weiss 2006; Musolin 2007).

Species distributions are expected to change dramatically in response to future rapid climate warming (Araújo and Rahbek, 2006), and generally climate-change modelling predicts that the risks of species loss will increase (Ohlemüller *et al.*, 2006). Therefore, improving our understanding of the factors controlling potential species distributions under future global warming scenarios has become a central goal in ecology today (Garzon *et al.*, 2011).

Prediction of known occurrences of global warming constitutes an important technique in analytical biology, with applications in conservation modelling of species' geographic distributions based on the environmental conditions of sites and reserve planning, ecology, evolution, epidemiology, invasive-species management and other fields (Peterson and Shaw, 2003; Scott *et al.*, 2002; Welk *et al.*, 2002). Sometimes both the presence and the absence of occurrence of climatic data are available for the development of models, in which case general-purpose statistical methods can be used for an overview of the variety of techniques currently in use (Elith, 2006; Guisan and Zimmerman, 2000; Scott *et al.*, 2002).

Global climate change is a severe concern to the international community because it may affect prospects for sustainable development (Agerup *et al.*, 2004). Global warming poses a significant threat to future economic activities and the wellbeing of a significant number of human beings (Jepma and Munasinghe, 1998). Among all economic sectors, the agricultural sector appears to be the most sensitive and vulnerable (Boko *et al.*, 2007). Plant production is influenced by climate factors such as temperature and rainfall. Each

crop has optimal conditions for growth. Therefore, any change in the climate can have a serious impact on the crop production sector. World agriculture, whether in developing or developed countries, remains very dependent on climate resources and conditions.

Various studies have been done to assess the impact of climate change on agriculture. It has been shown that at global level, the impacts will be small since production reduction in some areas is balanced by gains in others (Kane *et al.*, 1991). The IPCC studies on climate sensitivity in agriculture across the globe concluded that the tropical areas seem to be more likely to suffer negative consequences, while temperate climates and polar zones will gain in productivity. Developing countries' agricultural systems are vulnerable to climate change because they tend to be less capital and technology intensive and because they tend to be in climate zones that are already too hot and will probably get hotter (Mendelsohn, 2000). Many countries in tropical regions are expected to be more vulnerable to warming because additional warming will affect their marginal water balance.

Overall, climatic changes will affect agriculture either negatively or positively depending on the location. There is wide concern that the agricultural sector in Africa will be especially sensitive to future climate change and variability (Mendelsohn *et al.*, 2000). In the southern African regions, the effect of climate change could be exacerbated further due to its high-risk cropping environment and the marked intra-seasonal and inter-annual variability of rainfall (du Toit *et al.*, 2002).

South Africa is predicted to be vulnerable to climate change due to different factors such as being an energy and carbon intensive economy and being among the top twenty

greenhouse gas emitters in the world (Scholes *et al.*, 1999). In particular, South Africa is a largely semi-arid country where the bulk of farming is practised on marginal land. Frequent droughts are experienced, as well as a scarcity of water that is exacerbated by a high temporal and spatial variability of rainfall (Scholes *et al.*, 1999). Boko *et al.*, (2007) projected some key impacts regarding South Africa, such as a loss of between 51% and 61% of fynbos and succulent Karoo biome by 2050 because of climate change and many species losses in other biomes. The intensity of extreme events will significantly increase in South Africa.

In this study, the tomato crop was used. The tomato (*Lycopersicon esculentum*) belongs to the family of *Solanaceae*. It is commercially important globally, for both the fresh fruit market and the processed food industries. Tomato is grown under a wide range of climates in the field, ranging from short season cold climates to the warm humid tropics and hot deserts. It may also be grown under protection in plastic greenhouses and in heated glasshouses (Atherton and Rudich, 1986).

The tomato originated in the dry west coast of tropical South America. The growing season in this region has temperatures that are moderate with an average minimum night temperature of 15°C and average maximum day temperature of 19°C (Cooper, 1972). The plant thrives in temperatures between 10°C and 30°C and is tolerant of neither frost nor waterlogged conditions (Maree, 1993). The main factor that determines how fast a plant grows is temperature. Growth occurs when the temperature is above a certain minimum level called the developmental threshold. The developmental threshold in tomatoes is about 10°C; the upper limit for growth is about 43°C to 44°C, and the optimal

range is 26°C to 32°C (IPM Manual Group, 1985). The bigger the variation between night and day temperatures, the more the plants are inclined to have the lower leaves curl inside (Maree, 1993).

In summer, it is important that ventilation or shade is provided for the plants to ensure that the temperature stays below 35°C. Furthermore, the tomato culture has to be maintained in a stable moisture level throughout growth. It is important that from the time the first fruit sets, and after the establishment of the plants, watering should be done thoroughly every 7-10 days in cool to warm weather, and every 4-5 days during the hottest months, if there is no rain. Overhead watering is not recommended: it is preferable to use the flood or furrow method (Gilbert and Hadfield, 1992).

Tomato production is one of the important sources of contribution to the economic development of the South African agricultural sector. It is an important source of employment and a generator of foreign exchange. According to the National Department of Agriculture (2003), tomatoes are cultivated in nine provinces of South Africa: Limpopo, Mpumalanga, Eastern Cape, Northern Cape, Free State, Eastern Cape, Kwazulu–Natal, North West and Western Cape (Figure 1.1). The major production provinces of tomatoes are Limpopo, Mpumalanga and the Eastern Cape. The highest production comes from the Limpopo Province, especially in the Mooketsi (Tzaneen) district. Here the ZZ2 group of companies employs more than 6 000 people and distributes more than 130 000 tonnes of tomatoes to the fresh produce market every year (Tzaneen info, 2005). The production is, however, poor in the rest of the Limpopo Province because of larger time fluctuations in temperature and frost, to which the tomato crop is very sensitive (NDA, 2003).

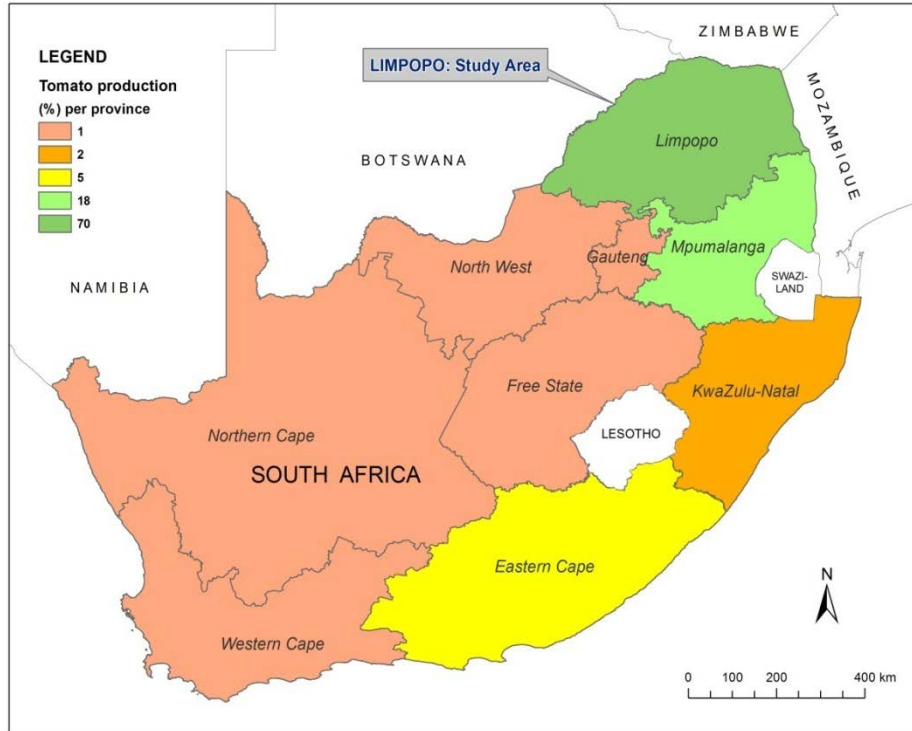


Figure 1.1. Percentage of tomato production per province in South Africa

The tomato crop is sensitive to climate variability because successful tomato production depends on climatic factors such as rainfall and temperature. Climate change refers to trends in the climate that may occur either because of natural forcing mechanisms or because of anthropogenic influences (IPCC, 2007). Climate change has been seen over the last 400 000 years, and greenhouse gas concentrations are at present peaking at their highest levels (Hardy, 2003). Over 100 years the change of climate has led to a gradual increase in the earth's average temperature called global warming. The earth's climate is also changing in the sense that weather systems that cause severe weather, such as tropical cyclones, are becoming more intense (Rosenzweig and Hillel, 1998; Hardy, 2003). For different agricultural areas, the impact of climate change will depend on

specific regional changes in atmospheric variables such as rainfall, temperature, environmental characteristics and agricultural structures (Bacsi *et al.*, 1991).

In agriculture, the main factors that are changing are atmospheric CO<sub>2</sub>, temperature, precipitation and evapotranspiration. According to Yeo (1999), the change in climate is expected to modify the biophysical environment in which crops grow. Plant responses to higher concentrations of atmospheric carbon dioxide (CO<sub>2</sub>) may be considered on different scales, ranging from the microscopic cellular level to the macroscopic agroecosystem level (Yeo, 1999). Photosynthesis, respiration and transpiration are the plant processes most directly affected by changing levels of carbon dioxide. Several interactions with elevated CO<sub>2</sub> are possible. For example, elevated CO<sub>2</sub> could reduce stomatal conductance and so reduce transpiration. Conversely, the climatic effects of elevated CO<sub>2</sub> (for example, increasing temperatures and evaporative demand) could increase transpiration, thereby causing an increase in growth rate (Yeo, 1999). Carbon dioxide is also an essential component in the process of photosynthesis, upon which life on earth ultimately depends. An enhanced CO<sub>2</sub> concentration in the atmosphere tends to increase the gradient between the external air and the air spaces inside the leaves, thus promoting diffusive transfer and absorption of CO<sub>2</sub> into the chloroplasts and their conversion to carbohydrates (Lemon, 1983; Acock and Allen, 1985; Drake and Leadley, 1991). The physiological effects of increased atmospheric CO<sub>2</sub> on plants may also have a significant consequence on organic soil matter, which in itself is a major link in the global carbon cycle. As a result, changing climate is likely to create climatic-soil patterns that have not previously been observed in particular areas (Rosenzweig and Hillel, 1998).

According to Niang-Diop *et al.*, (2005), the impact of climate change on agriculture in developing countries has been on the increase. As a result, some attempts have been made to estimate the impact of climate change on the agricultural sector (Winter *et al.*, 1996; Dinar *et al.*, 1998; Kumar and Parikh, 1998; Mendelson *et al.*, 2000). Crops stressed by climate change become more susceptible to attack by pests and diseases. The risk of crop loss in temperate regions can increase while crop pests move poleward with global warming (Porter *et al.*, 1991). Climate change may affect agricultural systems directly and indirectly. Directly, through changes in temperature, water balance, and atmospheric composition, as well as extreme weather events and indirectly through changes in the distribution, frequency, and severity of pest and disease outbreaks, incidence of fire, weeds infestations or variations in soil properties. The result of such direct or indirect effects will have negative impacts on production and distribution systems (Jepma and Munasinghe, 1998).

Only a few high-resolution scenarios of climate change over Southern Africa have been developed to date (Engelbrecht, 2005; Tadross *et al.*, 2006). Engelbrecht (2005) developed a practical climate change scenario for the period 2070-2100 using the Conformal Cubic Atmospheric Model (CCAM). He found that the future austral winter climate of southern and tropical Africa will be controlled by an intensification of the subtropical high-pressure belt. Frontal rain bands are simulated to shift to the south in the future climate, compared to their present day average position. Consequently, there is a general decrease in winter rainfall over the typical winter rainfall regions of South Africa in the model projection. A large area of the eastern subcontinent is simulated to experience an increase in rainfall in midsummer within the context of the future climate.



In the late summer most of southern Africa is simulated to become drier although the western interior of South Africa will experience significantly wetter conditions. The implications for tomato production in these and other scenarios of climate change projected for southern Africa need to be quantified.

The yearly variability in climate also impacts on crop yield. Climate variability deals with extreme events such as excessive precipitation, drought and hot or cold spells, together with any abrupt changes in the traditional patterns of the local, regional and global climate. The extreme climate events also often adversely affect land use planning, levels of agricultural yield, consistency in yield, cost of production, sowing, harvesting, irrigation needs, transportation, storage, pests and diseases, marketing, farm management, food security and many other socio-economic indicators. Furthermore, it causes massive loss of life and damage to property, including agricultural investment (Ogallo *et al.*, 1999).

## **1.2. Significance of the study**

This research project is focused on the impact of climate change and variability on tomato (*Lycopersicon esculentum*) production in the Limpopo Province of South Africa, which is particularly vulnerable to climate change. No study has been done previously in Limpopo concerning tomato production and climate change or variability. The region has a spatial variation of tomato production marked by fluctuations in weather parameters such as temperature and frost, to which the tomato crop is very sensitive. The Limpopo Province is located in the subtropics and mid-latitudes of Earth that are often characterised by a high degree of climate variability. As a result, agriculture in this region

is highly vulnerable to the extended periods of drought that sometimes occur. Conversely, during seasons when tropical circulation is dominant, flooding may occur over extensive areas within the province. The potential for climate change over the region, as induced by global warming, is therefore an issue of great importance to southern African agriculture. Global warming is expected to impact directly on agriculture by means of rising temperatures, changing rainfall totals, changes in seasonality and a larger degree of climate variability. There may also be secondary impacts, since climate change and enhanced climate variability may affect pests that are harmful to agriculture. It is therefore reasonable to expect that agricultural management will have to adapt to the new environment induced by global warming. In South Africa, tomatoes are largely produced in the Limpopo Province. This area is particularly vulnerable to climate variability and climate change.

### **1.3. Aim and objectives**

The main aim of this study is to determine how climate change may influence the distribution of tomato pests and therefore tomato production in the Limpopo Province, South Africa. Under this aim the following specific objectives of this study were:

- a) To analyse temperature trends and a five decades of heat waves in Limpopo
- b) To analyse the impact of climate variability on tomato production in Limpopo
- c) To analyse the effect of leafminer agromyzid pest distribution over Limpopo in a changing climate.

#### **1.4. Research questions**

This research set out to address the following questions:

- a) What are the temperature trends in the Limpopo Province?
- b) Is there any influence of climate variability on tomato production over the province?
- c) Are there heat waves in the province?

How are leafminer agromyzid pests distributed over the province in relation to changing climate?

#### **1.5. Hypothesis**

The production of tomatoes in the province is affected by climate change.

#### **1.6. Thesis outline**

In this thesis, the impact of global warming and the associated climate change on agriculture in South Africa was investigated. The impact of climate change and climate variability on insect pests that affect tomato production in the Limpopo Province of South Africa, and the tomato crop yield under conditions of climate change, were studied in particular. Additionally, the sensitivity of tomato production to inter-annual climate variability was evaluated. The present thesis has seven chapters, including an introduction, discussion and conclusion.

- Chapter 2 presents the study area, data and methodology of the research. The research was carried out in the northern province of South Africa (Limpopo). The climatic data used in the study were obtained from the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal. The climatic data were used to extract the catchment data (30 tertiary catchments) for the purpose of performing a spatial analysis of temperature over the Limpopo. In addition, the monthly regional tomato market data were obtained from the National Department of Agriculture. During the pre-processing stage, the daily average temperature (AvT) was calculated from the arithmetic averages of the daily maximum temperature (MxT) and minimum temperature (MnT). The diurnal temperature range (DTR) was computed by subtracting the daily MnT from the daily MxT. Monthly means were calculated from the daily average, minimum and maximum temperatures. Thereafter, temperature trends were calculated from the monthly averages over the 50-year period for each catchment. The trends were estimated by fitting a linear regression line on the monthly temperature data. (Zhang et al., 2000).
- Chapter 3 presents the analysis of temperature trends in Limpopo, South Africa, in which detailed analyses of trends in annual, seasonal minimum and maximum, temperatures, as well as the diurnal temperature range, were investigated for the period 1950-1999. In general, there was an increase of  $0.12^{\circ}\text{C}$  per decade in the mean annual temperature for the 30 catchments over a 50-year period. Also a non-uniform pattern of changes in temperature was evident across the different

catchments: 13% of the catchments showed negative trends while 87% showed positive trends in their annual mean temperature.

- Chapter 4 presents an analysis of HWs in Limpopo, South Africa over five decades (50 years). The results show that there was generally an increase of HW trends during 1950-1999 over the north-west, north and north-south of the province.
- Chapter 5 presents the impact of climate variability on tomato production in Limpopo. Particular attention was paid to the relationship between tomato production and monthly average temperatures as well as seasonal average temperatures over the Limpopo Province during the period 1971-2006.
- Chapter 6 presents leafminer agromyzid pest distribution over the Limpopo Province in a changing climate. This chapter demonstrates that the leafminer agromyzid pest and climatic factors exhibit a non-linear relationship best described by a polynomial function of order two while in general, the influence of climate change on the spatial distribution of the leafminer agromyzid pest over the Limpopo Province is noticeable.
- Finally, in Chapter 7, the results for this research are synthesised and the research findings are highlighted. In addition, recommendations for further research are provided.

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## Chapter 2: Study area, data and methodology

### 2.1. Study area

The study was conducted in the Limpopo Province, located in the northern part of South Africa (approximately 22-25° S, 27-32°E) (Figure 2.1). Limpopo is one of the developing provinces in South Africa and is particularly vulnerable to the impact of climate change due to its exposure to extreme weather events (Cook *et al.*, 2004). The province has three distinct climatic regions: the Lowveld region, which is characterised by arid and semi-arid climates, the Middle- and Highveld regions, which experience a semi-arid climate, and the Escarpment, which experiences a sub-humid climate (Limpopo Department of Agriculture, 2008).

This province experiences long sunny days and dry weather conditions on most days and has almost year-round sunshine. During the summer months, the heat is often interrupted by a short thunderstorm coming sometimes from the extreme heat of the day (Limpopo Department of Agriculture, 2008). It can get very hot in summer (October and March), with temperatures rising to 27°C in summer and 20°C in winter. It only rains in summer and annual precipitation is about 400-600mm (Anon, 2007). Although communities in the Limpopo region may have a greater ability to adapt to the long-term changes in climate, such as increased seasonal temperatures and changed patterns of precipitation, the province is nevertheless afflicted by the frequency of extreme weather events. Extreme weather events are described by the World Meteorological Organization (WMO) as “hazardous meteorological or hydro-meteorological phenomenon, of varying but short duration (minutes, hours, days to a couple of weeks) and of varying geographical extent,

with the risk of causing major damage, serious social disruption and loss of human life, requiring measures for minimising loss, mitigation and avoidance, and requiring detailed information about the phenomenon (location, area or region affected, time, duration, intensity and evolution) to be distributed as soon as possible to the responsible authorities and to the public” (WMO, 2004). This includes weather phenomena at the extremes of historical distribution, especially severe or unseasonal weather.

This province is very important for tourism because of the presence of a number of national parks, such as the Kruger National Park and the Limpopo Transfrontier Park. Furthermore, though the province has a large rural population, it has great biodiversity and the region is extensively farmed (Reason *et al.*, 2005).

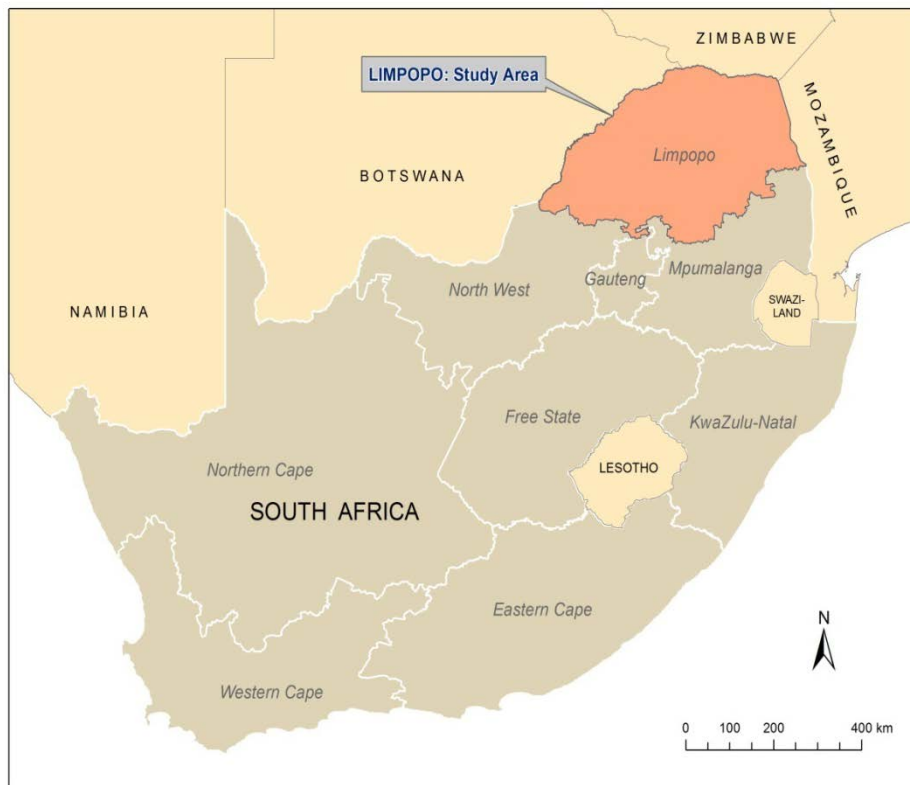


Figure 2.1. Map of the study area: the Limpopo Province

## 2.2. Data and methodology

Data used in the study were provided by the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal. Data provided consisted of daily maximum and minimum temperatures from hydroclimatic data collected from more than 970 qualifying temperature stations, over the 50-year period from 1950-1999. The data were quality controlled using infilling and record extension techniques developed by Schulze and Maharaj (2004). A time series at each of 429 700 one arc minute ( $\approx 1.7\text{km} \times 1.7\text{km}$ ) raster points covering South Africa was derived, using regionally and seasonally determined lapse rates and other physically appropriate spatial interpolation approaches. More details on this method can be obtained from Schulze and Maharaj (2004).

During the pre-processing stage, the daily average temperature (AvT) was calculated from the arithmetic averages of the daily maximum temperature (MxT) and minimum temperature (MnT). The diurnal temperature range (DTR) was computed by subtracting the daily MnT from the daily MxT. Monthly means were calculated from the daily average, minimum and maximum temperatures. Thereafter, temperature trends were calculated from the monthly averages over the 50-year period for each catchment. The trends were estimated by fitting a linear regression line on the monthly temperature data. This procedure for identifying trends is used widely (Arora *et al.*, 2005; Mote, 2003) and has also been applied to identify trends at specific weather stations in South Africa (Kruger and Shongwe, 2004).

The catchment data obtained made it possible to perform a spatially continuous analysis in Limpopo. Data for 30 tertiary catchments across Limpopo were analysed in this study. The present study focuses on the temperature events and extreme temperatures that were defined according to the temperature categories used by the South African Weather Service in the forecasting section. However, the temperature thresholds are defined for forecasting purposes, which means a day is defined as very hot, hot, cool or cold. In this case, a very hot day is defined as a day with a maximum temperature equal to or higher than 35°C. A moving average was calculated, defined as the average of a series of numbers over a period of time, which is constantly updated by dropping the oldest value and then adding the newest value and recalculating the average. Towards the calculation of HWs, the frequency of extreme temperature events at each catchment was calculated.

The monthly regional tomato market data were obtained from the National Department of Agriculture in 2009. According to government statistics, the Limpopo Province contributes 66% of tomatoes to the South African fresh produce market (NDA, 2009). Due to the imperfect and lack of documentation from tomato farmers in the country, the monthly average tomato market data (these were used as an indicator of tomato production) were calculated by weighting the total number of tomatoes distributed monthly in the South African fresh tomato markets by 2/3.

Climatic variables considered were the 35-year averaged observed temperature obtained from the Climate Research Unit (CRU) for the period 1971-2006. The data were obtained from the monthly mean climate fields of 0.5 ° x 0.5 ° grid resolutions over the Limpopo Province of South Africa. The mean climate surfaces were constructed from 35-year (1971-2006) station observation fields, which were then interpolated on the climate grid

surfaces. In this study, the mean monthly temperature values were calculated to derive seasonal averages. The autumn season commences from March to May (MAM), winter from June to August (JJA), spring from September to November (SON) and summer from December to February (DJF). Additionally, STATISTICA software was used to estimate the factor of climate in the current yield trends by applying the regression models to observed trends in climate variables for a period of 35 years from 1971-2006.

To assess the relationship between the time series of tomato production and climate change proxies, the first-difference time series methodology was employed. The first-difference time series considered here is the difference in values from one year to another year as described in Lobell *et al.*, (2005) and Nicholls, (1997). Furthermore, a multiple linear regression analysis was used: here, the first difference in yield is considered the response variable, first differences of average temperature, minimum average temperature and average maximum temperature as the second variable. Additionally, the spatial and temporal patterns of the significant correlation values were used to determine relationships between tomato production and average temperature in Limpopo during various months and seasons. Composites of temperature and tomato yield were presented in the form of a scatter plot in order to study the characteristics of extreme temperatures and weather events and dependency.

The Conformal Cubic Atmospheric Model (CCAM) is a General Circulation Model (GCM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Marine and Atmospheric Research in Australia (McGregor, 2005). The model may be integrated in variable-resolution mode with high resolution over an area of interest using the Schmidt stretching factor, thereby allowing it to function as a regional

climate model (Engelbrecht *et al.*, 2009). CCAM replaced the limited area nested climate model Division of Atmospheric Research Limited Area Model (DARLAM) that was used for regional climate modelling applications (Engelbrecht *et al.*, 2002). Variable-resolution global modelling offers vast flexibility for dynamic downscaling from other GCMs or reanalysis data, effectively requiring only sea surface temperatures (SSTs) and optionally, far-field winds from the global model in which it is nudged (Wang *et al.*, 2004).

The model uses a quasi-uniform grid, which is obtained by projecting the six panels of a cube onto the spherical surface of the earth (McGregor and Nguyen, 1999). Since the grid has a fairly uniform resolution over the globe, it avoids problems associated with normal latitude-longitude grid projections that require filtering in the vicinity of the poles due to the clustering of grid points (McGregor, 2005). CCAM employs a two-time-level, semi-implicit discretisation of the hydrostatic primitive equations (McGregor, 2005). The model also makes use of a semi-Lagrangian scheme for horizontal advection, which, in combination with the semi-implicit procedure, ensures numerical stability when using large time steps (McGregor, 2005).

The climatic data were collected from Circulation Cubic Atmospheric Model (CCAM). This is a Global Circulation Model (GCM), which may be used in variable resolution mode to function as an Resolution Climate Modelling (RCM) That is, the model may be integrated with high horizontal resolution over the area of interest, with the resolution gradually decreasing as one moves away from the area of interest. Compared to the more traditional nested limited-area (the modelling approach for example, McGregor, 1996), variable-resolution modelling provides great flexibility for dynamic downscaling from



any global model, essentially requiring only sea-surface temperatures and, optionally, far-field winds from the host model (Wang *et al.*, 2004). It also avoids other problems that may occur with limited-area models, such as reflections at lateral boundaries. CCAM is formulated on a quasi-uniform grid, derived by projecting the panels of a cube onto the surface of the earth. The model can be run in either stretched mode for variable-resolution regional modelling, or in a non-stretched mode to provide quasi-uniform resolution globally. CCAM employs a two-time-level semi-implicit hydrostatic formulation. A semi-Lagrangian horizontal advection with bi-cubic spatial interpolation is used (McGregor, 1996), with total-variation-diminishing vertical advection. The model uses an un-staggered grid, with winds transformed reversibly to/from C-staggered locations before/after gravity wave calculations (McGregor, 2005). More details on the geometrical aspects and dynamical features of CCAM can be found in McGregor (2005).

The pest data were collected from the laboratory measurement on the effect of temperature on the various population parameters of the pest (Zhang *et al.*, 2000). STATISTICA software was used to come up with the polynomial equation, which gives the coefficient and becomes the model parameter. In addition, the model parameters were taken to the model simulation CCAM using Matrix Laboratory (MATLAB) software and the different values that were obtained were then plotted to the GIS to see the pest distribution over the Limpopo Province.

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## **Chapter 3:      Analysis of Temperature Trends over the Limpopo Province, South Africa**

*Article published*

**Tshiala MF, Olwoch JM and Engelbrecht FA (2010). Analysis of temperature trends over the Limpopo Province, South Africa, *Journal of Geography and Geology (JGG)*. Vol. 3, No. 1.**

### 3.1. Abstract

Detailed analyses of trends in annual, seasonal minimum and maximum temperatures, as well as the diurnal temperature range, were investigated over the Limpopo Province, South Africa, for the period 1950-1999. Using daily data from 30 catchments, three temperature variables were calculated: average, maximum and minimum. Overall, there was an increase of  $0.12^{\circ}\text{C}$  per decade in the mean annual temperature for the 30 catchments over a 50-year period. A non-uniform pattern of changes in temperature was evident across the different catchments: 13% of the catchments showed negative trends while 87% showed positive trends in their annual mean temperature. Furthermore, 20% of catchments showed negative trends while 80% of catchments showed positive trends in their diurnal temperature range. The seasonal trends showed variability in mean temperature increase of about  $0.18^{\circ}\text{C}$  in winter and summer  $0.09^{\circ}\text{C}$  per decade. The significance of this work lies on the linkage of temperature to the hydrological cycle.

**Keywords:** annual temperature trends, seasonal temperature trends, diurnal temperature trend, the Limpopo, South Africa, hydrology

### 3.2. Introduction

Several studies investigating temperature trends in South Africa have been published in the literature. Muhlenbruch (1992) reported a decrease in maximum temperatures but an increase in minimum temperatures in South Africa between 1940 and 1989. This pattern was most pronounced during the spring season from September to November (SON), but reversed in the autumn period. These findings were later contrasted by Karl *et al.* (1993) who reported an increase in both maximum temperatures and minimum temperatures but a decrease in the diurnal temperature range in South Africa for the period 1951 to 1991. Jones (1994) reported consecutive cooling and warming periods from 1885 to 1915 and 1915 to 1945 respectively. The paper also reported a slight cooling period from 1945 to 1970, followed by a rapid warming period from 1970 to 1990. Hughes and Balling (1995) reported an increase of  $0.11^{\circ}\text{C}$  in maximum and  $0.12^{\circ}\text{C}$  in average temperatures per decade over the period 1960 to 1990. These trends were significant for both non-urban and urban stations.

Kruger and Shongwe (2004) argued that the average temperatures in South Africa for the 1990s were significantly warmer than preceding decades:  $18.48^{\circ}\text{C}$  for 1991 to 2003 compared to  $18.18^{\circ}\text{C}$  for 1960 to 1990. The average temperature trend from 1991 to 2003 was  $0.09^{\circ}\text{C}$  per decade, compared with  $0.11^{\circ}\text{C}$  per decade from 1960 to 1990. It was also found that there was a relatively rapid increase in average temperatures in the early 1960s, which consequently caused a general increase in temperature over the whole period from 1960 to 1990. While the average trend in annual mean temperatures of  $0.13^{\circ}\text{C}$  per decade for 1960 to 2003 is significant, non significant trends of  $0.04^{\circ}\text{C}$  per

decade and  $0.01^{\circ}\text{C}$  per decade were found for 1960 to 1982 and 1983 to 2003, respectively.

In particular, Kruger and Shongwe (2004) found a significant increase in temperature between 1960 and 2003 for the three stations Bela Bela, Polokwane and Musina situated in Limpopo in north-eastern South Africa. This paper aims to provide a more continuous picture of temperature trends over the Limpopo Province by considering trends in temperature for all catchments within the province. Furthermore, the results for temperature trends from the different studies reported on above do not provide a consistent picture of temperature trends over South Africa and the Limpopo in particular.

South Africa is known to be a water stressed country (Schulze, 2000 and 2001; RSA, 2002; IWMI, 1996; Ochieng and Otieno, 2004). Temperature changes influence the hydrological cycle processes directly or indirectly (Parry *et al.*, 2001). An increase in temperature causes the intensification of the hydrological cycle that results in increased evaporation and precipitation. That is, temperature changes may lead to shifting patterns of precipitation, the spatial and temporal distribution of runoff, soil moisture and groundwater reserves, as well as an increase in the frequency of droughts and floods (Arora *et al.*, 2005). Indeed, Parry *et al.*, (2001) reported a steep rise in the water shortage curve when plotted against rise in temperature. Schulze, (2000 and 2001) reported that South Africa is situated in a region with increasing levels of water quality problems, amalgams of population growth and issues of social and economic development. Further stresses on water resources arising from potential climate change will intensify these problems over much of the country and the wider southern African region.

There could also be knock on effects on soil characteristics, since temperature and water content are important soil physical factors for plant growth. Non-optimum levels of water and temperature conditions can strongly affect plant development, especially at the early stages of growth (seed germination and emergence) (Helms *et al.*, 1996). Identification of temperature and rainfall trends over Limpopo is necessary in order for knock on effects on aspects such as soil and plant growth characteristics to be explored.

This paper aims to determine trends in the monthly, seasonal and annual, maximum and minimum temperatures, as well as the diurnal temperature range over Limpopo from daily temperature records over a period covering five decades. Results from this analysis can be used as a base to investigate the impacts of temperature on agriculture and water. Results from the analyses will also add more knowledge about past climatic variability and provide a platform for understanding the regional impacts of global warming and climate change.

### **3.3. Regional setting**

This study focuses on the Limpopo Province located in the northern part of South Africa (approximately 22-25°S, 27-32°E). Limpopo is one of the developing provinces in South Africa and is particularly vulnerable to the impact of climate change because of its exposure to extreme weather events (Levey and Jury, 1996; Tennant and Hewitson, 2002; Cook *et al.*, 2004). The province has three distinct climatic regions: the Lowveld region, which is characterised by arid and semi-arid climates, the Middle- and Highveld areas, which are considered semi-arid, and the Escarpment, which experiences a sub-humid climate (the Limpopo Department of Agriculture, 2008).



This province experiences long sunny days and dry weather conditions on most days and has almost year-round sunshine. During the summer months, warm days are often interrupted by a short-lived thunderstorm (Limpopo Department of Agriculture, 2008). It can get very hot in summer (October and March), with average temperatures rising to 27°C in summer and 20°C in winter. The bulk of the precipitation occurs in summer, and annual rainfall totals range from about 400-600mm over most of the province (Anon, 2007). Although communities in the Limpopo Province may have a greater ability to adapt to long term changes in climate, such as increased seasonal temperatures and changed patterns of precipitation, they are nevertheless severely stressed by the frequency of the occurrence of extreme weather events (defined as weather phenomena that are at the extremes of the historical distribution, especially severe or unseasonal weather, WMO, 2004.). This province is very important for tourism because of the presence of a number of national parks, such as the Kruger National Park and the Limpopo Transfrontier Park. Furthermore, though the province has a large rural population, it has great biodiversity and the region is heavily involved in farming (Reason *et al.*, 2005).

### **3.4. Data and methodology**

Data used in the study were provided by the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal. Data provided consisted of daily maximum and minimum temperatures from hydroclimatic data collected from more than 970 qualifying temperature stations, over the 50-year period 1950-1999. The data were quality controlled using infilling and record extension techniques developed by Schulze and Maharaj (2004). A time series at each of 429 700 one arc minute ( $\approx 1.7\text{km} \times 1.7\text{km}$ ) raster points covering South Africa was derived, using regionally and seasonally

determined lapse rates and other physically appropriate spatial interpolation approaches. More details on this method can be obtained from Schulze and Maharaj (2004).

During the pre-processing stage, the daily average temperature (AvT) was calculated from the arithmetic averages of the daily maximum temperature (MxT) and minimum temperature (MnT). The diurnal temperature range (DTR) was computed by subtracting the daily MnT from the daily MxT. Monthly means were calculated from the daily average, minimum and maximum temperatures. Thereafter, temperature trends were calculated from the monthly averages over the 50-year period for each catchment. The trends were estimated by fitting a linear regression line on the monthly temperature data. This procedure for identifying trends is used widely (Arora *et al.*, 2005; Mote, 2003) and has also been applied to identify trends at specific weather stations in South Africa (Kruger and Shongwe, 2004).

The following linear trends function was applied to the monthly temperature values of the catchments:

$$f(x,t) = ax(t) + b \quad (3.1)$$

Where  $t$  (months) = 1, 2, ..., 600;  $x(t)$  is the monthly (e.g., average, maximum and/or minimum temperature) and  $a$  is the linear trend (in °C/Month). Furthermore, the annual and seasonal temperature averages were calculated for each of the catchments, and the corresponding trends were calculated. Seasons were defined following the usual conventions for winter: June to August (JJA) and summer: December to February (DJF).

In addition, the trends were investigated using the Mann-Kendall test, which is a non-parametric test and can be used to analyse trends of temperature data (Hall *et al.*, 2006; Capodici *et al.*, 2008). The  $n$  time series values ( $X_1, X_2, X_3, \dots, X_n$ ) are replaced by their relative ranks ( $R_1, R_2, R_3, \dots, R_n$ ) (Starting at 1 for the lowest up to  $n$ ). The Mann-Kendall statistic  $S$  is:

$$S = \sum_{i=1}^{n-1} \left[ \sum_{j=i+1}^n \text{sgn}(R_i - R_j) \right] \quad (3.2)$$

Where

$$\text{sgn}(x) = \begin{cases} 1 & \forall x > 0 \\ 0 & \forall x = 0 \\ -1 & \forall x < 0 \end{cases}$$

If the null hypothesis  $H_0$  is true, the  $S$  is approximately normally adjusted with

$$\mu = 0$$

$$\sigma = \frac{n(n-1)(2n+5)}{18}$$

The  $z$ -statistic is therefore

$$z = \frac{|S|}{\sigma^{0.5}}$$

### 3.5. Results and discussion

#### 3.5.1. Mean monthly temperature over Limpopo

Analysis of the mean monthly temperature over the Limpopo Province is depicted in Figure 3.1. From the analysis, it was found that the highest temperature in the province was in the months of October to March. While certain months (for example, December and January) experienced a peak average temperature of 27°C, there were minimal differences in temperature across the months, all averaging at around 22°C. The graph simply shows the intra-annual cycle in temperature that is driven by radiation.

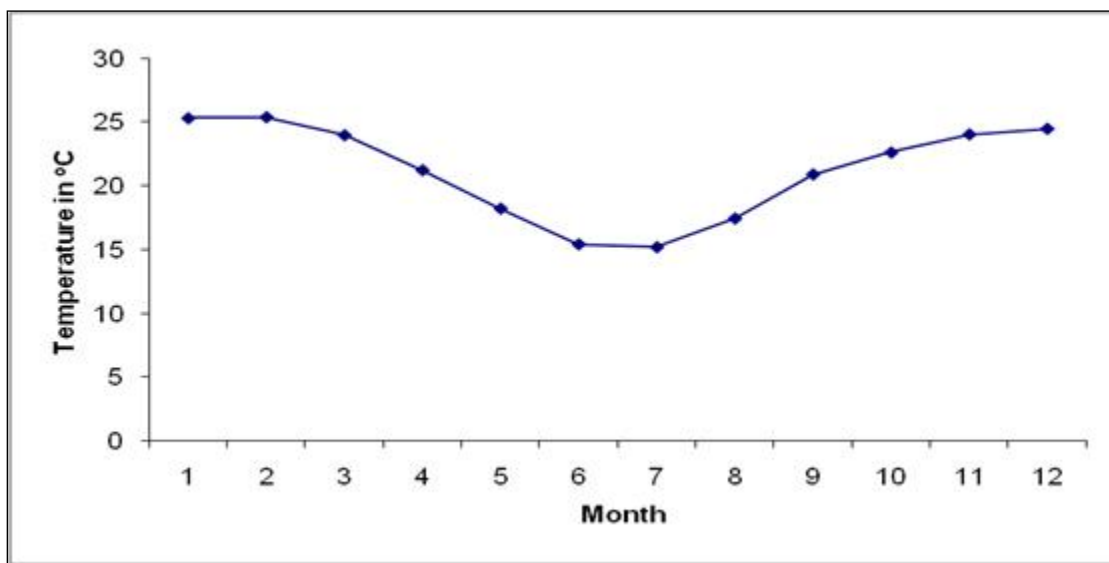


Figure 3.1. Monthly mean temperature in degree Celsius (°C) from 1950-1999 over the Limpopo Province

A clear intra-annual pattern is discernible in Figure 3.2 below. Further, a seasonal signature in the variability of temperature is also depicted, with the peak average temperature ( $>24^{\circ}\text{C}$ ) registered during the summer season. The Limpopo Province exhibits low temperature fields during the winter season. For instance, the months of June and July exhibit characteristic low average temperatures ranging between  $15^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  over the period 1950-1999.

### **3.5.2. Trends in mean annual maximum, minimum and mean temperature**

Figure 3.2 shows that the majority of the considered catchments (70%) showed positive trends in the annual mean maximum temperature (AMMxT), with 63% of the catchments displaying positive trends in the annual mean minimum temperature (AMMnT). Furthermore, the analysis of average temperature (AvT) exhibited positive trends for 87% of the catchments.

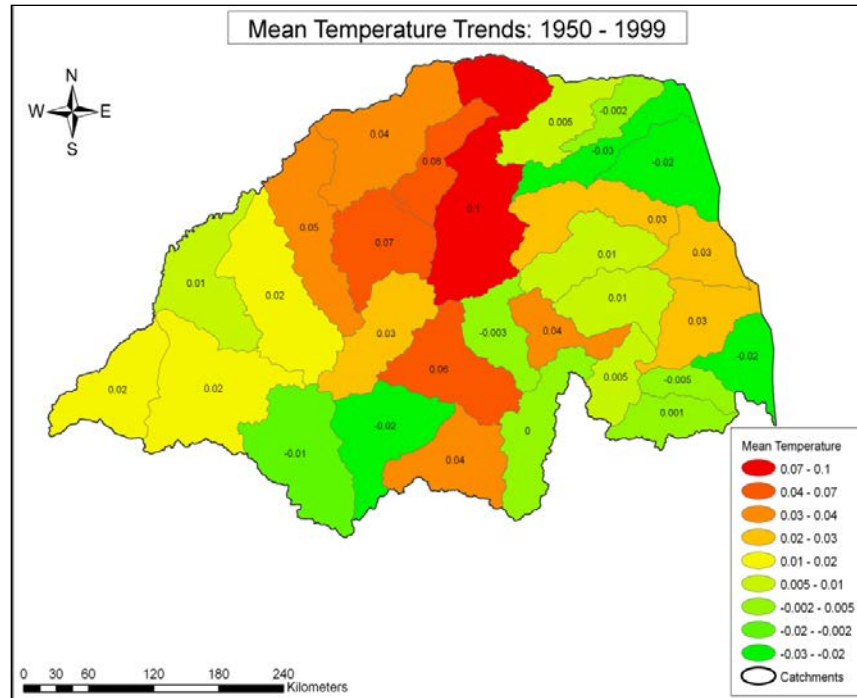


Figure 3.2. Temperature trend (°C/decade) in mean annual temperature for the period 1950-1999

As seen in Figures 3.2, 3.3, and 3.4, most of the catchment area showed a positive trend in annual average, mean maximum and minimum temperatures over the period 1950-1999. These results confirm that during the period 1950-1999 temperature trends in Limpopo were generally positive, consistent with the results of Kruger and Shongwe, 2004.

Detailed analysis of mean annual average temperatures shows that the highest positive mean annual trend recorded among the 30 catchments over the Limpopo was 0.1°C per decade, whilst the largest negative trend is -0.03°C per decade. Not all areas in the province exhibited the same trend, with the northern portions warming up faster. The general rising trends in temperature could have implications for evaporation and water management in the province.

Trends were investigated using the Mann-Kendall test as described earlier and the results show that there were evidences of significant trends in mean annual maximum, minimum and mean temperature at a 0.01 significance level for all the catchments as the computed Z statistics were found to be 1.957; for temperature minimum the z-statistics were found to be 3.973 and the average temperature with Z-statistics 3.145. This shows a generally increasing trend. Figure 5 shows that the majority of the considered catchments (70%) showed positive trends in the annual mean maximum temperature (AMMxT), with 63% of the catchments displaying positive trends in the annual mean minimum temperature (AMMnT).

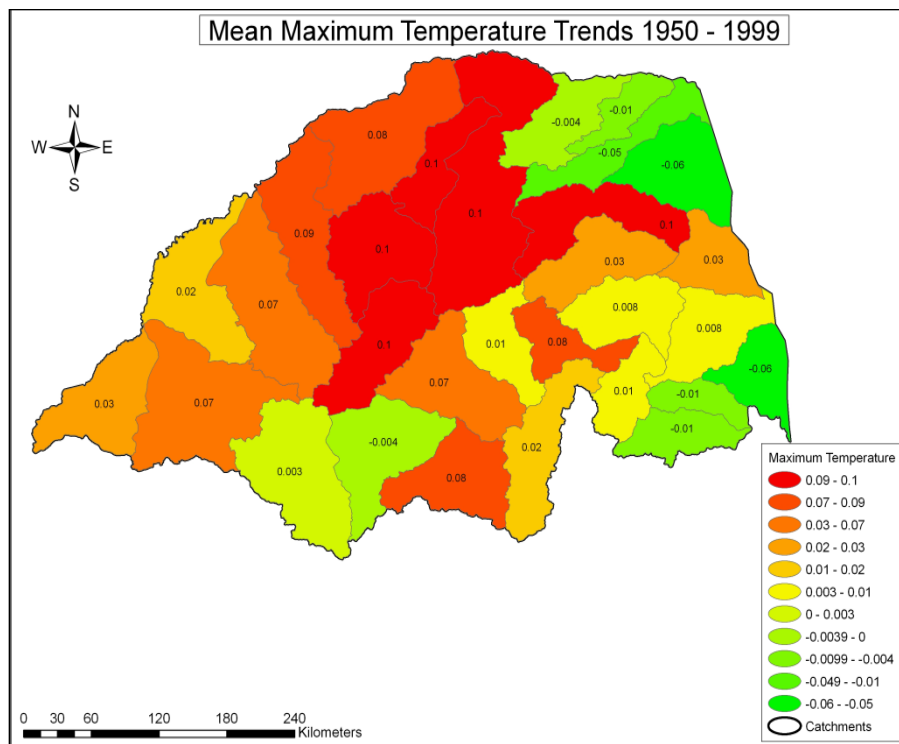


Figure 3.3. Trend (°C/decade) in mean maximum annual temperature for the period 1950-1999

The analysis of AMMxT (Figure 3.3) shows that different catchments experienced varying maximum temperature trends, with the north-western parts warming up the fastest. The present results corroborate those of Kruger and Shongwe (2004) who demonstrated that there was a significant temperature increase between 1960-2003, based on data from three stations. From the results of the trends found by Kruger and Shongwe, the Limpopo in general has a pre-dominating positive trend in temperature, with the trend of 0.1°C for the period 1960-2003. These results are consistent with those found in this analysis, which is showing a trend of 0.1°C per decade during the period of 1950-1999 over Limpopo.

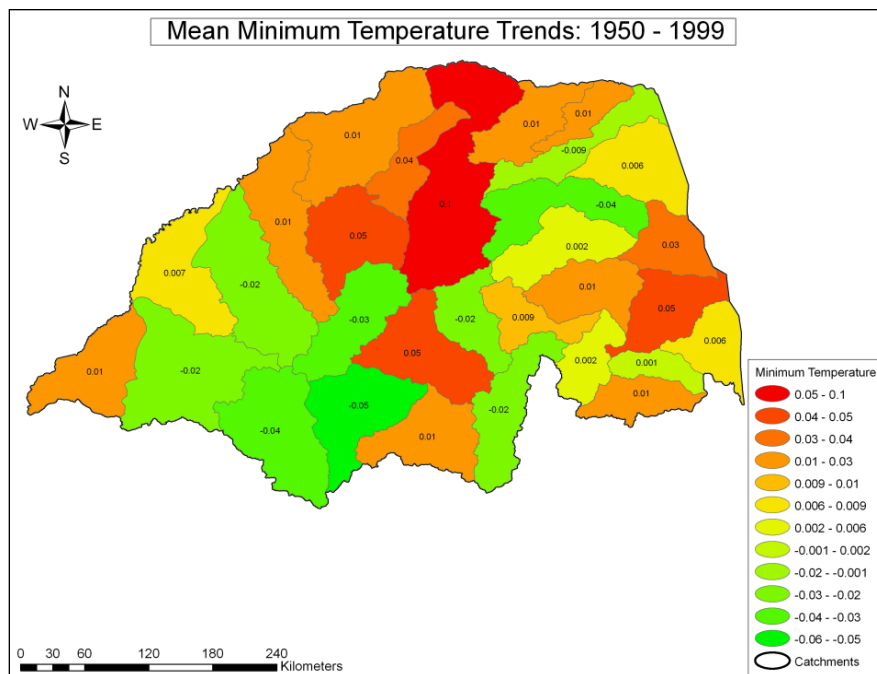


Figure 3.4. Trend (°C/decade) in mean minimum annual temperature for the period 1950-1999

Figure 3.4 above shows that the mean minimum annual temperatures over the period 1950-1999 in the Limpopo Province have increased by 0.001 to 0.1°C in the central parts



as well as in the other parts compared to the mean annual temperature, which showed more warming in the northern and central parts of the province than the others by 0.01 to 0.1°C.

### **3.5.3. Seasonal trends**

As illustrated in Figure 3.5 seasonal temperature trends exhibit variations in temperature over catchments and certain periods. Overall, the majority of the seasons showed a positive trend over the period of 50 years. The mean temperature trends of the 30 catchments per decade were found to be 0.18°C and 0.09°C for winter and summer respectively. In winter the majority of catchments, ~87 % (See Figure 3.5), depicted positive trends, while 13% of the catchments showed negative trends. Summer seasonal trends (Figure 3.5) followed a similar pattern but with winter exhibiting the highest mean temperature trend of 0.18°C. These results indicate that temperature trends over the 50 years from 1950-1999 are not consistent between seasons. Trends were investigated using the Mann-Kendall test as described earlier and the results show that there was evidence of significant trends in the summer period at a 0.05 significance level for all the catchments as the computed Z statistics were found to be 2.543. During the winter period the results showed statistical significant trend at 0.01, which is an increasing trend, this computed Z statistics were found to be 3.145.

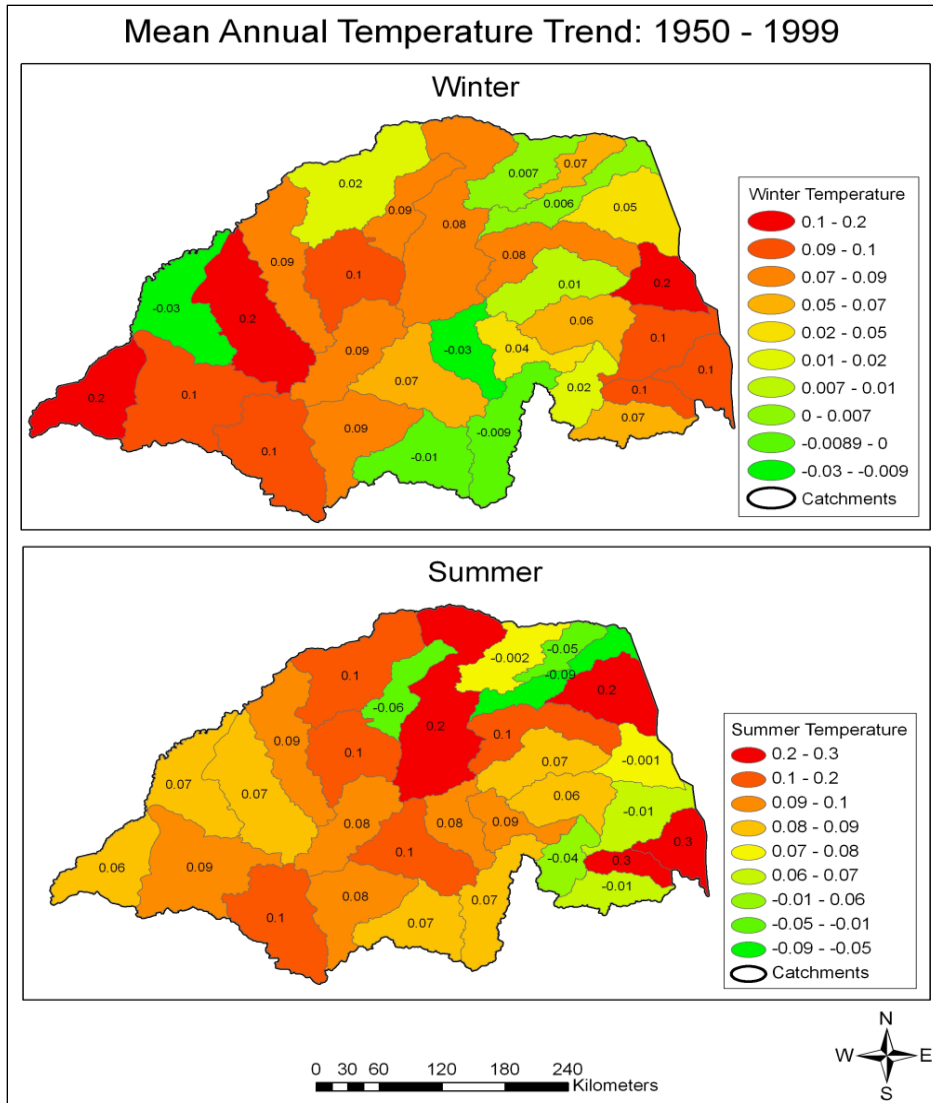


Figure 3.5 Trend ( $^{\circ}\text{C}/\text{decade}$ ) in mean winter and summer annual temperature for the period 1950-1999

In Figure 3.5 seasonal temperature trends exhibit variations in temperature over catchments and certain periods. Overall, most of the seasons showed a positive trend over the period of 50 years.

#### 3.5.4. Trends in diurnal temperature range (DRT)

In the present paper, we define DRT as the temperature difference between the minimum and the maximum registered (here, the term registered is used to denote either actual measurements or model simulations) temperature over a period of twenty-four hours starting from 00h00 (at midnight). A careful analysis of temperature trends for a period of 50 years (starting from 1971) found that about 80% of the catchments showed positive trends while 20% showed negative trends (Figure 3.6).

The term positive/negative is used here to signify a consistent increase/decrease in temperature over a given time span. This definition is restricted to linear changes as expressed in Equation 1. Nevertheless, at regional scales, the results may not necessarily be the same and this could be associated with different local factors such as soil moisture; by influencing evaporative cooling, the ground albedo and the ground heat capacity. This effect tends to be most influential in the occurrence of extremely hot days as reported by Durre *et al.* (2000). For example, catchments found in the northern central interior of the Limpopo Province had higher temperatures than the rest of the province (Figure 3.6).

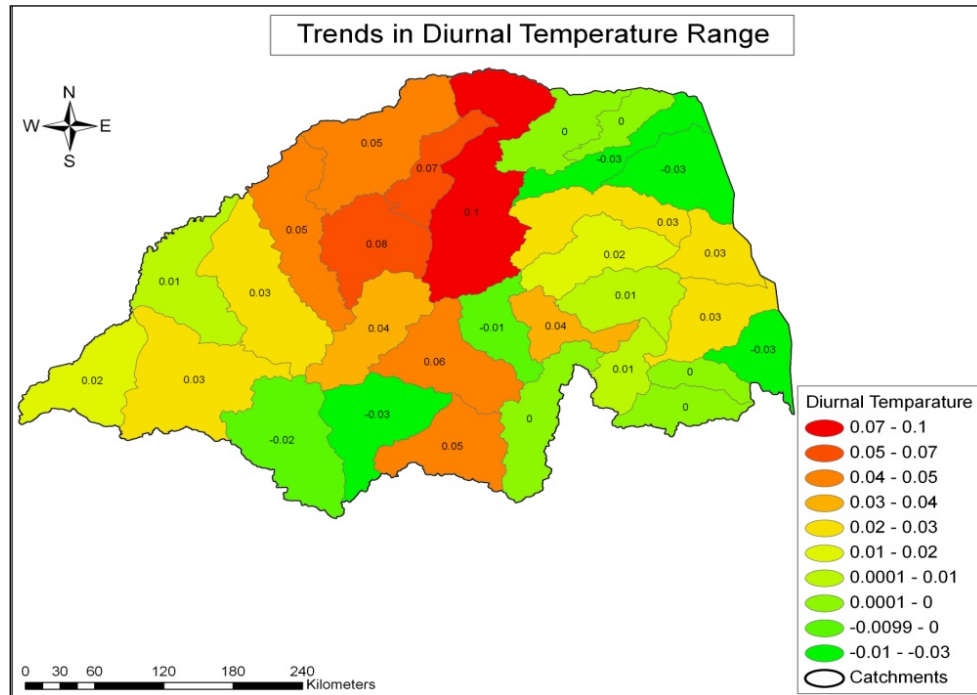


Figure 3.6. Trends in diurnal temperature range ( $^{\circ}\text{C}/\text{decade}$ ) for the period 1950-1999

It has been reported that a global average positive temperature trend over land has been linked to a large increase in the Tmin (Karl *et al.*, 1993; Easterling *et al.*, 1997; Jin and Dickinson 2002). The increase in Tmax has been observed to be at a much smaller rate, resulting in a decreasing trend in DTR. This magnitude is comparable to the mean warming itself. As an identifiable characteristic of recent climate change, this trend is important in diagnosing the force responsible for the change, and in particular the anthropogenic component.

However, the cause of the DTR trend is still poorly understood, as is its relation to anthropogenic forcing. The higher albedo of clouds decreases the downward solar radiation during the day, and thereby reduces Tmax. Indeed, observational studies link

the decreasing DTR to coincident increases in precipitating clouds (Karl *et al.*, 1993). These low base clouds are particularly effective in reflecting sunlight, and changes in their frequency of occurrence would be expected to have the strongest impact on the DTR. Clouds also produce more downward long-wave radiation, thus increasing night-time cloud cover, which would increase  $T_{min}$  and thereby decrease the DTR. However, the tendency of the diurnal cycle of cloud cover over global land areas during recent years is currently unknown.

### **3.6. Discussion and conclusions**

The global average surface temperature has increased by  $0.6 \pm 0.2^{\circ}\text{C}$  over the last century and it is expected that by 2100 the increase in temperature could range between 1.4 to  $5.8^{\circ}\text{C}$  (IPCC, 2007). Temperature changes have not been uniform globally, but have varied over regions and different parts of the lower atmosphere. In the South African context, a rise in temperature has been reported by Hughes and Balling (1999) and Kruger and Shongwe (2004). This study departs from many others reported in the existing literature and therefore adds a significant contribution to our understanding of the possible effects of temperature changes over Limpopo.

Overall, there was an increase of  $0.12^{\circ}\text{C}$  in the mean annual trend for the 30 catchments over the 50-year period. A non-uniform pattern of changes in temperature was evident across the different catchments. The long-term fluctuation in temperature has been represented by computing the linear trends in the data records. Although the variability of temperature trends exhibits a spatial dependence, (Figure 3.2) these variations are nevertheless unrelated to the large-scale modes of variability that could be linked to

climate change. These trends are undoubtedly real and the warming is substantial enough to have significant impacts on the hydrology and ecosystems of the region.

In our analysis of trends of DTR over Limpopo, it was also observed that the variations in the local temperature trends are not synchronised. Each catchment exhibits unique trends; for instance, positive DTR trends seem to occur more in the northern and central regions of the province. This result provides additional and specific information that corroborate with the general increase in temperature over Limpopo, reported by Kruger and Shongwe (2004), who concluded their findings based on a study involving a small number of stations in the province. Trends in seasonal temperatures showed that temperature trends are not uniform throughout the year, (Figure 3.5) with winter being the season with highest temperature trends on average and spring being the season with lowest trends.

In general, there is no spatial coherence in the results of temperature trends for specific seasons. Monthly trends of mean annual temperatures showed general patterns between the catchments with spatial and temporal dependence. The mean maximum, minimum and average annual temperature shows positive trends on average in the majority of the catchments. January and December exhibited the highest monthly temperature. Further, the mean annual temperatures had distinct varied characteristics as evidenced from a mixture of modes of fluctuations with different time scales. From these findings, increasing extreme rainfall events and rising temperature patterns provide favourable conditions for the geographical expansion of, for example, vector borne diseases such as malaria and East Coast fever. The assertion is derived from the several mathematical models as well as surveillance and direct observations reported in the literature (Olwoch

*et al.*, 2008). In addition, climate impact on human health will interact with those relying on rural livelihoods in particular (Midgley *et al.*, 2007).

The contribution of these findings to livelihoods in Southern Africa corroborates the findings reported by the Food and Agricultural Organisation (2004), whereby temperature changes were used as proxies to estimate that Southern African households were more susceptible to climate variability and drought and that these households were increasingly being threatened by desertification processes, degradation of land and water resources and loss of biodiversity. Although rain-fed farming is a high-risk enterprise, it is also a way of life and people are committed to making the best of the scarce resources at their disposal. However, droughts tend to reduce production to below already marginal levels, thus threatening subsistence farming. These conditions occur where the local economy is least diversified and where almost everyone depends either directly or indirectly on agriculture. Frequent exposure to drought causes agricultural production to be out of equilibrium with seasonal conditions, representing an inability on the part of most smallholders to adjust land use to climate variability. In conclusion, the significance of this work lies in the linkage of temperature to hydrological cycle and on the influence of temperature on weather and climate. As a result, this study contributes to further understanding of how temperature trends would influence water resources and weather as well as climate over Limpopo Province.

### **3.7. Acknowledgement**

The authors acknowledge the South African Weather Service and the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-

Natal for the provision of the weather data. The Canon Collins Trust in Cape Town and the University of Pretoria are gratefully acknowledged for financial assistance.

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## **Chapter 4: Five decade analysis of heat waves in the Limpopo Province, South Africa**

*Manuscript submitted for publication to the*

*Applied Ecological Environmental Research (AEER)*

**Tshiala, M.F., Olwoch, J.M., Engelbrecht, F.A. and Botai, J.O (2010). Five  
decade analysis of heat waves in the Limpopo Province, South Africa**

#### 4.1. Abstract

Extreme climatic phenomena have been a subject of investigation for decades because of their impacts on social-economic and health systems. In particular, recent studies have indicated a possible increase in the occurrence of severe weather events attributed to the enhanced greenhouse effect. In the present study, the occurrence of heat waves (HWs) over Limpopo and possible increases in their frequency of occurrence was studied. Studying HW occurrences over the Limpopo region is important due to their impact on agricultural production as well as on human health and the ecosystem. Results from the current study indicate that during the period 1950-1999, the Limpopo Province displayed frequency of occurrence of HW events, while during the four seasons the trends of HWs were not monotonic over the five decades.

**Key Words:** heat waves, climate change, Limpopo, South African climate.

## 4.2. Introduction

Increased incidence of extreme events such as heat waves, droughts and storms is already apparent in the climate record for the last five decades (IPCC 2007), and it is expected that their return time will continue to decrease in future as a consequence of global climate change (De Boeck *et al.*, 2010). For the Southern African region to date, most climate change studies have focused on shifts in the mean climatic conditions such as temperatures and rainfall, rather than focusing on changes in extreme events such as floods, dry spells and heat waves (HWs) (Della-Marta *et al.* 2007, Tadross *et al.*, 2006, Engelbrecht *et al.* 2009). However, both the shift in mean temperatures and an increase in the variance of the temperature probability density as a result of enhanced greenhouse gas forcing may cause the frequency of occurrence of hot episodes to increase significantly (Della-Marta *et al.*, 2007).

Currently there is no universally accepted definition of HWs and different authors have defined HWs according to the subject of the study (De Boeke *et al.*, 2010). Robinson (2000), defined a HW as an extended period of unusually high atmosphere related stress, which causes temporary modifications in daily life and which may have unfavourable health consequences for the affected population. According to Lopez-Diaz (2004), HWs are successive days with maximum and minimum temperatures above percentile-based thresholds. The South African Weather Service (SAWS, 2008) defines a HW is an event where the maximum temperature is 5°C warmer than the average maximum temperature for the warmest months of the year in that area for three consecutive days. However, De Boeck *et al.*, (2010) argued that an absolute threshold (such as 5°C) does not take into

account climatic variability, which is, for example, much lower in the tropics than in regions like Western Europe. Despite the variety of possible definitions, HWs are receiving growing scientific attention as a result of their impact on health and their reported increase in the near future as a result of global warming (Easterling *et al.*, 2000, Wigley and Raper, 2001).

Bernard and McGeehin (2004) reported that since 1998 in the United States, HWs caused more weather related fatalities annually than any other natural disaster, statistically about 400 deaths per year. According to Ebi and Meehl (2007), HWs affect human health through heat stress and such conditions can lead to an increase in mortality. Over the period 1979 to 1999 more than eight thousand deaths were recorded due to HWs and 3 829 deaths were attributed to weather conditions (Donogue *et al.*, 2003) in the United States. Jones *et al.*, (1982) reported that HWs caused a 64% increase in mortality in Kansas around July 1980 and a 57% increase in mortality in St. Louis. In 1995 Chicago had 696 excess deaths due to HWs (Whitman *et al.*, 1997, Semenza *et al.*, 1999) and 119 in 1999 (Palecki *et al.*, 2001). In France 14,947 deaths in 2003 were due to diverse causes directly attributable to heat (Poumadere *et al.*, 2005).

The climate of the Limpopo Province in north-eastern South Africa is known to be highly variable and prone to the occurrence of dry spells, droughts and HWs (DEAT, 2004). The formation of HWs over the region is known to occur, in particular, when tropical cyclones or losses are present in the Mozambique Channel to the north-east (DEAT, 2004). Under such a circulation pattern, air that rises over the Mozambique Channel diverges in the upper atmosphere before sinking over north-eastern South Africa, thereby inducing adiabatic warming and the formation of HWs.

However, despite the Limpopo Province being prone to the occurrence of HWs, and despite the potential impacts of HWs on human health and agriculture over the region, the climatological frequency of occurrence of HWs and how this may be expected to change under enhanced anthropogenic forcing, has not been investigated rigorously. The fact that such a study is overdue is also emphasised by evidence that climate change over South Africa can already be detected (DEAT, 2004).

Indeed, a number of climate models have indicated a distinct geographic pattern of future changes in the occurrence of HWs (Lopez-Diaz, 2004). Over the Southern African region in particular, the strengthening of the subtropical high-pressure belt and the more frequent formation of mid-level high pressure systems over the region (Engelbrecht *et al.*, 2009), may lead to the more frequent formation of HWs in a greenhouse gas warmed climate.

This paper aims at identifying possible trends in the frequency of occurrence of HWs and extreme temperature events over a 50-year period from daily temperature records. It aims simultaneously to develop present day climatology of the occurrence of HWs over the region. An enhanced understanding of the climatological characteristics of HWs over Limpopo, as well as possible trends in their occurrence, may be of benefit to the agricultural and human health sectors in the region. Furthermore, the results from the analyses might enhance insight knowledge of the past climatic variability and future climate change over Limpopo.



### 4.3. Study area

The study was conducted in the Limpopo Province in north-eastern South Africa with latitudinal and longitudinal boundaries of approximately 22°-25° S and 27°-32° E. Limpopo is one of the developing provinces and is particularly vulnerable to climate variability and change due to its exposure to extreme weather events (Levey and Jury 1996, Tennant and Hewitson 2002, Cook *et al.*, 2004).

Polokwane, the capital city of the province, is situated approximately at the centre of Limpopo and it lies at 1 312 m. The Limpopo Province has three distinct geographical regions: the Lowveld region where the climate ranges from subtropical in the south to semi-arid in the north, the Middle- and Highveld that exhibits a semi-arid climate and the Escarpment that experiences a sub-humid climate (Limpopo Department of Agriculture 2008).

This province generally experiences long sunny days and dry weather conditions. During summer, a heat thunderstorm commonly occurs. It can get very hot in summer (October and March), with the average January maximum temperature over the province being about 27°C. The average winter maximum is about 20°C. Rainfall mostly occurs in summer, with annual totals varying between 400-600mm across the province. However, over the escarpment and adjacent Lowveld areas to the east, annual totals are considerably higher (Anon 2007).

A large portion of the rural population depends on rain fed subsistence farming and is particularly vulnerable to climate variability and change. The occurrence of high frequency prolonged dry spells, in conjunction with heat waves in particular, have

devastating consequences for rain fed agriculture. The province also houses a number of national parks, such as the Kruger National Park and the Limpopo Transfrontier Park and has great biodiversity as well as extensive farming activities (Reason *et al.*, 2005). All of these are vulnerable to climate variability and change.

#### **4.4. Data and methodology**

Climate data used in the study were provided by the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal. Data provided included the daily maximum and minimum temperatures collected from more than 970 qualifying temperature stations across South Africa for the 50-year period 1950-1999. The data were quality controlled using infilling and record extension techniques developed by Schulze and Maharaj (2004). Time series were generated at each of 429 700 one arc minute ( $\approx 1.7 \text{ km} \times 1.7 \text{ km}$ ) raster points covering South Africa, using regionally and seasonally determined lapse rates and other physically appropriate spatial interpolation approaches. More details of this method can be obtained from Schulze and Maharaj (2004).

The catchment data obtained made it possible to perform a spatially continuous analysis over Limpopo. Data for 30 tertiary catchments across Limpopo were analysed in this study. The present study focuses on the temperature events and extreme temperatures that were defined according to the temperature categories used by the South African Weather Service in the forecasting section. However, the temperature thresholds are defined for forecasting purposes, which means a day is defined as very hot, hot, cool or cold. In this case, a very hot day is defined as a day with a maximum temperature equal to or higher

than 35°C. In addition, a moving average was calculated. This is defined as the average of a series of numbers over a period of time that is constantly updated by dropping the oldest value and then adding the newest value and recalculating the average.

For the calculation of HWs, the frequency of extreme temperature events at each catchment was calculated. In this study the definition of HWs used is an event where the maximum temperature is 5°C warmer than the average maximum temperature for the warmest months of the year in that area, for three consecutive days (SAWS, 2008).

The following algorithm summarises the calculation of HWs:

1) From the time series of the mean monthly maximum temperature at each catchment, the month of the year that is the warmest on the average,  $m_w$  was determined. 2) For each daily measurement of maximum temperature,  $T_{mx}$  was calculated. Furthermore, using  $T_{mx}$  for all the months over the 50-year period,  $T_{mx}$  temperature was 5°C higher than the mean maximum temperature of the warmest month, for three consecutive days, that is, find

$$t_w^m(d) > T_{mx}(m_w) + 5^\circ\text{C},$$

Then the numbers of HW days were counted -that is all days that occur within HW events as described in (2)

#### **4.5. Results and discussion**

In the following sections extreme temperatures and temperature events as well as trends of HW frequencies are presented.

#### 4.5.1. Extreme temperatures and temperature events over the Limpopo

Table 4.1. The maximum temperature extreme indices

No.	Maximum temperature extreme indices
1	Very hot days: $T_x \geq 35^\circ\text{C}$
2	Hot days: $30^\circ\text{C} \leq T_x < 35^\circ\text{C}$
3	Hot-days events: $T_x \geq 30^\circ\text{C}$ for 3-5 days

The analysis results for maximum temperature indices are depicted in Figures 4.1 and 4.2. Figure 4.1 shows a decadal moving average that occurred during the 1950s to the 1999s, which was recorded within a decade during the 50-year period. Thereafter, their decadal frequency steadily increased. These results corroborate with reviews reported in Mason (2001).

The inter-annual variability in temperature as demonstrated here and reported in earlier reviews could be linked with irregular and low frequency of variability between warm (El Niño) and cold (La Niña) conditions (Trenberth1991). An upward trend in the number of very hot days is depicted in Figures 4.1-4.3 from 1950-1999. Again, the increasing number of very hot days is generally linked to dry conditions. Similar results were reported by Mason (2001) over South Africa. The conditions were partly attributed to the atmospheric response of El-Nino Southern Oscillation (ENSO) events that are often

linked to changes in the sea-surface temperature in the tropical Indian Ocean (Nicholson 1997; Goddard and Graham 1999).

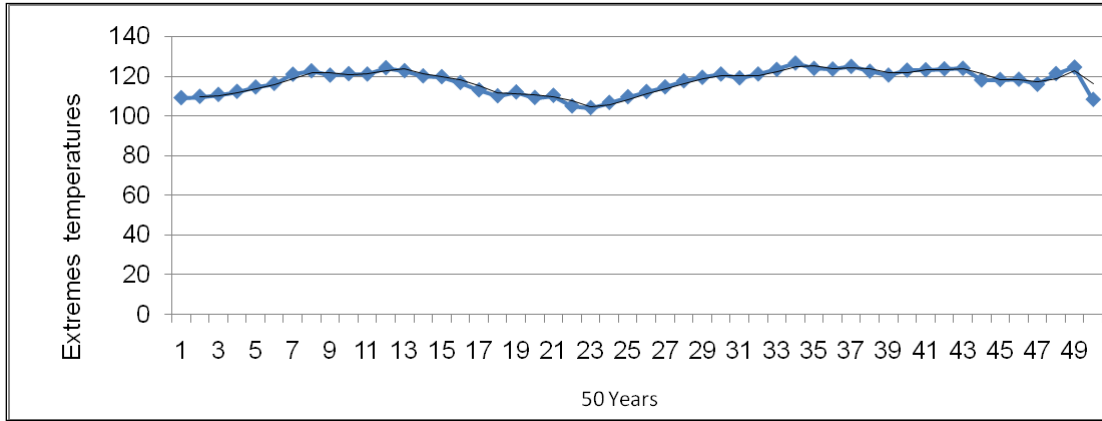


Figure 4.1. Observed moving average:  $T_{mx} \geq 30^{\circ}\text{C}$  from 1950-1999

Figure 4.1 shows a decadal moving average of 50-year period from 1950-1999, where the observation was on the extreme temperatures for  $T_{mx} \geq 30^{\circ}\text{C}$  from 1950-1999.

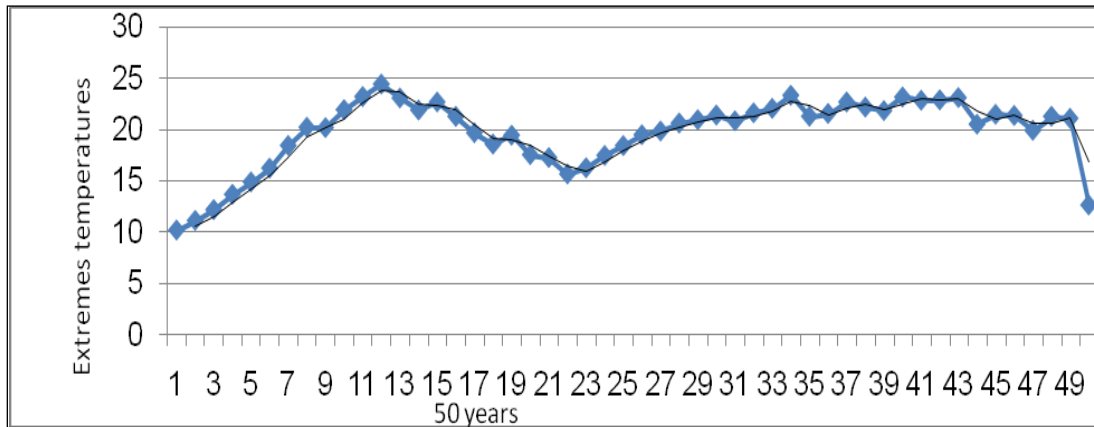


Figure 4.2. Observed moving average:  $T_x \geq 35^{\circ}\text{C}$  from 1950-1999

Figure 4.2 displays a decadal moving average of extreme temperatures during the five decades from 1950-1999 over the Limpopo Province:  $T_{mx} \geq 35^{\circ}\text{C}$  from 1950-1999.

## **4.5.2. Trends in HW frequencies**

The analysis of yearly trends in HWs show that five decades (1950-1999) in the Limpopo Province had variable occurrences of HWs over different catchments and some similarities in the trends of HWs within the catchments. Based on SAWS criteria for defining a HW, the period 1950-1999 displayed the highest HW trends, in particular towards the north-west, north and north-south of the Limpopo Province.

In addition, the total average trends of HW frequency for the whole province from 1950-1999 were found to be about 1.2.

### **4.5.2.1. Trends in the annual frequency of occurrence of HWs over the Limpopo Province 1950-1999.**

The annual frequency of occurrence of HWs over the Limpopo Province 1950-1999 was analysed.

The highest frequency of occurrence of heat waves occurred in the southern part of the province and in the northern part of the Limpopo valley. Trends of HW frequencies are lower in areas with pronounced Escarpment and Lowveld in the east (Figure 4.3).

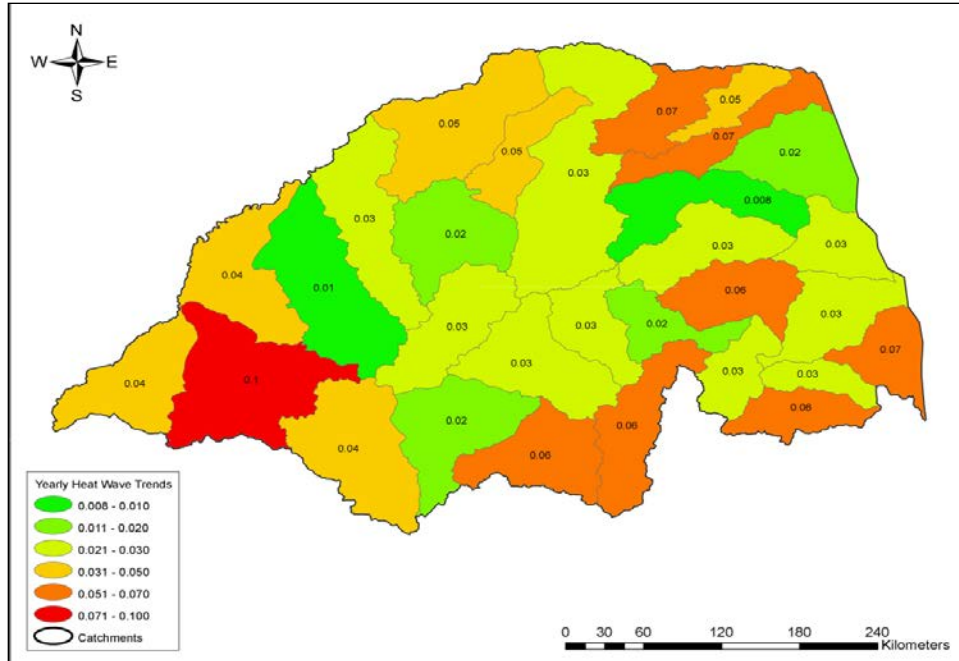


Figure 4.3. Trends in the annual frequency of occurrence of HWs over the Limpopo Province 1950-1999

#### 4.5.2.2. Trends in the seasonal frequency of occurrence of HWs over the Limpopo Province 1950-1999.

The frequencies of HWs using the seasonal HW trends frequency from the 1950s to the 1999s were analysed. In this section, the following seasonal trends were demonstrated: trends in the autumn, winter, spring and summer frequency of occurrence of HWs over the Limpopo Province during 1950-1999.

#### 4.5.2.2.1 Trends in autumn frequency of occurrence of HWs over the Limpopo Province during 1950-1999.

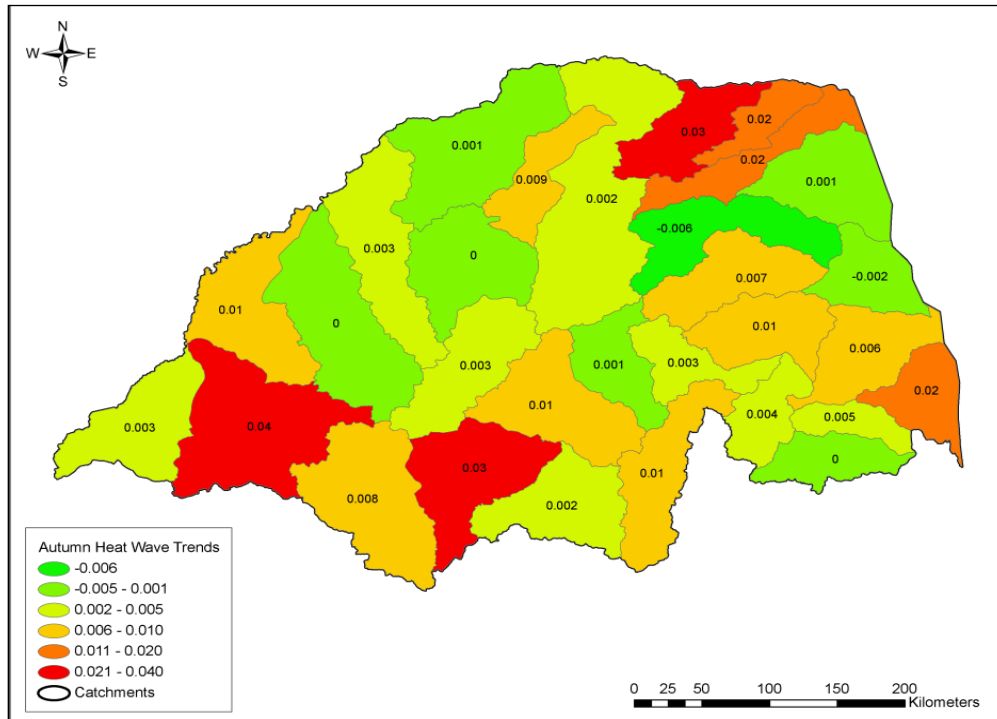


Figure 4.4. Trends in autumn frequency of occurrence of HWs over the Limpopo Province during 1950-1999

Trend analysis of HWs in Figure 4.4 shows high HW trends in the northern parts of the Limpopo Province because of housing development and certain mining activities in the area. However at the border in the north-east almost no presence of HW trends in some of the areas was detected because of the influence of the Kruger National Park, which with its vegetation, creates a microclimate. There are lower HW trends in the other areas because of presence of the conservation areas as well as forestry. In the south-west there are vacant lands and few conservation areas, although towards the northern part there are agricultural fields.



**4.5.2.2.2. Trends in the occurrence of HWs in winter over the Limpopo Province during 1950-1999**

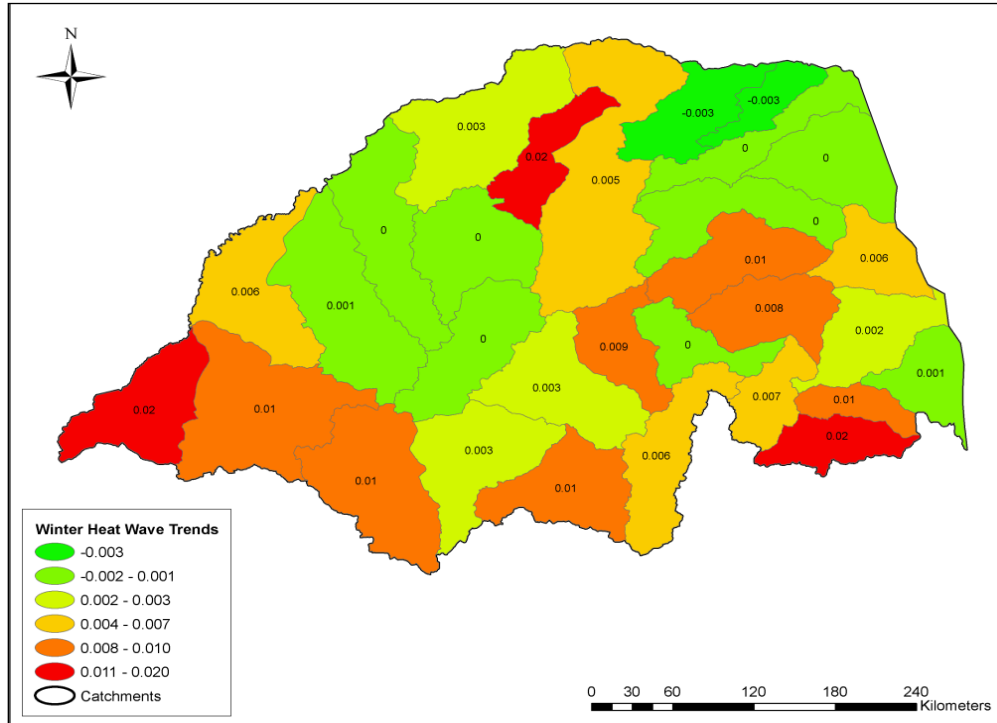


Figure 4.5. Trends in the occurrence of HWs in winter over the Limpopo Province during 1950-1999

Figure 4.5 shows lower trends of HW frequency over the north-east of the province because of vegetation and trends of HW frequency are lower over the Escarpment areas and Lowveld in the east.

#### 4.5.2.2.3. Trends in the occurrence of HWs in spring over the Limpopo Province during 1950-1999.

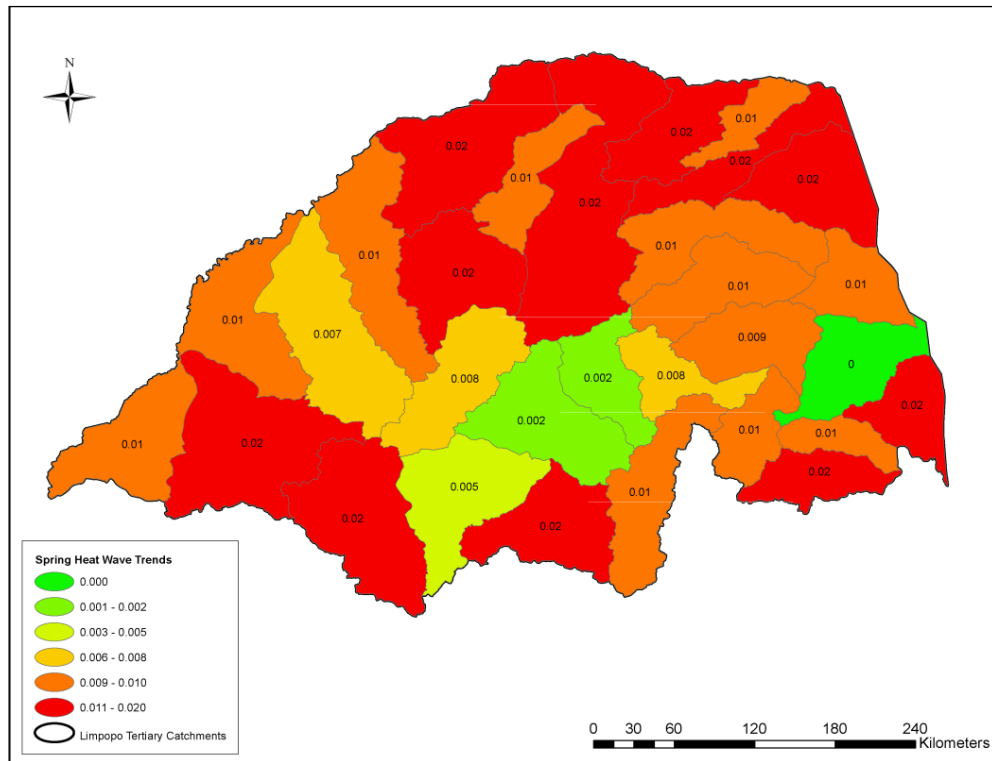


Figure 4.6. Trends in the occurrence of HWs in spring over the Limpopo Province during 1950-1999.

Trend analysis of HWs in Figure 6 shows high HW trends in more than three-quarters of the Limpopo Province because of winds during that period, which the temperature from build-up and certain mines and spread it over the province. However, some of the catchments are not showing any sign of trends of HW frequency because of vegetation and the vacant lands.

#### 4.5.2.2.4. Trends in the occurrence of HWs in summer over the Limpopo Province during 1950-1999.

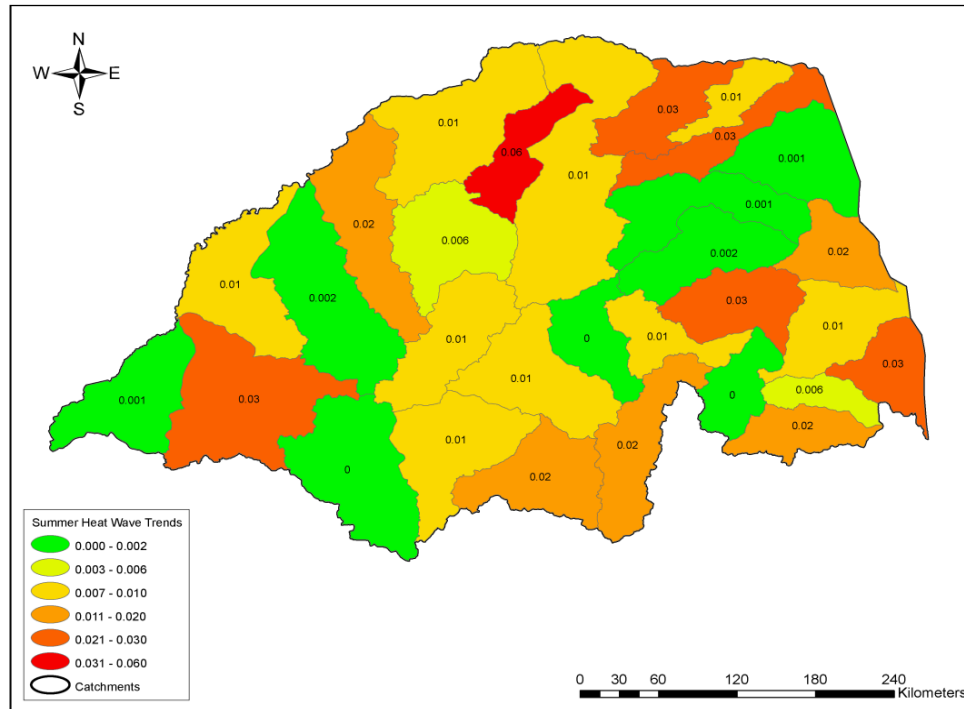


Figure 4.7. Trends in the occurrence of HWs in summer over the Limpopo Province during 1950-1999.

According to the analysis in Figure 5.7, there is HW trends frequency displaying in some of the areas, especially those close to mines and with more buildings. However, trends of HW frequencies are lower over the Escarpment and Lowveld areas.

#### 4.6. Conclusions and implications

This paper presents a 50-year analysis of HWs in the Limpopo Province. The results show that there was generally an increase of HW trends during 1950-1999 over the north-west, north and north-south of the province. Whether or not the increase in HWs was due to climate change is beyond the scope of this paper. However, many studies report that

there will be an increase in HWs with further climate change. The fact that trends in HW events are not monotonic suggests that specific local topographic and environmental conditions influence the pattern of occurrence of HWs in the study region. This also emphasises a need for a localised, as opposed to a regional, investigation into HW patterns, particularly in setting up adaptation strategies (techniques).

In summary, these results provide a baseline upon which further studies on the effects of HWs on lifestyle, human comfort and human health, particularly in the light of potential temperature increases associated with the current overall global warming, could be conducted. The present analysis raises major questions concerning the societal adaptation strategies to the occurrence of HWs and points towards the need for robust forecasting of the future frequency and intensity of HWs in South Africa.

It is evident from the existing literature as well as from the present study that HWs have strong socio-economic impacts (Boeck *et al.*, 2010). As a result, findings from the current study could stimulate further studies on the effects of HWs on health, particularly on the elderly and other susceptible population groups.

#### **4.7. Acknowledgements**

The authors acknowledge the South African Weather Service and School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal for the provision of the weather data, and the Canon Collins Trust in Cape Town for the financial assistance. The comments of the anonymous reviewers that helped to clarify many points, especially in the analyses of HWs as well as the University of Pretoria are gratefully acknowledged.

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## **Chapter 5: Impact of climate variability on tomato production over the Limpopo Province, South Africa**

*Article published*

**Tshiala MF and Olwoch JM (2010). Impact of climate variability on tomato production over Limpopo Province, South Africa. *African Journal of Agricultural Research (AJAR)*, Vol. 5 (21), pp 2945-2951.**

## 5.1. Abstract

The relationship between tomato production, monthly average temperature and seasonal average temperature over the Limpopo Province, South Africa during the period 1971-2006 was investigated using statistical regression analysis methods. The motivation for selecting the Limpopo for this study lies in the fact that the province contributes about 66% of the tomato production in South Africa. The results showed yearly peak values of tomatoes in the range of 200 000-228 000 tons from 2000-2006. In this study, we analysed the correlation of tomato records in Limpopo with climatic variables in order to assess the climate change effects on tomato production and food security in South Africa.

Our results show that tomato yield increased by a factor of 2 from 1971-2006. Particularly during autumn, spring, summer and winter, tomato yield increased by a factor of 2 respectively. Except February and June, the majority of months registered positive trends in tomato production. These could be attributed to the application of robust farming practices and improved technology over the same period. However, the trend analysis results demonstrate that there are possible negative impacts of climate change on crop yield, especially to farmers without advanced technology and good modern agricultural practices.

**Key Words:** climate variability, climate change, temperature, tomato production, Limpopo, South Africa.

## 5.2. Introduction

Climate is a primary determinant of agricultural productivity. Climate influences the types of vegetation that can grow in a given location (Box, 1981; Woodward, 1987). In this context, agriculture is a complex sector involving different driving parameters (such as physical, environmental, economic and social). It is now well recognised that crop production is very sensitive to climate change (McCarthy *et al.*, 2001), with different effects according to regions. According to the IPCC, the analysis on climate change impact shows that there is a general reduction of potential crop yields and a decrease in water availability for agriculture and population in many parts of the developing world (IPCC, 2001). The main drivers of agricultural responses to climate change are biophysical effects and socioeconomic factors. There is a biophysical effect on crop production by changing the meteorological variables, including rising temperatures, changing precipitation regimes and increasing levels of atmospheric carbon dioxide (McCarthy *et al.*, 2001). Biophysical effects of climate change on agricultural production depend on the region as well as the agricultural system, and the effects vary over time (Adams, 1998). In fact, the increase of the temperature limit crop yield by accelerating the plant development, affecting the floral organs and fruit formation and the functioning of the photosynthetic apparatus.

The Limpopo Province is situated in the north of South Africa, which is a tropical region. According to Mendelsohn and Dinar, 1999, the tropical regions of the developing world are particularly vulnerable to potential damage from environmental changes because large areas of these regions are covered by poor soils, which have already made much of the land unusable for agriculture. Small-scale farmers who are predominant in the

province and who have little capital will not be able to pursue the new strategies that will be required to adapt to the change in climate.

Tomatoes are a major vegetable crop and commonly grown by both poor and rich farmers in South Africa. They are used worldwide as a fresh vegetable or as an ingredient in food preparation. Currently, they are one of the main vegetables used for hawking by small-scale entrepreneurs in the informal sector. The crop is also grown commercially and provides a large number of jobs in South Africa. For instance, in 1998 about 5 465 hectares (ha) of tomatoes were planted in South Africa, creating direct employment opportunities for 16 395 people (Anon., 1999).

Traditionally agriculture in South Africa has been the largest employer in the economy (Meyer, 1998). However, the contribution of agriculture to total employment has declined from 30% in 1971 to 13% of the economically active population in South Africa in 2000 (Abstract of Agricultural Statistics, AAS, 2002). According to the National Department of Agriculture (NDA, 2000), commercial farms provide livelihoods and housing to about six million family members of 1 million employees and additionally, provide for their educational needs. There are also 240 000 small farmers who provide a livelihood to more than one million of their family members and occasional employment to another 500 000 people. In South Africa, the important tomato producing areas are situated in Onderberg (Mpumalanga), Pongola and Nkwalini (KwaZulu-Natal) and Trichardts and the Limpopo Province (Pietersen 1999, unpublished).

The aim of the study was to identify the contribution of one of the environmental variables, such as climate variables, particularly temperature, on tomato yield. The

regression statistical analysis methodology was used to evaluate the response of tomato production to various climatic conditions.

### **5.3. Study area**

Limpopo is one of the developing provinces in South Africa and is particularly vulnerable to climate change impact, partly because of the area's exposure to extreme weather events and because of its sensitive economies. It also has a high number of rural dwellers dependent on natural resources, although communities in the Limpopo region may have a greater ability to adapt to long-term changes in climate, such as increased seasonal temperatures and altered precipitation patterns (for example, decreased snow cover). Sometimes dams in the Limpopo get so full because of heavy rainfall so that they flow onto the farms and destroy plants and in that way, economic production falls (Thomas *et al.*, 2005).

The Limpopo Province is a main tomato growing area in South Africa, producing 66% of the total annual tonnage of tomatoes (NDA, 2009). The main production areas are Letaba, which is producing on 3 259 hectares while areas around Mooketsi and Musina produce about 859 ha. Tomatoes are also planted in smaller areas in Giyani, Polokwane and Mokopane districts. The total annual production of tomatoes is about 227 990 tons of the total South African production, which is 345 440 tons, two thirds of the national tomato production (NDA, 2009).

Most of this production comes from the Mooketsi area where the Bertie van Zyl farm is the dominant grower in the northern parts of the province. The company produces and

transports approximately 150 000 tons of tomatoes annually to various markets in the country.

#### 5.4. Data and methodology

The monthly regional tomato market data were obtained from the National Department of Agriculture in 2009. According to government statistics, the Limpopo Province contributes 66% of tomato production to the South African fresh produce market (NDA, 2009). Due to the imperfection of and lack of documentation from the tomato farms in South Africa, the monthly average tomato market data (these were used as an indicator of tomato production) were calculated by weighting the total number of tomatoes distributed monthly in the South African fresh tomato market, by 2/3 as expressed in Equation 1.

$$P\{(\theta, \phi); T\} = P_0\{(\theta, \phi); T\} \times \frac{66}{100} \quad (1)$$

Here,  $P\{(\theta, \phi); T\}$  and  $P_0\{(\theta, \phi); T\}$  is the spatial-temporal (where  $\{\theta; \phi \& T\}$  are the longitude, latitude and time epoch) average production of tomatoes in Limpopo and South Africa respectively. The 2/3 weighting factor used here is based on the NDA definition of the spatial distribution of tomatoes grown in South Africa.

Climatic variables considered were the 35-year averaged observed temperature obtained from the Climate Research Unit (CRU) for the period 1971-2006. The data were obtained from the monthly mean climate fields of 0.5 ° x 0.5 ° grid resolutions over the Limpopo Province of South Africa. The mean climate surfaces were constructed from 35-year (1971-2006) station observation fields, which were then interpolated on the climate grid surfaces. In this study, the mean monthly temperature values were calculated to derive

seasonal averages. The autumn season is from March to May (MAM), winter from June to August (JJA), spring from September to November (SON) and summer from December to February (DJF). Additionally, STATISTICA software was used to estimate the factor of climate in the current yield trends by applying the regression models to observed trends in climate variables for a period of 35 years from 1971-2006.

To assess the relationship between the time series of tomato production and climate change proxies, the first-difference time series methodology was employed. The first-difference time series considered here is the difference in values from one year to another year as described in Lobell *et al.*, (2005) and Nicholls (1997). Furthermore, a multiple linear regression analysis was used. (The first difference in yield is considered the response variable, first differences of average temperature, minimum average temperature and average maximum temperature as the second variables). Additionally, the spatial and temporal patterns of the significant correlation values were used to determine relationships between tomato production and average temperature in Limpopo during the various months and seasons. Composites of temperature and tomato yield were presented in the form of a scatter plot in order to study the characteristics of the extreme temperatures, weather events and dependency.

## **5.5. Results and analysis**

### **5.5.1. Trend in tomato production in the Limpopo Province (1971-2006)**

The results (Figure 5.1) indicate that there is an increase in tomato production in Limpopo for certain years and there is some decrease of production in certain periods because of the sensitivity of the tomato crop to climate change and variability. The

reduction in tomato production in some of the years was mainly due to droughts experienced in the region. The tomato yield during 1971-2006 was in a range of 98 806 tonnes to 228 873 tonnes.

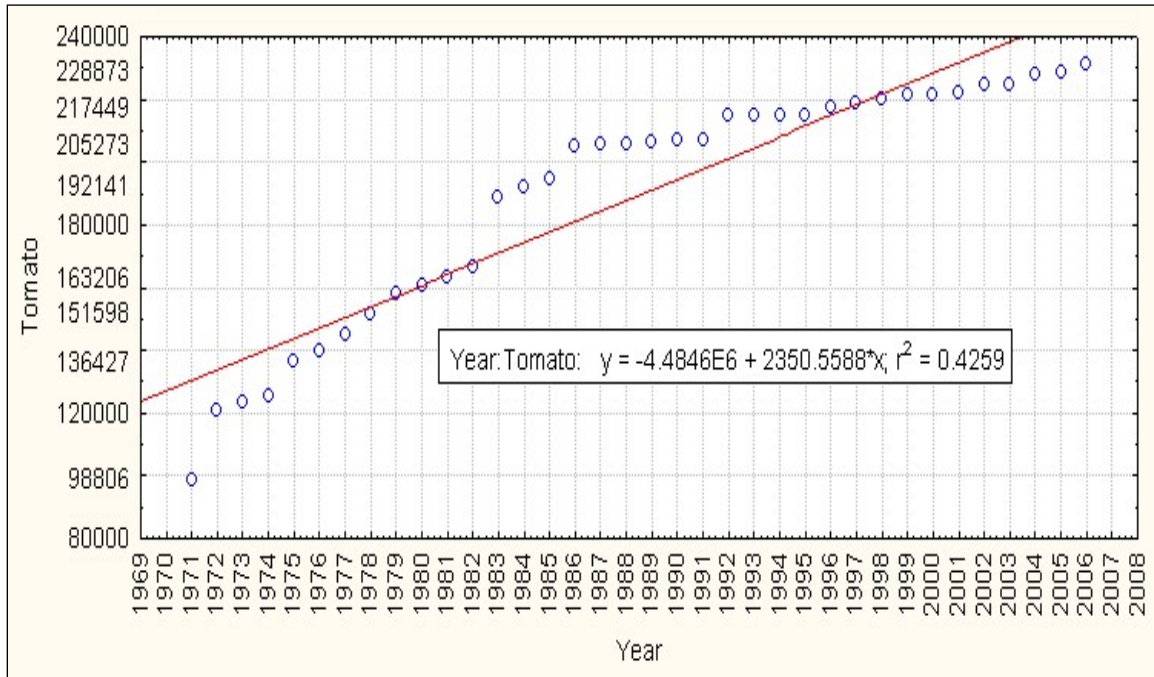


Figure 5.1. Trend of tomato production per tonnage in the Limpopo Province (1971-2006)

Figure 5.1 shows the trend of tomato production in Limpopo: tomato yield increased by a factor of 2 from 1971-2006. Thus, the response of tomato production during that period of 35 years was more favourable. Figure 5.1 displays the patterns of tomato production yearly per tonnage. This shows that the largest values during tomato yield were in the last decades where temperatures were high. From our analysis, the trend of tomato production in Limpopo, tomato yield increased by a factor of 2 during the period of 1971-2006 was not significant (see, for example,  $R^2=0.425$ ; pvalue 0.004)



### 5.5.2. Relationship between tomato production and average temperatures during

#### 1971-2006

The figure below (Figure 5.2) shows the trend of average annual maximum temperature and tomato production in Limpopo. It shows a more erratic pattern of temperature and tomato yield in the country.

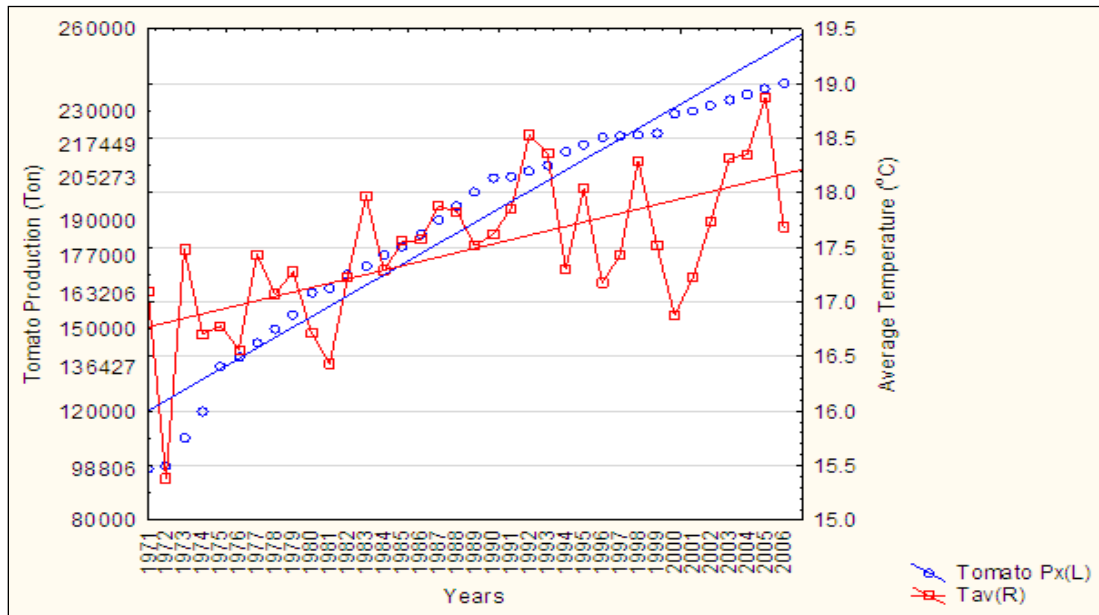


Figure 5.2. Trend of average annual maximum temperature and tomato production in the Limpopo Province (1971-2006)

As depicted in Figure 5.2, minimum temperature was recorded between 1971-1990 and for the years 1991 to 2006 a maximum temperature was recorded. This indicates that the relationships do appear to change through time.

The estimated impacts of climate on yield trends were statistically significant for the tomato yield, especially since 1980 (Figure 5.2) (see, for example,  $R^2=0.242$ ; pvalue

0.002). These inferred impacts reflect only the climate influences that were captured by the empirical models.

### 5.5.3. Seasonal tomato production as related to temperature average in °C (1971-2006)

#### 5.5.3.1. Seasonal production of tomatoes in relation to temperature in °C during autumn (1971-2006)

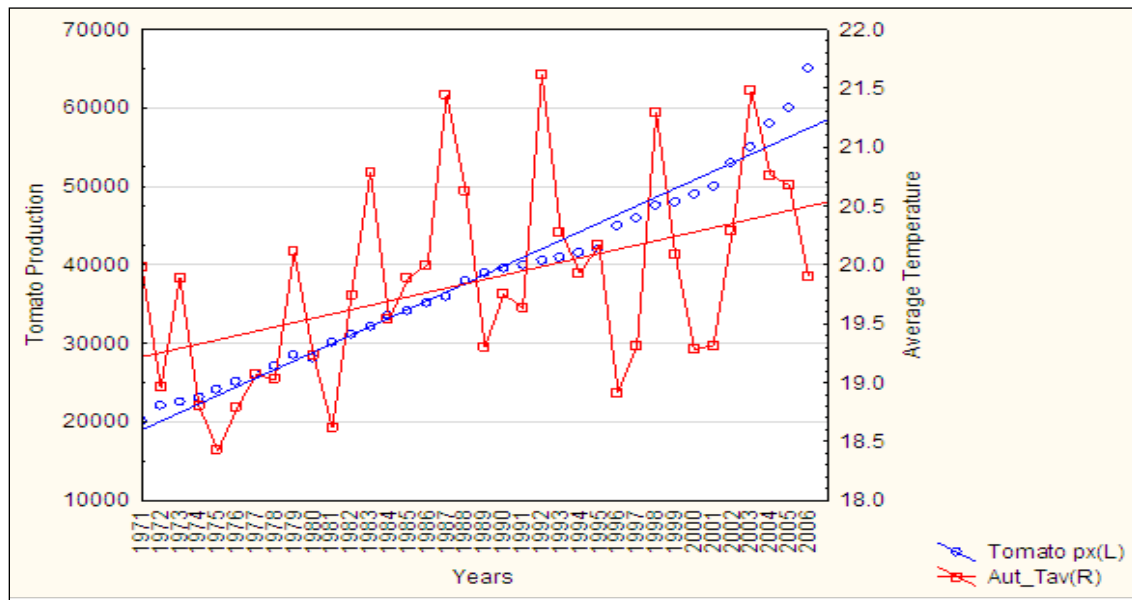


Figure 5.3. Seasonal production of tomatoes in relation to temperature average in °C during autumn (1971-2006)

In autumn, the regression analysis shows that the regional average changes in yields during the past years were less, although the last decades showed an increase of production, despite the slight increase in the average temperature during the last decades. Figure 5.3 shows an increase in tomato yield by a factor of 2 from 1971-2006 due to the technology used, because South Africa is a water stressed country.

Seasonal production of tomatoes in relation to the temperature average in °C during autumn (1971-2006) was statistically significant for the tomato yield, especially since 1980 (figure 5.3). (See, for example,  $R^2=0.329$ ; pvalue 0.0025.)

### 5.5.3.2. Seasonal production of tomatoes in relation to temperature in °C during spring (1971-2006)

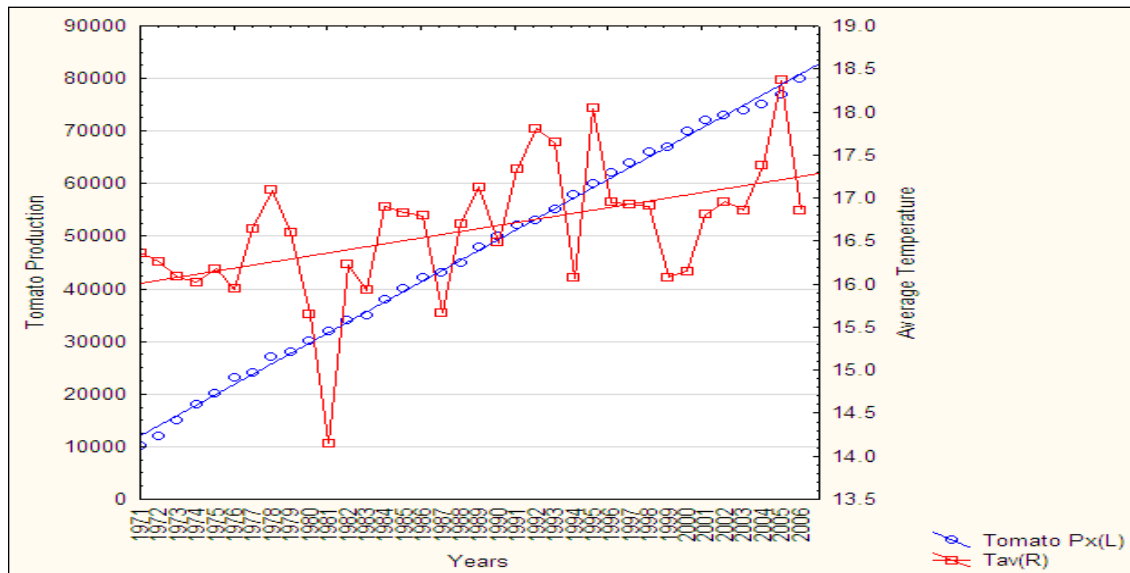


Figure 5.4. Seasonal production of tomatoes in relation to temperature average in °C during spring (1971-2006)

In spring, the average temperature increased to 23°C, which indicated a good period for tomato production in that particular period of the year. These days, with advanced technology in the field of farming, adaptation techniques have helped to counterbalance yield losses, hence tomato yield increased by a factor of 3 during that particular period (1971-2006). Seasonal production of tomatoes in relation to temperature average in °C during spring (1971-2006) was statistically significant for the tomato yield, especially since 1980. (See, for example,  $R^2=0.116$ ; pvalue 0.041.)

### 5.5.3.3. Seasonal production of tomatoes in relation to temperature in °C during summer (1971-2006)

As depicted in Figure 5.5 tomato yield during the summer season increased by a factor of 2 from 1971-2006. Larger tomato yields were evident in the year 2006 and this yield could be attributed to favourable weather conditions: higher temperatures were also beneficial to production.

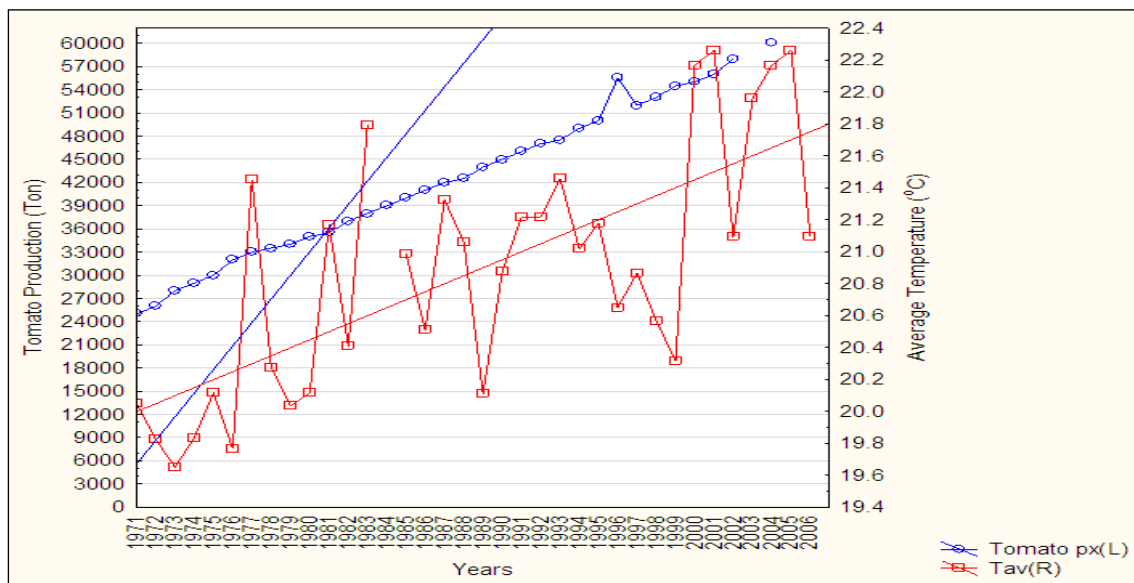


Figure 5.5. Seasonal production of tomatoes in relation to the temperature in °C during summer (1971-2006).

The estimated seasonal production of tomatoes in relation to the temperature in °C during summer (1971-2006) was statistically significant for the tomato yield, especially since 1980. (See, for example,  $R^2=0.224$ ; pvalue 0.003.)

### 5.5.3.4. Seasonal production of tomatoes in relation to temperature in °C during winter (1971-2006)

Figure 5.6 shows a slight increase in tomato yield over the years, because of the use of the new agricultural technology in tomato farming. Tomato yield increased by a factor of 3 during 1971-2006. This is probably caused by irrigation systems applied as an adaptation technique.

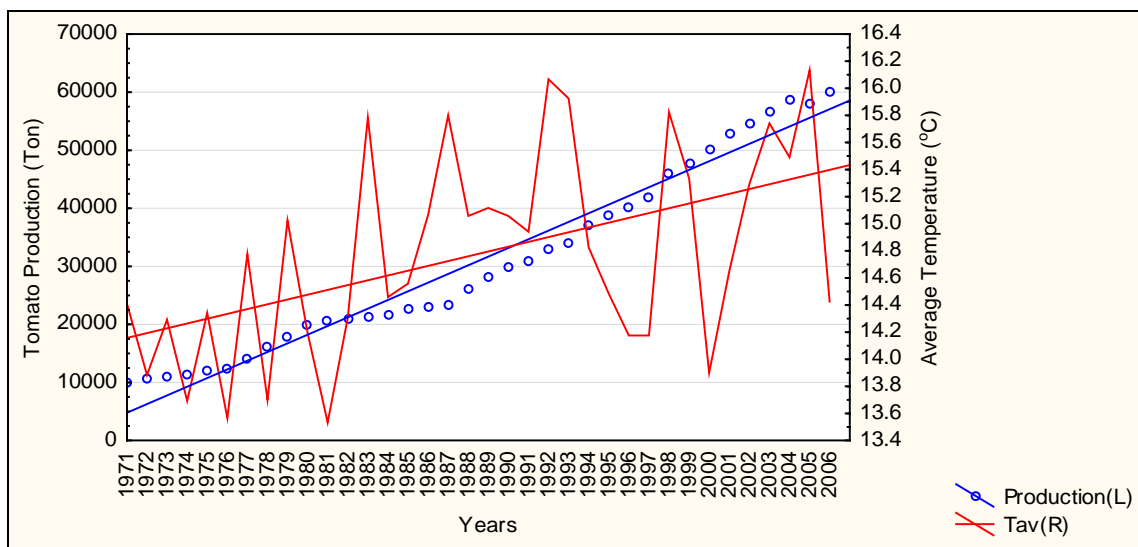


Figure 5.6. Seasonal production of tomatoes in relation to temperature in °C during winter (1971-2006)

The estimated seasonal production of tomatoes in relation to the temperature in °C during winter (1971-2006) was statistically significant for the tomato yield, especially since 1980. (See, for example,  $R^2=0.192$ ; pvalue 0.007.)

### 5.5.3.5 Relationship between tomato production and average rainfall during

1971-2006

The figure below (Figure 5.7) shows the trend of average annual rainfall and tomato production in Limpopo. It shows a more erratic pattern of rainfall and tomato yield in the province.

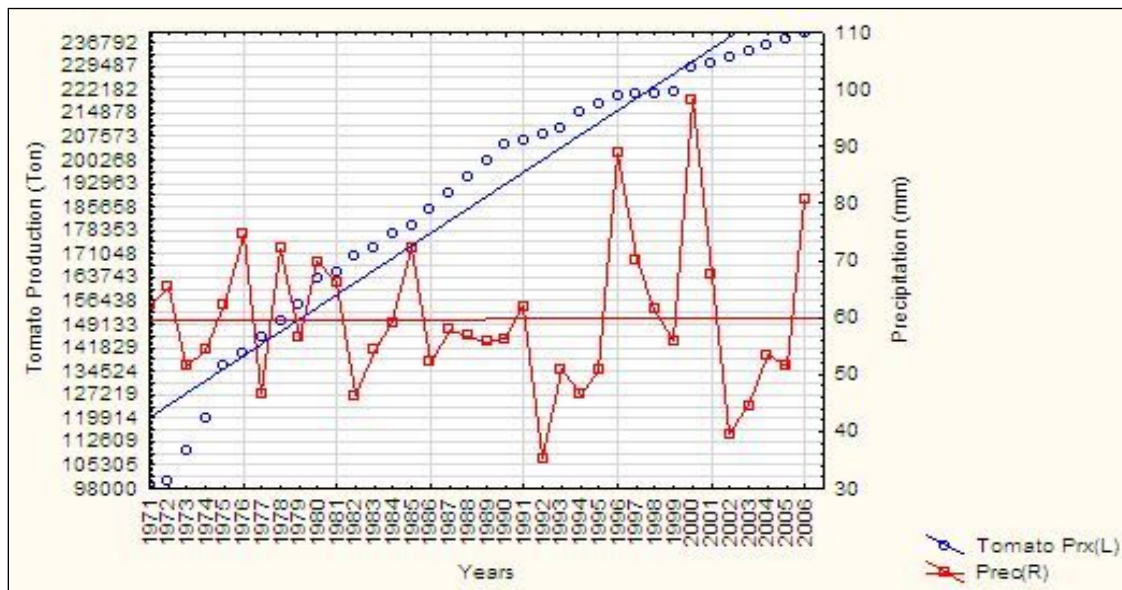


Figure 5.7. Trend of average annual rainfall and tomato production in the Limpopo Province (1971-2006)

As depicted in Figure 5.7, minimum and maximum rainfalls were recorded between the years 1971-2006. This indicates that the relationships do appear to change through time.

The estimated impacts of climate on yield trends were statistically significant for the tomato yield, especially since 1990 (Figure 5.7) (see, for example,  $R^2=0.946$ ;  $p$ value 0.001). These inferred impacts reflect only the climate influences that were captured by the empirical models.

### 5.5.4. Seasonal tomato production as related to rainfall average in °C (1971-2006)

#### 5.5.4.1. Seasonal production of tomatoes in relation to rainfall in mm during autumn (1971-2006)

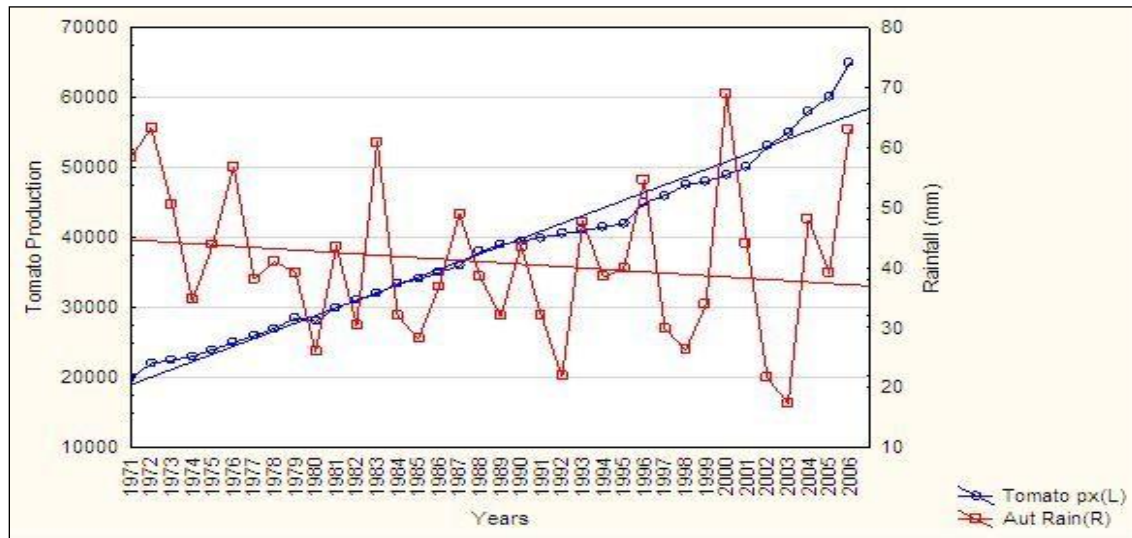


Figure 5.8. Seasonal production of tomatoes in relation to rainfall average in mm during autumn (1971-2006)

In autumn, the regression analysis shows that the regional average changes in yields during the past years were less, although some of the years showed an increase of production, despite the slight increase in the average rainfall during the last decades. Figure 5.8 shows an increase in tomato yield by a factor of 2 from 1971-2006 due to the technology used, because South Africa is a water stressed country.

Seasonal production of tomatoes in relation to the temperature average in mm during autumn (1971-2006) was statistically significant for the tomato yield, especially since 1996 (figure 5.8). (See, for example,  $R^2=0.9725$ ; pvalue 0.0030.)

### 5.5.4.2. Seasonal production of tomatoes in relation to rainfall in mm during spring (1971-2006)

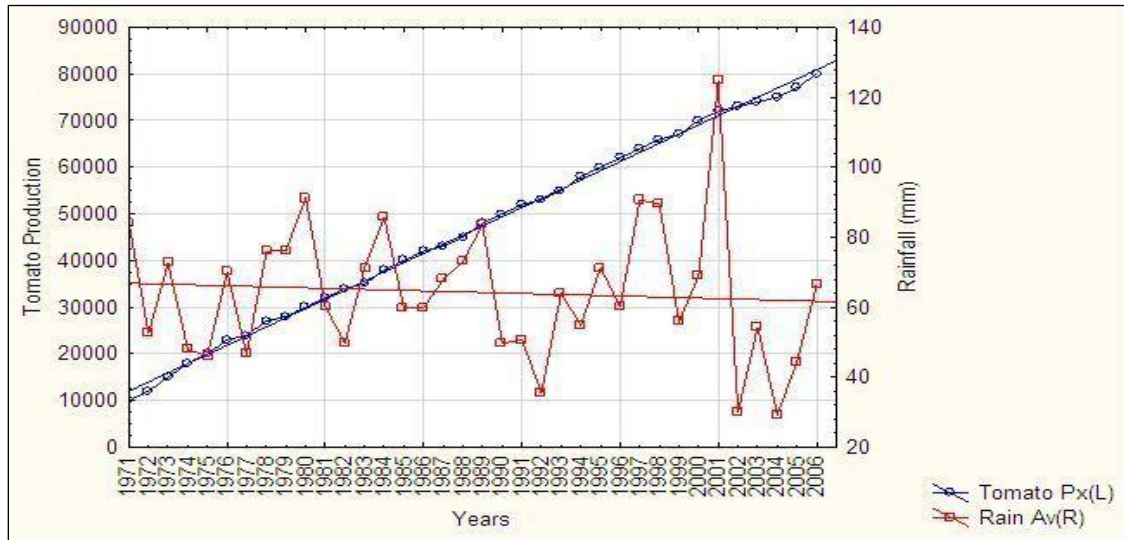


Figure 5.9. Seasonal production of tomatoes in relation to rainfall average in mm during spring (1971-2006)

In spring, the average rainfall increased to 120 mm, which indicated a good period for tomato production in that particular period of the year. These days, with advanced technology in the field of farming, adaptation techniques have helped to counterbalance yield losses, hence tomato yield increased by a factor of 3 during that particular period (1971-2006). Seasonal production of tomatoes in relation to rainfall average in mm during autumn (1971-2006) was statistically significant for the tomato yield, especially since 1980. (See, for example,  $R^2=0.9981$ ; pvalue 0.006)

### 5.5.4.3. Seasonal production of tomatoes in relation to rainfall in mm during summer (1971-2006)

As depicted in Figure 5.10 tomato yield during the summer season increased by a factor of 2 from 1971-2006. Larger tomato yields were evident in the year 2006 and this yield



could be attributed to favourable weather conditions: higher temperatures were also beneficial to production.

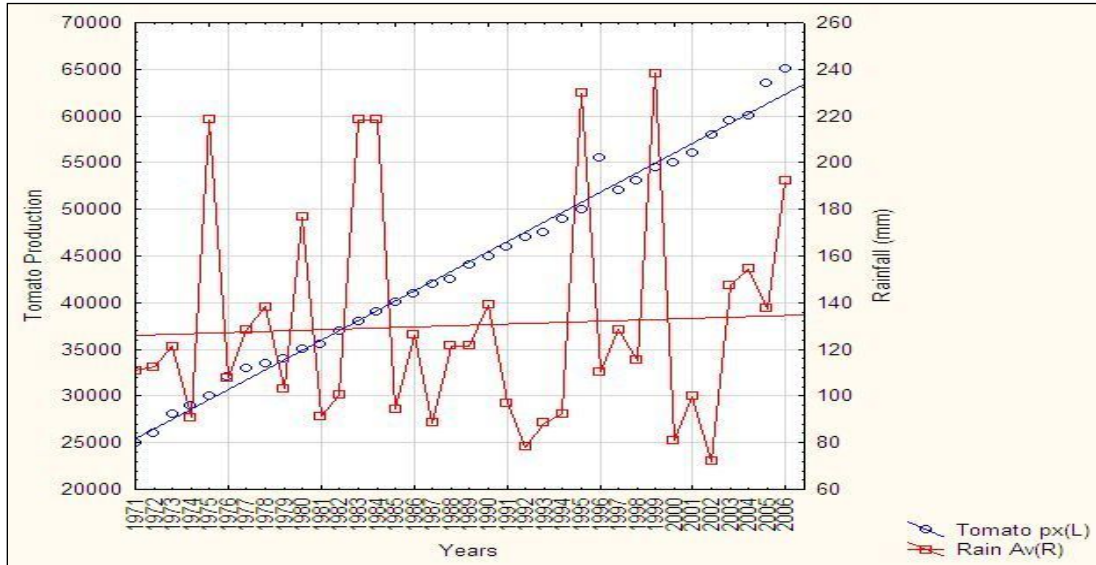


Figure 5.10. Seasonal production of tomatoes in relation to the rainfall in mm during summer (1971-2006).

The estimated seasonal production of tomatoes in relation to the rainfall in mm during summer (1971-2006) was statistically significant for the tomato yield, especially since 1999. (See, for example,  $R^2=0.9911$ ; pvalue 0.003.)

#### 5.5.4.4. Seasonal production of tomatoes in relation to rainfall in mm during winter (1971-2006)

Figure 5.11 shows a slight increase in tomato yield over the years, because of the use of the new agricultural technology in tomato farming. Tomato yield increased by a factor of 3 during 1971-2006. This is probably caused by irrigation systems applied as an adaptation technique.

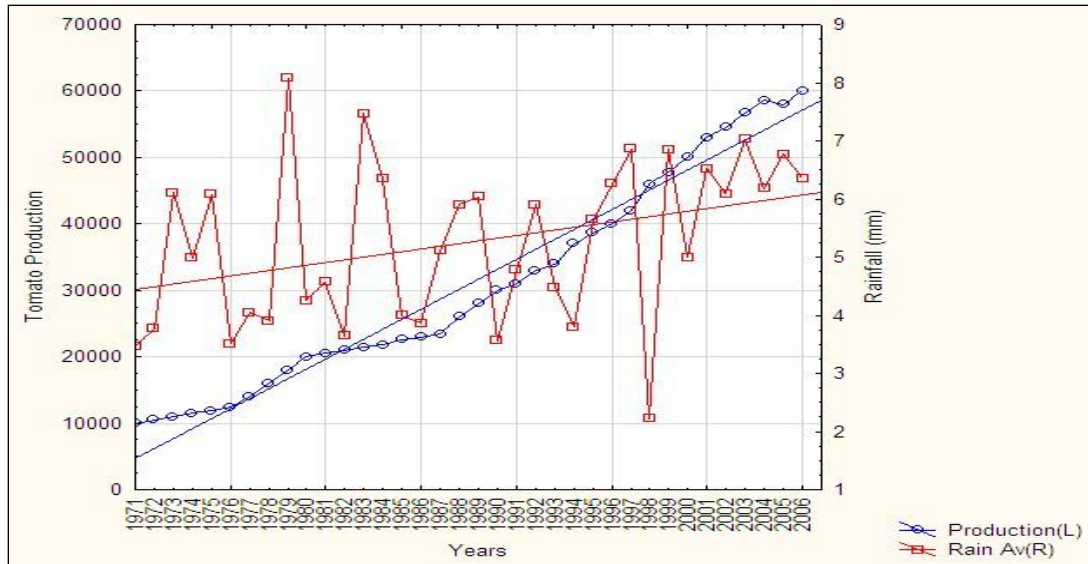


Figure 5.11. Seasonal production of tomatoes in relation to rainfall in mm during winter (1971-2006)

The estimated seasonal production of tomatoes in relation to the rainfall in mm during summer (1971-2006) was statistically significant for the tomato yield. (See, for example,  $R^2=0.9661$ ; pvalue 0.003.)

### 5.5.5. Monthly tomato production

In Figure 5.12 the trend of monthly tomato production was analysed from January to December.

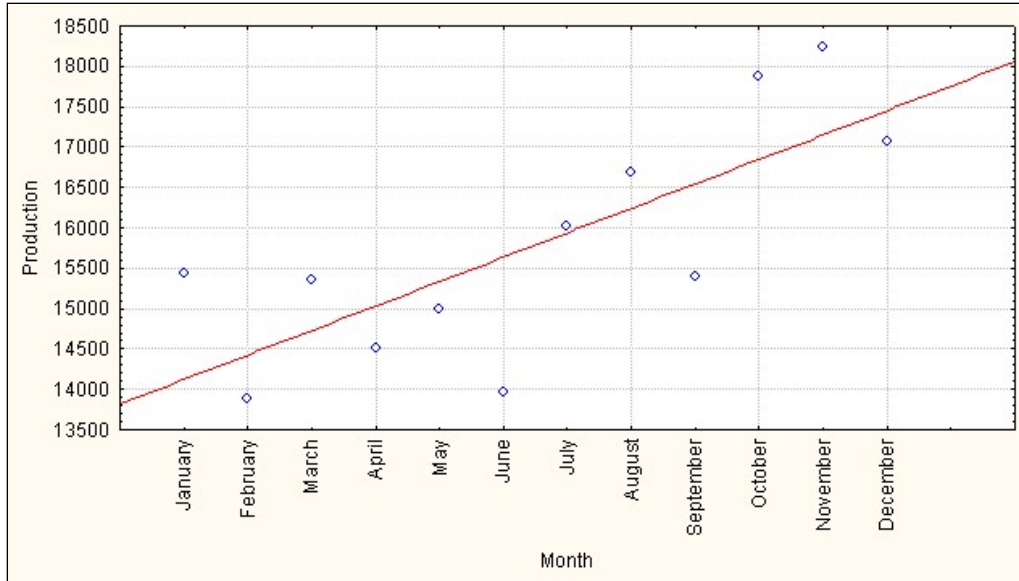


Figure 5.12 Monthly production trends

Figure 5.12 shows that the estimated impacts of climate on tomato yield trends was statistically significant throughout the months, except for February, April and June, which show fewer yields. The estimated seasonal production of tomatoes in relation to the temperature in °C during summer (1971-2006) was statistically significant for the tomato yield, especially since 1980. (See for example,  $R^2=0.192$ ; pvalue 0.004). Overall, Table 5.1. depicts a summary of the correlation and the associated significance between tomato production and rainfall as well as temperature over various seasons in Lipompo province, South Africa.

Seasons	Tomato production versus Rainfall		Tomato production versus Temperature	
	pvalue	R <sup>2</sup>	pvalue	R <sup>2</sup>
Summer	0.68	0.004	0.0001	0.46
Spring	0.7	0.004	0.003	0.230
Winter	0.02	0.135	0.006	0.200
Autumn	0.460	0.016	0.005	0.207
Overall	0.990	0.00001	0.00002	0.416

Table 5.1 above shows the correlation and significance between Tomato production and Rainfall as well as temperature.

## 5.6. Discussion

Plant scientists and ecologists currently examine historical records as signs of biological responses to climate change trends. Changes in climatic factors such as temperature, solar radiation and precipitation influence crop production. While an elevated atmospheric carbon dioxide (CO<sub>2</sub>) concentration (above some threshold) has the effect of increasing plant photosynthesis and therefore increasing crop yield (Kimball, 1993), the changes in temperature and precipitation might a) hasten plant development and b) alter water and nutrient budgets, thereby causing plant stress. An increase in CO<sub>2</sub> is known to affect the mineral elements such as iron, zinc, manganese and sulphur present in tomatoes. In addition, weeds and other beneficial and harmful insects and microbes present in agro-ecosystems respond to changes in climatic factors. This supports the generally positive response of most invasive and noxious weeds due to the increasing atmospheric CO<sub>2</sub> levels, as reported by Ziska, (2003).

Tomatoes are an important vegetable that is prone to heat stress. Optimal temperature values for leaf development, fruit addition and fruit growth in tomatoes is about 22-25 °C.

The distribution of the tomato crop is determined by the climatic resources in a given area. The field temperature in the Limpopo Province averages around these optimal values and therefore could be associated with the high production of tomatoes. Temperatures exceeding 25°C are likely to reduce tomato production. Assuming a non-linear tomato yield response and optimal temperature values, it is expected that there could be about a 10% drop in tomato yield for 1°C rise in temperature above 25°C.

Agriculture in emerging economies such as South Africa has not directly benefited from optimising the adaptive areas for tomato crops. The variability of tomato production between years as demonstrated in this study could be linked to the seasonal weather effects (and these effects also influence how insects, diseases and weeds affect tomato production). While the effect of temperature on tomato production has spatial and temporal dependence (for example, locality and season of sowing), the response of tomato production to future climate change and climate variability will depend on management practices such as the type and levels of water and nutrients present. In order to maintain or increase tomato yields under climate change, an assessment should be conducted that a) identifies present yield thresholds and b) helps select appropriate adaptation strategies to support tomato-cropping systems in future.

## **5.7. Conclusions**

This study examined the correlation of climate change factors such as temperature and rainfall on tomato production. The results from the present study can be used as a baseline to understand the consequences of climate change and climate variability on agriculture. The analysis utilised STATISTICA software to estimate the factor of climate

in the current yield trends by applying the regression models to observed trends in climate variables for a period of 35 years from 1971-2006. It was noted that although there were some relationships between average minimum, maximum, average temperatures and average rainfall as well as seasonal temperatures and seasonal rainfall also tomato production in the Limpopo Province, some of the extreme temperature conditions did not affect the production.

The present analysis of the linkage between temperature and rainfall as well as tomato production indicates that tomato yield in the Limpopo Province during 1971-2006 has been increasing, which can be attributed to good farming practices, application of fertilizers and the use of irrigation systems. However, it is likely that dependency observed from our analysis does not account for all other environmental factors and therefore these results could be too optimistic because they are based on a capital-intensive agricultural system with significant adaptive capacity. Regarding the climate variables used in this study, particularly temperature, there is sufficient evidence to conclude that agriculture could be affected by future climate change and climate variability, as the results demonstrate a correlation between temperature and tomato production, also a correlation between rainfall and tomato production in the Limpopo Province.

## **5.8. Acknowledgements**

The authors acknowledge the Canon Collins Trust in Cape Town for financial assistance.

The University of Pretoria is gratefully acknowledged.

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## **Chapter 6: Leafminer agromyzid pest distribution over the Limpopo Province in a changing climate**

*Article published*

**M.F. Tshiala, J.O. Botai and J.M. Olwoch (2012). Leafminer Agromyzid pest distribution over the Limpopo Province under changing climate *African Journal of Agricultural Research (AJAR)* (Published 2012) Vol. 7 (48) DOI:10.5897/AJAR12.1570. pp. 6515-6522**

## 6.1. Abstract

The objective of the study was to assess the impacts of climate change on the spatial distribution of the leafminer agromyzid pest over the Limpopo Province, South Africa. In the study the Conformal Cubic Atmospheric Model (CCAM) simulated climate scenarios: a) the current climatology (1981-2010), b) projected near future climatology (2041-2070) and c) the projected distant future climatology (2071-2100). In particular, the linkage between the model simulated temperature and the pest population parameters (that is, the intrinsic rate of increase ( $r_m$ ), net reproduction ( $r_o$ ), mean generation time ( $t_g$ )) were modelled by empirical functions based on laboratory temperature measurements. The empirical functions (derived from the correlation between temperature and  $r_m$ ,  $r_o$ ,  $t_g$ ) were used to simulate spatial distribution of the leafminer agromyzid pest under a changing climate. The present analysis illustrates that the leafminer agromyzid pest and climatic factors exhibit a non-linear relationship best described by the polynomial function of order 2 while in general, the influence of climate change on the spatial distribution of the leafminer agromyzid pest over the Limpopo Province was noticeable. This work contributes towards our understanding of the impact of climate change on the population dynamics of the leafminer agromyzid pest, which hence affects tomato production in the Limpopo Province, South Africa.

**Keywords:** tomato pests, leafminer, climatic variables, the Limpopo Province

## 6.2. Introduction

The polyphagous leafminer agromizyd pest continues to depict high adaptability, invading many countries and causing damage to many crops (Costa-Lima *et al.*, 2010) despite the varied inherent ecosystems. In particular, the tomato crop (which is an important vegetable globally) is among many crops that are damaged by leafminers. The tomato crop (*Lycopersicon esculentum*) is grown around the world, both outdoors and under glass, for fresh market consumption and for processing and requires protection from a variety of pests, including pathogens, weeds, nematodes, insects and other arthropods (Lange and Bronson, 1981).

Leafminers have a relatively short life cycle. The time required for a complete life cycle of leafminers in warm environments is 21 to 28 days, so various generations can occur annually in tropical climates. Leibee (1984) determined the growth cycle of leafminers at a constant of 25°C and reported that about 19 days were required from egg deposition to emergence of the adult.

Development rates increase with temperatures up to about 30°C, thereafter, further increases in temperature become detrimental to the growth of leafminers and larvae experience high mortality. Minkenberg (1988) indicated that at 25°C the egg stage required 2.7 days for development, the three active larval instars required 1.4, 1.4 and 1.8 days respectively and the time spent in the puparium was 9.3 days. In addition, there was an adult preoviposition period that averaged 1.3 days. The temperature threshold for development of the various stages after the oviposition period is 6-10°C, except that laying of eggs required an average temperature of 12°C (Minkeberg, 1988).

As reported in Kocmankova *et al.*, (2008), climatic and weather conditions during the different seasons are the main factors influencing the intensity and the occurrence of pests. Climatic factors such as temperature, precipitation, humidity, wind speed and direction directly influence pest distribution and growth by affecting their rate of development, reproduction, distribution, migration and adaptation. Furthermore, indirect effects can occur through the influence of climate on the insects' host plants, natural enemies and inter-species interactions with other insects (Porter *et al.*, 1991).

Additionally, temperature and water availability are among the most important abiotic factors that can influence insect abundance and distribution (Chown, 2002). Temperature tolerance has been the most studied among polyphagous leafminers and was the subject of a recent review by Kang *et al.*, (2009). According to Lange and Bronson (1981), managing insect pests on a regional scale is very difficult and complex. Furthermore, forecasting insect pests in space and time in heterogeneous landscapes requires updated knowledge of pest population levels and their position in the managed space, as well as an estimate of their future population levels and the way their surrounding habitat may affect these levels (Horowitz and Ishaaya, 2004).

Several studies that predict pest distribution have been reported in the literature. Aragon and Lobo (2012) used a previously developed protocol designed to estimate the climatic favourability of the western corn rootworm (WCR) and derived potential distributions of WCR for current and future climatic conditions. Their results demonstrated that a northward advancement of the upper physiological limit was linked to climate change, which might increase the strength of outbreaks at higher latitudes. On the other hand, Hlásny *et al.*, (2011) used the Phenology Model of Ips (PHENIPS) model to evaluate

climate change impacts on the distribution and voltinism of spruce bark beetle in the Czech Republic. Further, Estay *et al.*, (2008) used simple models, such as Ricker's classic equation, to study the predictive capacity of the dynamic behaviour of insect populations. A related study was conducted by Ghini *et al.*, (2008) who assessed the potential impact of climate change on the spatial distribution of coffee nematodes (races of *Meloidogyne incognita*) and leaf miner (*Leucoptera coffeella*), by using a Geographic Information System.

In this study, we examined the potential geographical distribution of the leafminer agromyzid pest under a range of climate change scenarios using an insect population model. Different pest population parameters a) intrinsic rate of increase ( $r_m$ ): this is the rate of increase per head under specified physical conditions, in an unlimited environment where the effects of increasing density do not need to be considered (Birch, 1948), b) the net reproductive rate ( $R_0$ ): the rate of multiplication in one generation (Lotka, 1945) and c) the mean generation time ( $t_g$ ) which is the average time elapsing from reproduction in one generation to the time the next generation reproduces (Chubachi, 1979). In the present research, temperature was considered as the most important climatic factor because it is the key environmental driver of the development of the insect's life cycle (Edelson and Magaro, 1988; Harrington *et al.*, 2001). Temperature is also a climatic variable whose future changes are estimated with a good measure of confidence (Houghton *et al.*, 2001).

The aim of the present analysis was therefore to investigate the linkage between the leafminer population parameters and temperature over the Limpopo Province because the province contributes the highest proportion of tomato production to the southern Africa

market. The investigation was based on the dynamically downscaled climatic factors under the present, near and distant future climate scenarios of some selected GCMs by a) assessing the climatic influence on the spatial distribution of leafminer over the Limpopo Province, b) using the empirical relationship between temperature and certain population parameters to project future distribution of leafminer in the Limpopo Province based on the projected temperature scenarios.

### **6.3. Study area**

The Limpopo Province is situated in the north of South Africa about 22-25°S, 27-32°E (Figure 6.1). There are three distinct climatic regions over the Limpopo Province: the Lowveld, Highveld and Middleveld climatic regions. The province experiences summer rainfall with warm to hot summer temperatures and cool winters. The Lowveld region can be characterised by hot and dry conditions, with no frost and an average rainfall of 450mm per annum. Additionally, the province has a few high potential areas for dry land crop production and many opportunities for extensive ranching and irrigated fruit and crop production. The drier lands in the western and northern parts of the province are mainly devoted to extensive livestock farming and game ranching with cropping and mixed farming enterprises in the better areas. More intensive commercial field crop farming is mainly confined to the south central plains. The north-eastern region of the province is characterised by subsistence farming. Susceptibility to drought and the scarcity of water pose a threat to stability and future development of agriculture in the Province. Agriculture nevertheless remains vital for the future well-being of the economy of the northern province.

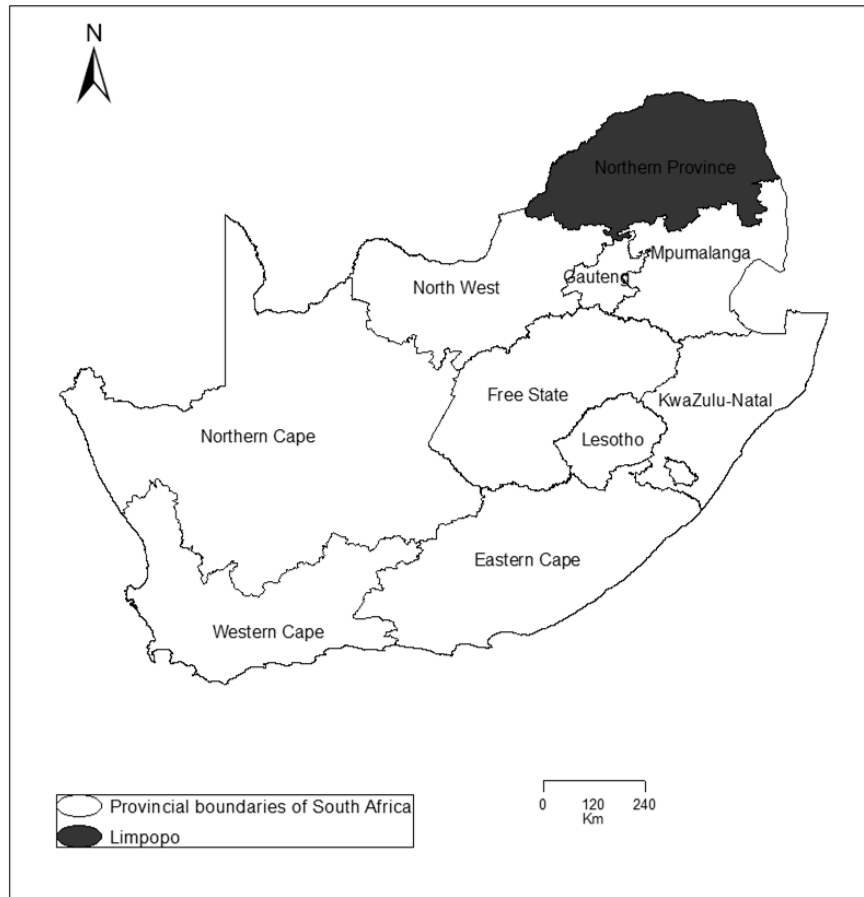


Figure 6.1. Location of the Limpopo Province of South Africa (shaded area)

The site for this study was selected because the Limpopo Province is an important tomato growing area in South Africa, producing 66% of the total annual tonnage of tomatoes (NDA, 2009). Leafminer pest is also one of the major pests attacking tomato crops causing a major yield reduction on tomato production. The control of leafminer poses serious challenges due to its biology and quarantine and variations in temperature strongly affect the insects' physiology, phenology and spatial distribution (Harrington *et al.*, 2001).

Last, future projections using a range of climate models for South Africa correlate with historical temperature increases across the country, resulting in warmer temperatures and extremely hot days. Rainfall is projected to increase in intensity and in total over the eastern portion of the country. Drought is, however indicated for the Limpopo Province in summer (NDA, 2009) with implications for various sectors including agriculture.

## **6.4. Materials and methods**

### **6.4.1. Data**

The climatic data used in this study were obtained from the Circulation Cubic Atmospheric Model (CCAM) developed at the Commonwealth Scientific and Industrial Research Organization (CSIRO) Marine and Atmospheric Research in Australia (McGregor, 1996). More details on the geometrical aspects and dynamical features of CCAM can be found in McGregor (2005). The CCAM data sets were validated before they could be used to simulate the distribution of the pest. In the validation process considered in the present study, temperature measurements (hereafter observations) were extrapolated to a CCAM grid by using the cubic weighted averaging method.

The purpose of the validation was to assess the representativeness of the CCAM data sets. As depicted in Figure 6.2, the range of the differences between the CCAM temperature data and the actual temperature data is less than 3.5°C with a 1.985 standard deviation (SD). The grid resolution of CCAM is a coarse-resolution since the area under consideration is quite small and therefore it is expected that the temperature fields will be as homogenous as possible; hence the small value of the difference in temperature. Furthermore, based on the visual interpretation of Figure 6.2, the spatial distribution of



temperature field across the study area is smooth due to the spatial averaging. There is, however, a noticeable south-north positive gradient in the temperature field (see Table 6.1).

Laboratory measurements of temperature as climatic variables used to model the empirical relationship between temperature and some selected populations parameters of the pest were adopted from Zhang *et al.*, (2000). Thereafter, the pest model parameters were established: these were the empirical functions (that is, the polynomial functions) of the population parameters. Furthermore, a statistical analysis was carried out using STATISTICA version 10; the effect of temperature on the variables was tested by linear regression and the differences in population parameters were compared using regression analysis.

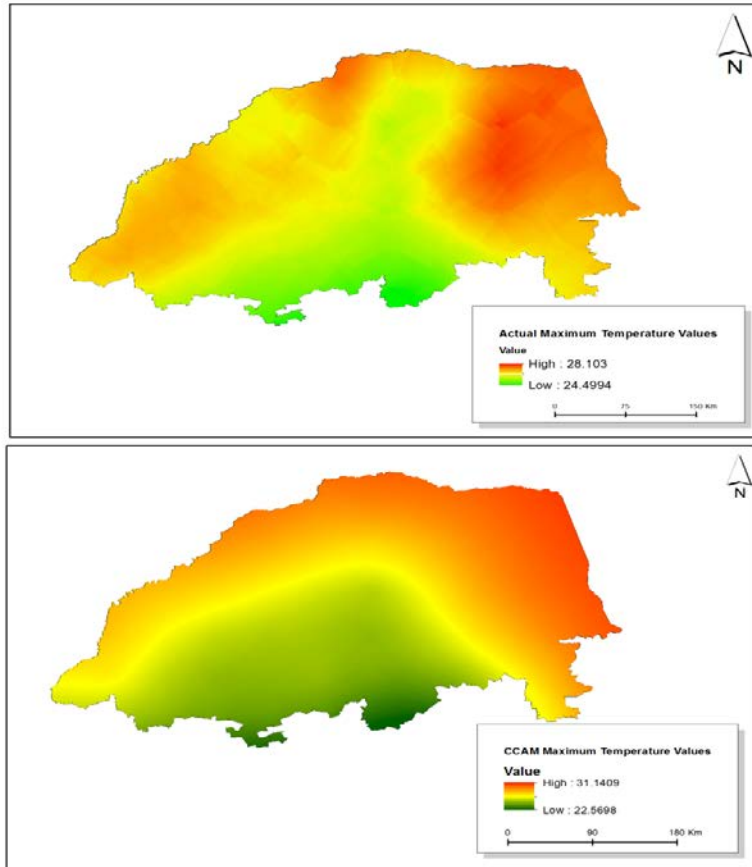


Figure 6.2. Differences between maximum actual temperature value and CCAM temperature values in degree Celsius ( $^{\circ}\text{C}$ )

Table 6.1. Statistics of the CCAM simulation and the observations

Statistics	Max.	Min.	Mean	STD
CCAM simulations	31.14	22.56	28.20	1.96
Observations	26.07	25.7	25.92	0.067
Differences	3.94864	1.73632	2.28	1.893

### 6.4.2 Pest model development

The pest model used in the present study considered three population parameters of leafminer population dynamics:  $r_m$ ,  $r_o$  and  $t_g$ . For further quantitative information (expressions) on the population parameters, refer to Birch (1948). The focus of the present analysis is to investigate the linkage between population parameters and temperature over the Limpopo Province based on the dynamically downscaled climatic factors under the present, near and distant future climate scenarios of some selected GCMs. Empirical functions (see Table 6.3) derived from laboratory measurements reported in Zhang *et al.*, (2000), and presented in Table 6.2 are used to build the relationships between the climatic factors and the selected leafminer population parameters.

As depicted in Table 6.3, simple and parsimonious second-order polynomial functions could be used to sufficiently describe the empirical relationship between temperature and the selected population parameters. The most significant terms (coefficients A, B and C) of the empirical functions exhibit different values across the population parameters.

The coefficients A, B and C characterise the linkage between temperature and population parameters. In particular, the linear relationship between temperature and population parameters is described by coefficient B while the non-linear relationship between temperature and population parameters is accounted for by coefficient C. Coefficient A is constant and also accounts for the outliers in the model.

Table 6.2. Population parameters of leafminer in five temperature treatments (Zhang *et al.*, 2000).

Temperature (°C)	Intrinsic rate of increase ( $r_m$ )	Net reproductive rate ( $r_0$ )	Mean generation time ( $t_g$ )
15	0.0374	5.1331	43.7
20	0.1297	66.9149	32.4
25	0.2199	112.8628	21.5
30	0.2667	116.819	17.8
35	0.2192	26.5109	14.9

Table 6.3. Empirical relationship between temperature (T) and population parameters based on the laboratory experiment depicted in Table 6.2.

Population parameter	Empirical function based on the range $15.0 \leq T \leq 35.0$ ;	Range of the most significant coefficients
Intrinsic rate of increase, ( $r_m$ )	$r_m = A + BT + CT^2$	$2.0 \leq B \leq 5.0$ ; $-0.08 \leq C \leq -0.02$
Mean generation time, ( $t_g$ )	$t_g = A + BT + CT^2$	$10.0 \leq B \leq 40.0$ ; $-6.0 \leq C \leq -3.0$ ;
Net reproduction rate, ( $r_0$ )	$r_0 = A + BT + CT^2$	$140 \leq B \leq 200$ ; $-26.0 \leq C \leq -24.0$

## 6.5. Results

Intrinsic rate of increase of leafminer *agromyzid* under present, near- and distant future climate change scenarios were analysed. From our analysis, the effect of temperature on the intrinsic rate of increase ( $r_m$ ) parameter under the present climate change scenarios during the period of 1981-2010 was not significant, (i.e., for example,  $R^2=0.6682$ ; pvalue 0.0572). The spatial distribution of normalised  $r_m$  values based on the dynamically downscaled GCMs by CCAM over the Limpopo Province under the present climate change scenarios (1981-2010) is depicted in Figure 6.3.

From the current temperature data, it can be observed that during the 30-year period investigated in this study, the southern parts of the Limpopo Province experienced optimal temperatures that are favourable for population increase.

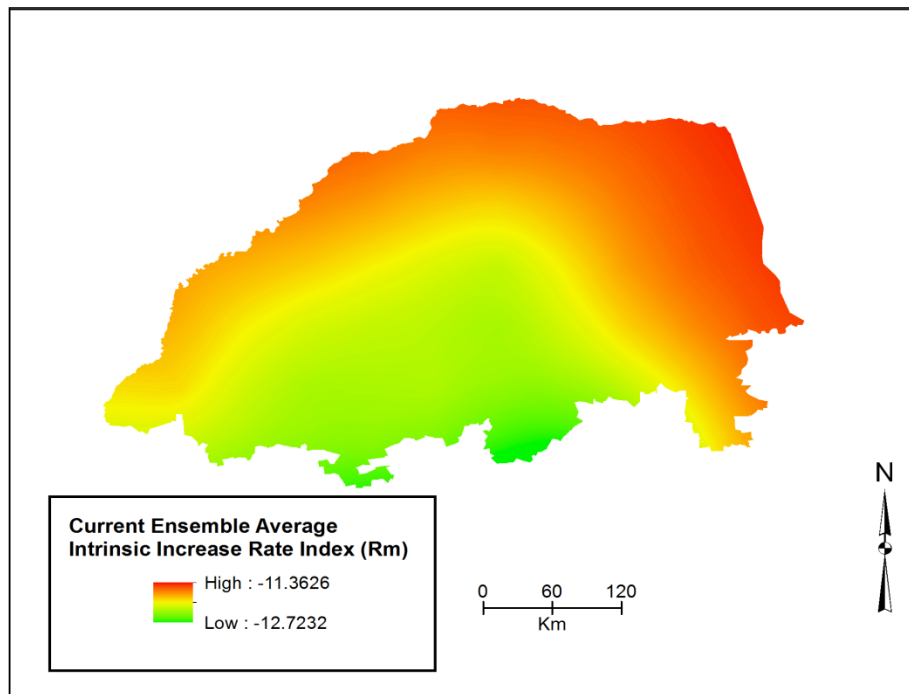


Figure 6.3. Intrinsic rate of increase ( $r_m$ ) of leafminer *agromyzid* under present climate change scenarios (1981-2010).

As depicted in Figure 6.3, using the median (-11.36) as a threshold value, a high proportion of the study area has a higher value of  $r_m$  (~75% of the study area is covered by  $r_m$  values which are greater than the median), implying that temperature variability of the current climate change scenarios will most likely affect  $r_m$ . The analyses suggest a substantial increase in the pest population over the Limpopo Province, which is more pronounced along the northern border.

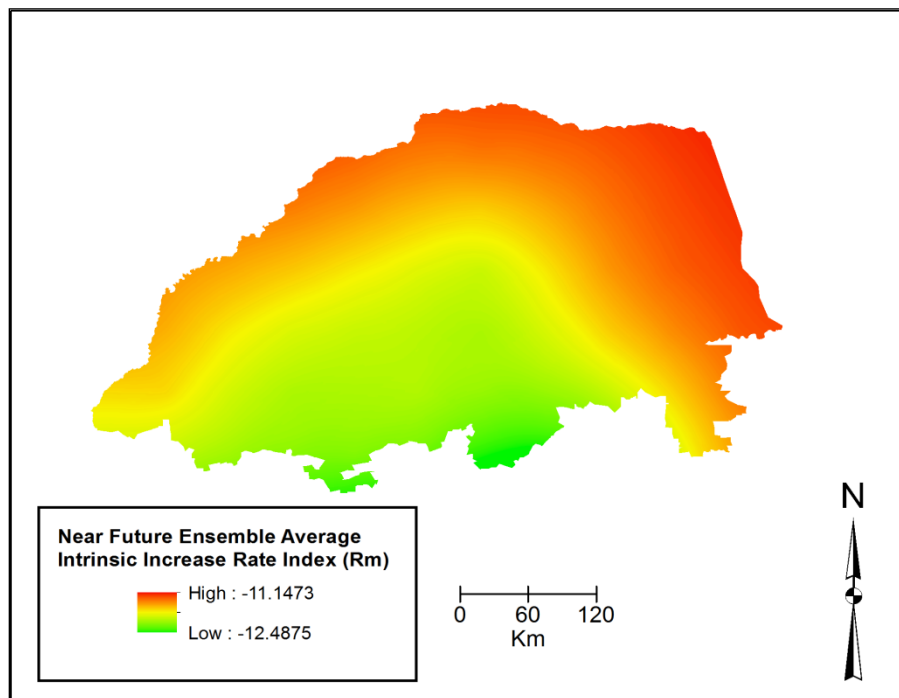


Figure 6.4. Intrinsic rate of increase ( $r_m$ ) of leafminer under near future climate change scenarios (2041-2070)

Figure 6.4 illustrates the intrinsic rate of increase corresponding to the near future climatic period (2041-2070) which exhibits an optimal temperature of 30°C in the region towards the south of the Limpopo Province: this condition is favourable for increasing the pest population in the near future. Notwithstanding the optimal temperature in the near future climatic period, this analysis demonstrates that a large proportion of the study

area has a low values of  $r_m$  implying that temperature variability in the near future will not be likely to affect  $r_m$ .

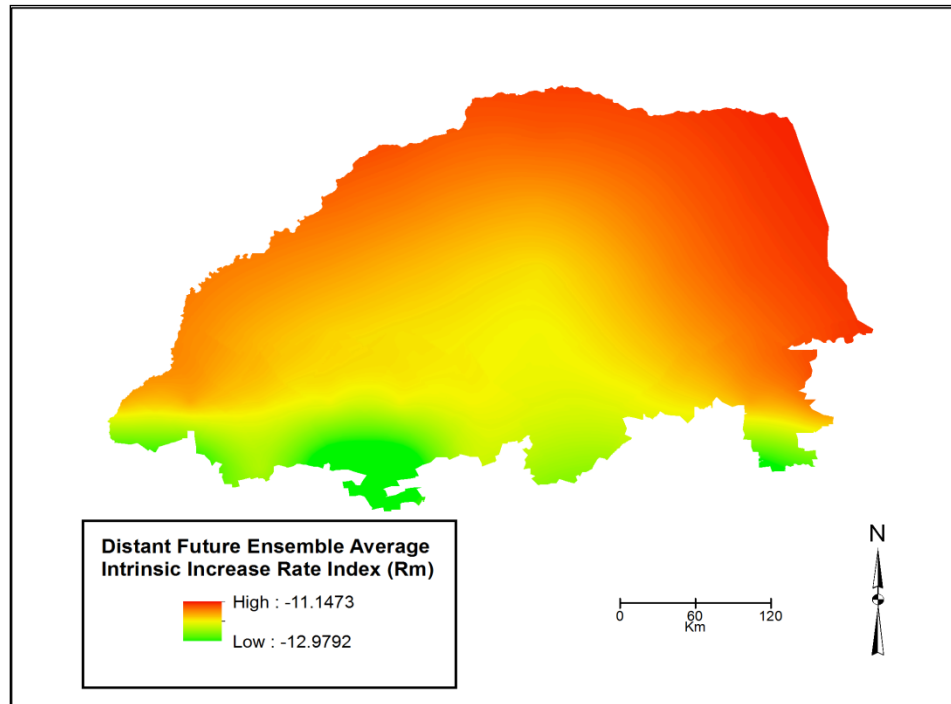


Figure 6.5. Intrinsic rate of increase ( $r_m$ ) of leafminer under distant future climate change scenario (2071-2100)

### 6.5.1. Normalised $r_m$ index in the distant future 2071-2100

The spatial distribution of the normalised  $r_m$  index as derived from the distant future temperature over Limpopo as presented in Figure 6.5 illustrates that a large proportion of the study area has a high values of  $r_m$ . This suggests that temperature variability of the distant climate period as simulated by CCAM will probably not influence the pest population. The analysis further depicts that a high proportion of the study area has a high value of -11.1473 and the rest of the study area has the low value of -12.9792. The  $r_m$  distant future has a standard deviation (SD) of 0.445. The  $r_m$  difference between the current, near future and distant future is -0517.

### 6.5.2. Net reproduction rate of leafminer under present, near- and distant future climate change scenarios

The effect of temperature was not significant between the different constant temperature and the net reproduction rate ( $r_0$ ) (pvalue 0.0633;  $R^2=0.0854$ ). As depicted in Figure 6.6 temperatures could have a dominant influence on the rate of multiplication of leafminer generations during 1971-2010 over the southern parts of Limpopo, while the temperature changes would have a negative response to  $r_0$  over the northern, eastern and western part of Limpopo.

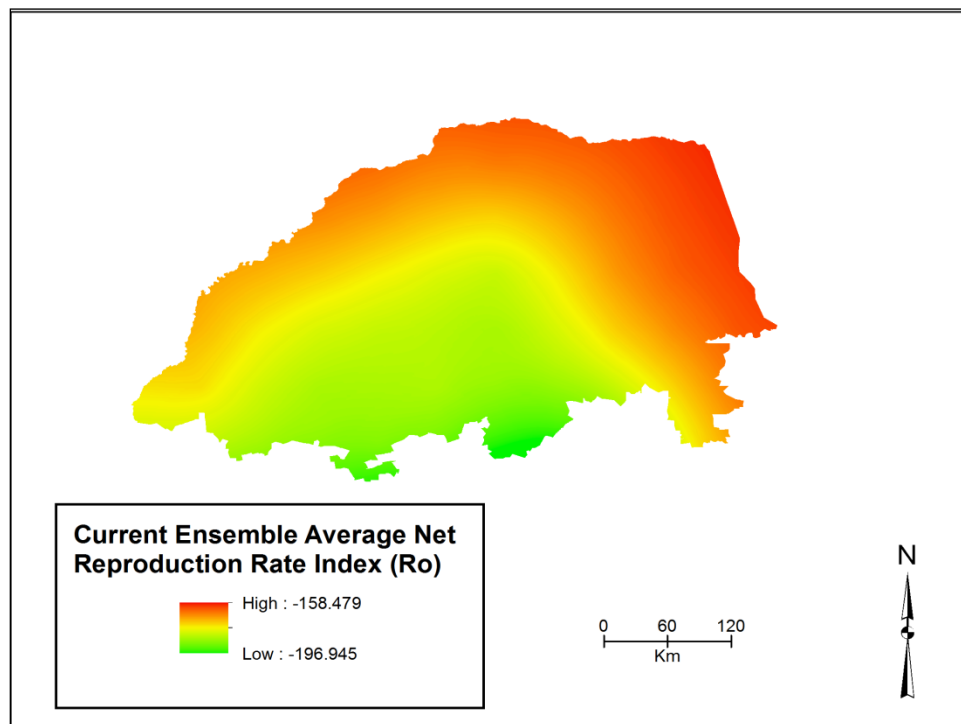


Figure 6.6. Net reproduction rate ( $r_0$ ) of leafminer under present climate change scenarios (1981-2010)

In general, the projected distribution of normalised  $r_0$  of leafminer in the current climate change scenarios during 1981-2010 over Limpopo showed a high rate of multiplication of each generation when the temperature was high. In particular, Figure 6.6 demonstrates



that 73% of the study area has a higher value of  $r_0$  (-158.4). This implies that change of temperature as simulated from the near future climate change scenarios will most likely affect  $r_0$  and therefore the population of the leafminer.

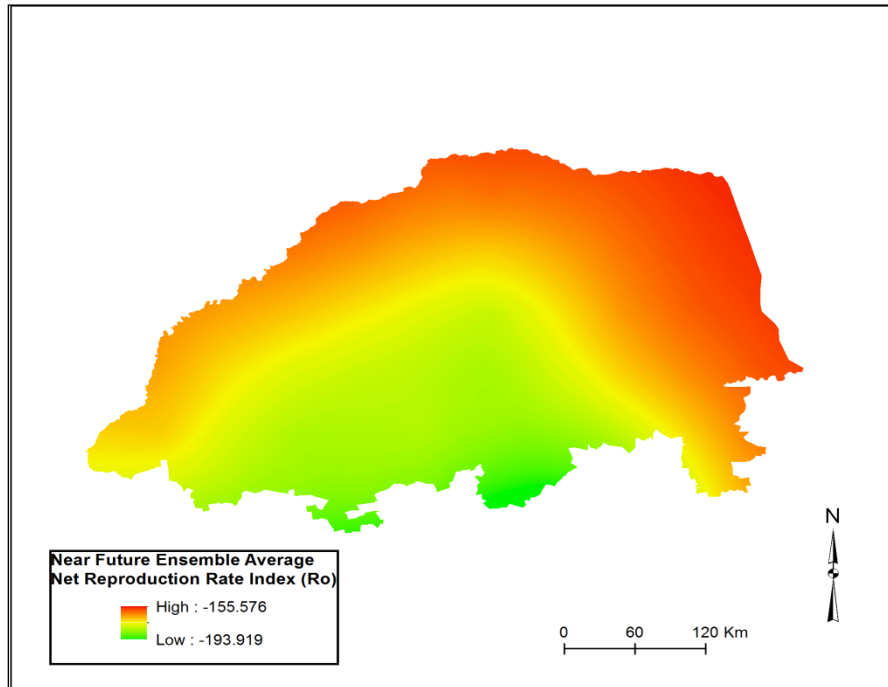


Figure 6.7. Net reproduction rate ( $r_0$ ) of leafminer under near future climate change scenarios (2041-2070)

As shown in Figure 6.7, the projected distribution of the normalised  $r_0$  of leafminer in the near future climate change scenarios during 2041-2070 over Limpopo points to a high rate of multiplication in each generation of the leafminer and this corresponds to optimal temperatures favourable to population growth of pests. It shows that the high proportion of the study has a high value of  $r_0 = -155.5$  and the lowest proportion of the study area has a lowest value of  $r_0 = -193.9$ . However, the standard deviation (SD) has a value of 8.734 while the statistical mean average has the value of -167.388. This implies that change in

temperature as simulated from the near future climate change scenarios will most likely affect  $r_0$ .

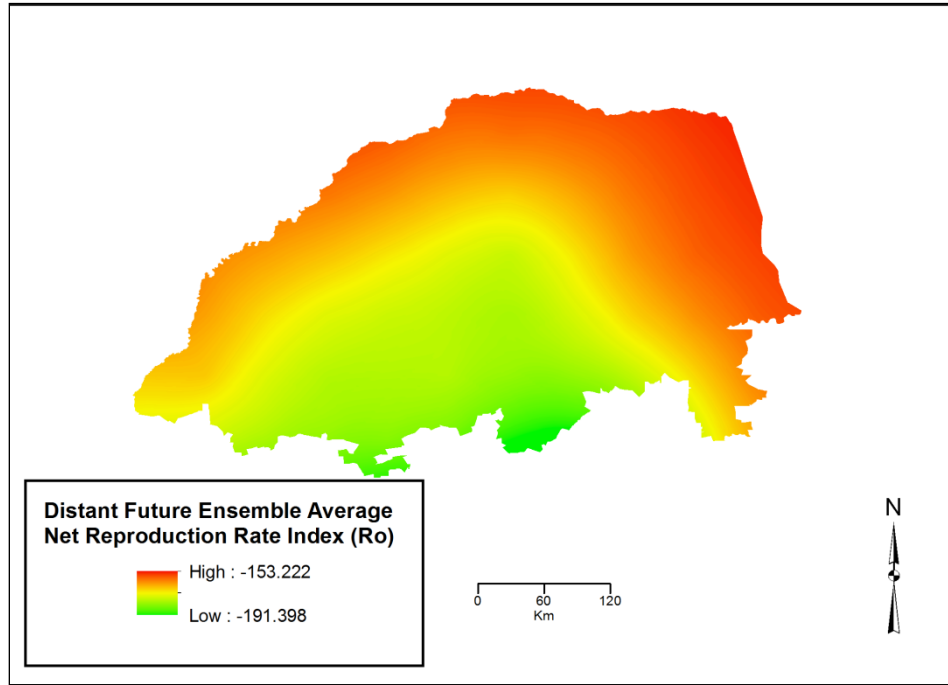


Figure 6.8. Net reproduction rate ( $r_0$ ) of leafminer under distant future climate change scenarios (2071-2100)

Figure 6.8 depicts maximum/minimum values of  $r_0$  over the northern/southern region of the Limpopo Province suggesting spatial variability of  $r_0$  during the distant future climatic period. In particular, 24% of the study corresponds to the  $r_0$  minima based on the median threshold. This implies that future variability of temperature as simulated from the distant future climate change scenarios will most likely have an effect on  $r_0$ . Consequently, the distant future climate period could result in an increase in the pest population over most parts of the Limpopo Province.

### 6.5.3. Mean generation time of leafminer under present, near- and distant future climate change scenarios

The effect of temperature in the present climate change scenarios was highly significant for the mean generation time (tg) parameter ( $F=35.829$ ;  $R^2=0.9227$ ;  $pvalue=0.009$ ). Figure 6.9 illustrates the effect of temperature on the tg between two successive generations of leafminer in the current climate change scenario. The maximum value of tg is 2.66 and the minimum value is -1.28 during present climatic period (1981-2010). About 80% of the proportion of the study area has a lower value of tg (-1.285), implying that temperature variability in the current climate change scenarios will most likely affect tg.

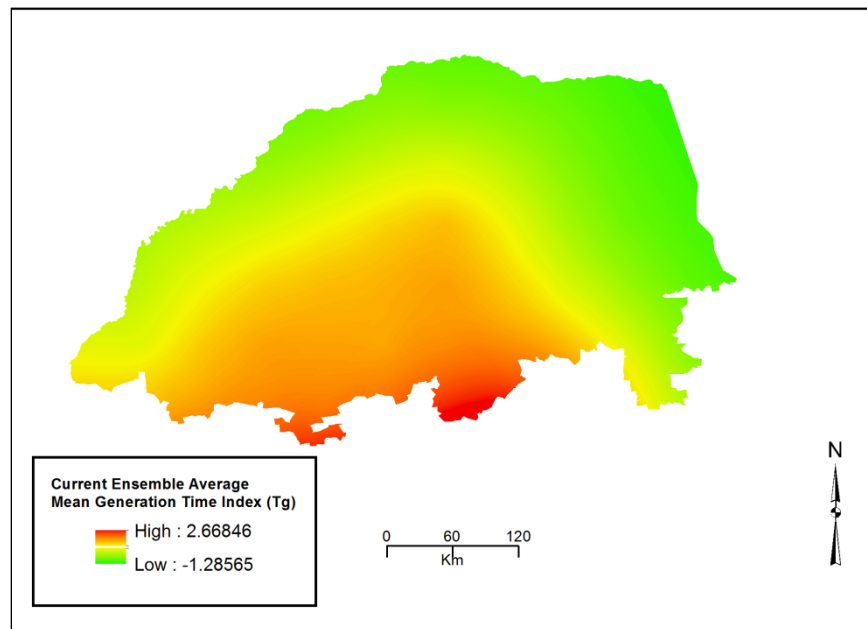


Figure 6.9. Mean generation time (tg) of leafminer under present climate change scenarios (1981-2010)

From the present analysis, the impact of the near future climatic period on the range of tg over the Limpopo Province was determined to be ~3.93. Overall, 29% of the study area exhibited tg values higher than the median value implying that temperature variability of the near future climate change scenarios will probably not affect tg.

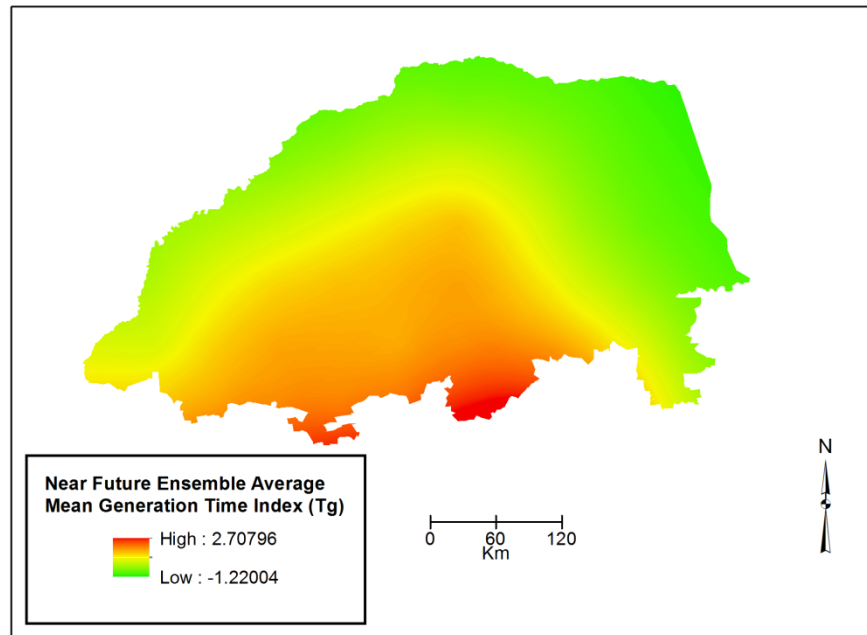


Figure 6.10. Mean generation time (tg) of leafminer under near future climate change scenarios (2041-2070).

Figure 6.11 represents the spatial variability of the mean generation time (tg) of leafminer in the distant projected future climate change scenarios. The study site exhibited a tg mean value ~0.8. Overall, 84% of the study area corresponded to have values lower than the median tg. This implies that future variability in temperature as simulated from the distant future climate change scenarios will most likely not have a noticeable effect on tg. Furthermore, the spatial distribution of tg during the distant future suggests a north-south gradient.

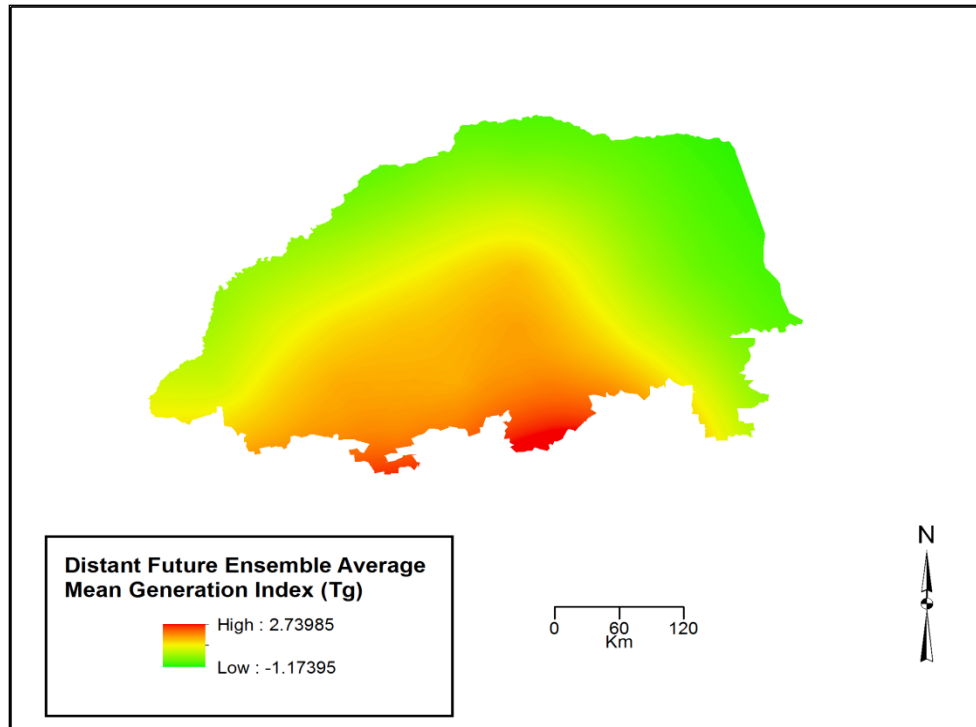


Figure 6.11. Mean generation time (tg) of leafminer according to distant future climate change scenarios (2071-2100)

#### 6.5.4. Differences between the future and present-day parameters

As depicted in Figure 6.12, the range of the differences between the future and present-day parameters is less than 3.5°C with a 1.985 standard deviation (SD). Based on the visual interpretation of Figure 6.12, the spatial distribution of temperature field across the study area is smooth due to the spatial averaging. There is however a noticeable south-north positive gradient in the temperature field.

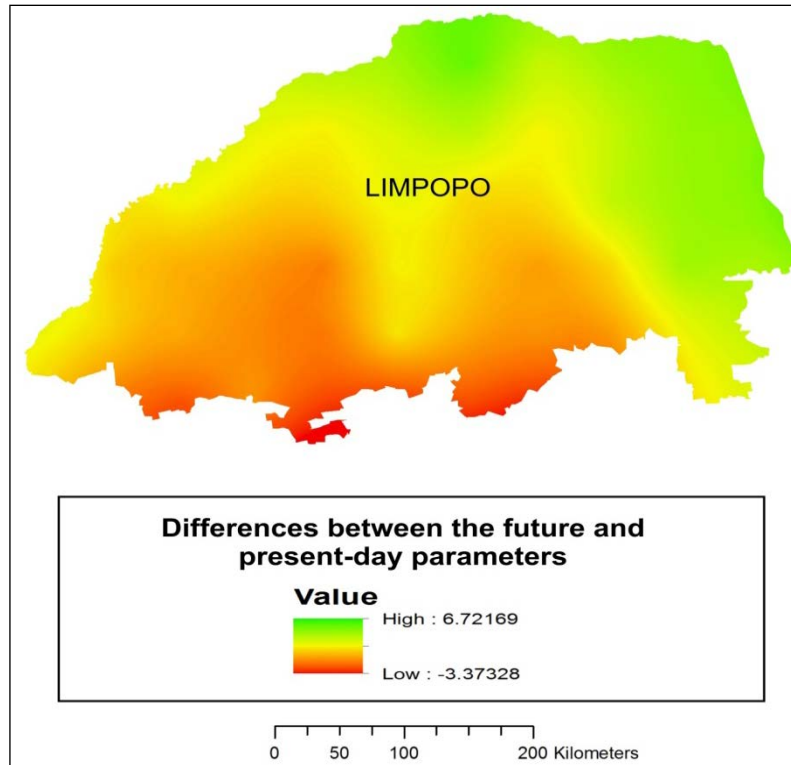


Figure 6.12. Differences between the future and present-day parameters

## 6.6. Discussion and conclusion

Several studies have shown that the development and survival of the leafminer are significantly affected by temperatures (Wu, 1997; Petitt, 1991). Our results allude to the fact that certain population parameters of leafminer agromyzid were influenced by changes in temperature under different climatic periods.

In particular, according to CCAM simulations of the current climatic period a large proportion of the study area exhibited higher values of  $r_m$  suggesting that the temperature variability during the climatic period will most likely affect  $r_m$ . The  $r_m$  values under the current and near future climatic periods were, however, inversely related. Additionally, a large proportion of the study area exhibited values of  $r_m$  higher than median during the

climatic period of the near future, implying that temperature variability of the near future climate will not be likely to affect  $r_m$ . A similar observation was also found for the distant future climatic period.

About 73% of the study corresponds to the maxima of  $r_o$  based on the median threshold value implying that temperature variability of the current climate change scenarios will most likely affect  $r_o$ . The current  $t_g$  has a higher value of  $t_g$  implying that temperature variability in the current climate change scenarios will most likely affect  $t_g$ . The distribution of leafminer agromyzid across the Limpopo Province appears to be influenced by temperature variability across different climatic conditions. Although insects do not live in a stable environment without temperature fluctuation, the results of studies under constant temperatures are still very useful in understanding the population dynamics of various insects (Summers *et al.*, 1984).

This study contributes towards an understanding of the effects of a broad range of temperature variability on the demography of leafminer agromyzid on tomato crops over the Limpopo Province, which has not been previously studied. Our results demonstrate that different population parameters ( $r_m$ ,  $r_o$  and  $t_g$ ) are subtly affected by temperature variability over the different climatic periods as simulated by CCAM. A summary of statistics describing the relationship between temperature and population parameters ( $r_o$ ,  $r_m$  and  $t_g$ ) of leafminer agromyzid is presented in Table 6.3.

As above in Table 6.3, under the current climate change scenario (1981-2010) the high proportion of the study is dominated by the  $t_g$  while in the near future scenario (2041-

2070) the high proportion of the study area is covered by the  $r_o$ . In addition, in the distant future scenario (2071-2100) a high proportion of the study area is dominated by  $t_g$ .

In general, the impact of temperature on the distribution was not unexpected. This is because in the northern province, the tomato producers are using irrigation systems throughout the year and the crop is the host of leafminer. The analysis shows that  $r_m$ ,  $r_o$  and  $t_g$  parameters respond differently to the different scenarios of CCAM simulations. In this regard, the results corroborate prior work on the climatic effects on the population parameters of pests published in the literature (Walther *et al.*, 2002; Bale *et al.*, 2002; Parmesan *et al.*, 2007; Merrill *et al.*, 2008).

Based on the findings of the present study, the following inferences emerge; a) the view that climate conditions are the primary factor controlling the distribution of insect pests populations is supported; b) temperature will certainly affect the growth and the development of the leafminer agromyzid, as discussed by Leibee (1984). The study considered that the ideal condition for growth of the leafminer agromyzid is at a constant temperature of 25°C, while the development rates increase with temperatures up to about 30°C; however temperatures above 30°C are usually unfavourable and larvae experience high mortality; c) the population parameters of leafminer agromyzid are sensitive to climatic change and trends across the Limpopo Province, implying that the pest population could be affected by continued global warming.

It should be noted that all parameters in the present study were estimated at temperatures under laboratory conditions and that factors such as host plants and population density



have not been taken into consideration yet they have an effect on the leafminer development and fecundity (Petitt and Wietlishach, 1994).

In conclusion, our current assessment of the impact of temperature as simulated by CCAM for different climatic periods on the distribution of the leafminer agromyzid pest introduces new questions: a) how do the combined biotic and abiotic conditions influence leafminer agromyzid pest distribution over Limpopo? b) do/will different GCMs reproduce the observed influence? c) how optimal are the derived empirical functions that link climatic factors to the population parameters of leafminer agromyzid pest? In conclusion, it is noted that more attention should be devoted to field experiment(s) to obtain results that are more applicable.

## **6.7. Acknowledgements**

The author would like to gratefully acknowledge the financial assistance from the Canon Collins Trust for the scholarship. We also thank Dr Francois A. Engelbrecht from the Council for Scientific and Industrial Research (CSIR) for providing us with the CCAM data. The University of Pretoria is gratefully acknowledged.

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## **Chapter 7: Conclusions and recommendations**

### **7.1. Summary**

The overall goal of the research reported in this thesis is to improve the understanding of the interrelations between climate change and tomato production in the Limpopo Province of South Africa, with special focus on the analysis of temperature trends and heat waves, as well as leafminer agromyzid pest distribution over the Limpopo Province in a changing climate.

The tomato crop is sensitive to climate variability and change because successful tomato production depends on climatic factors such as rainfall and temperature. The Limpopo Province has a spatial variation of tomato production that is thought to be coupled with fluctuations in weather parameters such as temperature and frost, to which the growth conditions of tomato crop are also very sensitive.

The Limpopo Province is located in the subtropics and mid-latitudes of Earth, which is often characterised by a high degree of climate variability. As a result, agriculture in this region is highly vulnerable to the extended periods of drought that sometimes occur. Conversely, during seasons when tropical circulation is dominant, flooding may occur over extensive regions. The potential for climate change over the region, as induced by global warming is therefore an issue of great importance to southern African agriculture. Climate change is expected to impact directly on agriculture because of rising temperatures, changing rainfall, changes in seasonality and a larger degree of climate variability.

The aim of this study was to determine how climate change could influence the distribution of tomato pests and therefore tomato production in the Limpopo Province.

The following were the objectives of the study:

- To analyse temperature trends and a five decade period of heat waves in the Limpopo Province
- To analyse the impact of climate variability on tomato production in the Limpopo Province
- To analyse the effect of leafminer agromyzid pest distribution in the province in a changing climate.

The observations were made from the weather data and pest laboratory experiments. This combine together conducted an attempt to model simulation and correlations extreme events, as well as model development (pest and temperature).

## **7.2. Scientific contributions**

The present analysis of the linkage between temperature and tomato production indicates that tomato yield in the Limpopo Province during 1971-2006 has increased, probably through the use of good farming practices, application of fertilizers and the use of irrigation systems.

It is believed that this thesis is the first study that has considered the effect of climate change and climate variability on tomato production in Southern Africa.

The following is a summary of the scientific contribution:

- The present study analysed the characteristics of temperature trends in the Limpopo Province. The results demonstrated that the highest temperature in the Province was found to be in the months from October to March. The mean temperature trends of the 30 catchments per decade were found to be  $0.18^{\circ}\text{C}$  and  $0.09^{\circ}\text{C}$  for winter and summer respectively. In general, an increase of  $0.12^{\circ}\text{C}$  was found in the mean annual trend for the 30 catchments over the 50-year period. In the analysis of DTR done over Limpopo, it was observed that the variations in the local temperature trends are not synchronised. Each catchment exhibits unique trends, for instance positive DTR trends seem to occur more in the northern and central regions of the province. Trends in seasonal temperatures showed that the temperature trends are not uniform throughout the year, with winter being the season with the highest temperature trends on average and spring being the season with the lowest trends. Overall, there is no spatial coherence in the results of temperature trends for specific seasons. From these findings, increasing extreme rainfall events and rising temperature patterns provide favourable conditions for the geographical expansion of, for example, vector borne diseases such as malaria and East Coast fever.
- For the first time the present study analysed the frequency of occurrence of HWs in the Limpopo Province. The results from the five decades of heat waves show that there was generally an increase of HW trends during 1950-1999. The total average trends of HW frequency for the whole province from 1950-1999 were found to be about 1.2.



- The influence of climate variability on tomato production over the Limpopo Province was analysed. In particular, the present analysis investigated the linkage between temperature and tomato production. Results indicate that tomato yield in Limpopo during 1971-2006 increased, probably due to the use of good farming practices, application of fertilizers and the use of irrigation systems. There is more evidence that agriculture could be affected by future climate change and climate variability, because the results demonstrate a correlation between temperature and tomato production in the Limpopo Province.
- For the first time, the CCAM simulated climate scenarios: a) the current climatology (1981-2010), b) projected near future climatology (2041-2070) and c) the projected distant future climatology (2071-2100) was used to study the relationship between pest distribution and temperature. The study on the leafminer agromyzid pest distributed over Limpopo shows that climate conditions are the primary factor controlling the distribution of the insect pest populations. The study considered that the ideal condition for growth of the leafminer agromyzid is at a constant temperature of 25°C, while the development rates increase with temperatures up to about 30°C; however, temperatures above 30°C are usually unfavourable and larvae experience high mortality. Furthermore, the population parameters of the leafminer agromyzid were found to be sensitive to climatic change and trends across the Limpopo Province imply that the pest population could be affected by continued global warming.

### 7.3. Conclusion

The main aim of this study was to determine how climate change might influence the distribution of a tomato pest in the Limpopo Province by the use of different population  $r_m$ ,  $r_o$  and  $t_g$  parameters and variability of temperatures over different climatic periods simulated by CCAM data. In this thesis three of the chapters have already published to the peer reviewed journals. In Chapter Three, during the pre-processing stage, the daily average temperature (AvT) was calculated from the arithmetic averages of the daily maximum temperature (MxT) and minimum temperature (MnT). The diurnal temperature range (DTR) was computed by subtracting the daily MnT from the daily MxT. Monthly means were calculated as well. Subsequently, temperature trends were calculated from the monthly averages over the 50-year period for each catchment. In Chapter Four, the assessment was done on the five decade analysis of HW in Limpopo. From the analysis of yearly trends in HW, the results showed that for five decades (1950-1999) in Limpopo there were variable occurrences of HWs over different catchments and some similarities of the trends of HWs within the catchments. Therefore, the results from the current study indicate that during the period 1950-1999, the Limpopo Province displayed the frequency of occurrence of HWs events, while during the four seasons the trends of HWs were not monotonic over the five decades.

In Chapter five, the analysis was done on the impact of climate variability on tomato production in Limpopo and the monthly regional tomato market data were obtained from the National Department of Agriculture in 2009. Climatic variables that were considered were the 35-year averaged observed temperature and rainfall obtained from the Climate Research Unit (CRU) for the period 1971-2006. In Chapter Four, regarding the climate

variables used in this study, particularly temperature, there is sufficient evidence to conclude that agriculture could be affected by future climate change and climate variability, because the results demonstrate a correlation between temperature and tomato production, as well as a correlation between rainfall in the Limpopo Province.

In Chapter Six, the assessment of the impact of temperature as simulated by CCAM for different climatic periods on the distribution of leafminer agromyzid pest have given rise to new questions: a) how do the combined biotic and abiotic conditions influence leafminer agromyzid pest distribution over Limpopo? b) do different GCMs reproduce the observed influence? c) how optimal are the derived empirical functions that link climatic factors to the population parameters of the leafminer agromyzid pest? In conclusion, more attention should be devoted to semi-field experiments to obtain more applicable results.

#### **7.4. Challenges**

The research done during this study had some challenges. First, there was no money allocated for this research and therefore travelling for the training on the use of the CLIMEX software package was not possible. Second, it was difficult to get more than thirty years of climatic data without any gaps: most of the climatic data from the National Weather Service have gaps and the data were not clean. Third, because of imperfect documentation and lack of documentation from the tomato farmers in South Africa, the monthly average tomato market data (these were used as an indicator of tomato production) were calculated by weighting the total number of tomato production distributed monthly to the fresh produce market in South Africa, by 2/3. Furthermore, the

pest data of tomato crops were non-existent. This is the reason the laboratory measurements of temperature as climatic variables were used to model the empirical relationship between temperature and some selected population parameters of the pest adopted from Zhang *et al.*, (2000). It was remarked that more attention should be devoted to field experiment(s) to obtain more applicable results.

### **7.5. Recommendations for future research**

In this study it was demonstrated that frequent exposure to drought causes agricultural production to be out of equilibrium with seasonal conditions. It is therefore recommended, especially for most smallholder farmers, that they adjust land use to climate variability. In order to maintain or increase tomato yields, given the continuing trends of climate change, assessment studies have to be done to identify present yield thresholds, and to help select appropriate adaptation strategies to support tomato cropping systems in future. In this study temperature was the climatic factor used in the study on the impact of climate variability on tomato production in Limpopo. The recommendation would be to use some other factor as well, like rainfall, humidity or water vapour.

The findings from the five decades of HWs within the catchment provide a baseline upon which further studies on the effects of HWs on lifestyle and human comfort, particularly in the light of potential temperature increases associated with the current overall global warming, can be conducted. Furthermore, the findings from the current study could stimulate further studies on the effects of HW on health, particularly on the elderly and other susceptible members of society.

It is also recommended that a further study must be done on leafminer agromyzid pest distribution over the Limpopo Province under a changing climate in a semi-field experiment to obtain more applicable results. In addition, the factors such as host plants and population density must be considered because they also have an effect on leafminer development and fecundity. In addition, an experiment must be done in the laboratory concerning different species of leafminer damaging tomato crops. The analysis could also answer the following questions: how do the combined biotic and abiotic conditions influence leafminer agromyzid pest distribution over Limpopo? Do different GCMs reproduce the observed influence? And how optimal are the derived empirical functions that link climatic factors to the population parameters of the leafminer agromyzid pest?