Impacts of Climate Change on Accumulated Chill Units at Selected Fruit Production Sites in South Africa

by

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CONTENTS

DECLARATION

I declare that the dissertation hereby submitted for the degree of Magister Scientiae Agriculturae in Agrometeorology at the University of the Free State is my own independent work and has not previously been submitted by me at another university or faculty. I further more cede copyright of this dissertation in favour of the University of the Free State.

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ABSTRACT

Climate is an important aspect of crop production, determining the suitability of a given region to deciduous fruit production and largely controls the yield and quality thereof. Climate has always been variable, but there is strong evidence of global and regional-scale climate change since the advent of the industrial era. In South Africa mean surface temperatures have revealed an increasing trend over the last century. South Africa is renowned for its quality export fruit, but deciduous fruit production is already marginal under current conditions. Problems related to climate change will add strain to fruit growers and impact directly on livelihoods within the main production regions. It takes a considerable time to establish fruit orchards, thus it is even more important for these producers to take climate change in consideration. Since deciduous fruits require winter chilling to break dormancy, the main objective of this study was to determine the effect of climate change on accumulated chill units at three sites in South Africa, namely Bethlehem, Ceres and Upington.

Observed winter temperature data were obtained for the base period 1981 – 2010, while projected temperatures up to 2100 were acquired from a Global Climate Model (GCM). Hourly temperatures were derived from these daily minimum and maximum temperatures by means of a Temporal Downscaling Model. The Utah Model and the Daily Positive Utah Chill Unit Model were used to quantify winter chill, accumulated over each winter season from 1981 – 2100. Cumulative distribution functions were used to identify shifts in industry related thresholds for accumulated positive chill units (PCUs). The results indicated that the impacts of climate change vary among regions. Historical accumulated PCUs showed no significant trend for Bethlehem, but a decreasing trend for both Ceres and Upington. The GCM projections indicated a continuation of these trends over the course of the 21st century, thus resulting in an increase in deficient winter chill problems in Ceres and Upington in future. Potential adaptations involve cultivar and/or rootstock selection, microclimate manipulation and the use of chemical rest-breaking agents.

Keywords: Adaptation strategies, Deciduous fruit, Temporal Downscaling Model

OPSOMMING

Klimaat is ŉ belangrike aspek van gewasproduksie en bepaal die geskiktheid van 'n gegewe streek vir die produksie van sagtevrugte en beheer grootliks ook die opbrengs en kwaliteit daarvan. Klimaat is nog altyd veranderlik, maar daar is sterk bewyse van globale en plaaslike-skaal klimaatsverandering sedert die aanvang van die industriële era. In Suid-Afrika toon gemiddelde oppervlaktemperature 'n warm tendens oor die afgelope eeu. Suid-Afrika is bekend vir sy kwaliteit uitvoervrugte, maar met sagtevrugte produksie reeds marginaal onder die huidige toestande, sal probleme weens klimaatsverandering meer druk op vrugteprodusente plaas en die lewensbestaan binne die hoofproduksiestreke beïnvloed. Dit neem 'n geruime tyd om sagtevrugteboorde te vestig, dus is dit selfs belangriker vir dié produsente om klimaatsverandering in ag te neem. Omrede sagtevrugte winterkoue benodig om rus te breek, was die hoof doel van hierdie studie om die effek van klimaatsverandering op geakkumuleerde koue-eenhede te bepaal by drie streke in Suid-Afrika, naamlik Bethlehem, Ceres en Upington.

Waargenome wintertemperatuurdata is verkry vir die basisperiode 1981 – 2010, terwyl geprojekteerde temperature tot 2100 bekom is van 'n Globale Klimaatmodel (GKM). 'n Temporale Afskalingsmodel is gebruik om uurlikse temperature af te lei van hierdie daaglikse minimum en maksimum temperature. Die Utah Model en die Daaglikse Positiewe Utah Koue Eenheid Model is gebruik om winterkoue te bepaal, geakkumuleer oor elke winterseisoen van 1981 – 2100. Kumulatiewe verspreidingsfunksies is gebruik om verskuiwings in industrie-verwante drempels vir geakkumuleerde positiewe koue eenhede (PKE) te identifiseer. Die resultate dui dat die impak van klimaatsverandering wissel tussen streke. Historiese geakkumuleerde PKE het geen betekenisvolle tendens vir Bethlehem getoon nie, maar dalende neigings vir beide Ceres en Upington. Die GKM-projeksies toon 'n voortsetting van hierdie tendense deur die 21ste eeu, wat dui op 'n toename in probleme met gebrekkige winterkoue in Ceres en Upington in die toekoms. Potensiële aanpassings behels kultivar- en/of onderstamkeuse, mikroklimaat-manipulasie en die gebruik van chemiese rusbrekingsmiddels.

Sleutelwoorde: Aanpassingstrategieë, Sagtevrugte, Temporale Afskalingsmodel

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LIST OF ABBREVIATIONS AND SYMBOLS

ARC	Agricultural Research Council
CCAM	Conformal Cubic Atmospheric Model
CDF	Cumulative Distribution Function
CSIRO – Mk3.5	Commonwealth Scientific and Industrial Research Organisation (Australia) GCM
DPCU	Daily Positive Chill Unit
ECHAM5/MPI	Max Planck Institute (Germany) GCM
FAO	Food and Agricultural Organisation
GCM	Global Climate Model
GFDL – CM2.0	Geophysical Fluid Dynamics Laboratory (USA) GCM version 2.0
GFDL – CM2.1	Geophysical Fluid Dynamics Laboratory (USA) GCM version 2.1
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
ISCW	Institute for Soil Climate and Water
MAE	Mean Absolute Error
ME	Model Efficiency
MIROC3.2	University of Tokyo (Japan) GCM
NCEP	National Centre for Environmental Prediction
PCU	Positive Chill Unit
RCM	Regional Climate Model
RMSE	Root Mean Square Error
SAWS	South African Weather Service
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature

TDM	Temporal Downscaling Model
UKMO – HadCM3	United Kingdom Meteorological Office – Hadley Centre GCM
UKMO	United Kingdom Meteorological Office
WMO	World Meteorological Organisation

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Climate change as defined by the Intergovernmental Panel on Climate Change (IPCC) refers to "a change in the state of the climate that can be identified by changes in the mean and/or variability of its properties and that persists for an extended period, typically decades or longer'' (IPCC, 2007). The relevant properties are most often surface variables such as rainfall, temperature and wind, but can also include derived variables such as storm and hail frequencies, drought indices, heat and chill units. Its causes may be attributed to natural occurrences (such as periodic changes in the earth's orbit, volcanic eruptions and variability in solar radiation) as well as human activities (e.g. increasing emissions of greenhouse gases, aerosols and land use changes) (IPCC, 2007; 2013). In contemporary society the term 'climate change' often refers to changes due to anthropogenic causes (IPCC, 2007).

Climate change is a reality as evidenced by the increase of average temperatures, melting of snow or ice, and rising sea levels and changes in other climate metrics such as chill and heat units (IPCC, 2007; Midgley & Lötze, 2011; IPCC, 2013). It is widely recognised that there has been a noticeable rise in global mean surface temperatures during the last century (Figure 1.1), and that this rise cannot be explained unless human activities are accounted for (IPCC, 2007; 2013). The rate of this increase in the global mean surface temperature also increased during the second half of the 20th century (Figure 1.2) (Davis, 2011; IPCC, 2013). This is emphasised by the fact that the ten warmest years on record have all occurred since 1998 (WMO, 2011).

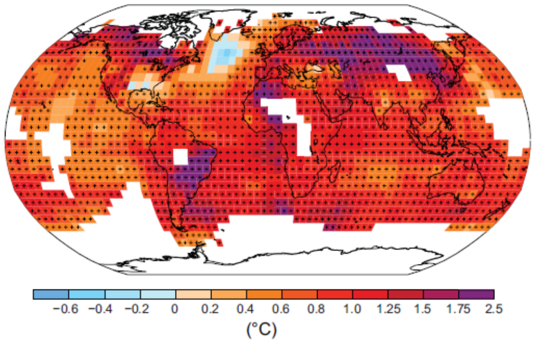

Figure 1.1 Observed changes in mean surface temperature from 1901 to 2012. Grid boxes where the trend is significant at the 10% level are indicated by a plus sign, while white grid boxes represent areas with incomplete data records (IPCC, 2013). Data sourced from three combined land-surface air temperature (LSAT) and sea surface temperature (SST) data sets (HadCRUT4, GISS and NCDC MLOST).

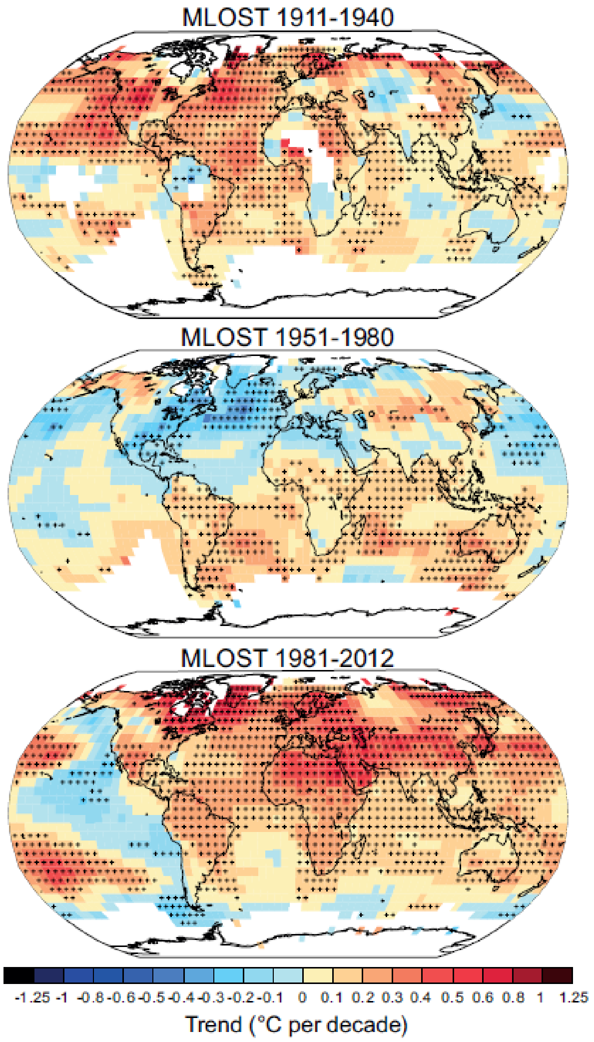

Figure 1.2 Trends in mean surface temperature for three non-consecutive 30-year periods (1911 – 1940; 1951 – 1980; 1981 – 2012). Grid boxes where the trend is significant at the 10% level are indicated by a plus sign, while white grid boxes represent areas with incomplete data records (IPCC, 2013).

There is strong evidence, based on analysis of mean temperature anomalies, of this warming on a regional scale in South Africa with the biggest changes observed over the interior continental regions (Davis, 2011). The annual mean temperature anomalies for 2013 from the preliminary data of 21 climate stations across South Africa was on average about 0.3ºC above the reference period (1961 – 1990) (Figure 1.3). An average warming trend of 0.13ºC per decade was indicated by these particular climate stations, and was statistically significant at the 5% level. The mean temperatures of the previous 17 years were all above normal (SAWS, 2014). The anomalies are also larger in more recent years, suggesting that the rate of increase in minimum and maximum temperatures is increasing. This is consistent with findings from Hulme *et al.* (2001), Kruger & Shongwe (2004), Hewitson *et al.* (2005), Midgley *et al.* (2005) and Benhin (2006).

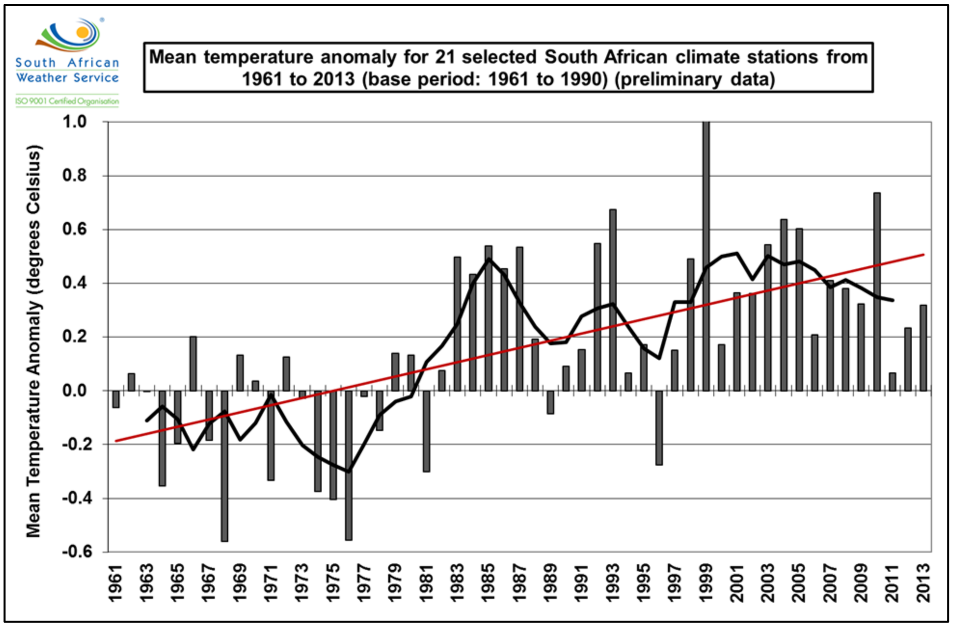

Figure 1.3 **Mean annual temperature anomalies observed across South Africa for the period 1961 – 2013 (SAWS, 2014).**

Global mean temperatures are expected to continue to rise over the 21st century under persistent greenhouse gas emissions. It is further predicted that by the end of the century temperatures will be 1.5 to 4.8°C above the pre-industrial levels (IPCC, 2013). It is further predicted that by the end of the century temperatures will be 1.5 to 4.8°C above the pre-industrial levels, depending on the specific emission scenario (IPCC, 2013). It is also anticipated that the mean temperatures for the south western fruit production areas of South Africa will increase with 1 to 2°C (Midgley & Lötze, 2011). These conditions may also be accompanied by lower autumn and winter rainfall and a much shorter winter season in terms of temperature (Hewitson *et al.,* 2005). The occurrences of both cold and warm days are expected to change globally with a marked decrease in cold day frequency and an increase in warm day frequency by the end of the century (Figure 1.4). Like any other country, South Africa is bound to be affected by climate change and its consequences and it is therefore unlikely that climatic conditions for agricultural production will remain stable (Luedeling *et al.,* 2011).

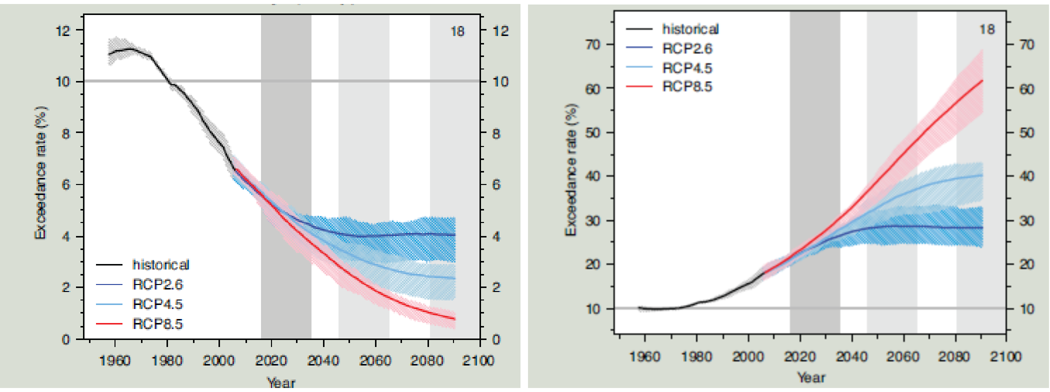

Figure 1.4 **Global projections of the occurrence (left) of cold days – percentage of days annually with daily maximum temperature below the 10th percentile and (right) warm days – percentage of days annually with daily maximum temperature above the 90th percentile for 1961 – 2100 (IPCC, 2013).**

The deciduous fruit production industry in South Africa is well established and primarily aimed at supplying fresh grapes, apples, pears, peaches, nectarines, cherries, plums and apricots to the export market. Peaches, pears, apricots and grapes are also processed and supplied as either canned or dried products to the international and local markets (Hortgro, 2013). In South Africa, 22 650 ha are established under grapes with 32 570 ha under pome fruit and 19 280 ha under stone fruit (Hortgro, 2013).

The Western Cape is traditionally the main fruit production province in South Africa, with the largest concentration of fruit growers and 74% of the total area planted. Fruit production in other provinces offers specific niche marketing opportunities, such as apples from the eastern Free State and peaches from Limpopo and grapes from the Northern Cape (Hortgro, 2013).

The Northern Cape accounts for 15% and the Eastern Cape for 8% of the total area planted. The Northern Cape is important for table grape production, with 48% of all vineyards in South Africa established in this province (Hortgro, 2013). The Eastern Cape, mainly the Langkloof Valley, accounts for 19 and 12% of the area planted under apples and pears, respectively.

The coldness of winter has a major influence on deciduous crops' yield and quality of flowers and fruits, as well as the timing of flowering (Ballard *et al.,* 1987; Allan, 2004). Successful cultivation of many deciduous fruits depends on the fulfilment of the winter chilling requirement, which is cultivar specific (Luedeling *et al.,* 2011). Deciduous fruit trees need to be exposed to a certain amount of chilling temperatures for a sufficient period of time during the rest period to break dormancy and to begin flowering (Baldocchi & Wong, 2008). The chilling requirement of deciduous fruit is typically measured in terms of chill units, chill hours and chill portions and estimation of all these depend on the model used to simulate the chilling requirement (Luedeling *et al.,* 2009). Deciduous fruits, such as apples produced under conditions of inadequate winter chill, require the use of artificial rest-breaking treatments to achieve satisfactory bud break, fruit set, yield and fruit quality (Cook & Jacobs, 2000; Midgley & Lötze, 2011). The accumulation of chill metrics (such as chill hours and chill units) are expected to decrease due to climate warming and may eventually reach a critical threshold at which apple production will no longer be sustainable commercially in current marginal areas. This can also be the same to other deciduous fruits produced in the same area (Midgley & Lötze, 2011). The rate at which chill metrics (chill hours and or/ chill units) decrease varies per season, with different phenological results, and between colder and warmer production areas (Midgley & Lötze, 2011).

Changes in climate can also impact directly on livelihoods, food security and potentially how communities, economies and political systems function (Idso, 2011; IPCC, 2013). Global food security is indeed threatening population and economic growth and if estimates of the amounts of additional food needed to feed the increasing population of the planet prove to be correct, humanity will still fall short of being able to adequately feed the 9.1 billion people expected to be inhabiting the earth by the year 2050 (Idso, 2011).

Since farms often remain in production for years to decades, consideration of future expected winter chill is necessary in times of threatening climatic changes (Baldocchi & Wong, 2008; Luedeling *et al.,* 2009). Many fruit producing areas might receive inadequate chilling due to climate change by the time at which the deciduous trees reach physiological maturity (Luedeling *et al.,* 2009). In some areas trees are hardly fulfilling their chilling requirements under current climate conditions; such production might become less viable in the near future due to climate change resulting in increased temperatures (Lobell *et al.,* 2007). Since the markets for deciduous fruit are becoming more and more competitive in the face of marginal climatic conditions for their production, producers will need to adapt to changes in climate (Midgley *et al.,* 2005).

Monitoring of chill unit accumulation by the fruit growers and insurance companies in South Africa helps them in minimising the loss and also contributes towards yield forecasting. Since climate plays an important role in the production of deciduous fruit, it is important to determine and understand the effects of climate change in deciduous fruit production in order to adapt orchard practices accordingly.

1.2 RESEARCH QUESTIONS AND OBJECTIVES

From the foregoing discussion it is clear that climate change is a reality with several sources reporting on observed temperature increases for South Africa. Agricultural impact studies have shown that climatic change could potentially alter crop yields or lead to changes in agricultural practices (Midgley *et al.,* 2005; Walker & Schulze, 2008; Luedeling *et al.,* 2011). Historically, major grain crops have been the focus of most of these agricultural impact studies, whereas the impact on fruit production has not enjoyed the same attention (Luedeling *et al.,* 2011). Since deciduous fruit production depends on winter chill for bud break, it is highly vulnerable to climatic change (Midgley & Lötze, 2011). This agricultural sector is an important contributor towards the gross domestic product of South Africa, and employs thousands of workers annually. The following research questions thus arise:

1) Will climate metrics such as winter chill units be influenced by climate change?
2) Will deciduous fruit production be influenced by potential changes in winter chill units?
3) What adaptation strategies are available to producers in this sector?

In order to address these research questions the main objective of this study was to determine the effect of climate change on winter chill units within the study areas, namely Bethlehem, Ceres and Upington. Specific objectives therefore included:

1) To develop a temporal downscaling model to obtain hourly temperatures from daily minimum and maximum temperatures;
2) To determine the historical impact of climate change on winter chill units within the study areas; and
3) To determine the possible future impact of climate change on winter chill units within the study areas.

1.3 ORGANISATION OF THE REPORT

The remainder of the dissertation is structured as follows: Chapter 2 is a literature review on climate change, dormancy, chilling requirements and the calculation of chill units. A comparison of various chill unit models are also provided along with a discussion of selected fruit types within the study areas.

In Chapter 3 a description of the study areas and a motivation for their selection is provided, followed by a description of the observed climate data which was obtained from the Agricultural Research Council and South African Weather Service. Global Climate Model (GCM) data is discussed as well as the methods used to analyse both observed data and GCM data.

Chapter 4 presents the results of the study by means of tables and graphs with brief explanations pertaining to them. All the results are in the same sequence as the process description outlined in Chapter 3. Chapter 5 summarizes the main findings and provides possible adaptation strategies which can be used by the producers to deal with impacts of climate change on chill units.

CHAPTER 2

LITERATURE REVIEW

2.1 CLIMATE CHANGE

In Section 1.1 it was noted that climate change refers to any long term change in the mean and/or variability of a climatic element. Climate change is a global phenomenon and its impacts will be mostly felt on a local level (IPCC, 2001; 2007; 2013). Over the past 100 years the earth has experienced an approximate 0.8°C increase in global mean annual temperature (IPCC, 2013). This warming trend is likely to continue, increasing at drastic rates. IPCC (2007) indicated that the global mean surface temperature is already approximately 0.7°C above pre-industrial levels. This is 0.1°C higher than what was estimated in 2001. If it continues to increase at this rate the average global temperature will be 9°C above the pre-industrial levels by the year 2100 (Davis, 2011).

Climate change is not a recent event; instabilities in weather patterns over time are a natural occurrence. However, human generated greenhouse gas (GHG) emissions in the form of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are resulting in changes to the climatic patterns beyond natural rates (IPCC, 2001; 2007; Rosenzweig *et al.,* 2008). Recent reports authored by the world's foremost scientists confirm that the increased rate of change is indeed human-induced, due to the release of GHG by the burning of fossil fuel and changed land use practices (IPCC, 2007; Rosenzweig *et al.,* 2008). Even if humans could halt greenhouse gas emissions immediately, the expected warming rate would still be approximately 0.2°C per decade for the next two decades (IPCC, 2007).

Climate change is not just manifested in an alteration of a single climatic element, such as temperature, but a change in many interlinked climate variables such as temperature, rainfall, humidity, frost, winter chilling (chill units) and heat units. Each change is unified and plays a part in contributing to the overall effect on crop yield and land productivity (Kimball *et al.,* 2002; Midgley *et al.,* 2004; Walker & Schulze, 2008).

Climate change has an effect on the economy and food security of countries through a variety of channels (Stern, 2006; World Bank, 2007; Garnault, 2008; Yu *et al*., 2010). The effect of climate change on agriculture can be divided in direct and indirect effects (Benhin, 2006; IPCC, 2007; Walker & Schulze, 2008). Direct effects can be in the form of physical changes in climate, for example changes in rainfall patterns, temperature, wind directions and other metrics such as chill units and heat units, which affect the productivity of crops and their geographic distribution (IPCC, 2007; World Bank, 2007; Yu *et al.,* 2010). Climate change can also indirectly affect the agricultural industry through consumer behavioural patterns which are driven by environmentally friendly products such as the green products and environmental issues (IPCC, 2007; World Bank, 2007). In order to understand the impact that climate change has on agriculture better one needs to study the scientific evidence of global and regional climate change, its causes, and its projected effects.

Climate change is usually discussed in worldwide terms however; its effects vary quite dramatically among different regions of the earth (IPCC, 2001; 2007; 2013). It is because of this spatial variation that local or regional studies are required to understand the local effects of climate change (Corney *et al.,* 2010; IPCC, 2013).

Over the previous decades the average annual temperature increased with 0.13°C per decade between 1960 and 2003 for South Africa (Benhin, 2006). Scientists predicted a temperature increase of 0.2 – 4°C for the 2050s (2041 – 2070) relative to the period of 1981 – 2010, depending on how quickly people change the way they do things (Benhin, 2006; Walker & Schulze, 2008; IPCC, 2013). To avoid the worst impacts of climate change, people need to limit the emissions of greenhouse gases to the atmosphere that leads to avoid global temperature increase of 2°C above pre-industrial levels (IPCC, 2007). Although 2°C is not much, such a change in the average global temperature is expected to have an impact on the frequency and intensity of storms, seasonal droughts and floods, flowering and fruiting times of crops, and crop selection (IPCC, 2007; Davis, 2011).

Climate variability is one of the main causes of variable crop yields and in future, extreme weather events like storms, heavy rains, drought, and floods may become more frequent, impacting negatively on agricultural yields (Joubert, 1994). Even slight changes in local climate can influence agricultural production on a regional scale. A limited number of studies have focused on the potential effect of climate change on chill accumulation and its negative impacts on horticulture at large (Legave *et al.,* 2008; Wand *et al.,* 2008; Harrington *et al.,* 2010; Darbyshire *et al.,* 2011).

Climate change and variability can also have a negative effect on consumers through a strong impact on food availability and price stability, which is one of the reasons for the recent increase in fruit and vegetable prices (Joubert, 1994). Climate change may result in a number of impacts on crop production, while management decisions need to be considered in a holistic manner to ensure sustainability over the long-term.

2.2 DORMANCY

Dormancy is a phase of development that occurs annually and this helps trees in tolerating cold winter temperatures (Saure, 1985; Lang *et al.,* 1987; Sheard, 2001; 2008). It has a major impact on the production of deciduous fruits, due to its influence in processes such as flowering and vegetative growth (Sheard, 2001; 2008). When plants are dormant they require enough exposure to chill temperatures for bud break and the continuation of normal growth in the spring (Linsley-Noakes *et al.,* 1994; 1995). The factors initiating dormancy vary among different species and even among different cultivars, as a result of climatic adaptation to the conditions in their place of origin (Vegis, 1964; Li *et al.,* 2003; Palonen, 2006). Information and knowledge of bud dormancy comes from the studies done on temperate deciduous trees, especially fruit crops such as apples and stone fruit (Dennis, 1994). Hormonal control has been suggested as the mechanism, with early research suggesting the process is controlled by a balance of growth promoters and inhibitors (Dennis, 1994). It was suggested that temperature stimulates hormones such as indoleacetic acid, gibberellins, abscisic acid, and ethylene, which then control dormancy breaking (Seeley, 1990; Horvath, 2009).

Dormancy prevents seeds from germinating and buds from opening in the autumn or winter when favourable conditions for growth and survival are not sustained for more than a few days at a time (Bonner, 2008). Temperate fruit trees primarily exhibit embryonic seed dormancy. Seeds generally require a period of cold stratification, ideally between 3 and 6°C, although limited dormancy release may still occur at temperatures up to 15°C followed by warm incubation to overcome dormancy (Bonner, 2008).

Dormancy is not a uniform state within the development of plants, but is rather a phenomenon covering a spectrum of different physiological conditions (Saure, 1985). Lang *et al.* (1987) defined dormancy as "a temporary suspension of visible growth of any plant structure containing a meristem". There are three types of dormancy, namely paradormancy, endodormancy and ecodormancy (Figure 2.1).

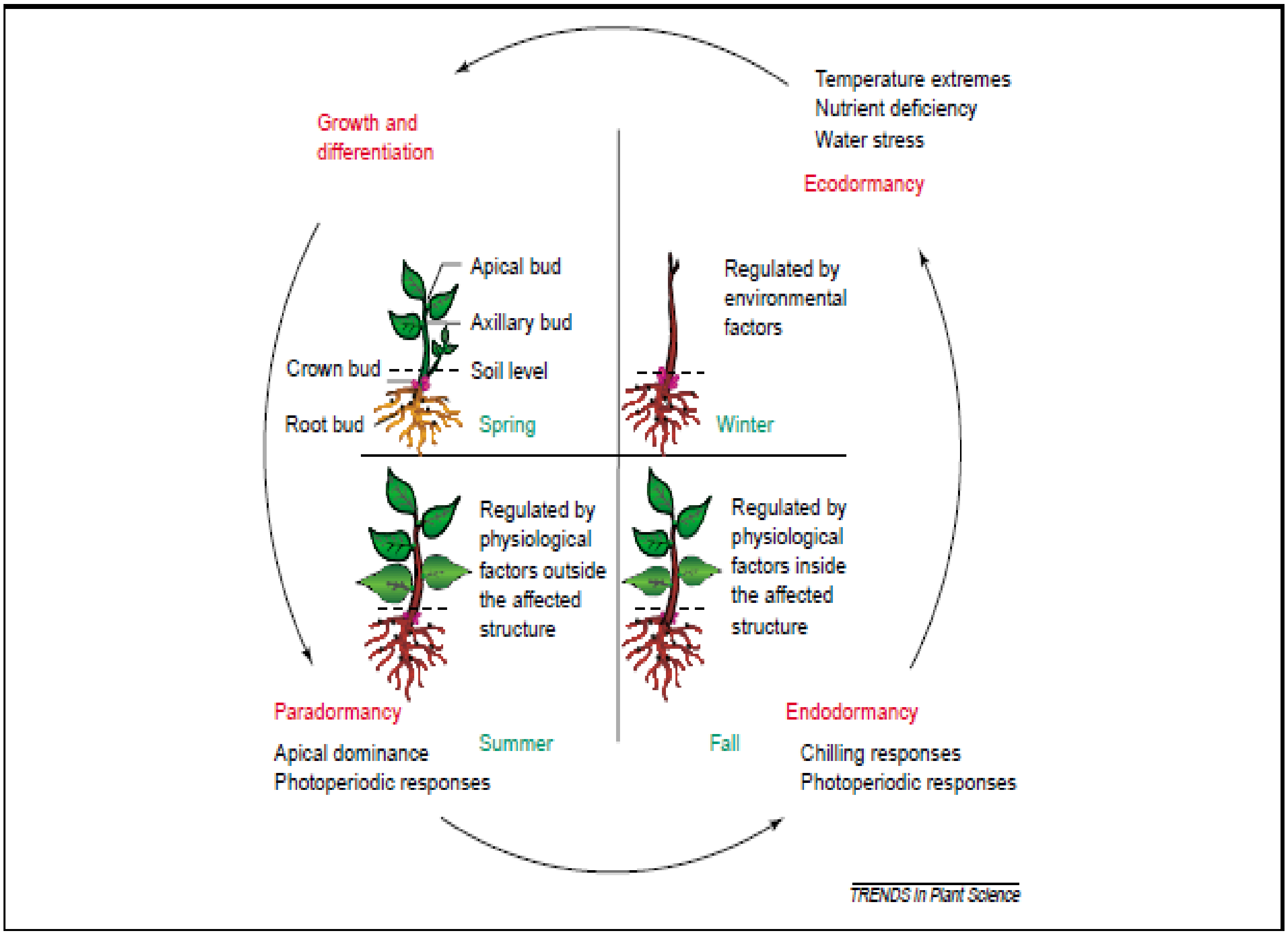

Figure 2.1 **Signals and typical seasons corresponding to the different types of dormancy (Horvath *et al.*, 2003) (The fall season is referred to as autumn in South Africa).**

2.2.1 Paradormancy (Correlative inhibition)

Paradomancy is the suspension of growth caused by factors outside the meristems but within the plant. It is the inhibitory influence of one plant organ over another for example apical dormancy (Ballard *et al.,* 1987). Lang *et al.* (1987) stated that paradormancy is regulated by physiological factors outside the affected structure of the plant for example photoperiod. Paradormancy was also defined as growth termination due to alternative resource needs (Lang *et al.,* 1987; Kester & Gradziel, 1996). Apical dormancy is where the terminal bud suppresses growth of lateral buds. A number of hormones play a role in this inhibition of growth such as auxin and cytokins. Horvath *et al.* (2003) stated that basipetally transported auxin is regarded as the main signal regulating paradormancy.

During paradormancy morphogenic factors are produced in tissue other than the meristematic structures, such as a leaf, bud scale, apex, fruit flesh and others (Lang *et al.,* 1987). Paradormancy allows the plant to devote resources to reproduction and to control plant architecture, maximizing light harvesting while allowing for regeneration of the damaged shoots (Horvath *et al.,* 2003). This type of dormancy is synonymous with apical dominance and correlative inhibition, as it occurs in lateral buds; both can be overcome by physical (terminal bud removal) or chemical (growth regulators) treatments (Horvath *et al.,* 2003).

Other examples of paradormancy is the presence of multi-layer bud scales which restricts bud expansion in fruit trees, and the thick base of the petiole of grape leaves suppressing bud enlargement and growth (Horvath *et al.,* 2003). The thick endocarps of seeds that are rich in water soluble inhibitors preventing seeds from germinating is also an example of paradormancy (Horvath *et al.,* 2003).

2.2.2 Endodormancy (Rest)

Endodormancy is an internal condition rendering apical meristems growth despite favourable external conditions (Saure, 1985; Lang *et al.,* 1987; Kester & Gradziel, 1996; Horvath *et al.,* 2003). Endodormancy occurs in early winter for deciduous fruit trees and prevents buds from growing until spring (Lang *et al.,* 1987). Endodormancy is the stage where growth is controlled by plant growth regulators within the bud. When the tree is dormant it will not resume growth even when placed in a favourable environment with adequate moisture, long day length and warm temperatures (Ballard *et al.,* 1987). According to Ballard *et al.* (1987) environmental conditions such as moisture stress, shortened day length and cooler night temperatures promote the induction of endodormancy.

Faust (1989) indicated that the age of the tree, soil fertility, soil moisture, plant growth rate and autumn temperatures all influence the initiation of dormancy. Endodormancy is internally controlled by physiological factors inside the meristem. These factors change in response to temperature and photoperiod (Lang *et al.,* 1987; Erez, 2000).

The molecular biology of endodormancy were studied in poplar cottonwood (*Populous deltoides*), grapes (*Vitus vinifera*) and also on potato (*Salanum tuberosum*) (Horvath *et al.,* 2003). A number of physiological studies were done on forced bud break of deciduous fruit trees such as apples, pears, cherries, apricots, peaches and almonds in growth chambers (Ashcroft *et al.,* 1977; Viti & Monteleone, 1991; Egea *et al.*, 2003). Other methods studied for the determination of bud break included morphological studies, shoot-tip culture and correlation models on flowering date and temperatures during rest (Kester *et al*., 1977; Alonso *et al*., 2005).

Chilling requirement is the amount of cold needed to break endodormancy and if the chilling requirement of deciduous fruit trees are not met, delayed bud break or prolonged dormancy will occur. This will affect flowering and growth of the tree resulting in poor fruit quality and yield (Kester & Gradziel, 1996).

2.2.3 Ecodormancy (Quiescence)

It is dormancy due to unfavourable environmental conditions for growth, usually due to cold temperatures (Lang *et al.,* 1987). Ecodormancy also includes dormancy due to unstable environmental conditions which are nonspecific in their effect over all plant metabolisms (Lang *et al*., 1987). After buds are exposed to a specific amount of chill in winter, they enter a state termed ecodormancy, or the “end of rest” where they are no longer regulated by internal plant growth regulators and can sense external factors, such as ambient warmth or cold temperatures and lack of water (Anderson *et al.,* 1986). Following endodormancy, ecodormancy is imposed on deciduous trees by external unfavourable conditions such as surface temperature and long photoperiod which induce critical signals that prevent bud growth (Fishman *et al.,* 1987; Horvath *et al.,* 2003). In deciduous trees there are sufficient signal transduction processes that regulate the responses to cold or drought to provide possible mechanism for growth inhibition such as plant hormones (ABA and ICK1) (Horvath *et al.,* 2003).

2.3 METHODS FOR QUANTIFYING WINTER CHILL

Temperature conditions are critical in determining winter chill exposure. The accurate quantification of winter chill can assist in predicting fruit quality and yield of the season (Lötze & Bergh, 2004). Winter chilling is the term used by scientists to refer to how effective the cold of winter has been (Allan, 2004). A chill unit in agriculture is a measurement to determine the plant's exposure to chilling temperatures (Richardson *et al.,* 1974; Atkinson *et al.,* 2004; Oukabli & Mahhou, 2007).

During winter, deciduous fruit trees accumulate the degree of coldness in order to determine when is it safe to initiate bud break and flowering (Luedeling & Brown, 2010). If winter chill is slightly below the amount required, bud break is delayed and flowering will occur over a longer period. This leads to problems with crop load management resulting in more thinning sprays as well as extended harvesting periods (Luedeling & Brown, 2010). For instance, a year of high winter chill will generally result in an earlier flowering period once temperatures starts rising during spring, and often a more compacted flowering season (Cesaraccio *et al.,* 2004).

Scientists refer to chilling temperatures as temperatures between freezing point and depending on the model, 7°C or even 16°C (Byrne & Bacon, 1992). A number of methods have been developed for measuring the effectiveness of winter chill, such as the Chilling Hours Model (Chandler, 1942; Bennett, 1949; Weinberger, 1950), Utah Model (Richardson *et al.,* 1974), Daily Positive Utah Chill Model (Linsley-Noakes *et al.,* 1994) and Dynamic Model (Fishman *et al.,* 1987). These models have structural similarities. All the models accumulate chill at hourly intervals, require summation of chill to estimate total chill exposure and operate within a defined chilling period (Luedeling *et al.,* 2009). These models differ greatly in their sensitivity to climate change making the choice of the model crucial when predicting the effects of climate change on winter chill (Luedeling *et al.,* 2009). However, studies on winter chill and chilling requirement often assume that the choice of the model is not important and that all models can be used interchangeably (Saure, 1985).

In application, chill models frequently accumulate chill over time and when a threshold amount of chill has been accumulated, chill is defined as fulfilled (Luedeling *et al.,* 2009; Zhang & Taylor, 2011). Different species require different threshold amounts of chill to break dormancy. These chilling requirements are defined according to different chill models used and therefore chill thresholds may differ for the same fruits. For instance, Ghariani and Stebbins (1994) reported chill thresholds for 43 apple and 38 pear cultivars using the Utah Model. Zhang and Taylor (2011) determined chill requirement for ‘Sirora’ pistachio using the Dynamic Model, while Baldocchi and Wong (2008) reported on thresholds defined for 18 fruit and nut cultivars using a model to investigate future chill conditions in California. Unfortunately it has been established that transfiguration factors between chill models are not possible (Baldocchi & Wong 2008).

Chill unit models serve three specific needs:

1. They provide producers with a relatively complete assessment of how particular cultivars fare under the current climatic conditions, which facilitates cultivar choice (Savage & Prince, 1972; Smith,1985);
2. They inform producers of the stage of phenological development during a growing season; the models can indicate whether frost protection is needed; and
3. Models which are more accurate can consistently predict maturity dates which improve the market delivery of fruits.

Cesaraccio *et al.* (2004) stated that several chill estimation models presented in literature predict the time of bud break in the season. Accurate chilling models can also help researchers assess the effect of climate variability on fruit production in different areas (Southwick *et al.,* 2003). The following sections describe models which are mostly used throughout the world to estimate or calculate winter chilling.

2.3.1 Chilling Hours Model

The Chilling Hours Model (Chandler, 1942) is the oldest method to quantify winter chill and is still widely used. It is sometimes referred to as the Weinberger Model (Bennett, 1949; Weinberger, 1950) as it was modified to simply calculate the number of hours when the temperature (T) fell below 7.2°C (sometimes changed to 7°C). It soon became apparent that freezing temperatures did not contribute to winter chill accumulation, leading to the exclusion of such temperatures (Bennett, 1949). At a given time *t* (measured in hours since the start of the dormancy season) the number of chilling hours (CH_t) can be calculated as (Chandler, 1942):

$$CH_t = \sum_{i=1}^{t} T_{7.2} \; with \; T_{7.2} \begin{cases} 0℃ < T < 7.2℃ & : 1 \\ else & : 0 \end{cases} \qquad \textbf{[Eq. 2.1]}$$

The Chilling Hours Model is very simple but it does not include many of the observed effects of temperature on chill accumulation, such as the negative effect of high temperatures (Luedeling *et al.,* 2011). The step-change structure of the model forces compact limitations to chill accumulation, for example, 7.2°C will accumulate zero chill hours. Given the knowledge already existing on the chilling process the level of accuracy is unlikely to be defendable (Luedeling *et al.,* 2011).

2.3.2 Utah Model (Richardson Chill Units Model)

The Utah Model of Richardson *et al.* (1974) was developed for peaches in areas with very cold winters, but it is now widely used in deciduous fruit growing areas worldwide. It contains a weight function assigning different chilling efficiencies to different temperature arrays, including negative contributions by high temperatures. The accumulation of chilling in the Utah model for an hour at a given temperature is calculated using the weighting system described in Table 2.1. The model takes into account the deterioration in chill accumulation efficiency above and below 7ºC. It also accounts for the negation effects of short periods of warming during winter. Although a few adjusted versions of the weight function exist, the weights from the original publication (Richardson *et al.,* 1974) are used to describe the model which is most widely used. For this study the threshold values were modified slightly in order to avoid confusion which may have surfaced due to the gaps between them in the original version of Richardson's table.

Table 2.1 Calculation of chill units from hourly temperature data applying the Utah Model (adapted from Richardson *et al*. (1974)

Temperature (°C)	RCU (per hour)
T < 1.5	0
1.5 ≤ T < 2.5	0.5
2.5 ≤ T < 9.2	1
9.2 ≤ T < 12.5	0.5
12.5 ≤ T ≤ 16	0
16 ≤ T ≤ 18	−0.5
T ≥ 18.0	−1.0

Richardson *et al.* (1974) suggests that a full chill unit can be acquired when the temperature in an hour is between 2.4 and 9.2°C. This model was adopted by the South African deciduous fruit industry in the southern part of the Western Cape (Linsley-Noakes *et al.,* 1995). High temperatures ≥12.5°C does not contribute to the chill accumulation, while temperatures below 1.5°C are also not considered effective for chilling. The chilling accumulation always start when the first positive chill units occur, and chilling negation due to exposure to higher temperatures does not occur when at least 75% of the chilling requirement has been satisfied before exposure to such higher temperatures (Schwartz *et al.,* 1997). Higher temperatures counteract the positive effects of chilling and negative chill units are applied when temperatures exceed a threshold of 16°C (Richardson *et al.,* 1974; Linsley-Noakes *et al.*, 1995).

2.3.3 Daily Positive Utah Chill Unit Model (DPCU) (Infruitec Model)

Saure (1985) stated that the calculation of positive chill units has highlighted the importance of low temperatures for dormancy release and the delaying effects of higher temperatures. Linsley-Noakes *et al.* (1994) found the Utah Model to be inaccurate under South African conditions, especially in the warm deciduous fruit growing areas with high winter day time temperatures greater than 20°C. The high negative totals during warm winter days led to inaccurate and negative Utah chill unit totals, even though adequate chilling was received by low chill trees. A modification of the Utah Chill Unit Model was proposed by Linsley-Noakes *et al.* (1994) which is known as Daily Positive Utah Chill Unit Model (DPCU).

Chill units for each hour are summed over every 24 hours and if the total for the 24-hours period is negative the total chill unit for that day is counted as zero, but if the total is positive, it is added to the already accumulated chill units. These units were originally called “modified Utah chill units” (Linsley-Noakes, *et al*., 1994; Sheard, 2001), then Positive Daily Richardson Units (Allan *et al.,* 1994), and finally Daily Positive Utah Chill Units (PCUs) (Linsley-Noakes, *et al.,* 1995). This model has been found to give a more accurate estimation of winter chilling in areas with mild to very cold winters (Allan, 1999).

2.3.4 Dynamic Model (Erez Model)

The Dynamic Model (Fishman *et al*., 1987; Erez *et al.,* 1990) was originally developed for warm winter areas in Israel. The model was based on the hypothesis that the level of dormancy completion depends on the level of a certain dormancy breaking factor (Erez *et al.,* 1990; Allan, 2004). The Dynamic Model is currently the only model that explains experimental evidence from controlled temperature studies in Israel (Erez *et al.,* 1990). The main findings from these trials were that moderate temperatures enhanced previous chilling, and that only recently accumulated chilling was subject to negation (Erez *et al.,* 1990). Warm temperatures can destroy this intermediate product. As soon as a certain quantity of intermediate product has accumulated, it is irreversibly transformed into a chill portion, which can no longer be destroyed (Figure 2.2). The Dynamic Model postulates that winter chill accumulates in a two-step process. Initially, cold temperatures lead to the formation of an intermediate product. Once a certain quantity of this intermediate product has accumulated, it can be transformed into a so-called chill portion by a process requiring relatively warm temperatures. The equations used to calculate chill portions are more complex than the other models (Erez *et al.,* 1990).

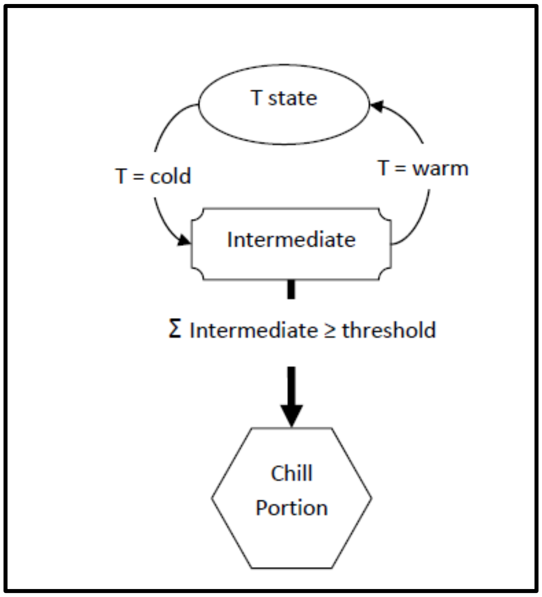

Figure 2.2 **Key aspects of the Dynamic Model, for hourly temperatures, T (°C). Depending on the initial temperature (T state) the creation of an intermediate product is prompted (Darbyshire *et al.,* 2011).**

The Dynamic Model only considers the impact of high temperatures in influencing the production of an intermediate product, which is linked to time (Zhang & Taylor, 2011). Once a sufficient amount of the transitional product is formed a chill portion is irreversibly created, and cannot be reversed by high temperatures later in the season.

2.3.5 Comparison between chill models

The Chilling Hours Model is old and many studies have found it to perform poorly in predicting bud break (Ruiz *et al.,* 2007; Perez *et al.,* 2008; Zhang & Taylor, 2011). However, this model has been used in California to investigate future chilling conditions (Baldocchi & Wong, 2008).

In a study by Luedeling and Brown (2010) it was indicated that winter chill models are not comparable, and that conversion factors between different winter chill metrics vary substantially around the globe. They further stated that data on chilling requirements should thus always be supplemented with information on the study duration, study area conditions under which the requirements were determined and more especially the models used and the references regarding the chill unit requirements for the fruit type as per specific areas.

Luedeling and Brown (2010) studied the comparability of chill models globally which indicated the differences between models on a large global scale, across various climates with substantial temporal resolution. They used the Chill Hours, Utah and Dynamic Models in their analysis on crops. It was found that the chill models are not proportional and conversion factors could not be established. Darbyshire *et al.* (2011) support the global assessment done by Luedeling and Brown (2010) under Australian conditions. They measured historical trends in chill accumulation using the Utah, Dynamic and Chill Hours Models. The magnitude and direction between the chill models vary with interpretation of recent trends and there is contradiction between chill models in some locations.

Darbyshire *et al.* (2011) analysed four chill models in Australian perennial fruit locations ranging from low chill to high chill sites for the period 1911–2009 to determine how they can be ranked. The Dynamic and Utah Models were found to perform well but the Chill Hours Model performed poorly in comparison. They concluded the use of the Chill Hours Model for sweet cherry in these locations was no longer appropriate.

In South Africa the DPCU was developed using nectarine cultivars. Linsley-Noakes *et al*. (1995) suggested that if the total accumulated chill units are negative over a 24-hour period then the total accumulated will be counted as zero, but if it is positive it is added to the seasonal total. This is the model that is currently used to compare chilling accumulation between seasons in deciduous fruit production areas in South Africa. Linsley-Noakes *et al.* (1995) also developed tables of approximate PCUs based on the daily minimum and maximum temperatures recorded in a Stevenson screen. These approximate PCUs can serve as a useful guide although the results tend to be lower than those obtained by hourly calculation (Allan & Burnett, 1995).

Viti *et al.* (2010) did a comparison between Utah and Dynamic Models in determining the chilling requirement for apricot cultivars in Spain. Their results showed that the Dynamic Model was less sensitive to changes in temperature and was more accurate than the Utah Model. Perez *et al*. (2008) studied the application of four chill models in different climatic regions in Chile. The analysis over two seasons concluded that the Chilling Hours Model was ineffective at distinguishing subtropical and temperate climates. The model was unable to account for inadequate chill units in Thompson Seedless grapes at the subtropical site. The Utah Model was found to better distinguish between the regions, with the Dynamic Model being good in explaining the local differences.

Ruiz *et al.* (2007) verified the suitability of the Chill Hours, Utah and Dynamic Models in predicting flowering in ten apricot cultivars over a period of three years at Murcia in Spain and Tuscany in Italy. The Chill Hours Model was found to be unreliable and inconsistent, with the difference in recorded chill requirement between seasons as great as 30%. It was then discovered that the Utah and Dynamic Models reported similar chill requirements with strong correlations between them. They concluded that either the Utah or Dynamic Model could be used reliably.

Zhang and Taylor (2011) conducted a five year study to estimate chill requirements of Sirora pistachio in Australia. They used the Chill Hours Model, Utah and Dynamic Models to estimate chill requirements by forcing cuttings in growth compartments. Through their experiments, they found it difficult to determine a chill threshold using either the Chilling Hours Model or the Utah Model due to large variability in calculated chill thresholds between the seasons. Zhang and Taylor (2011) also found that the Dynamic Model was shown to be more reliable and a threshold chilling requirement of 59 portions was established for Sirora pistachio. The study indicated that the Dynamic Model reliably performs similarly or better than the other tested chill models in Australia. The model includes many observed effects on chill including ideal chilling temperatures and the negation effects of high temperatures as well as the positive influence of moderate temperatures on chill accumulation. The model is non-stationary in nature which would be expected to better reflect biological processes.

The DPCU similarly contains optimum chilling temperatures and the negative influence of high temperatures. Nevertheless, when using this model, chill that is accumulated early in the season can be reversed by late season high temperatures. The DPCU was derived from the Utah Model which does not include the negation aspects of high temperatures. It has been found to perform better than the Utah model in mild winter locations in South Africa and within the deciduous fruit production sites (Linsley-Noakes *et al.,* 1994) and described walnut phenology well in California.

2.4 CHILLING REQUIREMENT

The amount of cold needed by a plant to resume normal spring growth following the winter dormancy period is commonly referred to as its chilling requirement (Ghariani & Stebbins, 1994). The prevention of bud break through a time-measuring mechanism (chill requirement) is a key ecological factor in temperate perennial plant survival (Atkinson *et al.,* 2004). Plants must be exposed to low temperatures to satisfy the chilling requirement for growth to resume (Erez, 1995). When the chilling requirement is fulfilled and if the environment is favourable plants will resume growth (Ballard *et al.,* 1987).

Chill requirements are genetically determined, but differences in also exist between buds, with flower buds having a lower chilling requirement than vegetative buds (Sheard, 2001). Some authors reported that chilling and post dormant heat requirement in stone fruit and pears are correlated (Darbyshire *et al.,* 2011). Cultivars with a high chilling requirement also have a high heat requirement in spring which may be advantageous in avoiding frost damage (Darbyshire *et al.,* 2011).

Chilling requirements differ between different fruit types as indicated in Table 2.2, but it also vary significantly between cultivars originating in different parts of the world. Climate conditions of a specific planned commercial production site is therefore of utmost importance when selecting temperate tree cultivars (Luedeling & Brown, 2010).

Table 2.2 Chilling requirements (accumulated positive chill units) of selected fruit crops (ARC-Intruitec, 1997)

Fruit type	Cultivar	Production area	Chilling requirement	PCUs
Apples	Braeburn	Bethlehem, Ceres	High	800 – 1 000+
	Pink Lady	Bethlehem, Ceres	Medium	450 – 800
	Fuji	Bethlehem, Ceres	High	800 – 1 000+
	Golden Delicious	Bethlehem, Ceres	High	800 – 1 000+
	Granny Smith	Bethlehem, Ceres	Medium to low	<800
	Royal Gala	Bethlehem, Ceres	High	800 – 1 000+
	Star King	Bethlehem, Ceres	High	800 – 1 000+
Pears	Packman’s Triumph	Ceres	Medium to low	450 – 800
	Bon Chretien	Ceres	High	800 – 1 000+
	Forelle	Ceres	Low	450 – 600
	Rosemarie	Ceres	Medium to low	<800
	Ceres	Ceres	Medium	450 – 800
Peaches	Transvalia	Bethlehem	Low	450 – 600
	San Pedro	Ceres	Low	450 – 600
	Bonnigold	Ceres	Low	450 – 600
	Talana	Bethlehem	Medium	450 – 800
	Bokkeveld	Ceres	Low	450 – 600
Sweet Cherries	Bing	Bethlehem	High	1 000+
	Stella	Bethlehem	High	1 000+
Table grapes	Sultana	Upington	Medium	450 – 800
	Merbein seedless	Ceres, Upington	Medium	450 – 800

If winter chill decline due to climate change, production limitations are likely to increase and large numbers of trees might not fulfil their chilling requirements (Baldocchi & Wong, 2008). In such cases, crop failures will occur, while early senescence in trees will further reduce yield potential, leaving many production operations uneconomical (Saure, 1985; Gradziel *et al.,* 2007). Annual exposure to sufficient winter chilling temperatures is necessary for deciduous fruit trees to successfully break the dormant phase and start growing in spring.

2.5 SYMPTOMS OF INSUFFICIENT WINTER CHILL

Production of most fruit trees is marginal today, with trees barely meeting their chilling requirements in certain areas. It is not clear whether it is caused by climate or management practices in the orchards (Baldocchi & Wong, 2008). Determining change the likely impact of reduced winter chilling cannot be easily understood without knowledge and reference to the processes which influence flower bud development prior to chilling and those which occur during release from winter dormancy (Cook & Jacobs, 2000).

According to Carbone and Schwartz (1993), insufficient chilling occurs when temperatures during the dormant season are anomalously high. Insufficient winter chill can severely reduce fruit yield and quality and trees show delayed and irregular bud break, leading to inconsistent crop development (Luedeling *et al.*, 2009). It can also lead to adverse effects for production including sporadic and light bud break, poor fruit development, small fruit size and uneven ripening (Saure, 1985; Oukabli *et al*., 2003; Petri & Leite, 2004). This progression ultimately results in varying fruit sizes and stages of maturity at the time of harvest, which can reduce yield and value (Saure, 1985).

Pollination can be reduced by insufficient chilling resulting in reduced yields for cultivars that rely on cross pollination (Gradziel *et al.,* 2007). Insufficient chill can also lead to pollination and fertilisation problems (Brown *et al.,* 1989). Flower abnormalities associated with chilling in cherries include low pollen production and the malformation of pistils and ovaries which result in small and deformed blossoms (Brown *et al.,* 1989; Mahmood *et al.,* 2000; Oukabli & Mahhou 2007). Oukabli and Mahhou (2007) showed that vascular connections to the bud only become fully functional just before bud break. With insufficient chilling, vascular connections are not established and the flower abscises.

Failure to achieve sufficient chilling was an issue when stone fruit crops such as peaches and apricots were initially grown in semi-temperate locations, such as California, and more recently during the shift and expansion of deciduous fruit cultivation into sub-tropical, tropical and Mediterranean regions (Cook & Jacobs, 2000).

In response to this lack of chilling, advances have been made with the breeding of low-chill cultivars and the development of chemical rest breaking agents and other orchard management practices to induce bud break (Sedgley, 1990). Similarly, defoliation prior to endodormancy of apple grown in the tropics will induce a second crop (Janick, 1974). The chilling requirements of buds are often not fully satisfied and may lead to poor bud break, delayed bud break, extended flowering and flower abscission (Erez, 1987, Alburquerque, *et al.,* 2008). The main and most visible signs of insufficient chilling are:

1) Delayed bud break;
2) Reduced fruit set; and
3) Reduced fruit quality.

2.5.1 Delayed bud break

Trees which receive insufficient chilling during the winter will flower and sprout irregularly in spring, adversely affecting tree vigour and is often refer to delayed foliation or prolonged dormancy (Luedeling *et al.,* 2009). This is regarded as a classic symptom of insufficient chilling and in South Africa is a common problem in apple cultivars with high chill requirements such as Braeburn, Fuji, Golden Delicious, Royal Gala and Starking (Huysamer, 1997). In Ceres delayed bud break is also a common problem in pear cultivars such as Bon Chretien with high chill requirement. In pear cultivars autumn warming dramatically delayed flowering time especially for early cultivars. This indicates that there may be two phenomena occurring namely, a delay in foliation and increase in flowering irregularly. Crop potential may be influenced by extension of flowering. Vegetative buds are more sensitive than other buds when dormancy is abnormally prolonged (Black, 1952; cited by Saure, 1985).

Symptoms of prolonged dormancy for sweet cherries are delayed, protracted and very weak leaf development resulting in bare shoots that become increasingly shorter due to shorter internodes and also more swollen with each growth flush. Other symptoms of prolonged dormancy in sweet cherries are early senescence of flowers, lack of spur formation and early senescence of flowers (Saure, 1985; Darbyshire *et al.,* 2011). Prolonged dormancy in peaches can be characterised by irregular bud break, delayed flowering leading to a prolonged blossoming phase (Weinberger, 1954). In a study done by Citadin (1999) it was indicated that the long exposure to chilling might have caused an advance in the beginning of bloom. Exposures to chilling temperatures might have triggered bud break as it was discovered that the flower buds had lower chilling requirements as compared to leaf buds. It was also recognized that heat influences bud break in flower buds, and winter chill reduces the heat requirement for bud growth (Citadin, 1999).

During dormancy, chilling temperatures are associated with changes in carbohydrate contents and substances such as nucleic acids, proteins, polyamines, amino acids, organic acids and in the respiration rate that may be related with bud break and the time of bloom (Wang & Faust, 1987). Inadequate chilling, associated with warm winters, may results in abnormal patterns of bud break and development in temperate fruit trees (Mauget & Rageau, 1988).

The growth rate of deciduous fruit tree growing in temperate climates decreases during dormancy. However, in subtropical areas, warm temperatures causes continuous consumption of carbohydrates which are needed for bud break in the spring season and which cause physiologic imbalances (Citadin, 1999).

2.5.2 Reduced fruit set

Fruit set and growth is a stepwise process that requires pollination, fertilization and subsequent seed development (Byrne & Bacon, 1992). Hormonal stimulus from the developing embryo prevents the fruit from dropping and causes the ovary to enlarge. The initial enlargement and development of the fertilized ovary is called fruit set. In response to inadequate chilling of peach trees, flowering can be delayed due to abnormalities in pistil and pollen development and fruit set is reduced (Byrne & Beacon, 1992). In many peach/nectarine cultivars flowers drop before shuck split (Luedeling *et al.,* 2009). But in other tree cultivars buttons form from flowers that apparently have set but never develop and ripen into a normal fruit. The fruit remains small and misshapen as they ripen, because the seed within the fruit is already dead (Luedeling *et al.,* 2009). Because buttoning is not visible early in the season, it is difficult to thin the abnormal fruit and the developing buttons serve as a food source and over winter site for insects and diseases (Luedeling *et al.,* 2009).

A study done by Mahmood *et al.* (2000) on *Prunus avium* has shown that when plants were chilled at 4ºC for 360 hours, the number of fruit that set were lower compared to those chilled for up to 1 440 hours. When chilling is inadequate peaches will still form flowers that are smaller than normal without style and stigmas. These developing flowers may fail to set fruit, but if fruit set occur, fruit will be of poor quality due to short pedicels (Mahmood *et al*., 2000). Another study conducted on the sweet cherry cultivar Stella showed that the extension of the chilling period to more than 50 days at 4°C resulted in an increase in the number of flowers per tree. The ability of the flowers to set fruit, however, did not increase. Thus even though the chilling period was extended it did not have any additional benefits to the number of flowers or fruit set. Tehranifar *et al.* (1998) also found that the numbers of flowers per plant were not influenced by chilling temperature while fruit set appears to be influenced. The interaction between vegetative vigour and fruit production suggests that fruit set is modified.

The thinning of fruit during the commercial production reduces number of fruit which set to ensure fruits of a large size and quality with a long storage life (Mahmood *et al.,* 2000). If *Prunus avium* is exposed to increasing levels of winter chill it will result in an increased number of flowers per tree and an enhancement in the remaining flowers' ability to set fruit (Mahmood *et al.,* 2000).

2.5.3 Reduced fruit quality

Reduced fruit quality due to insufficient amount of chill is cultivar dependent (Byrne & Bacon, 1992). Effects of inadequate chilling on fruit quality are probably the least researched but are very common and perhaps most important (Byrne & Bacon, 1992; Luedeling *et al.,* 2011). The effect of inadequate chill on leaf growth and fruit set are dramatic, but the effects of insufficient chill on fruit quality are delicate (Byrne & Bacon, 1992; Luedeling *et al.,* 2009; Luedeling *et al.,* 2011).

Insufficient chilling can cause many peach cultivars to have an enlarged tip and reduced firmness. Furthermore, fruit ground colour may be greener than usual, possibly due to the fruit losing firmness (Softer) before the ground colour can fully change from green to yellow. The extent of these quality problems depends on the cultivar and the degree of chilling deficiency (Byrne & Bacon, 1992).

In regions where inadequate chill occur smaller size apples are produced. Grebeye & Berg (2000) suggested that the reason for this may be due to pre-anthesis differences in fruit cell number. Royal Gala apples produced in the Western Cape where smaller compared to fruit in other parts of South Africa. The number of cells within the reproductive buds can be related to winter chill.

2.6 DECIDUOUS FRUIT TYPES OF THE STUDY AREAS

Most deciduous and temperate fruit trees originate from cold-winter climates (Luedeling *et al.,* 2011). Different species are selected to be planted on a particular location based on their places of origin. Species which are grown in high altitudes and cold climates are likely to require high chill. Deciduous fruits trees grown in lower altitudes with warmer winter temperatures require lower winter chill (Campbell, 2007).

Campbell (2007) stated that in the last 30 years many warm climate countries wanted to grow apples, including sub-tropical countries. In these countries, new plantings were established in the mountainous areas for more winter chill. Cultivars selected for these warmer areas of the world, such as Florida, West Australia, South Africa, Israel, Indonesia and Brazil were based on their winter chilling requirements. Early flowering cultivars needs fairly low chill, whereas late flowering cultivars requires high chill (Campbell, 2007). In South Africa deciduous fruits produced in the selected study areas differ in terms of the fruit type, cultivar and rootstock depending on the environmental conditions of the area (Huysamer, 1997).

2.6.1 Apples

Apples (*Malus communis*) belong to family Rosaceae (Campbell, 2007). Trees originated from central Asia, where its wild ancestor, *Malus sieversii*, is still found today (Janick *et al.,* 1996; Campbell, 2007). Apples have been grown for thousands of years in Asia and Europe and have been present in the tradition and religions of various cultures (Campbell, 2007).

The average summer temperature for growth should be between 21 and 24°C (Ballard *et al.,* 1987). Apples grow and produce better fruits in regions where the trees experience uninterrupted rest in winter and abundant sunshine in spring for good colour development (Janick, 1974). Apples can be grown at an altitude of 200 – 2 700 m above sea level. Well-distributed rainfall of 1 000 – 1 250 mm throughout the growing season is most favourable for optimum growth and yields (Janick *et al.*, 1996; Chuine & Cour, 1999).

Ceres is regarded as the largest production area of apples in South Africa more especially for the high chill requiring cultivars such as Braeburn, Golden Delicious, Royal Gala and Starking (Huysamer[1] & North[2], 2015, Personal communication). The eastern Free State areas of Harrismith, Bethlehem, Reitz, Clarens and Fouriesburg also form a commercial apple production area where large-scale apple farming only started in 1996 (Phillips, 2013*)*. The cultivars planted in the Bethlehem area are Royal Gala (19 ha), Top Red (3 ha), Fuji (12 ha), Cripps' Pink/Pink Lady (21 ha) and Cripps' Red/Sundowner (7 ha) (Phillips, 2013). In South Africa, apple cultivars are mostly planted using the M793 rootstocks, as well as MM106, M29, M7 and M9 (the most dwarfing root stocks) depending on environmental factors such as soil type and climate (Huysamer, 1997). The chilling requirements for some of these cultivars are indicated in Table 2.2.

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2.6.2 Grapes

Grapes (*Vitus spp.*) are fruiting berries of the deciduous woody vines and belong to the family Vitaceae (This *et al.,* 2006). Table and wine grapes are planted in Upington and Ceres (This *et al.,* 2006).

Grapes generally require a hot, dry climate during its growth and fruiting periods. It is successfully grown in areas where temperature ranges between 15 and 40°C (This *et al.,* 2006). Temperatures below 15°C during winter are essential for dormancy (Nir & Lavee, 1993). The development and growth of buds are influenced by fulfilment of winter chill for cultivars which are specifically used for wine and raisins (Ozrovech[1], 2015, Personal communication). Areas with an annual rainfall not exceeding 900 mm are ideal for grape production (Walker *et al.,* 2007).

The production of raisins in South Africa is currently mostly dependent on two grape cultivars, namely Sultana and Merbein Seedless (Avenant, 1990; SATI, 2014). The chilling requirements for these cultivars are indicated in Table 2.2. The rootstocks most commonly used for sultana are 134B or Ramsey in the Upington area (Ozrovech[1], 2015, Personal communication). The amount of area planted under grapes in South Africa is about 24 568 ha, with about 9 446 ha planted in Northern Cape along the Orange River (SATI, 2014).

2.6.3 Peaches

Peaches (*Prunus persica)* are native to China. It is a member of the Rosaceae family, which also includes cherries, plums, apricots, almonds and a number of wild species (Schwartz *et al.,* 1997). Peaches are adapted to areas with warm growing seasons and are considered to be moderately winter hardy (Schwartz *et al.,* 1997). Peaches are stone fruit and initiate next year's reproductive buds in the current summer (Allan *et al.,* 1994). Due to early flowering, frost is problematic in most areas. Peaches grow in a wide range of climates from tropical to sub-arctic (Dozier *et al.,* 1990; Carbone & Schwartz, 1993; Bonhomme *et al.,* 1999).

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The branches of peach trees can withstand cold of up to -32°C, but flowers suffer damage at -2°C (Balandier *et al.,* 1993). A warm, dry growing season is desirable for best yield and quality (Kamas *et al.,* 1998).

In terms of area planted to dessert peaches in South Africa, the leading production area is Ceres at 20% (306 ha) followed by Piketberg at 17% (251 ha) and Limpopo Province and Wolseley/Tulbagh at 12% (188 ha and 179 ha) each. Klein Karoo and the Free State follow at 11% each. A total of 1 588 ha was planted to dessert peaches (Hortgro, 2010). The most common peaches cultivars which are planted in Ceres are Bokkeveld, San Pedro and Bonnigold and the cultivars which are being produced in Bethlehem are Monate, Rolees and Talana (North[1], 2015, Personal communication).

Other cultivars planted in South Africa are Keisie which accounted for 22% (1 431 ha), Oom Sarel at 11% (736 ha), Sandvliet at 11% (723 ha) and Prof Neethling at 9% (589 ha) (Hortgro, 2010). Most peach cultivars have low chilling requirements. The chilling requirements for some of these cultivars are indicated in Table 2.2.

2.6.4 Pears

Pears (*Pyrus cummunis*) are also part of the family *Rosaceae* (Chuine & Cour, 1999). The probable origin of the *Pyrus genus* is mountainous China (Kamas *et al.,* 1998). Pears are adapted to a wide range of climatic conditions and can tolerate temperatures as low as -26°C (in dormancy) and as high as 45°C (in growing period) (Kamas *et al.,* 1998). Because of their tolerance to a wide temperature range, they are grown in both temperate and subtropical conditions (Chuine & Cour, 1999).

In South Africa more than 40% of the pears are grown in the Koue Bokkeveld area of Ceres and Wolseley in the Western Cape. The cultivars are William's Bon Chretien which has a yellow skin when ripe, with a fragrant, sweet and juicy taste, and Packham's Triumph which are often unevenly shaped, green-yellow when ripe with a soft textured flesh (SATI, 2014).

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BP_1 and BP_3 are the two rootstocks mainly used for pears in South Africa. In Ceres Packham's Triumph also performed well on quince rootstocks QC51 a more dwarfing rootstocks (Jacobs & Cook, 2003). Newer quince rootstock available for pears that are dwarfing is Quince BA29 and Quince C51 (Stargrow, 2014).

The chilling requirements for some of these cultivars are indicated in Table 2.2. The pear industry in South Africa is very much export driven, but only about 38% of the total crop is exported in a fresh form (Ferrandi *et al.,* 2005). This is partly due to the large volume of Bon Chrétien, of which a significant percentage is processed. Other reasons include a fairly high percentage cull for various reasons, including sunburn, size and lack of adequate colour in the blushed cultivars (Ferrandi *et al.,* 2005).

2.6.5 Sweet cherries

Cherries (*Prunus* spp.) belong to the Rosaceae family (California Cherry Board, 2013). The two commonly cultivated cherry species are sweet cherry (*Prunus avium* L.) and sour cherry (*Prunus cerasus* L.) (Webster, 1996; Day, 2003).

The first successful cherry trees were planted in South Africa in 1905 on the farm Platkop in the Clocolan district after Harry Pickston had contacted German missionaries in South Africa with questions about growing cherries (GWK, 2014). A year later 5 ha of cherries trees were brought to Clocolan to be planted on a farm near Clocolan (GWK, 2014). The cultivars included Giant Heidel finger, Bing, Early River, Early Red and Elton. Some of the original cherry trees can still be seen on the farm today. These cultivars are still grown in the area. It is estimated that there are 500 ha of cherry trees in the eastern Free State concentrated mainly in the Ficksburg, Clocolan and Fouriesburg area (GWK, 2014). The rootstock used for cherries are Gisela 6, Mahaleb and Mazzard.

Cherry trees grow well in areas with long, warm summer days and cool nights (Bethell, 1988; Crisosto *et al.,* 2003). In late winter, normal blossoming and bud break require temperatures above 9°C, because cherry is highly susceptible to frost damage (Bethell, 1988; Lang, 2001).

However, adequate chilling is required to break dormancy which is about 1 000+ PCUs (Table 2.2) (Glozer, 2010). Once winter chilling has been acquired, moderately warm spring temperatures without extreme heat, cold, or frost is necessary for flower development and good overlap of pollinizer cultivars to set a viable crop (Sheard, 2008; Ingels & Arceo, 2012).

CHAPTER 3

MATERIALS AND METHODS

3.1 STUDY AREAS

The climate and soil characteristics of South Africa result in suitable conditions for the production of a great variety of fruit, including tropical fruits (e.g. bananas, mangoes, and litchis), subtropical fruits (e.g. avocados, citrus and pineapples) and temperate fruits (e.g. apples, peaches and grapes). The deciduous fruit grown in South Africa falls under the temperate fruit category (Hortgro, 2013) and include small fruit crops (e.g. grapes), pomes (e.g. apples and pears), stone fruit (cherries and peaches) and nuts (e.g. pecans and macadamias).

This study focused on deciduous fruits with a growth period from spring to late summer and a dormant period in winter. There are about 79 000 ha of deciduous trees and vines planted in South Africa with some 2.5 million metric tons produced in 2013 (Hortgro, 2013). During the same time period, there were 2 450 deciduous fruit farmers employing 114 453 people directly in the industry (Hortgro, 2013). Export earnings from this industry represented about 12% of South Africa's total earnings from agricultural exports (SA Info, 2014).

Figure 3.1 shows the main fruit production areas in South Africa while Table 3.1 indicate the amount of hectares under cultivation in 2013. Deciduous fruit is grown mainly in the Western Cape and in the Langkloof Valley in the Eastern Cape (SA Info, 2014) with smaller production areas along the Orange River, in the Free State, Mpumalanga and Gauteng.

Three different deciduous fruit producing areas were selected for this study. The three study areas were selected on the basis that they fall within different climatic regions and not under the same Global Climate Model (GCM) grid box (Section 3.2.2.3). Therefore, the study areas selected were Bethlehem, Ceres and Upington (Figure 3.2).

Table 3.1 Total area planted under decidous fruit in South Africa (Hortgro, 2013)

Fruit	Area (ha)
Grapes (dry and table)	26 631
Apples	22 443
Pears	12 034
Peaches	7 441
Plums	4 883
Apricots	3 020
Nectarines	2 239
Prunes	276

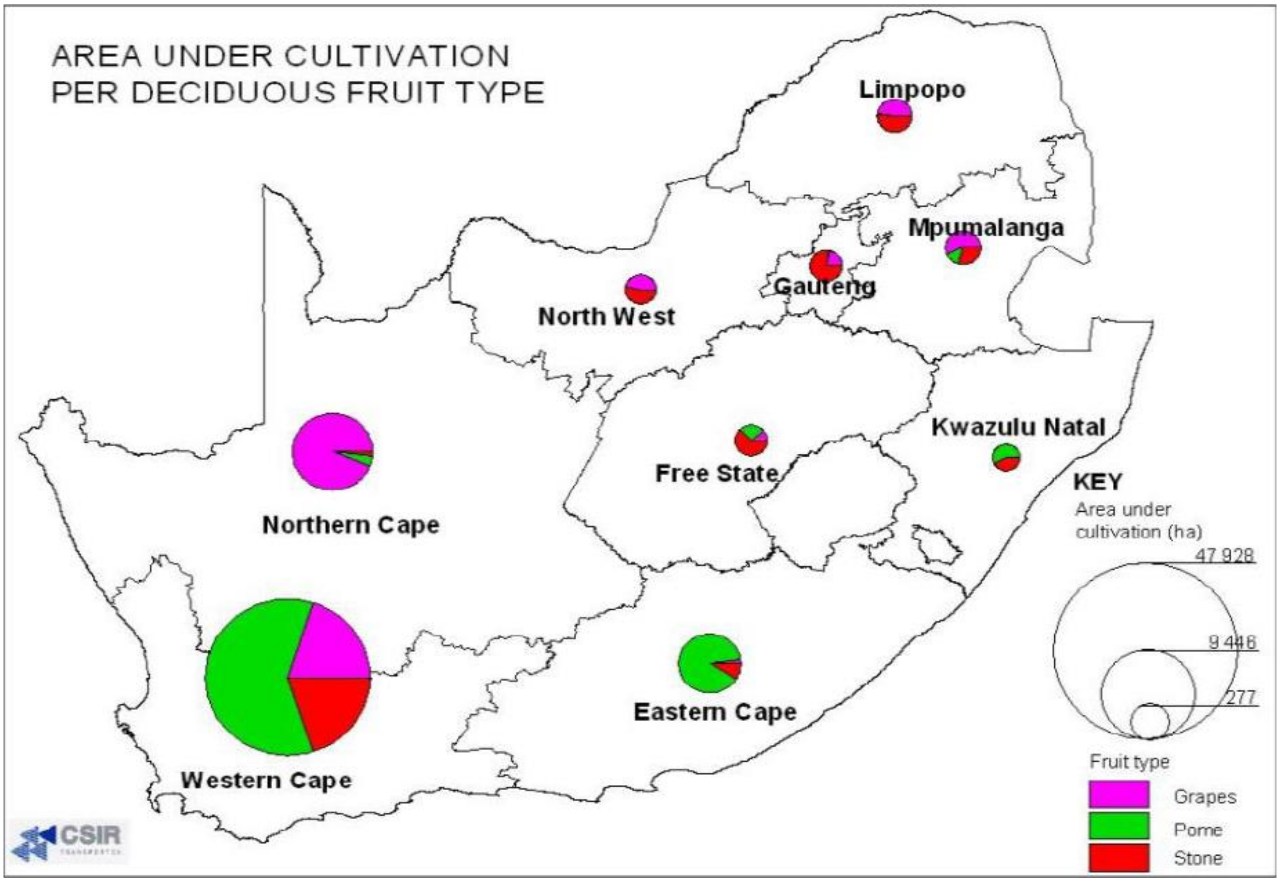

Figure 3.1 Area under cultivation per deciduous fruit type (Hortgro, 2013).

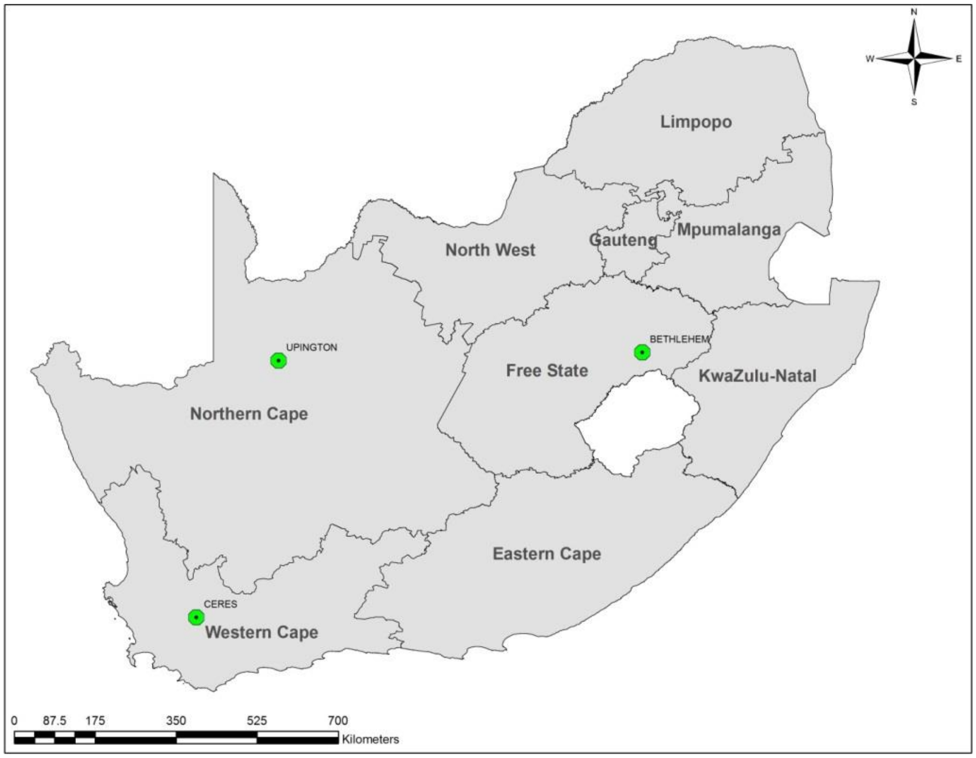

Figure 3.2 Map of South Africa indicating locations of the study areas.

3.1.1 Bethlehem

Bethlehem is in the north eastern part of the Free State Province (Figure 3.2). It is within the Thabo Mofutsanyane district municipality and is situated near the Maluti Mountains which form part of the Drakensberg mountain range. This area is known for the production of apples and cherries (Figure 3.1).

Bethlehem falls under the Moist Highveld Grassland climate region (Figure 3.3), characterised by summer rainfall which varies from about 900 mm on its eastern border to about 650 mm in the west. The rainfall is almost exclusively due to showers and thunderstorms and falls mainly in summer, from October to March, with the maximum fall occurring in January. The annual average number of thunderstorms varies between 75 and 100. These storms are often violent with severe lightning and strong (but short-lived) gusty south-westerly winds and are sometimes accompanied by hail (Schulze, 1994; Kruger, 2004).

This region has one of the highest hail frequencies in South Africa; about 4 to 7 occurrences per annum. Over the high lying areas snow is possible during the winter months. Snow occurs about 8 times annually towards the south with the frequency decreasing rapidly northwards (Schulze, 1994; Kruger, 2004). Average daily maximum temperature is roughly 27ºC in January and 16ºC in July but in extreme cases these may reach 38 and 26ºC, respectively. Average daily minima range from about 13ºC in January to -2ºC in July, whereas extremes can drop to 1ºC and -13ºC respectively. The period during which frost is likely to form lasts on average for about 120 days from May to September, though this period is longer towards the south (Schulze, 1994; Kruger, 2004). A summary of Bethlehem's climate data is provided in Table 3.2.

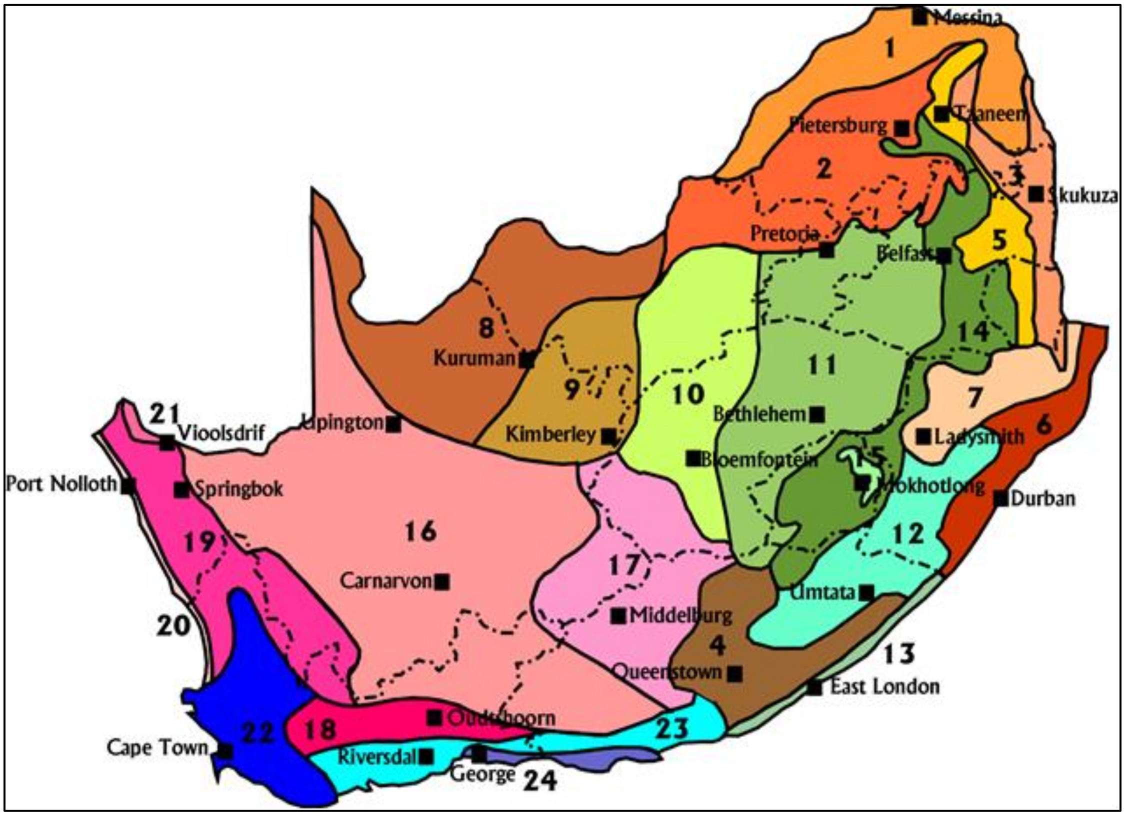

Figure 3.3 Climate regions of South Africa (Kruger, 2004).

1. Northern Arid Bushveld 2. Central Bushveld 3. Lowveld Bushveld 4. South-Eastern Thornveld 5. Lowveld Mountain Bushveld 6. Eastern Coastal Bushveld 7. KwaZulu-Natal Central Bushveld 8. Kalahari Bushveld 9. Kalahari Hardveld Bushveld 10. Dry Highveld Grassland 11. Moist Highveld Grassland 12. Eastern Grassland 13. South-Eastern Coast Grassland 14. Eastern Mountain Grassland 15. Alpine Heathland 16. Great and Upper Karoo 17. Eastern Karoo 18. Little Karoo 19. Western Karoo 20. West Coast 21. North-Western Desert 22. South-Western Cape 23. Southern Cape 24. Southern Cape Forest.

Table 3.2 Climate data over the period 1981 – 2010 for the three selected sites (after ARC-ISCW, 2013; SAWS, 2013)

Area	Latitude (S)	Longitude (E)	Altitude (m)	Mean Annual Rainfall (mm)	January Average T_{max} (°C)	July Average T_{max} (°C)	January Average T_{min} (°C)	July Average T_{min} (°C)
Bethlehem	28° 20′	28° 15′	1 680	680	27.2	16.4	13.2	-2.0
Ceres	19° 31′	33° 45′	250	720	30.7	17.9	16.6	6.1
Upington	21° 15′	28° 24′	840	94	35.5	20.8	19.8	4.1

3.1.2 Ceres

Ceres is in the south-western part of the Western Cape Province (Figure 3.2) and falls under the Cape Winelands district municipality. The town, named after the Roman goddess of fruitfulness, is the centre of one of the most important deciduous fruit producing areas in the Western Cape (Ceres Tourism, 2011).

Ceres consists of three diverse areas, each with its own unique landscape: the Warm Bokkeveld (a wide fertile valley and the centre of one of the richest agricultural regions of the Western Cape); Bo-Swaarmoed (to the east of Ceres, famous for its cherries); and the Koue Bokkeveld (a mountainous fruit and vegetable producing area to the north) (Ceres Tourism, 2011).

Ceres falls under the South-Western Cape climate region (Figure 3.3) characterised by winter rainfall from May to September, and having a warm to hot and dry summer. The rainfall is profoundly influenced by orographical features and it varies from 250 mm on the west coast to 1 400 mm at Jonkershoek (Schulze, 1994; Kruger, 2004). During the season of maximum rainfall one may normally expect 12 to 15 rain days per month whilst in the dry season this region experiences 4 to 5 rainy days per month. The mountains are occasionally snow-capped but the snow layer never persists throughout the winter. On average snow occurs on about 5 occasions per year, mainly in winter and early spring (Schulze, 1994).

The average daily maximum temperature is about 28ºC in midsummer and 17ºC in midwinter but extreme maxima can reach 30 and 43ºC, respectively (Schulze, 1994; Kruger, 2004). Average daily minimum temperature is about 15ºC in January and 6ºC in July, though extreme minima can fall to 4 and -5ºC respectively, depending on altitude. Prevailing winds in summer are from the south-east and in winter north-west which are frequently strong and may reach gale force. Sunshine duration varies from about 60% of the possible duration in July to over 70% in January (Schulze, 1994; Kruger, 2004). A summary of Ceres climate data is provided in Table 3.2.

3.1.3 Upington

Upington is in the Northern Cape Province (Figure 3.2). It falls under the Siyanda district municipality and is situated on the banks of the lower Orange River (Upington Tourism, 2013). A large portion of Upington’s economy is based on agriculture with table grapes (amongst others) being irrigated from the Orange River (Upington Tourism, 2013).

Upington falls within the Great and Upper Karoo climate region (Figure 3.3), characterised by dry conditions and extreme temperatures. Annual rainfall is less than 100 mm in the north-west and up to 300 mm in the east. Autumn rainfall, peaking in March, tends to be highly unpredictable and occurs in patches (Schulze, 1994; Kruger, 2004). On the interior plateau frost is common in winter.

Temperatures are subject to great seasonal and diurnal variation. The average daily maximum temperature in January is about 36ºC and in July 21ºC, whilst extremes can reach 46 and 32ºC, respectively. Average daily minima are about 20ºC in January and 4ºC in July with extremes reaching 5 and -10ºC, respectively. During summer winds from the south-west are more prevalent compared to winter when winds from the north tend to dominate (Schulze, 1994; Kruger, 2004). A summary of Upington’s climate data is provided in Table 3.2.

3.2 DATA TYPE AND COLLECTION

3.2.1 Historical observed data

The historically observed climate data used in this study was recorded by automatic weather stations within the study areas. Daily (and where available hourly) observed temperature data for Bethlehem, Ceres and Upington were obtained from the South African Weather Service (SAWS) and the Agricultural Research Council (ARC). Hourly temperature data was archived since 1980 for Bethlehem and 1969 for Upington, while only daily values were available for Ceres since 1981. Seeing as the analysis of winter chill required hourly temperatures (Section 2.3), daily values had to be downscaled temporally (Section 3.2.3). These downscaled hourly temperatures were used to construct a complete uninterrupted dataset for each of the three study areas for the climatic base period spanning 1981 to 2010. This data was used in the subsequent climate impact analysis (Section 3.3).

3.2.2 Predicted future climate data

Global Climate Models (GCMs) are the fundamental tools used for assessing future climate change (Engelbrecht *et al.,* 2011). These are complex computer models based on the laws of physics, which represent interactions between the different components of the climate system such as the land surface, the atmosphere and the oceans (Engelbrecht *et al*., 2011). GCMs can reliably project changes in temperature, because the physical processes responsible for warming are well-captured by the models (IPCC, 2007).

Future levels of greenhouse gas emissions in the atmosphere are dependent on our behavioural patterns and political influence through policies, and as the world continue to depend on fossil fuels the GCMs may be used to simulate climate under a range of emission scenarios (IPCC, 2007; Davis, 2011). A more detailed discussion of these emission scenarios is provided in Section 3.2.2.1.

The spatial resolution of GCMs ranges from 200 – 300 km grids which are too low to accurately represent the circulation patterns and physical processes that determine climate drivers at regional and local scales. In order to generate more detailed simulations of regional and local climate, downscaling methodologies may be employed (Wilby & Wigley, 1997; Davis, 2011). Information on downscaling is provided in Section 3.2.2.2.

3.2.2.1 Emission scenarios

As mention in Section 2.1, greenhouse gas (GHG) emissions in the form of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are resulting in changes to the climatic patterns beyond natural background rates (Rosenzweig *et al.,* 2008). Future GHG emissions are highly uncertain and determined by driving forces such as demographic development, socio-economic development and technological change (Nakićenović *et al*., 2000). By the end of the century the world will have changed in ways that are difficult to predict deterministically. The Intergovernmental Panel on Climate Change (IPCC) hence developed long-term emission scenarios for use in climate change analysis, including climate modelling and the assessment of impacts, adaptation and mitigation. These scenarios are described in detail in the IPCC Special Report on Emission Scenarios (SRES) (Nakićenović *et al*., 2000). A brief description of these scenarios is included here as the description of the GCM output data, which follows in Section 3.2.2.2, refers to them.

According to Nakićenović *et al*. (2000) the scenarios are alternative descriptions of how the future might unfold and are a suitable tool with which to analyse how driving forces may affect future emission outcomes and to gauge the related uncertainties. The prospect that any single emission scenario will transpire as described is highly uncertain. Four divergent storylines were developed to describe the relationships between emission driving forces and their evolution. These storylines add background for the scenario quantification (Nakićenović *et al*., 2000).

Each storyline embodies varying demographic, social, economic, technological, and environmental developments. All the scenarios based on the same storyline make up a "scenario family" (Nakićenović *et al*., 2000). The scenarios do not include further climate initiatives i.e. no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emission targets set by the Kyoto Protocol. Table 3.3 summarises the main characteristics of the four SRES storylines and scenario families as described by Nakićenović *et al*. (2000), while Figure 3.4 illustrates the range of GHG emissions under the different SRES scenarios.

Table 3.3 **Main characteristics of the four SRES storylines and scenario families (Nakićenović *et al*., 2000)**

SRES Scenario	A1	A2	B1	B2
Economy	rapid growth, substantial reduction in regional differences in per capita income	development is primarily regionally oriented, per capita economic growth are more fragmented and slower	rapid changes in economic structures toward a service and information economy, with reductions in material intensity	intermediate levels of development
Global Population	peaks in mid-century and declines thereafter	continuously increasing	peaks in mid-century and declines thereafter	continuously increasing (slower than A2)
Technology	rapid introduction of new and more efficient technologies	technological changes are more fragmented and slower than in other storylines	introduction of clean and resource-efficient technologies	more diverse technological change than in the A1 and B1
Socio-Political Aspects	increased cultural and social interactions, capacity building	self-reliance and preservation of local identities	improved equity, global solutions to economic, social, and environmental sustainability	local solutions to economic, social, and environmental sustainability
Underlying Theme	convergence among regions	heterogeneous world	convergent world	focuses on local and regional levels

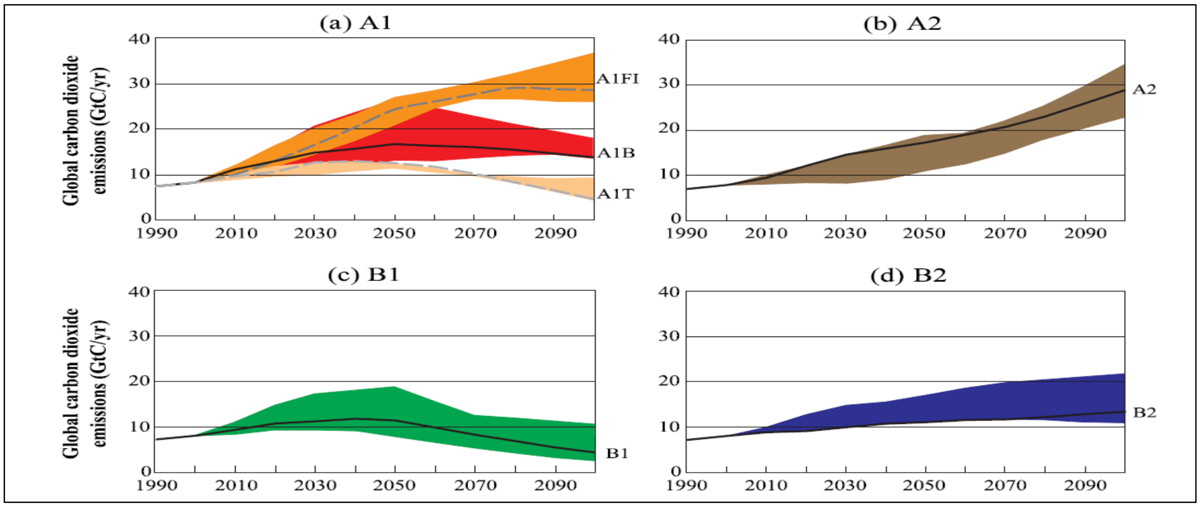

Figure 3.4 **Total global annual CO_2 emissions from 1990 to 2100 (in gigatonnes of carbon (GtC/yr)) under the various SRES scenarios (capital letters refer to the four scenarios described in Table 3.3 while each coloured emission band shows the range of projections within each group (Nakićenović *et al*., 2000).**

3.2.2.2 Downscaling of global climate model output

Downscaling activities are normally either spatial or temporal in nature. This spatial or temporal nature usually stems directly from the application of the downscaling procedure (Steyn, 2008). Certain studies require the use of either high resolution gridded data or the use of site-specific data, while other studies may require the use of hourly data, neither of which is catered for by large-scale GCMs.

Spatial downscaling is the term used to describe the process through which the projections from GCMs are translated to the regional and local scales (Wilby *et al.,* 2000), whereas temporal downscaling is the derivation of the finer-scale temporal data from coarser-scale information, e.g. hourly data from daily or monthly information (Steyn, 2008). Such downscaled projections at finer spatial scales are more useful in studies on the assessment of local and regional climate change impacts, adaptation and policy development (Wilby *et al.,* 2000).

Furthermore, downscaling techniques can either be classified as statistical or dynamical. Statistical downscaling first derives statistical relationships between observed small-scale variables and larger scale variables, using analogue methods, regression analysis, or neural network methods (Wilby & Wigley, 1997). Dynamical downscaling involves the nesting of a higher resolution Global Climate Model (GCM) within a coarser resolution GCM (Wilks & Wilby, 1999) or the use of stretched-grid climate models with higher resolution over a portion of the globe (Engelbrecht *et al.,* 2009).

The use of dynamical downscaling allows the demonstration of changes in the local climate, such as changes to seasonality, frequency and intensity of weather events and the relationships between different climate variables (Corney *et al.,* 2010). The use of dynamical downscaling does not only account for the dynamical relationship between local features and synoptic patterns in the present climate, but also allows these relationships to evolve into the future (McGregor, 2005). This method has been used for obtaining some of the most detailed projections of South Africa's future climate (Engelbrecht *et al.,* 2011).

3.2.2.3 Future climate projections used in this study

Projections of future climate change used in this study was obtained using conformal-cubic atmospheric model (CCAM) described by McGregor and Dix (2001; 2008) and McGregor (2005). CCAM was developed by the Commonwealth Scientific and Industrial Research Council (CSIRO) in Australia, while for South Africa the modified version is maintained and run by the Climate Studies, Modeling and Environmental Health Research Group of the Council for Scientific and Industrial Research (CSIR). Other climate projection studies using CCAM over southern Africa, including verification of the model's ability to simulate present-day climate, are described by Engelbrecht *et al.* (2009; 2011).

CCAM is a global climate model, formulated using a conformal-cubic grid which covers the globe but can be stretched to provide higher resolution over areas of interest (McGregor & Dix, 2001; Corney *et al.,* 2010). This gives more flexibility to downscaling experiments, allowing forcing of CCAM by sea surface temperatures (SSTs) and from GCMs (Katzfey *et al.,* 2009). CCAM includes a fairly complete set of physical parameterizations. The Geophysical Fluid Dynamics Laboratory (GFDL) parameterization for long-wave and short-wave radiation is used (Schwarzkopf & Fels, 1991; Corney *et al.,* 2010), with interactive cloud distributions determined by the liquid and ice-water scheme of Rotstayn (1997). The model employs a stability-dependent boundary layer scheme based on the Monin-Obukhov similarity theory (McGregor *et al*., 1993). The canopy scheme described by Kowalczyk *et al*. (1994) is used, with six layers for soil temperatures, six layers for soil moisture and three layers for snow. The cumulus convection scheme uses mass-flux closure, as described by McGregor (2003), and includes both downdrafts and detrainment.

A set of six ensemble members has been obtained by the CSIR. In these simulations, CCAM was applied as a variable-resolution GCM to simulate both present-day and future climate over southern Africa and surrounding oceans at a high spatial resolution of about 0.5° in latitude and longitude (Katzfey *et al*., 2009; Davis, 2011). Boundary forcing data were provided by six different coupled GCMs that contributed to Assessment Report 4 (AR4) of the IPCC, namely CSIRO Mk3.5, UKMO HADCM3, GFDL-CM2.1, GFDL-CM2.0, MIROC3.2 and ECHAM5/MPI-OM to provide ensemble members EN1 to EN6 as depicted in Figure 3.5. Boundary forcing data included the 1961 – 2100 simulated (but bias-corrected) sea-surface temperatures (SSTs) and sea-ice fields as well as topography, vegetation, surface albedo and surface roughness fields. All six ensemble members were obtained for the A2 emission scenario (Figure 3.5).

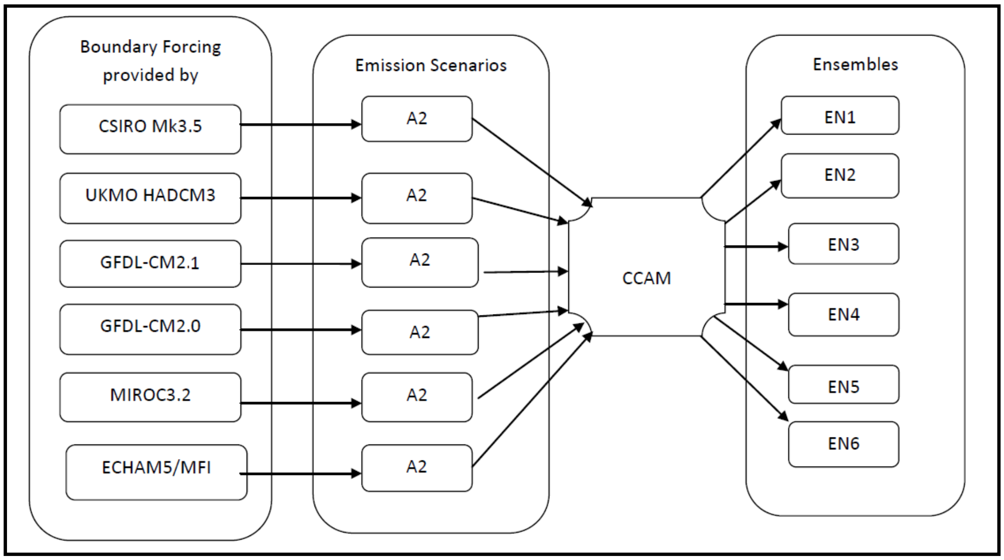

Figure 3.5 **Development of the six CCAM ensemble members.**

Output from three of the six ensembles were used in this study, namely EN1 (boundary forcing data provided by CSIRO Mk3.5), EN2 (boundary forcing data provided by UKMO HADCM3), and EN3 (boundary forcing data provided by GFDL-CM2.1) (Figure 3.5). The output comprised of gridded minimum and maximum temperatures at daily intervals for the period 1961 to 2100. Only the temperature data associated with the grid boxes encompassing the study areas were extracted. Since the analysis of winter chill required hourly temperatures (Section 2.4), it had to be temporally downscaled as discussed in the following section.

3.2.3 Temporal downscaling model and verification thereof

In Section 2.4 it was already mentioned that the calculation of winter chill according to the Utah Chill Units Model required hourly temperatures. Since a portion of the observed historical data and all ensembles of predicted future data only consisted of daily values, hourly temperatures had to be derived. This was facilitated by a Temporal Downscaling Model (TDM) which mainly employed idealized mathematical curves.

The process of deriving hourly values from daily minimum and maximum temperatures are by no means trivial as evident by the various studies on this topic (Richardson, *et al.,* 1974; Linvill, 1982; McCann, 1985; Eckersten, 1986; McFarland *et al.*, 1987; Linvill, 1990). Daytime heating and night time cooling is influenced by various factors such as day length, moisture content of the air, cloud cover, wind, occurrence of precipitation, introduction of new air masses, position relative to low and high pressure centres, soil heat flux and evaporative cooling at the surface.

In most of the TDMs developed, an underlying assumption is that minimum and maximum temperatures occur at regular intervals: the minimum temperature during the morning and the maximum temperature during the afternoon hours. These assumptions may not always be valid. For example, when a cold front moves through a region during the morning hours the maximum temperature may not occur during the afternoon. Likewise, the minimum temperature may have occurred later in the day. When it comes to historically observed data the time of observation may also play a role, especially when temperatures do not reach the preceding day’s temperature at observation time.

Thus, the recorded 24 hour minimum (maximum) temperature would have occurred at observation time on the preceding day. Although nothing can be done about the time of minimum and maximum temperature occurrence under natural conditions, using a 12 hour minimum (maximum) temperature will eliminate the time of observation problem. The method proposed by Linvill (1990) was used in this study for representing the daily temperature wave (hourly temperature calculation). If the time of maximum daily temperature was two hours after solar noon and the shape of the temperature curve responds to the daytime solar cycle, the temperature wave from sunrise to sunset can be described by (Linvill, 1990):

$$T(t) = (T_{max} - T_{\min}) \times \sin\left[\frac{\pi t}{DL+4}\right] + T_{min} \qquad \textbf{[Eq. 3.1]}$$

where: $T(t)$ is the temperature (in °C) at time t after sunrise;

T_{max} is the maximum temperature (in °C);

T_{min} is the minimum temperature (in °C); and

DL is the day length (in hours).

The temperature at sunrise was set equal to the observed minimum temperature for the day. A second expression was used to define night-time cooling starting after sunset. Minimum daily temperatures were thus reached near time of sunrise (Linvill, 1990):

$$T(t) = T_s - \frac{T_S - T_{\min}}{\ln(24 - DL)} \times \ln(t) \qquad \textbf{[Eq. 3.2]}$$

where: $T(t)$ is the temperature at time $t > 1$ hour after sunset;

T_S is the sunset temperature (in °C); and

T_{min} is the minimum temperature on the following morning (in °C).

The day length (DL) was calculated from the following algorithm developed by Stuff and Dale (1973; cited by Linvill, 1990):

$$CD = INTEGER(30.6 \times MOY + DOM - 91.3) \qquad \textbf{[Eq. 3.3a]}$$

$$DL = 12.25 + 3.34 \times tan\emptyset \times \cos(0.0172 \times CD - 1.95) \qquad \textbf{[Eq. 3.3b]}$$

where: CD is the climatological day number (numbered from 1 March);

MOY is the month of the year;

DOM is the day of the month; and

$\emptyset$ is the latitude (in º) with $\emptyset < 0$ in the southern hemisphere.

A computational problem arose with respect to the first hour after sunrise which was never clarified in Linvill (1989; 1990). As stated correctly the night-time cooling curve (Eq. 3.2) calculates the temperature *T(t)* at time $t > 1$ after sunset, implying it cannot be used when $t = 1$ hour after sunset as this setting yields the same value as for the sunset hour. Simply applying the daytime curve (Eq. 3.1) for another hour after sunset was not an option either as this was not its intended purpose or resulted in irregular cooling (viz. a perturbation in the cooling portion of the curve). The best option seemed to be to substitute $t = 1.5$ for the first hour after sunrise.

TDMs have limitations in real-world systems and they hardly imitate the exact real world system. Therefore any model should be verified to the degree needed for the model's intended purpose (Sargent, 2010). Chow and Geoff (2007) found that it is important to measure the significance of various conventional downscaling procedures and to determine whether they are acceptable for use in verification. Verification of TDM-derived hourly temperatures was done for only two study areas, namely Bethlehem and Upington, as their observed temperatures contained both hourly and daily minimum and maximum temperatures.

The choice of verification statistics were based on the literature and previous studies done on verification of models (Schlesinger, 1979; Reicosky *et al.,* 1989; Linvill, 1990; Cesaraccio *et al.,* 2004; Chow & Geoff, 2007; Sargent, 2010; Banks *et al.,* 2010). The statistics such as RMSE and MAE have been used as a standard statistical metric to measure the model performance in meteorology, air quality and climate research studies (Chai & Draxler, 2014). In addition to the standard "goodness of fit" measures (MAE; RMSE; R^2; ME) graphs such as scatter plots, histograms and CDFs were also used to judge model error subjectively.

3.2.3.1 Mean absolute error (MAE)

The MAE is defined as the sum of the absolute value of the difference between the predicted and observed temperature within the verification period (Hamilton, 1994). The MAE is a linear score meaning that all individual differences are weighted equally (Tsay, 2005). It measures the accuracy for continuous variables and is given by:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|x_i - y_i| = \frac{1}{n}\sum_{i=1}^{n}|e_i| \qquad \textbf{[Eq. 3.4]}$$

where: *n* is the number of observations;
y is the predicted temperature; and
x is the observed temperature at any time.

The MAE can range from 0 to ∞. The lower the value of MAE the better is the accuracy of the model. The MAE is appropriate in describing the uniformly distributed errors (Chai & Draxler, 2014).

3.2.3.2 Root mean square error (RMSE)

The RMSE is a quadratic scoring rule which measures the average magnitude of the error (Hamilton, 1994). Each value (hourly or daily temperature) generated by the model, *y,* is compared to the corresponding value from the real observed dataset, *x*. For *n* entries, the RMSE is given by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}} \qquad \textbf{[Eq. 3.5]}$$

where: *n* is the number of observations;
x is the observed temperatures; and
y is the predicted temperatures.

The RMSE is used to diagnose the variation in the errors of the predicted values. The RMSE ranges from 0 to ∞. Small RMSE values are desirable. The underlying assumption of the RMSE is that the errors are unbiased and follow a normal distribution (Chai & Draxler, 2014).

3.2.3.3 Coefficient of determination (R^2)

The R^2 conveys information on whether it is possible to predict the future outcomes of a variable on the basis of the given information (Draper & Smith, 1998). It provides a measure of how well future outcomes are likely to be predicted by the regression function. It can be defined as the variation of the dependent variable that can be explained by the regression line and the corresponding independent variable(s). The R^2 is given by:

$$R^2 = \left[\frac{1}{n}\frac{\sum(x-\overline{x})\,(y-\overline{y})}{\sigma_x\sigma_y}\right]^2 \qquad \textbf{[Eq. 3.6]}$$

where: n is the number of observations;
$\overline{x}$ is the mean of the observed values;
$\overline{y}$ is the mean of the predicted values;
σ_x is the standard deviation of the x values; and
σ_y is the standard deviation of the y values.

The R^2 provides information about the goodness of fit of a model and it measures how well the regression line approximates the observed data (Everitt, 2002). R^2 is bounded by $0 \le R^2 \le 1$ and can thus never be negative. An R^2 of 1 indicates that the regression line perfectly fits the data whereas an R^2 value of 0 is indicative of a useless model.

3.2.3.4 Model efficiency (ME)

The ME is commonly used to assess the predictive power of prediction models (Nash & Sutcliffe, 1970). However, it can also be used to quantitatively describe the accuracy of model outputs (such as discharge nutrient loadings, temperatures and concentrations) (Nash & Sutcliffe, 1970). In addition, ME measures how well a model, reproduces measured data (Nash & Sutcliffe, 1970). It is given by:

$$ME = 1 - \frac{\sum_{i=1}^{n}(x_i-y_i)^2}{\sum_{i=1}^{n}(x_i-\overline{x})^2} \qquad \textbf{[Eq. 3.7]}$$

where: n is the number of observations;
x is the observed values;

y is the predicted values; and

$\overline{x}$ is the mean of observed values.

ME can range from $-\infty$ to 1. If ME = 1, the model produces an exact prediction for each data point. A zero value of ME implies that a single measured mean is good as an overall predictor as the model. A negative value of ME indicates that the measured mean is a better predictor than the model. Essentially, the closer the model efficiency is to 1, the more accurate the model.

3.2.4 CCAM verification

The developers and users of GCMs, the decision makers using information obtained from the output of these models, and the individuals affected by decisions based on such output are all rightly concerned with whether a model and its results are correct (Sargent, 2010). This concern is addressed through verification of the model.

Since the model simulations were initialised once, on 1 January 1961, they were not expected to correspond to observed temperature fields after a few days. Any sensible verification therefore required the removal of the dependency on time from any verification scores. The use of point-data further implied that only aspects such as the mean and standard deviation of the CCAM simulations could be compared against observed values. Such a comparison was subsequently performed for the daily predicted minimum and maximum temperatures from EN1, EN2 and EN3 against the observed values from Bethlehem, Ceres and Upington for the full 30-year base period spanning 1981 to 2010. The analysis was conducted for the winter months (May, June, July, August) only.

3.3 PROCESS DESCRIPTION

This section aims to provide a stepwise description of the methodological process followed in this study. It can be seen as a rationale for the layout of Chapter 4 which focuses on the results and discussions.

The first step was to collect climate data for all the study areas as discussed in Section 3.2 and to verfiy the predicted values from the GCM as explained in Section 3.2.4. The historically observed temperature data for Bethlehem and Upington was obtained in the form of hourly and dialy intervals whereas the temperature data for Ceres was only obtained in daily intervals. As mentioned in Section 3.2.2.3, CCAM ensemble data for three ensembles (EN1, EN2 and EN3) provided daily minimum and maximum temperatures for the grid points falling over Bethlehem, Ceres and Upington. Figure 3.6 provides a graphical summary of this stage.

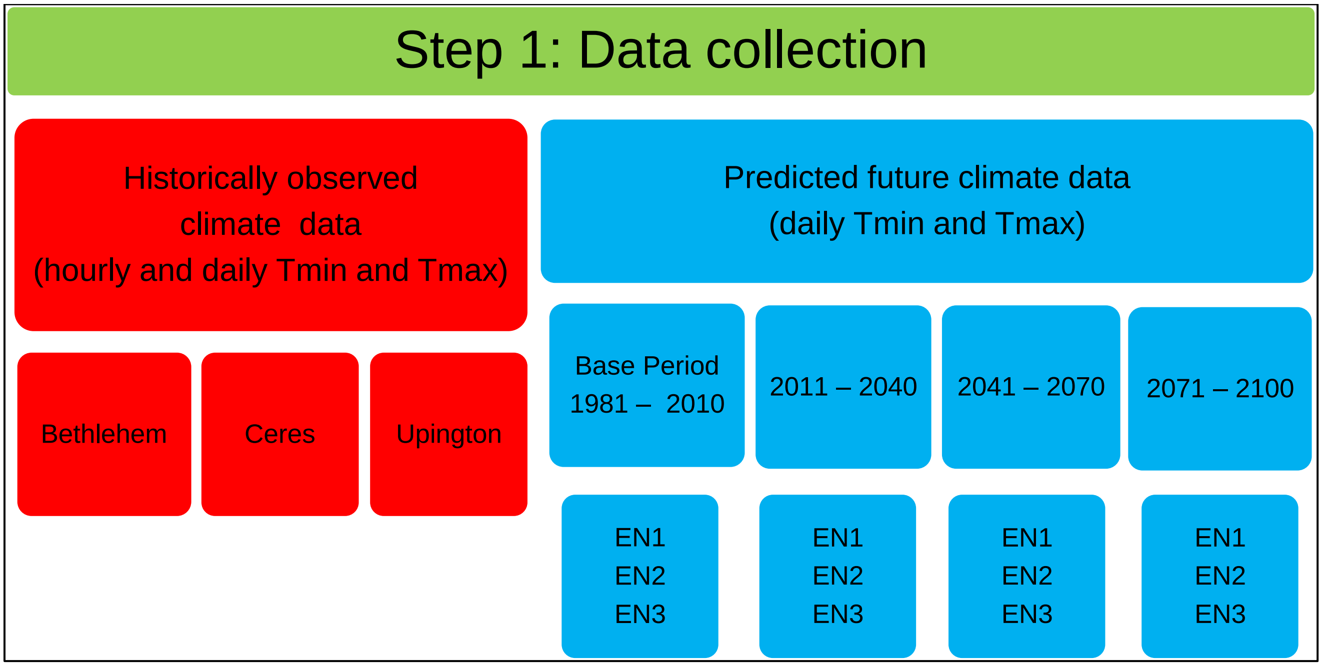

Figure 3.6 **Summary of data collection process.**

The second step was to verify the GCM. The verification was done to determine the accuracy of all three ensembles (EN1, EN2 and EN3) in reproducing the daily minimum and maximum temperature data for the base period 1981 – 2010 for all three study areas. The statistics outlined in Section 3.2.4 were applied in this verification process. This process is summarized graphically in Figure 3.7.

The third step was to develop and analyse the accuracy of the Temporal Downscaling Model (TDM) (Section 3.2.3). As mentioned in Section 3.2.1 and 3.2.2 the historical observed temperature data for Ceres contained only daily values, whereas the CCAM ensemble data also provided only daily minimum and maximum temperatures for the grid boxes falling over Bethlehem, Ceres and Upington.

A TDM was consequently used to obtain a full record of hourly temperatures for the period 1981 – 2100 (Figure 3.8). The statistical analysis to determine the TDM accuracy (Section 3.2.4) was performed only for two areas (Bethlehem and Upington) as they had both daily and hourly temperature records for the period 1981 – 2010. The verification was based on all winter days within this base period for which observed data was available (Section 3.2.3). Gaps in the data for Upington were encountered for the months of August 1989 and June 1992, which were subsequently omitted from the verification process. The process is summarized graphically in Figure 3.8.

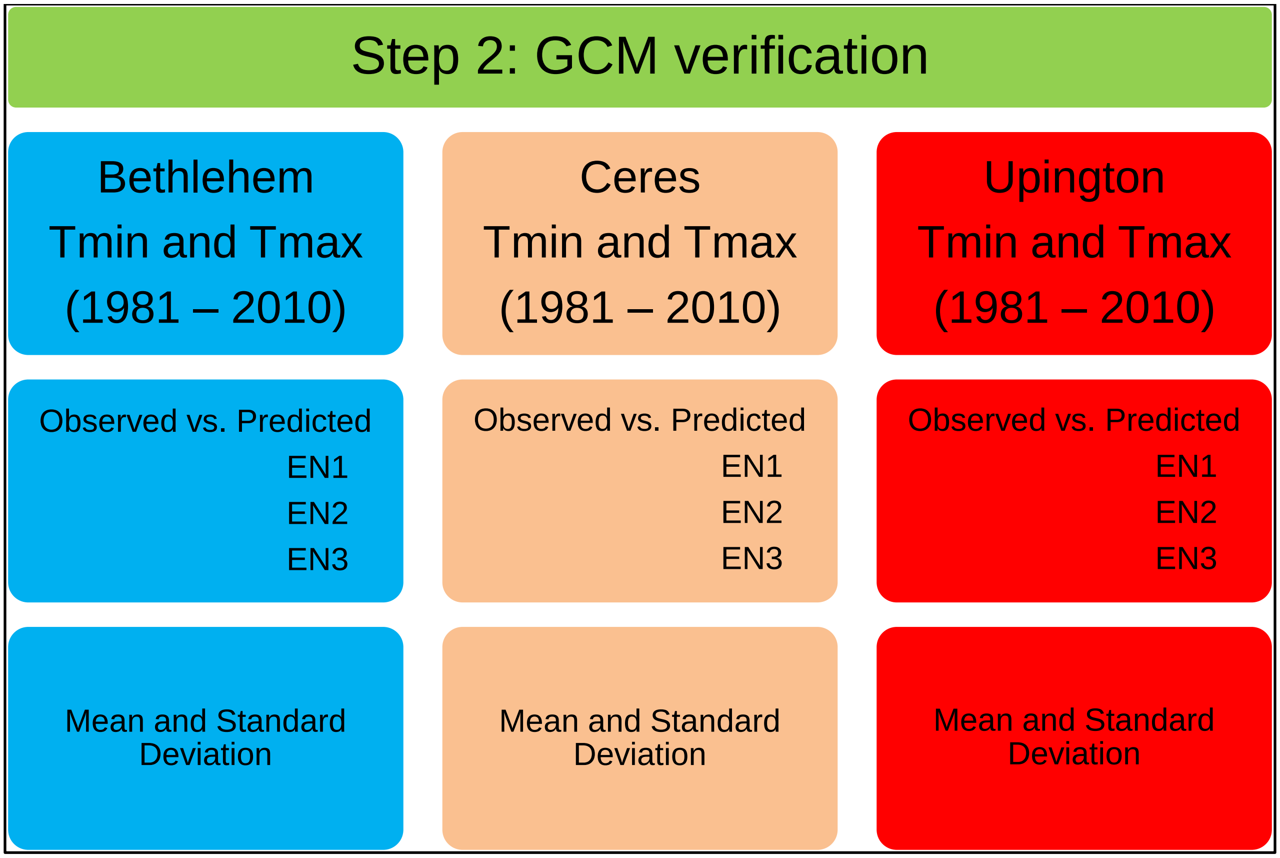

Figure 3.7 **Summary of GCM verification process.**

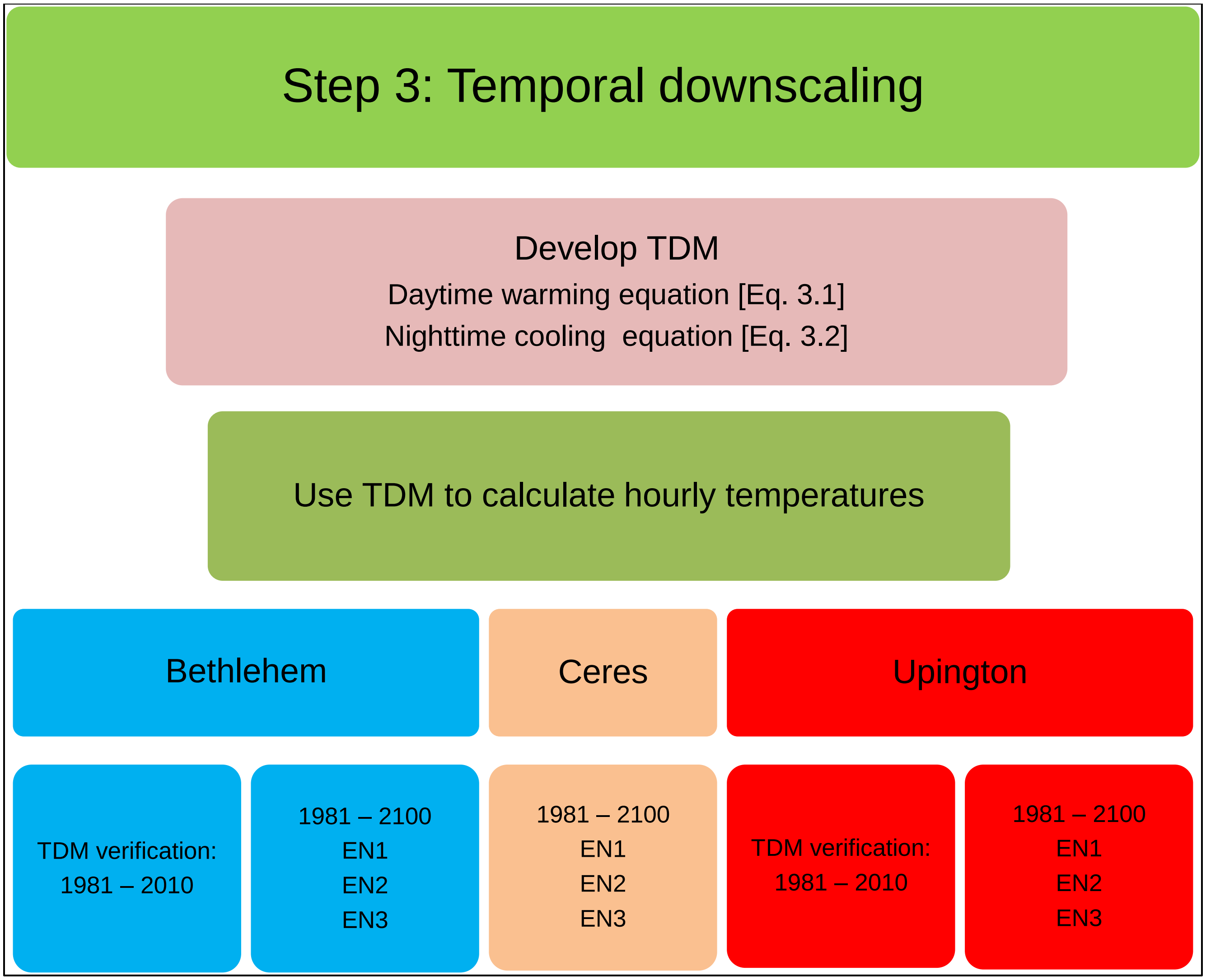

Figure 3.8 **Summary of temporal downscaling process.**

Once a complete set of hourly temperatures was obtained for each study area, the hourly chill units were calculated with the aid of the Utah Chill Units Model that the record chill in Richardson's units (Section 2.3.2), followed by calculation of the PCUs according to the DPCU which was discussed in Section 2.3.3. The PCUs were subsequently accumulated in order to determine the seasonal totals (Figure 3.9).

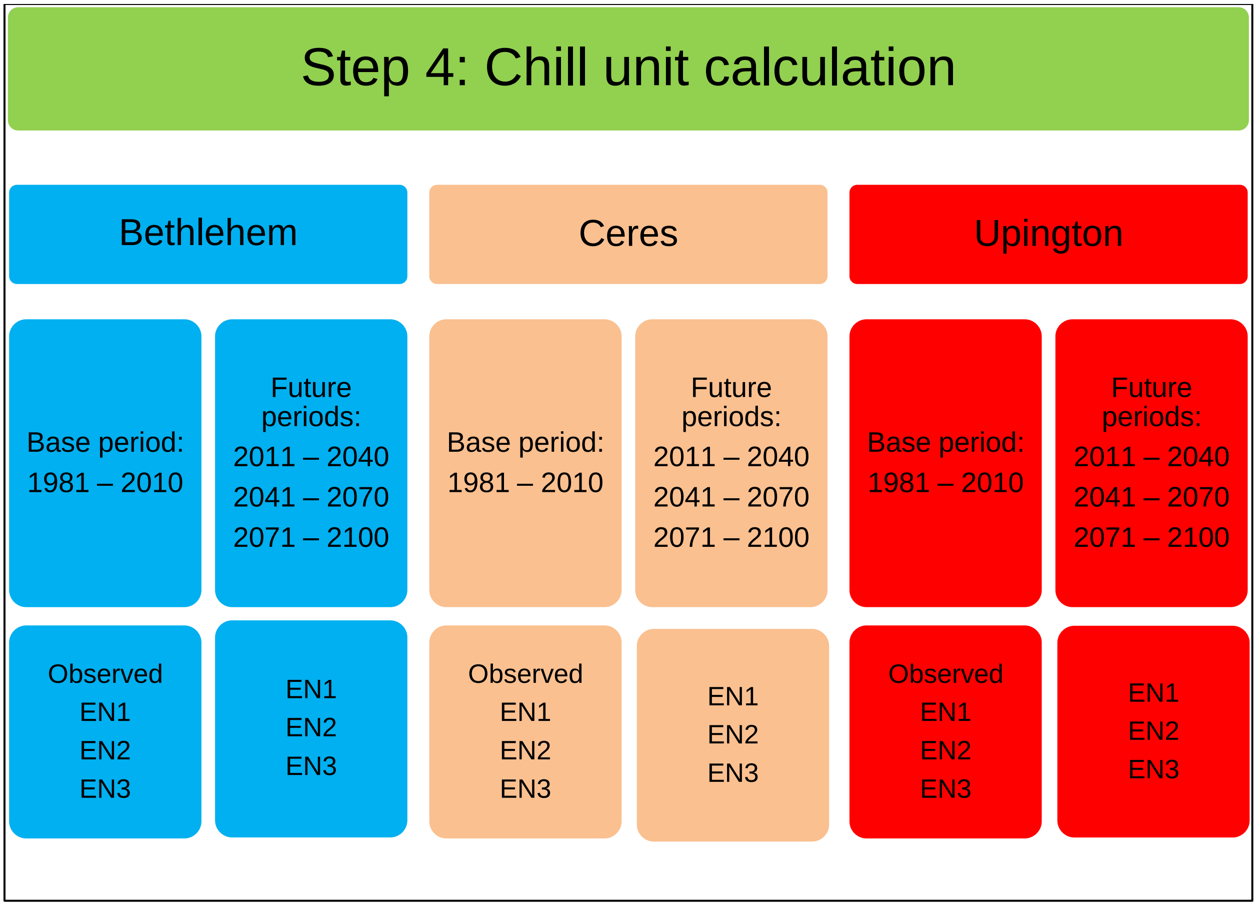

Figure 3.9 **Summary of chill unit calculation process.**

The historical and future calculated PCUs were subsequently analysed for (linear) trend over each future 30-year period (2011 – 2040, 2041 – 2070 and 2071 – 2100) and compared to the base period (1981 – 2010) for all three study areas. Cumulative Distribution Functions (CDFs) were used to determine the probability of accumulating certain threshold PCU values for all historical and futures periods. The linear trends were also calculated for each 30-year period and for each ensemble (Figure 3.10). If for example the climate change projection results should later indicate changes smaller than the GCM's standard error, the sensitivity to future climate forcing is said to be less than the model accuracy. In such cases the projected changes may result from model parameters rather than regional forcing. This process was repeated for each study area and the results were subsequently compared.

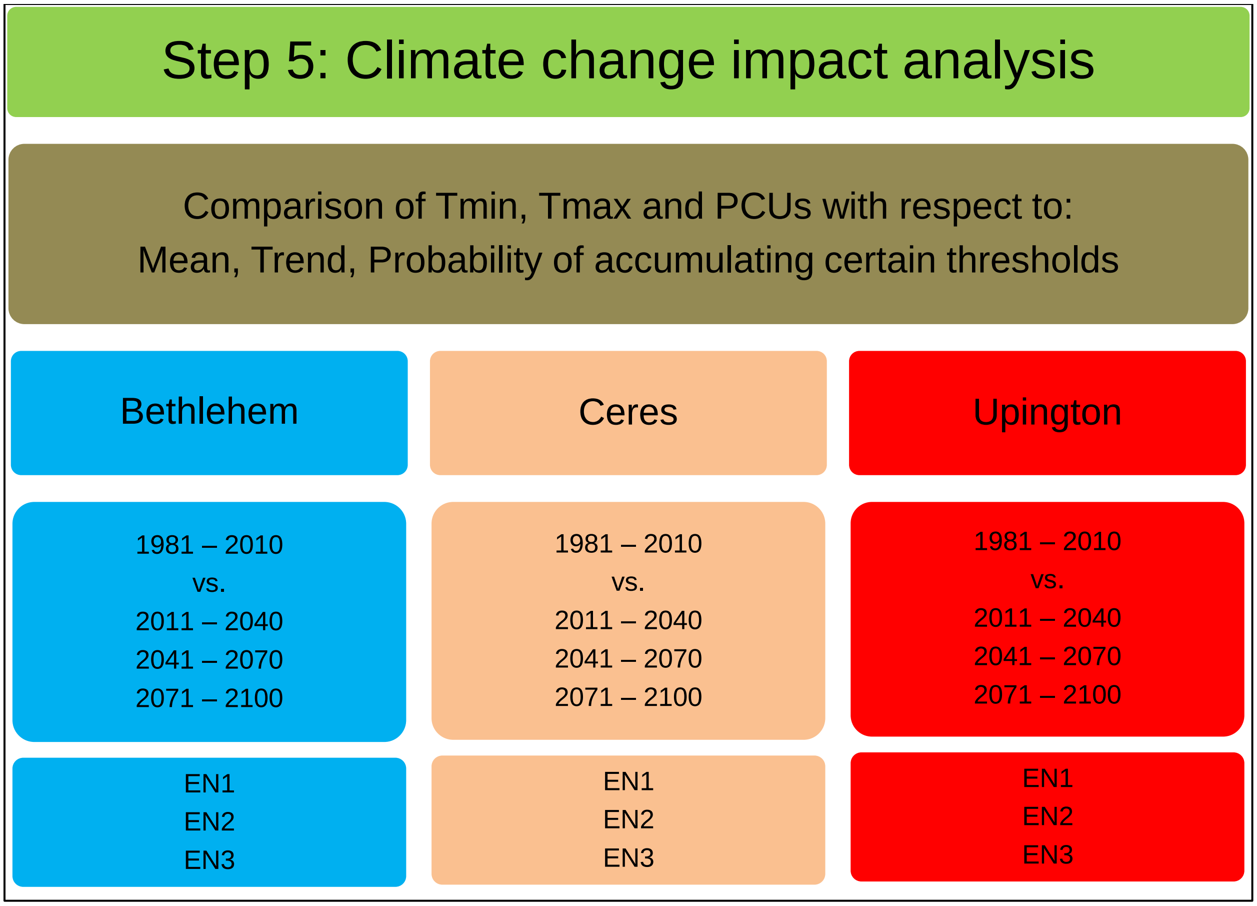

Figure 3.10 **Summary of the climate change impact analysis process.**

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

The results discussed in this chapter will follow the process description provided in Section 3.3. The first two sections will focus on the verification of daily minimum and maximum temperatures predicted by the GCM and hourly temperatures generated by the TDM over the base period (1981 – 2010). In the case of the GCM verification was performed for three ensemble members (EN1, EN2 and EN3) for all three study areas (Bethlehem, Ceres and Upington).

In the case of the TDM verification was performed for Bethlehem and Upington only for reasons noted in Section 3.2.3. After verifying these models, PCUs were calculated (Section 3.3) from historical observed temperature data over the base period for all three study areas. This process was repeated for each ensemble member for the entire period spanning 1981 – 2100.

The results of the climate change impact analysis focussed primarily on historically observed and predicted changes in minimum and maximum temperatures as well as PCUs. These were discussed for each study area in terms of changes in the mean, trend and probability of accumulating certain thresholds between each future 30-year period (2011 – 2040, 2041 – 2070 and 2071 – 2100) and the historical base period (1981 – 2010).

4.2 VERIFICATION OF CCAM

Verification is an important part of any modelling endeavour. As explained in Section 3.2.2.3 output from three of the CCAM ensembles were used in this study, namely EN1 (boundary forcing data provided by CSIRO Mk3.5), EN2 (boundary forcing data provided by UKMO HADCM3), and EN3 (boundary forcing data provided by GFDL-CM2.1). CCAM has been verified and used in numerous climate change impact studies over southern Africa (Olwoch *et al*., 2008; Coetzee *et al*., 2009; Engelbrecht *et al*., 2009; Zhu *et al.,* 2010; Engelbrecht *et al*., 2011; Lazenby *et al*., 2014). A point-scale verification of the ensemble datasets were performed against the observed daily minimum and maximum temperatures from Bethlehem, Ceres and Upington for the full 30-year base period spanning 1981 to 2010. It should be noted that the analyses were conducted for the winter months only.

It has long been recognised that forecasting skill decrease markedly with increasing lead time (van den Dool, 1994; Orrell, 2002; Lupo *et al*., 2012) due to the chaotic nature of the atmosphere. For this reason point-scale climate simulations are rather verified in terms of long-term mean and the standard deviation (Section 3.2.4).

Perhaps the most striking verification result was that the CCAM ensemble members exhibited a cold bias, while minimum temperature predictions performed significantly better than those for maximum temperatures across all three ensembles. In the case of the minimum temperatures for Bethlehem the mean compared well with only small differences of less than 1ºC between the observed and predicted values (Table 4.1). However, these same verification scores for the maximum temperature indicated that the CCAM predictions were on average 7ºC colder than the observed.

Table 4.1 Verification statistics for both minimum and maximum temperature predictions for Bethlehem from all three CCAM ensembles for the period 1981 – 2010

Bethlehem	**MEAN**		**Standard Deviation**	
	Tmn	**Tmx**	**Tmn**	**Tmx**
Observed	-0.30	17.75	3.59	3.46
EN1	-0.12	11.03	3.15	3.47
EN2	-1.06	10.82	2.98	3.38
EN3	-1.11	10.66	3.12	3.52

In the case of Ceres both minimum and maximum temperatures revealed a cold bias of approximately 4.5ºC (Table 4.2). This result compared well with Roux (2009) who indicated that CCAM grossly underestimated minimum temperatures over the Stellenbosch region (some 70 km to the southwest) by up to 6ºC in winter. Upington exhibited a similar cold bias of about 4ºC for minimum temperatures (Table 4.3), while the mean of the predicted maximum temperatures were approximately 6ºC lower than the observed mean over the verification period (1981 – 2010).

In all three study areas the differences in the standard deviation for both minimum and maximum temperatures were less than 1ºC, indicating that the general variability was conserved. Even if the model has large bias it does not necessarily affect the climate change signal, since the bias cancels out when the present day simulations are subtracted from the projections of the future climate change.

Table 4.2 Verification statistics for both minimum and maximum temperature predictions for Ceres from all three CCAM ensembles for the period 1981 – 2010

Ceres	MEAN		Standard Deviation	
	Tmn	Tmx	Tmn	Tmx
Observed	7.69	18.65	3.24	4.21
EN1	3.63	14.31	3.44	3.74
EN2	3.57	14.32	3.48	3.82
EN3	2.54	13.76	3.57	3.89

Table 4.3 Verification statistics for both minimum and maximum temperature predictions for Upington from all three CCAM ensembles for the period 1981 – 2010

Upington	MEAN		Standard Deviation	
	Tmn	Tmx	Tmn	Tmx
Observed	6.06	22.78	4.55	4.77
EN1	2.20	16.75	4.29	4.06
EN2	1.91	17.02	4.24	4.14
EN3	1.84	16.31	4.21	4.05

4.3 VERIFICATION OF THE TEMPORAL DOWNSCALING MODEL

In accordance with the discussions provided in Sections 3.2.3 and 3.3, the TDM was used to generate hourly temperatures from observed and/or predicted daily minimum and maximum values for the entire period spanning 1981 – 2100. This was done because the Utah Chill Unit Model required hourly temperature data. Verification of the simulated hourly temperatures was performed for Bethlehem and Upington for the climatic base period of 1981 – 2010. Ceres was excluded from this verification exercise as the historically observed data obtained from the ARC didn't contain hourly temperatures against which the simulated values could be verified.

The goodness of fit measures described in Section 3.2.3 was used to verify the TDM. In this case a very good fit was crucial as the TDM was developed specifically to operate at high resolution time scales. Table 4.4 contains a summary of the verification statistics for both Bethlehem and Upington. In general, the TDM performed exceptionally well over both areas with R^2 values above 0.94 (Figure 4.1). The temperature curves presented in Figure 4.2 for a randomly selected day within the verification period indicate the close correspondence between the observed and TDM derived hourly temperatures at both sites.

Table 4.4 **Verification statistics for hourly temperature predicted by the temporal downscaling model for both Bethlehem and Upington for the period 1981 – 2010**

	MAE	RMSE	R^2	ME
Bethlehem	1.18	1.61	0.95	0.94
Upington	1.22	1.63	0.94	0.95

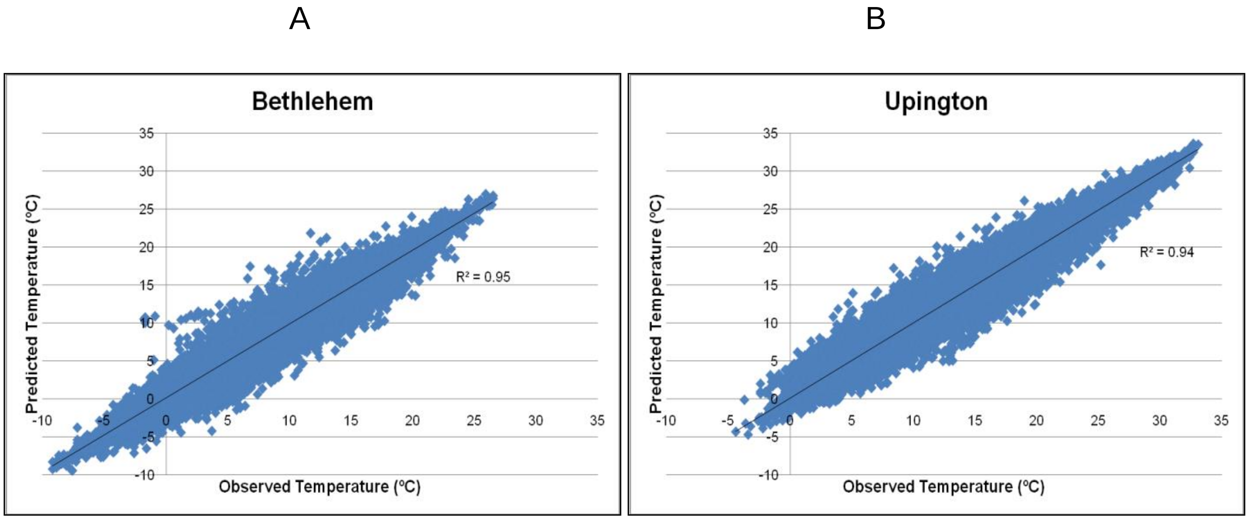

Figure 4.1 **Scatter plot of observed against predicted hourly temperatures for Bethlehem (A) and Upington (B) for the period 1981 – 2010.**

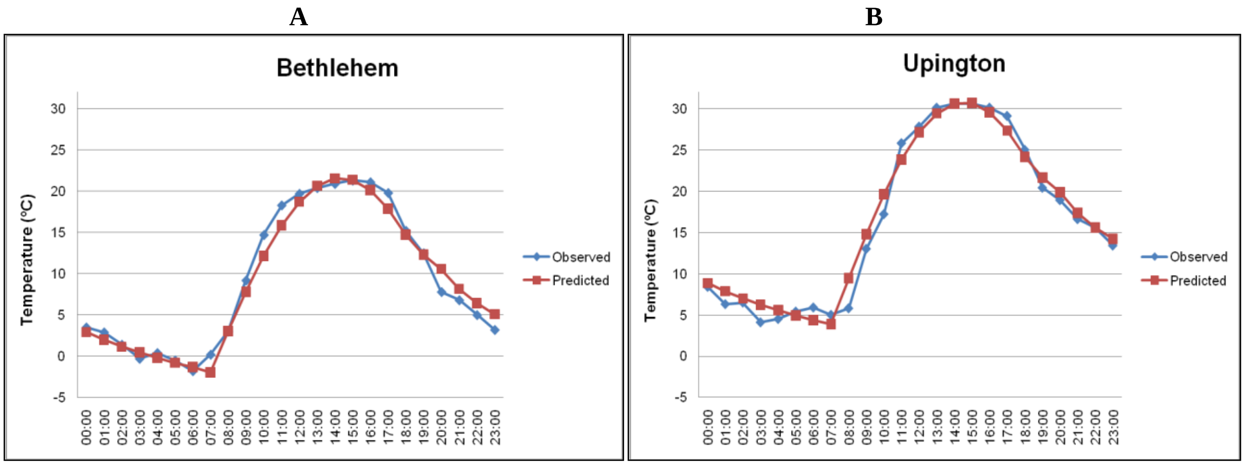

Figure 4.2 **Temperature curves for Bethlehem (A) and Upington (B) on 26 July 2006.**

An investigation into some of the outliers in Figure 4.1 revealed that these were likely produced by the TDM failing to simulate sudden temperature changes associated with frontal passages. An example of such a case is presented in Figure 4.3 where a cold front moved over Bethlehem during the afternoon of 27 August 1996.

It can be seen that the daytime curve faired reasonably well until the time of frontal passage (approximately 14:00 local time) where after the observed temperature dropped abruptly resulting in an increase in the forecast error until the night time cooling curve converged towards the next morning's minimum temperature. Figure 4.4 shows the position of the cold front on the day in question.

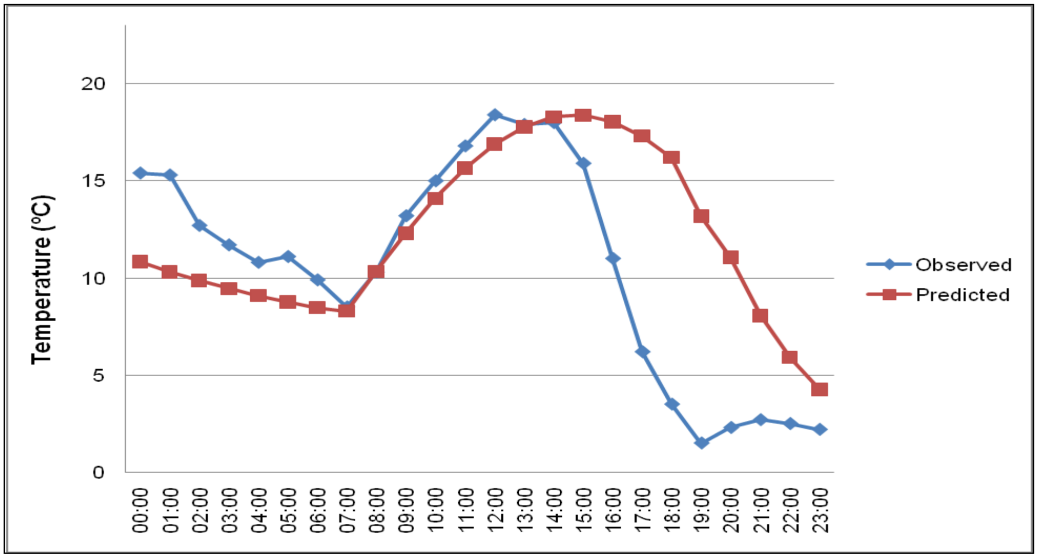

Figure 4.3 **Temperature curve for Bethlehem on 27 August 1996.**

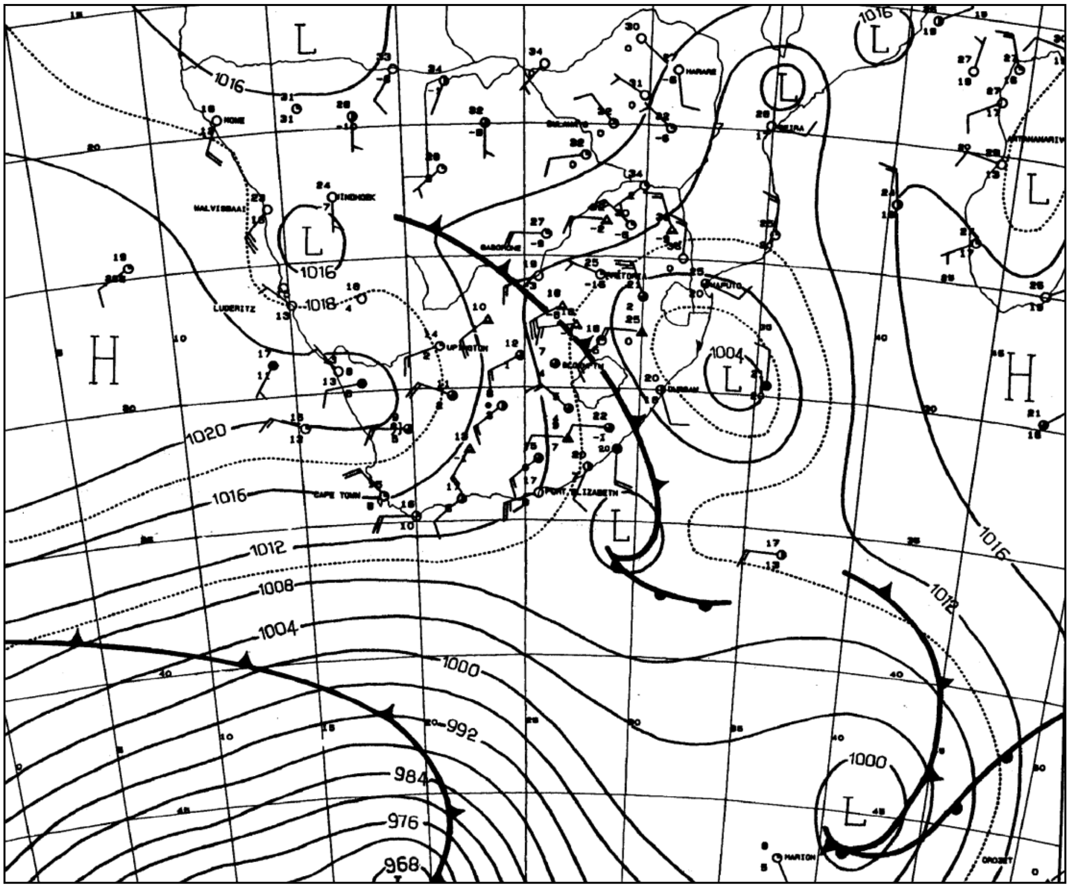

Figure 4.4 **Synoptic weather map of southern Africa, indicating a cold front over the eastern Free State at 14:00 on 27 August 1996.**

4.4 HISTORICALLY OBSERVED CLIMATE CHANGE IMPACTS

4.4.1 Bethlehem

The observed daily minimum and maximum temperatures for Bethlehem were averaged for each winter season (May – August) and analysed for trend over the climatic base period (1981 – 2010). Seasonally averaged minimum temperatures shown in Figure 4.5. The historical trend presented in Figure 4.6 for maximum temperature is consistent with climate change literature describing a general warming trend over South Africa (Kruger, 1994; Davis, 2011; Hewitson *et al.,* 2005). Although the R^2 value is very low, the positive slope in the trend line indicates an increase in the seasonally averaged maximum temperature of about 0.02ºC per annum. When accumulated over the entire 30-year period this resulted in an overall increase of about 0.6°C.

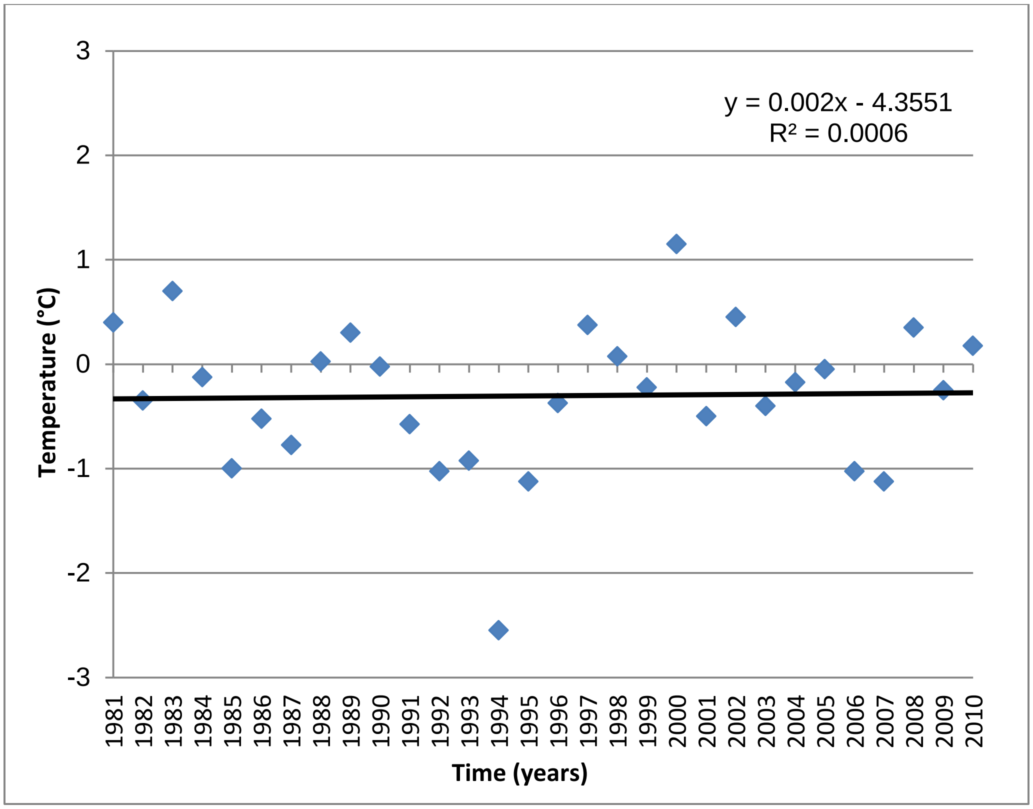

Figure 4.5 **Observed seasonally averaged minimum temperatures for Bethlehem for the period 1981 – 2010.**

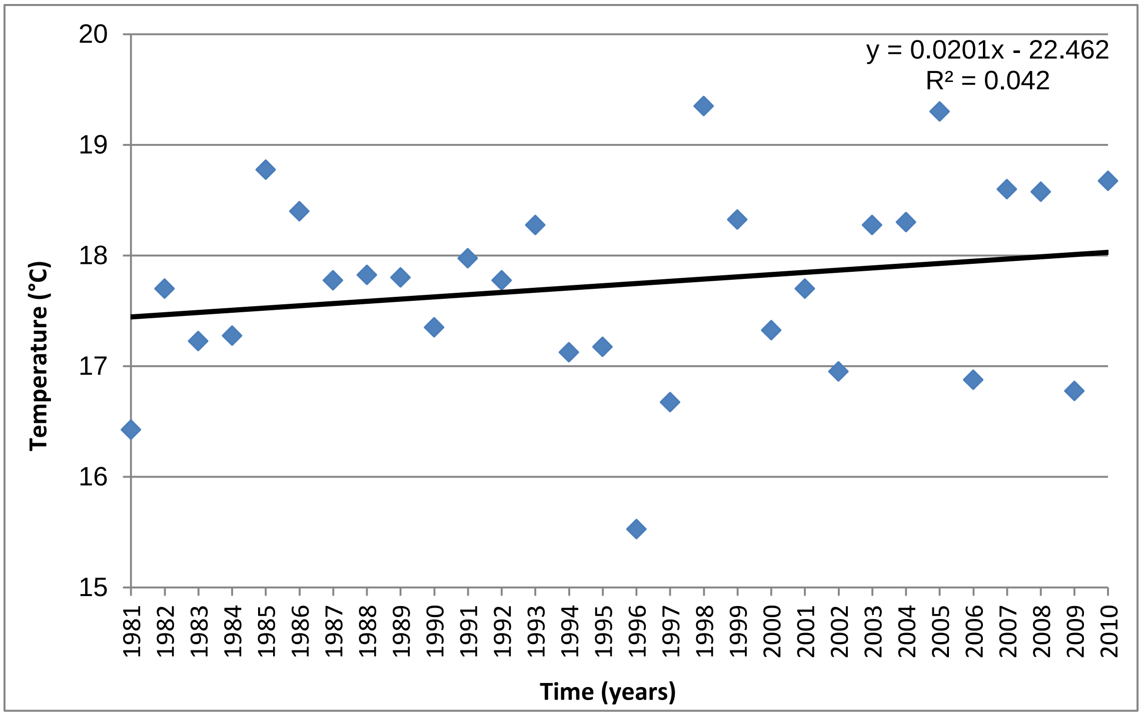

Figure 4.6 **Observed seasonally averaged maximum temperatures for Bethlehem for the period 1981 – 2010.**

PCUs were calculated from the hourly observed temperatures and accumulated for each winter season as described in Section 3.3. During the analysis of the historical trend, it was clear that there was no point in trying to fit a linear trend to the entire 30-year period as the accumulated PCUs showed a clear cyclic behaviour. Instead, linear trends were fit to three consecutive 10-year periods (Figure 4.7). These linear trend lines (for which the equations and coefficients of determination are provided in Table 4.5) revealed a general decrease of about 44 PCUs per year during the 1980s, an increase of 19.5 PCUs per year during the 1990s, followed by a decline of 3.9 PCUs per year during the 2000s. It was therefore interesting to note that 33% of the variation in accumulated PCUs could be explained by using a 4th order polynomial (indicated by the dashed blue line in Figure 4.7).

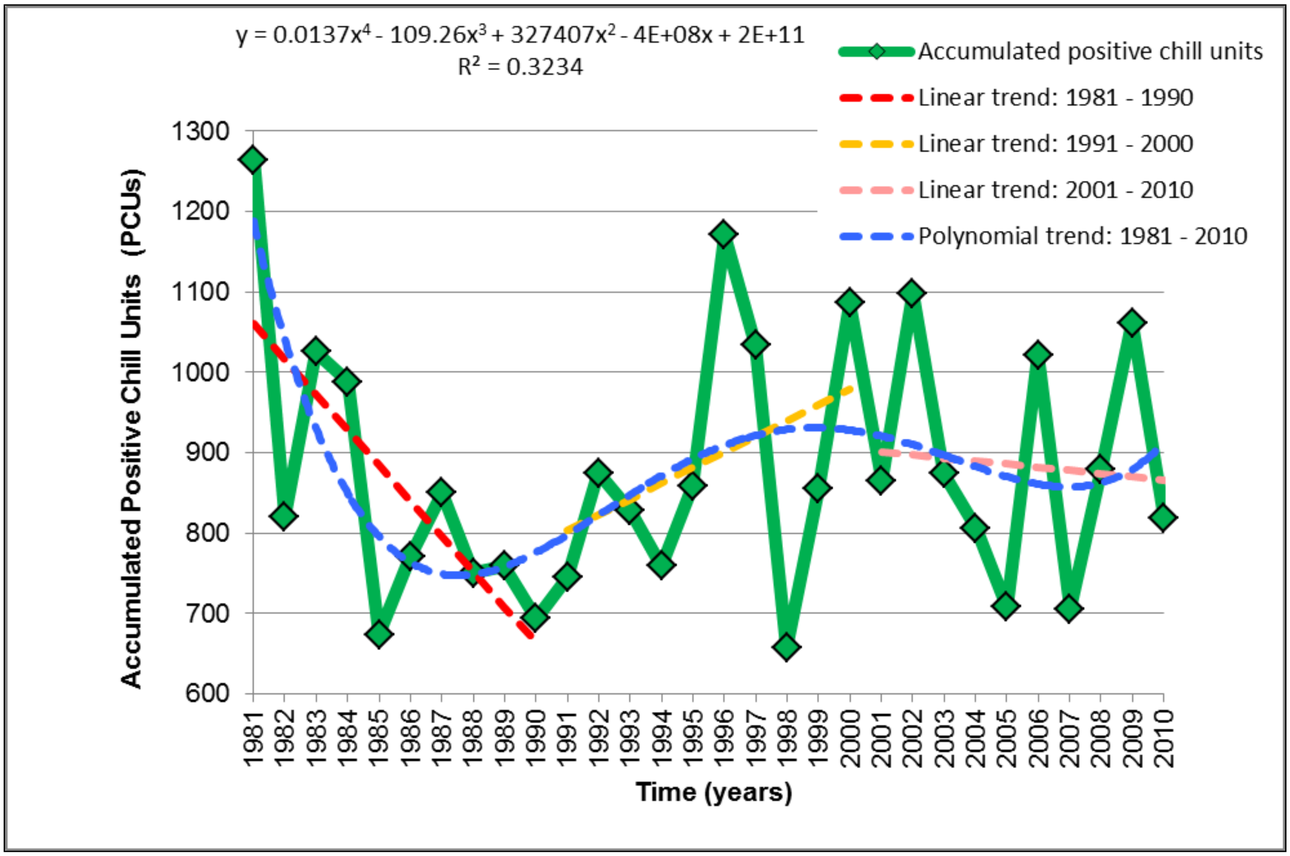

Figure 4.7 **Observed accumulated positive chill units for Bethlehem for the period 1981 – 2010.**

Table 4.5 **Simple linear regression results of accumulated positive chill units in Bethlehem versus time for three consecutive decades (shading corresponds to trend line in Figure 4.7)**

Decade	1981 – 1990	1991 – 2000	2001 – 2010
Equation	y= -44.02x + 88264	y = 19.52x - 38061	Y = -3.9x + 8705.3
R^2	0.53	0.13	0.01

The CDF for Bethlehem (Figure 4.8) revealed that the thresholds for below-normal and above-normal accumulated PCUs were 781 and 877, respectively. There was a 73% probability that the accumulated PCUs would not exceed 1 000 in a given season, while the chances of accumulating less than 600 PCUs are very slim. This implies that in terms of chilling requirements (Table 2.2), peach and apple cultivars like Cripp’s Pink and Granny Smith are well suited to this area, while cherries and cv.Royal Gala apples will encounter problems from time-to-time in terms of meeting their chilling requirements.

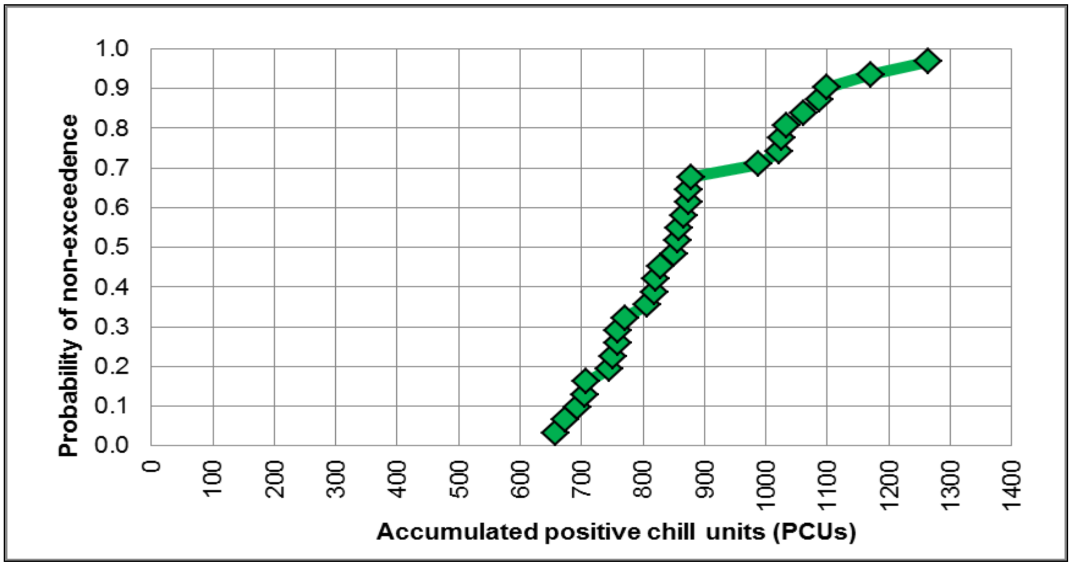

Figure 4.8 **Cumulative distributions function of accumulated PCUs for Bethlehem for the period 1981 – 2010.**

4.4.2 Ceres

The observed daily minimum and maximum temperatures for Ceres were averaged for each winter season (May – August) and analysed for trend over the climatic base period (1981 – 2010). As was the case in Bethlehem, there was no significant change in minimum temperature over the base period (Figure 4.9), while the maximum temperature increased by approximately 0.22°C per annum (Figure 4.10).

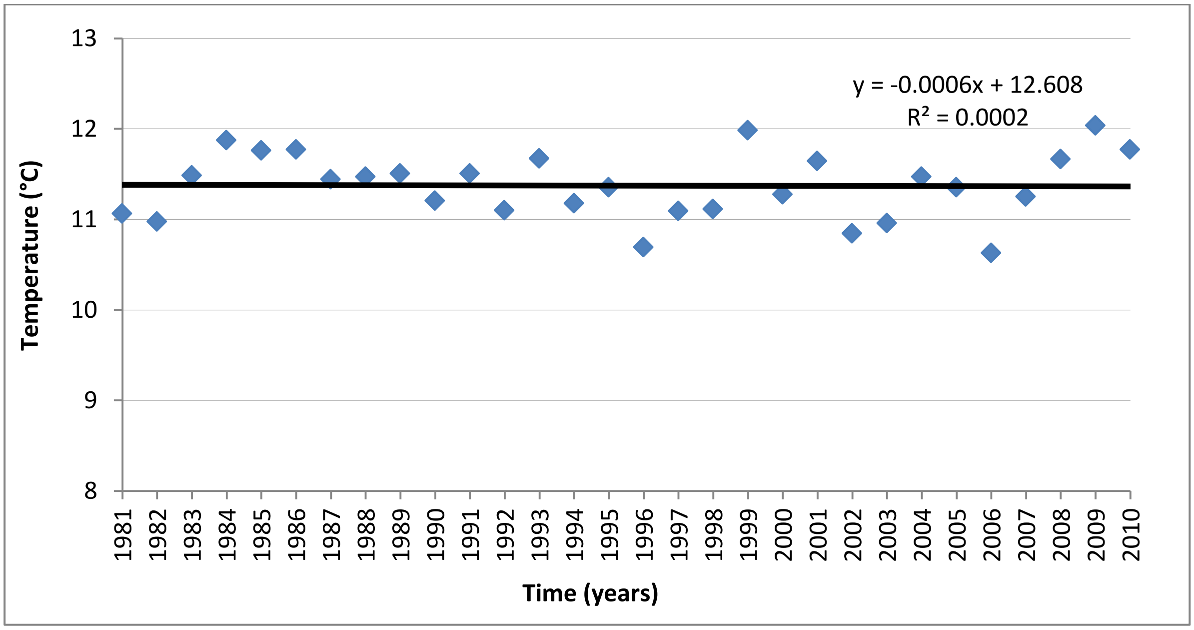

Figure 4.9 **Observed seasonally average minimum temperatures for Ceres for the period 1981 – 2010.**

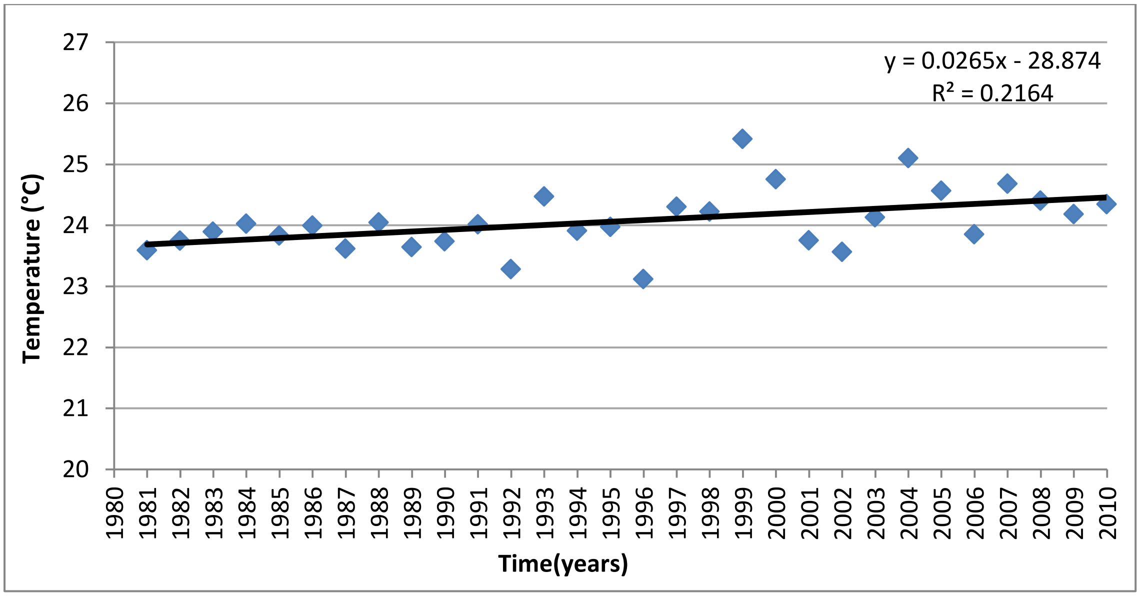

Figure 4.10 **Observed average maximum temperatures for Ceres for the period 1981 – 2010.**

The increase in especially maximum temperatures lead to a decrease in optimum temperatures for acquiring chill units (based on the Utah Model). Though not significant, it must also be noted that a decrease in minimum temperatures could have resulted in a decline in winter chill unit accumulation as temperatures below 1.5ºC lead to negation (Table 2.1). A decline in the amount of accumulated PCUs over time is clearly depicted by the linear trend in Figure 4.11. There was an annual decrease of 4.4 PCUs between 1981 and 2010. Production continued in spite of PCUs dropping below 600 during certain years.

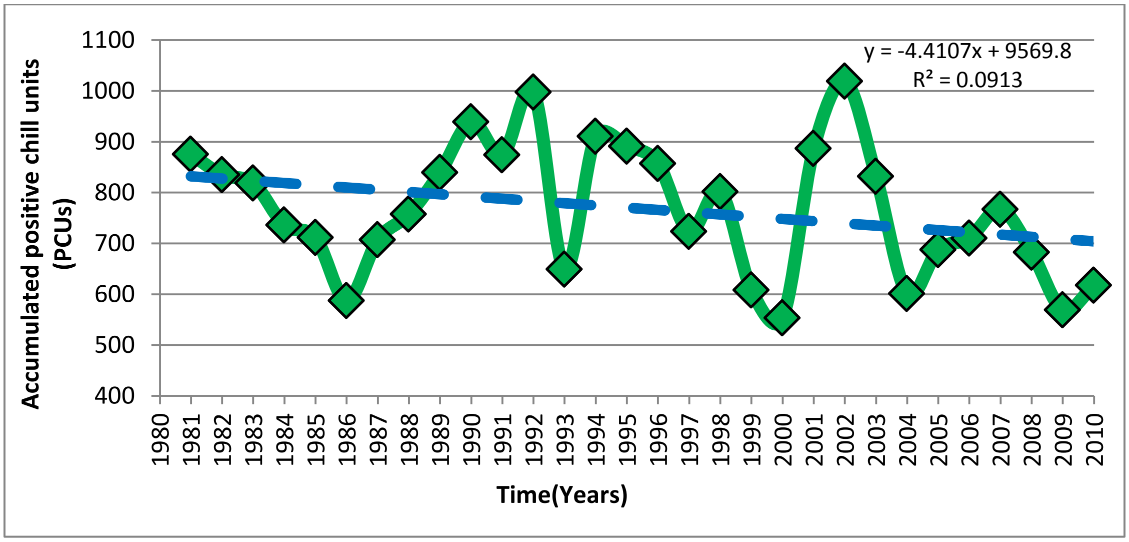

Figure 4.11 Observed accumulated positive chill units for Ceres for the period 1981 – 2010.

The CDF for Ceres (Figure 4.12) revealed that the thresholds for below-normal and above-normal accumulated PCUs were 708 and 838, respectively. There was a 94% probability that the accumulated PCUs would not exceed 1 000 in a given season while the probability of accumulating less than 600 PCUs was only 13%. Historically speaking, lower chill requiring fruits like peaches and certain apple and pear cultivars are better adapted to this area in terms of meeting their chilling requirements.

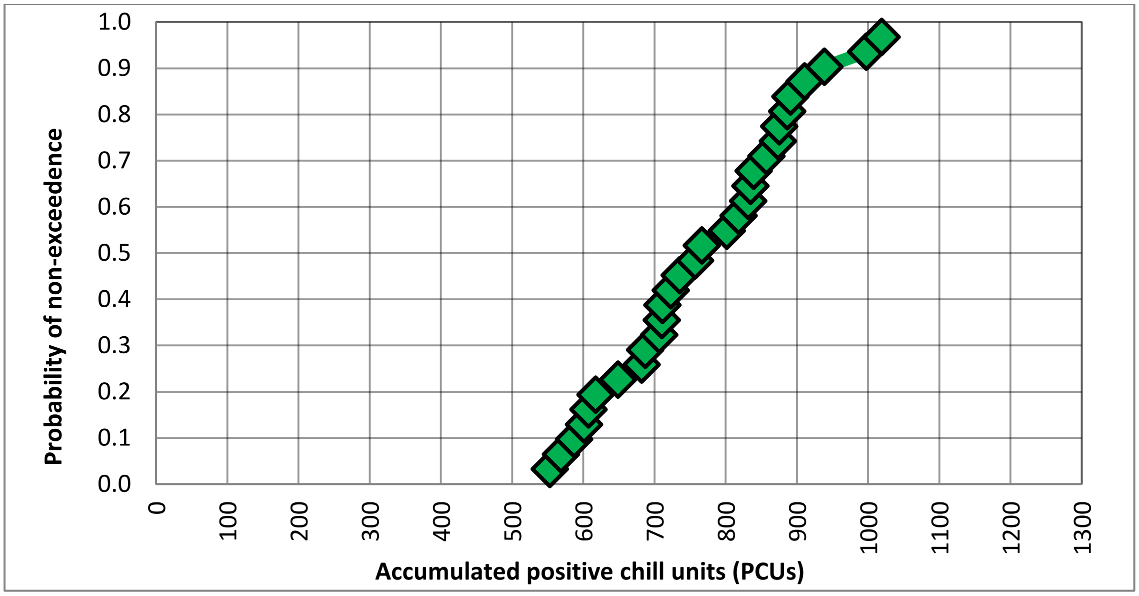

Figure 4.12 **Cumulative distributions function of accumulated PCUs for Ceres for the period 1981 – 2010.**

4.4.3 Upington

Unlike the other two sites, Upington exhibited a definite decreasing trend in the winter averaged minimum temperatures over the base period (Figure 4.13). In sharp contrast to the minimums, the maximum temperatures revealed a reasonably strong positive trend (Figure 4.14) with an observed average increase of about 0.05°C per annum. When accumulated over the full 30-year period this amounted to an overall increase of approximately 1.5°C.

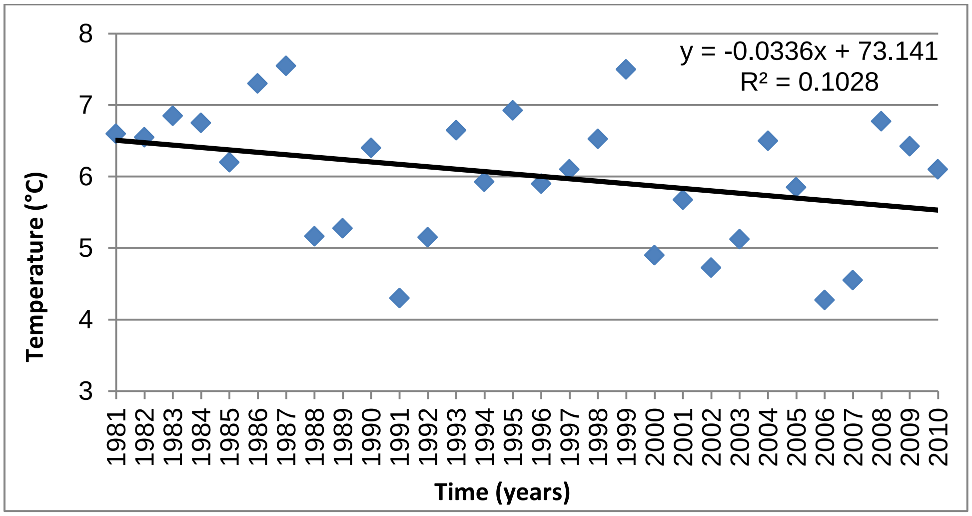

Figure 4.13 **Observed seasonally averaged minimum temperatures for Upington for the period 1981 – 2010.**

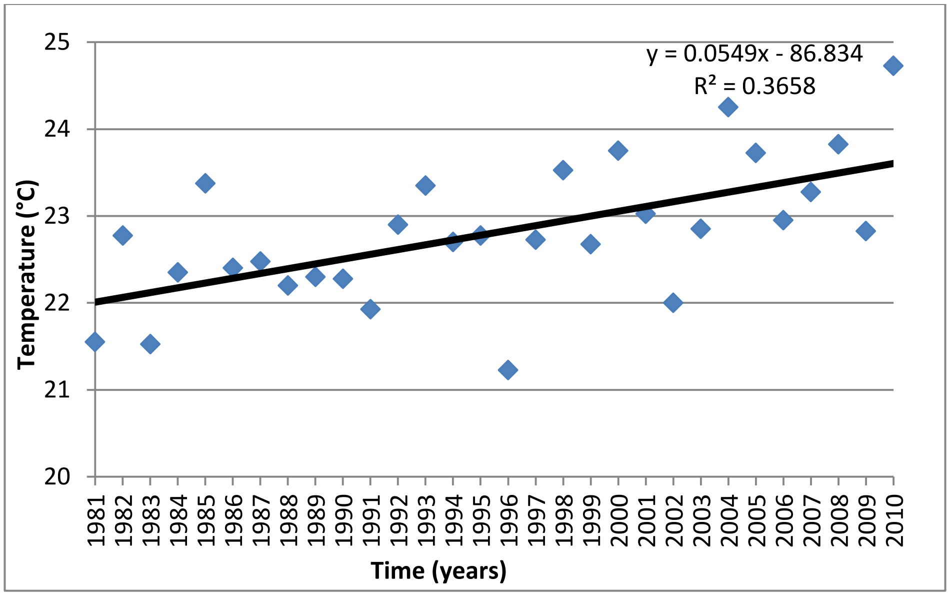

Figure 4.14 **Observed seasonally averaged maximum temperatures for Upington for the period 1981 – 2010.**

The linear trend line in Figure 4.15 shows that the overall effect of the above mentioned temperature changes is a decrease of about 2.6 PCUs per annum. Renowned for its warmer conditions, it is not surprising that Upington has the lowest chilling accumulation compared to the other two study areas. The thresholds for below-normal and above-normal accumulated PCUs were 391 and 475, respectively. Historically speaking, there is a 95% probability of the accumulated PCUs in Upington not exceeding 600 in a given season (Figure 4.16). Thus the fruits which are being produced in Upington must require less than 600 PCUs to be viable in the long run. This implies that only fruit with low chilling requirements (such as certain grape cultivars) should be cultivated in Upington.

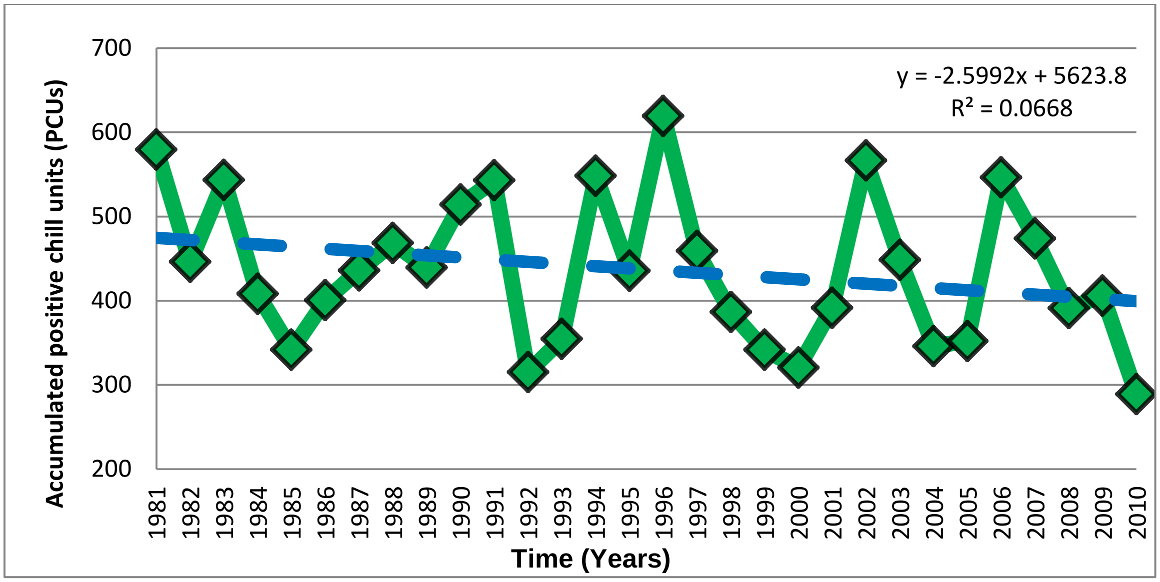

Figure 4.15 **Observed accumulated positive chill units for Upington 1981 – 2010.**

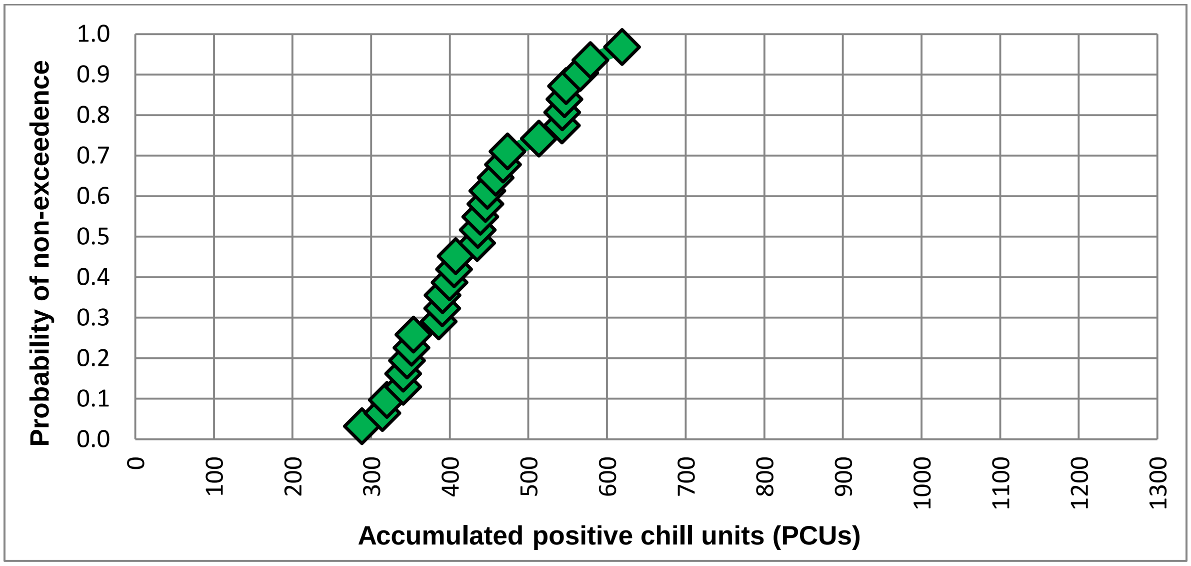

Figure 4.16 **Cumulative distribution functions of accumulated PCUs for Upington for the period 1981 – 2010.**

4.5 FUTURE TEMPERATURE TRENDS

Changes in the future climate was analysed with respect to the CCAM projections from the EN1, EN2 and EN3 ensembles (Section 3.2.2.3), which were all based on the A2 SRES scenario. Changes in temperature are summarized in Table 4.6 for all three study areas.

Table 4.6 Projected averaged minimum and maximum temperatures for the period 1981 – 2100

Study area	Variable	Base (1981 – 2010)			2011 – 2040			2041 – 2070			2071 – 2100		
		EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3
Bethlehem	T_{min} (ºC)	-0.8	-1.1	-1.1	-0.1	-0.5	-0.2	1.1	0.6	0.8	2.9	1.9	2.5
	T_{max} (ºC)	10.3	10.7	10.8	11.1	11.2	11.0	12.2	13.0	12.0	14.1	13.8	13.8
Ceres	T_{min} (ºC)	3.6	2.5	3.6	4.6	3.1	4.2	5.6	4.1	4.9	7.0	5.3	6.1
	T_{max} (ºC)	14.3	13.8	14.3	15.0	14.3	14.6	15.8	15.5	15.2	17.2	16.3	16.9
Upington	T_{min} (ºC)	2.2	1.8	1.9	3.1	2.4	2.7	4.5	3.9	3.9	6.5	5.1	5.8
	T_{max} (ºC)	16.7	16.3	17.0	17.7	16.7	17.3	18.8	18.7	18.4	20.5	19.5	20.6

4.5.1 Bethlehem

As described in Section 3.3, the average winter minimum and maximum temperatures for consecutive 30-year future periods were calculated and subsequently compared. The average minimum temperatures for the base period ranged from -1.1ºC to -0.8ºC between the three ensemble members and compared well with the actual observed average of -0.3ºC (as mentioned in Section 4.2 all three CCAM ensembles exhibited a cold bias). While Table 4.6 provided the average values for all three ensembles, Figure 4.17 clearly depicts a continuous increase in average minimum temperature from the subzero values over the base period to a balmier 3ºC towards the end of the century. The average maximum temperature also increased with about 4ºC towards 2100 (Figure 4.18). However, it should be noted that this increase is smaller than the model error of approximately 7ºC for all three ensembles for the base period (Section 4.2).

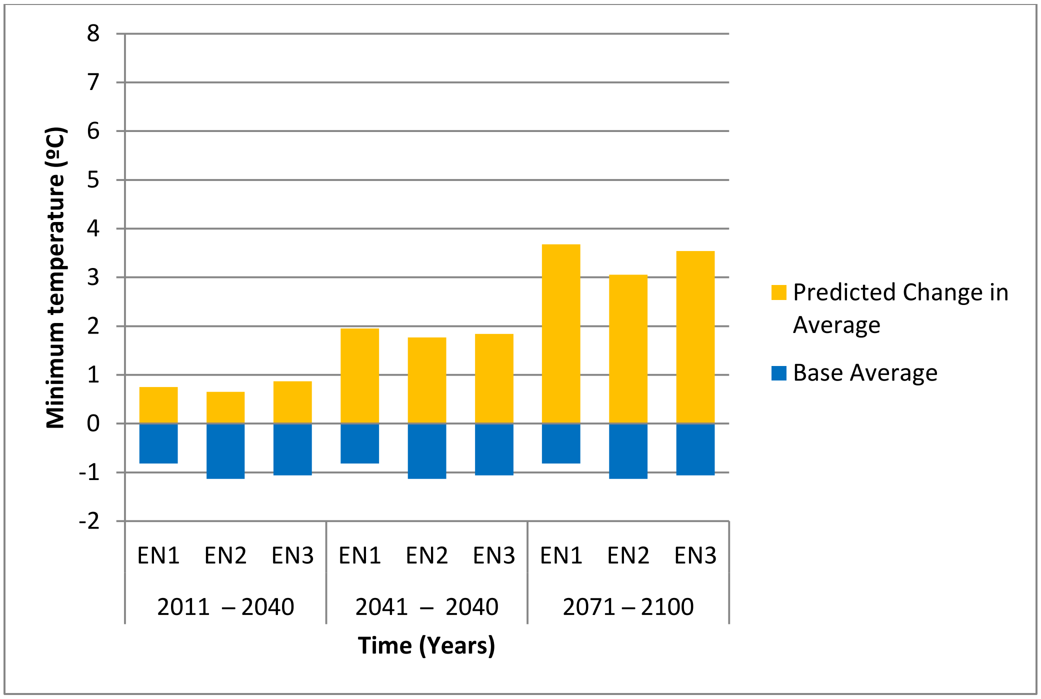

Figure 4.17 **Projected changes in minimum temperature for Bethlehem (2011 – 2100).**

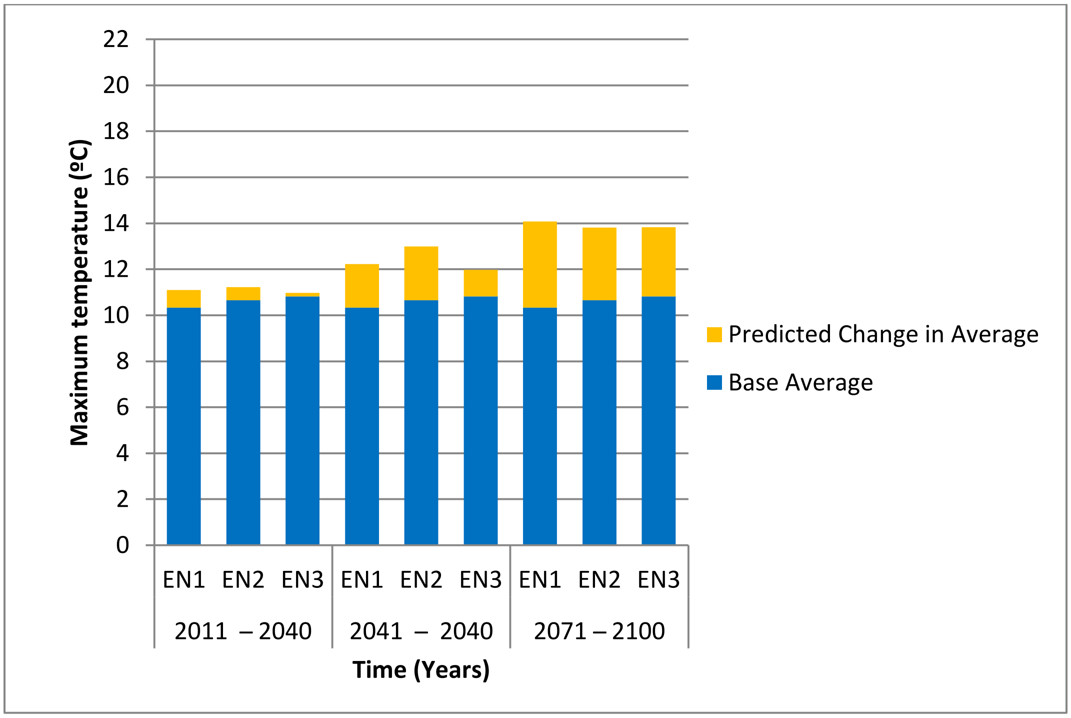

Figure 4.18 **Projected changes in maximum temperature for Bethlehem (2011 – 2100).**

4.5.2 Ceres

Figure 4.19 also reveal a steady increase in average minimum temperature from the predicted average of 3ºC above the base period to about 4ºC during the 2020s, 5ºC during the 2050s and 6ºC during the 2080s. The average maximum temperature also increased with about 2.5ºC towards 2100 (Figure 4.20).

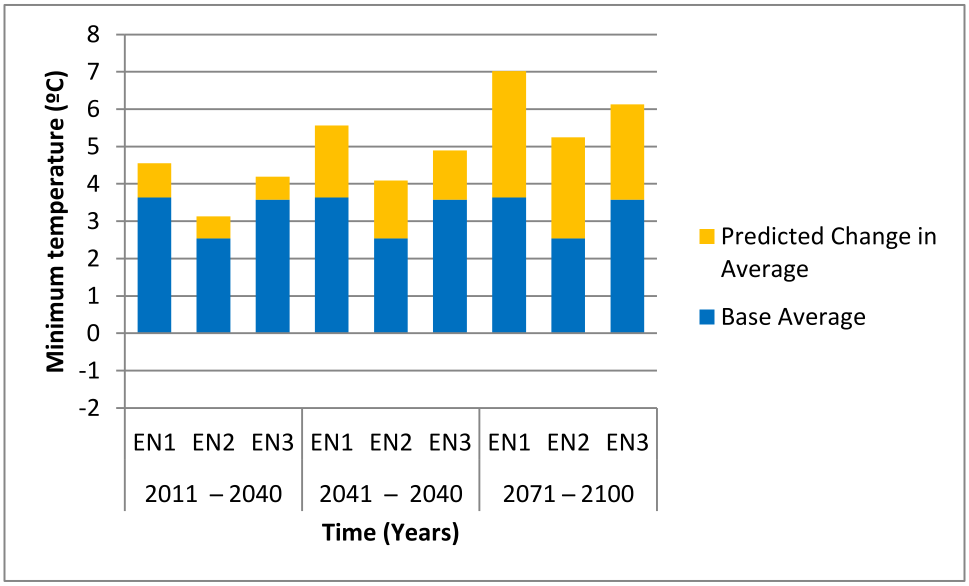

Figure 4.19 **Projected changes in minimum temperature for Ceres (2011 – 2100).**

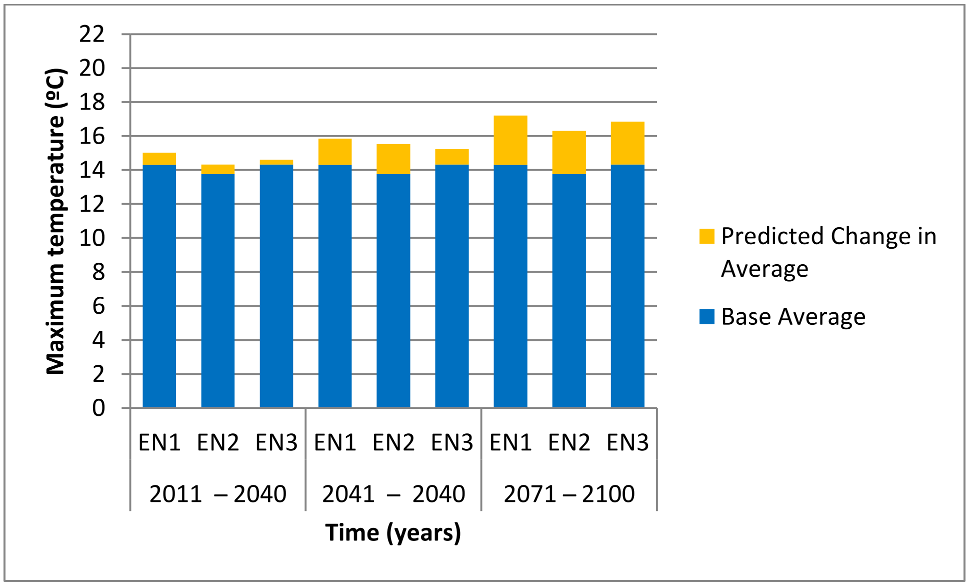

Figure 4.20 **Projected changes in maximum temperature for Ceres (2011 – 2100).**

4.5.3 Upington

In contrast to the observed decreasing trend over the base period (Section 4.4.3), the average minimum temperature is predicted to increase to about 5.5ºC by the end of the century (Figure 4.21). The maximum temperatures revealed an insignificant change towards the 2040s and a warming of about 3.5ºC towards the end of the century (Figure 4.22).

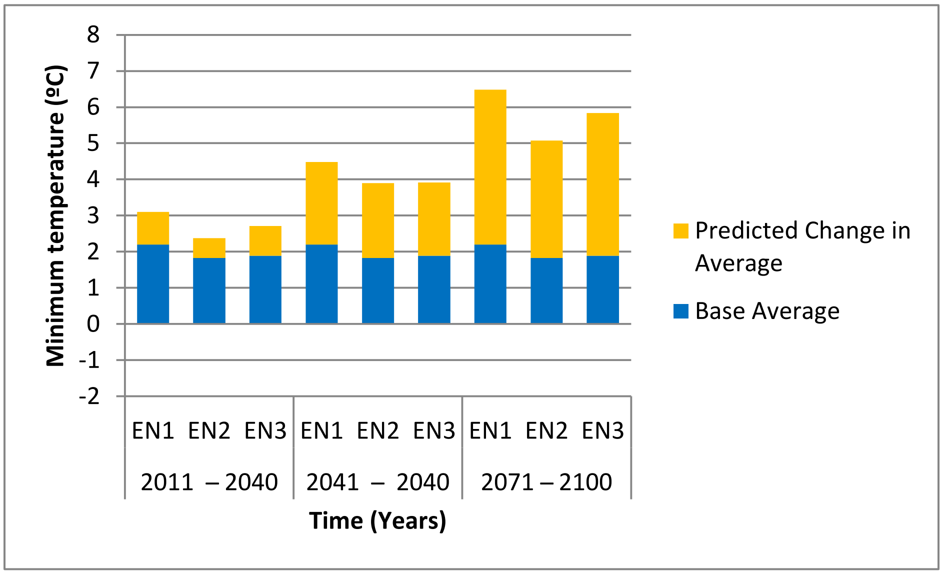

Figure 4.21 Projected changes in minimum temperature for Upington (2011 – 2100).

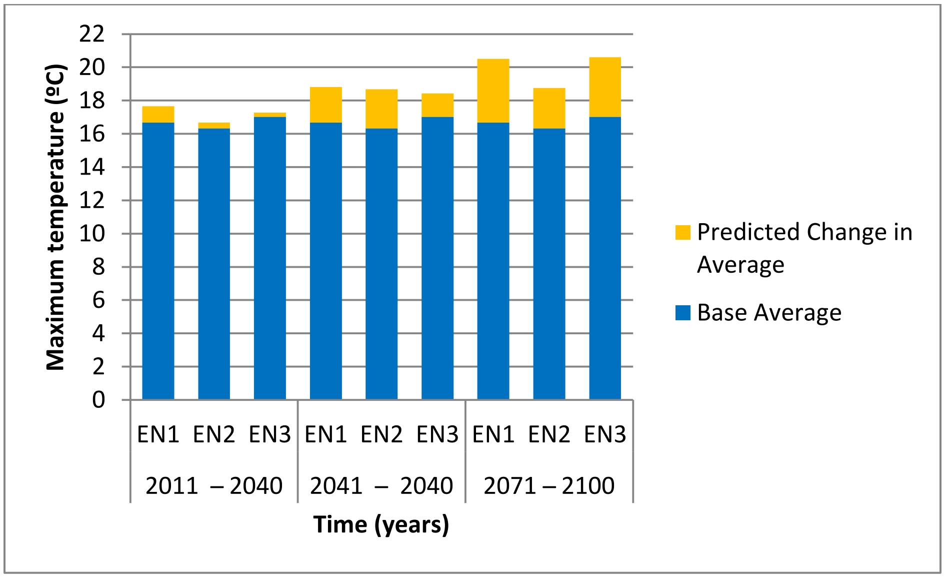

Figure 4.22 Projected changes in maximum temperature for Upington (2011 – 2100).

4.6 FUTURE CHILL UNIT TRENDS

To evaluate future trends in accumulated PCUs, the TDM was used to generate hourly temperatures from the projected daily minimum and maximum temperatures (Section 3.2.3). This was repeated for each CCAM ensemble member and study area for the period 2011 – 2100. Although the TDM performed well in estimating hourly temperatures over the base period (Section 4.3), all three CCAM ensembles exhibited a cold bias with respect to minimum and maximum temperatures over this period (Section 4.2). The influence of such a cold temperature bias on accumulated PCUs is unclear, especially when critical thresholds are being breached (refer to Table 2.1). However, the CCAM ensemble-derived values were on average 634, 837 and 627 PCUs higher for Bethlehem, Ceres and Upington, respectively. For this reason, instead of focusing on the industry related thresholds (600 and 1 000 PCUs used in Section 4.5), the decision was made to increase these thresholds with at least 600 PCUs to 1 200 and 1 600 PCUs when considering the future periods. In addition, future accumulated PCUs were rather compared to those calculated from ensemble-derived temperatures for the base period (as opposed to using the historically observed temperatures). The accumulated PCUs for the three consecutive 30-year periods could then also be compared against each other.

In the CDFs in the sections that follow, the accumulated PCUs for the base period was taken as the average from all three ensembles for the period of 1981 to 2010. This was done to present a less cluttered appearance. However, when calculating absolute or percentage changes between the future and base periods, the individual predicted ensemble mean PCUs were used.

4.6.1 Bethlehem

Upon comparing the CDFs of accumulated PCUs for the three ensembles (EN1, EN2 and EN3) for the future period of 2011 – 2040 against that for the base period (Figure 4.23), a clear shift towards the right is observed. This means the accumulated PCUs are expected to increase, particularly for EN1 and EN3. It can be seen that the probability of exceeding a threshold of 1 200 PCUs in a given season is almost certain for all three ensembles. The probability of not-exceeding a threshold of 1 600 PCUs was about 37%

for EN1 and EN3, and 67% for EN2. Most deciduous fruits can be grown in Bethlehem as long as the other climatic factors are conducive for their optimum growth and production. By the 2050s, the probability of not-exceeding a threshold of 1 600 PCUs was 23% for EN1 and EN3, and 78% for EN2 (Figure 2.24). The most notable feature in Figure 4.24 is the shift towards the left in the lower tail of the EN2 CDF, implying that the probabilities of the PCUs not exceeding lower thresholds (anything lower than 1 560 CPUs) was higher for the base period than during this future period. In order to facilitate quick look-up, the mean accumulated PCUs for Bethlehem for each 30-year period is provided in Table 4.7, while the projected changes are depicted in Figure 4.26. From the above it is evident that no significant changes in accumulated PCUs are expected in Bethlehem.

By the 2080s, the probability of not-exceeding a threshold of 1 600 PCUs was approximately 50% for EN1 and EN3, and 87% for EN2 (Figure 2.25). This implies that after exhibiting a reasonable increase in accumulated PCUs in the first part of the century, certain high chill requiring fruit types will now start to struggle once again as the critical threshold of 1 600 PCUs are seldom met.

To facilitate an easy comparison between ensembles and 30-year periods, the thresholds for below-normal and above-normal accumulated PCUs are provided in Table 4.7. From this table it is evident that the below-normal and above-normal thresholds for the 2020s were respectively 79 and 132 PCUs higher than for the base period. These same thresholds increased by 113 and 124 PCUs during the 2050s and with 30 and 108 PCUs by the 2080s. In the case of Bethlehem, there doesn’t seem to be a clear trend in terms of future changes in accumulated PCUs as judged by the threshold values provided in Table 4.7 and percentage changes in Figure 4.26. In general EN1 and EN3 show increases that peak between 8 and 13% by the 2050s, but then decline to only 4 – 6% towards the end of the century. EN2, on the other hand, peaks in the 2020s with a 4% increase in accumulated PCUs, which declines to a mere 1% increase over the base period values by the 2080s.

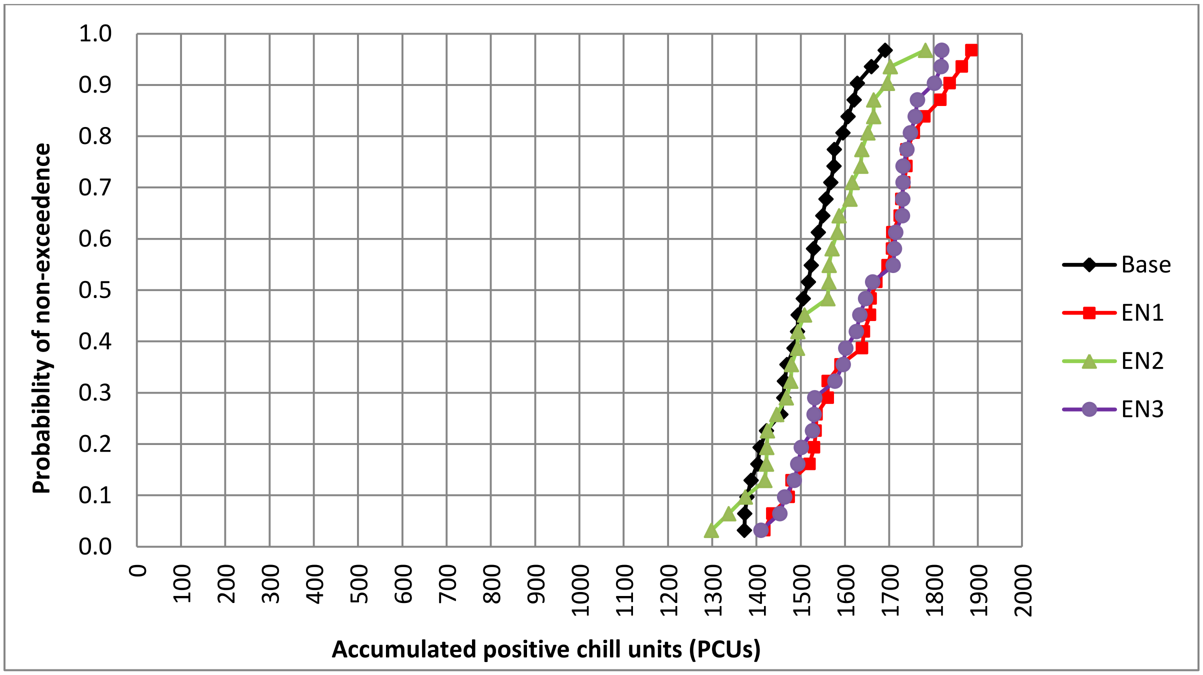

Figure 4.23 **Cumulative distribution functions for accumulated positive chill units for Bethlehem for the period 2011 – 2040.**

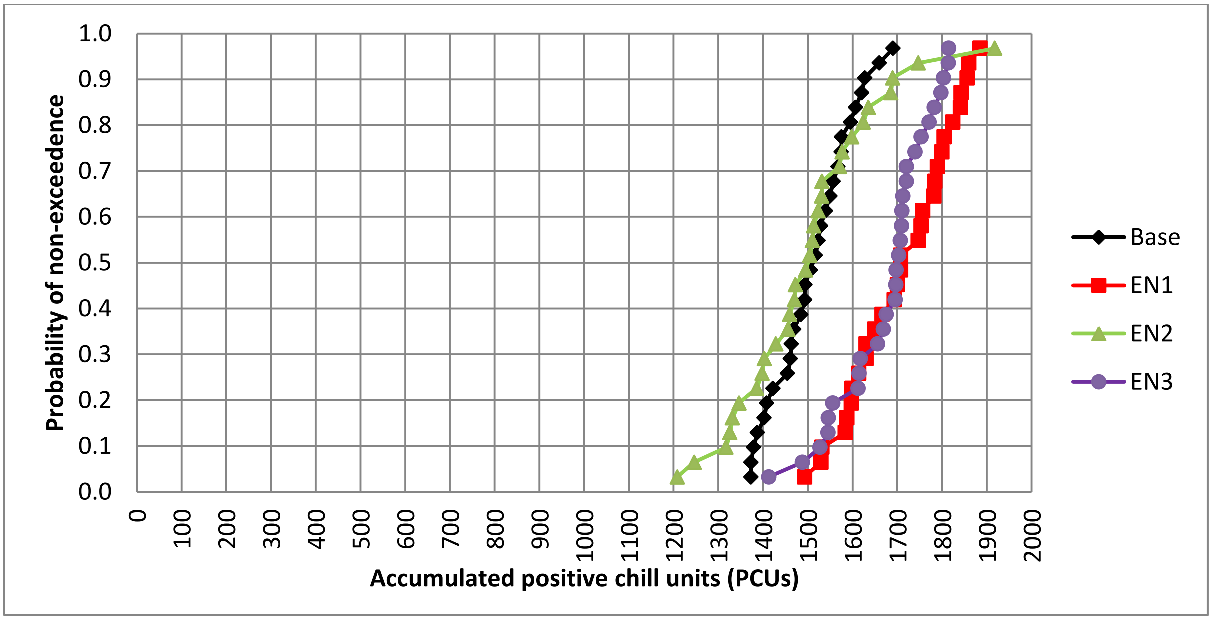

Figure 4.24 **Cumulative distribution functions for accumulated positive chill units for Bethlehem for the period 2041 – 2070.**

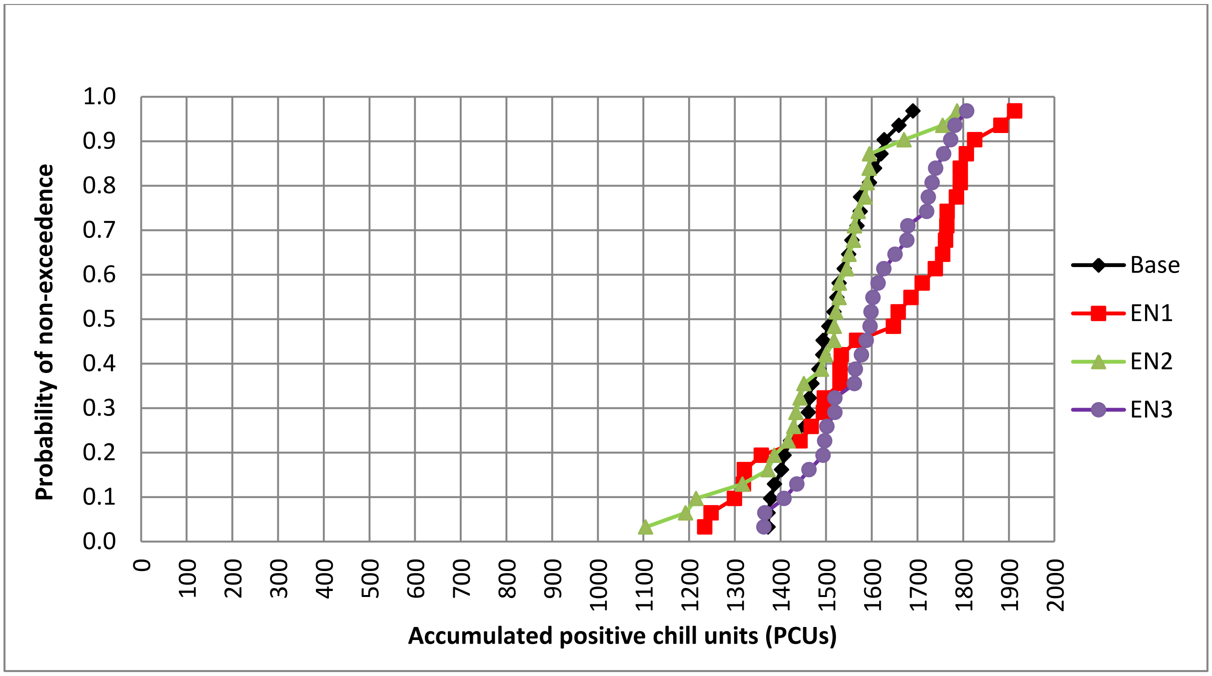

Figure 4.25 **Cumulative distribution functions for accumulated positive chill units for Bethlehem for the period 2071 – 2100.**

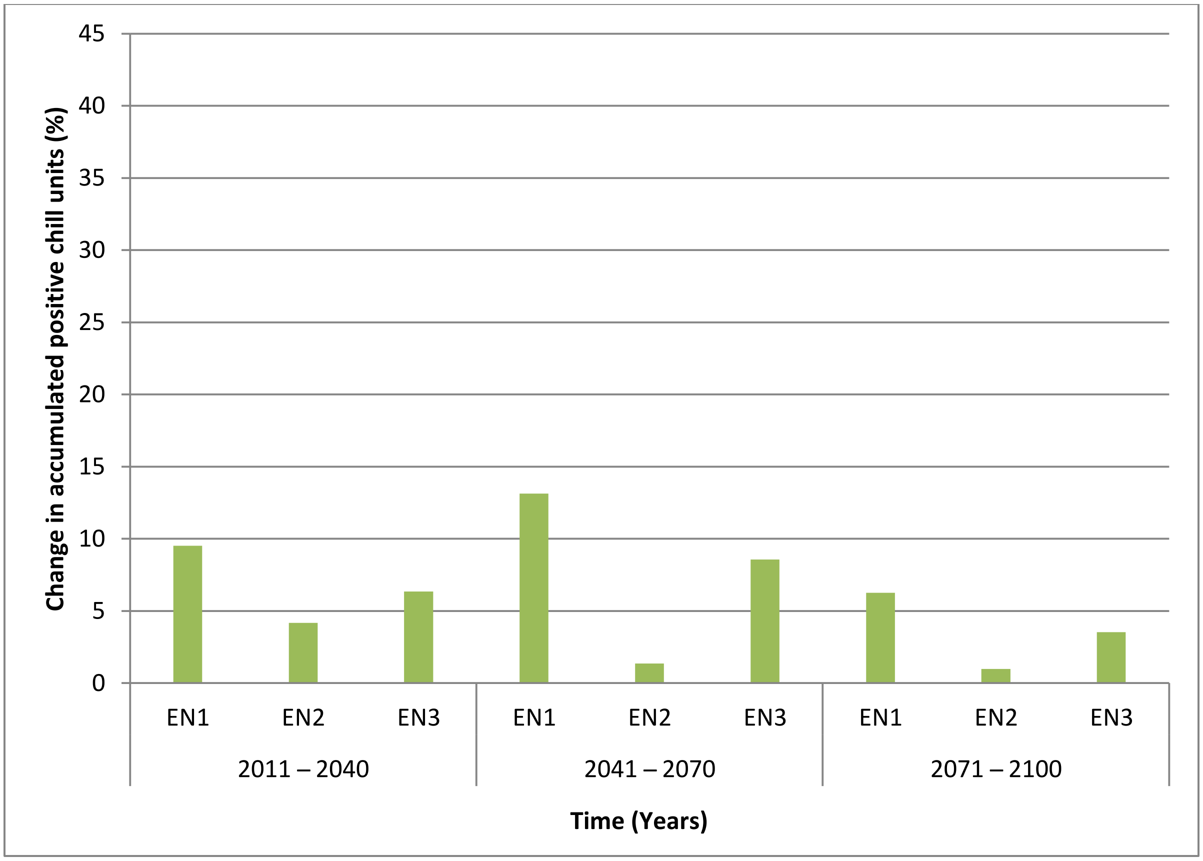

Figure 4.26 **Projected changes in accumulated positive chill units for Bethlehem (2011 – 2100).**

Table 4.7 **Mean accumulated positive chill units (PCUs) for Bethlehem for the period 1981 – 2100.**

Probability of non-exceedence (%)	Base (1981 – 2010)			2011 – 2040			2041 – 2070			2071 – 2100		
	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3
	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU
33.3	1465	1465	1465	1570	1478	1583	1637	1438	1661	1507	1446	1533
66.6	1554	1554	1554	1726	1602	1730	1784	1532	1718	1760	1557	1668

4.6.2 Ceres

Unlike Bethlehem, the CDFs of accumulated PCUs for Ceres exhibited a shift towards the left of the base. This means the accumulated PCUs are expected to decrease, only slightly towards the 2020s but increasingly more so by the end of the century (Figures 4.27 – 4.29 and Table 4.8). It can be seen that for EN2 the probability of not-exceeding a threshold of 1 200 PCUs in a given season is extremely low during the 2020s, but increases to about 12% by the 2050s and 29% by the 2080s. According to the same ensemble, the probability of not-exceeding a threshold of 1 600 PCUs was about 73% during the 2020s (Figure 4.27) and 91% by the 2050s (Figure 4.28).

By the 2080s the probability of not exceeding a threshold of 1 600 PCUs is extremely high for all three ensembles (Figure 4.29). In general, the projections indicate decreases in accumulated PCUs of 2 – 5% by the 2020s, 7 – 17% by the 2050s, and 20 – 34% towards the end of the century (Figure 4.30). This culminates in a loss of between 320 and 540 PCUs by the 2080s.

From the discussion in Section 4.5 it already became clear that high chill requiring fruit types will encounter problems under present conditions, while moderate chill requiring fruit types will prosper. Towards the end of the century, the moderate chill requiring fruit types will also start to experience shortages in accumulated PCUs in three out of 10 years.

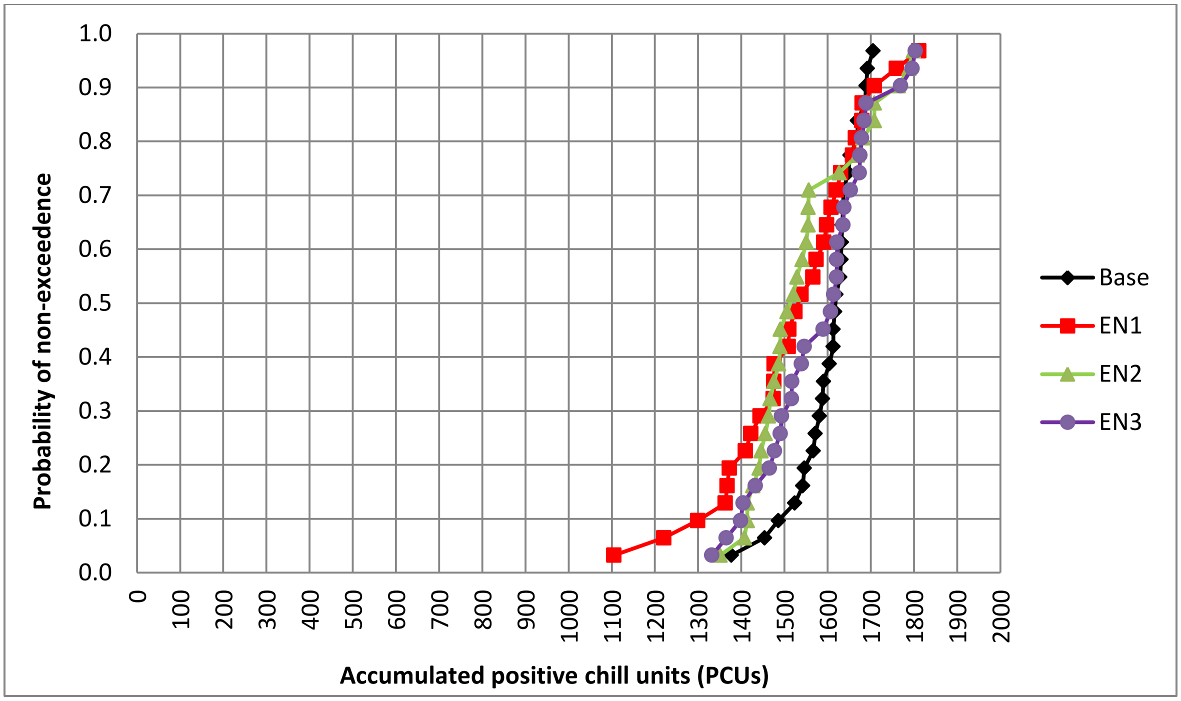

Figure 4.27 Cumulative distribution functions for accumulated positive chill units for Ceres for the period 2011 – 2040.

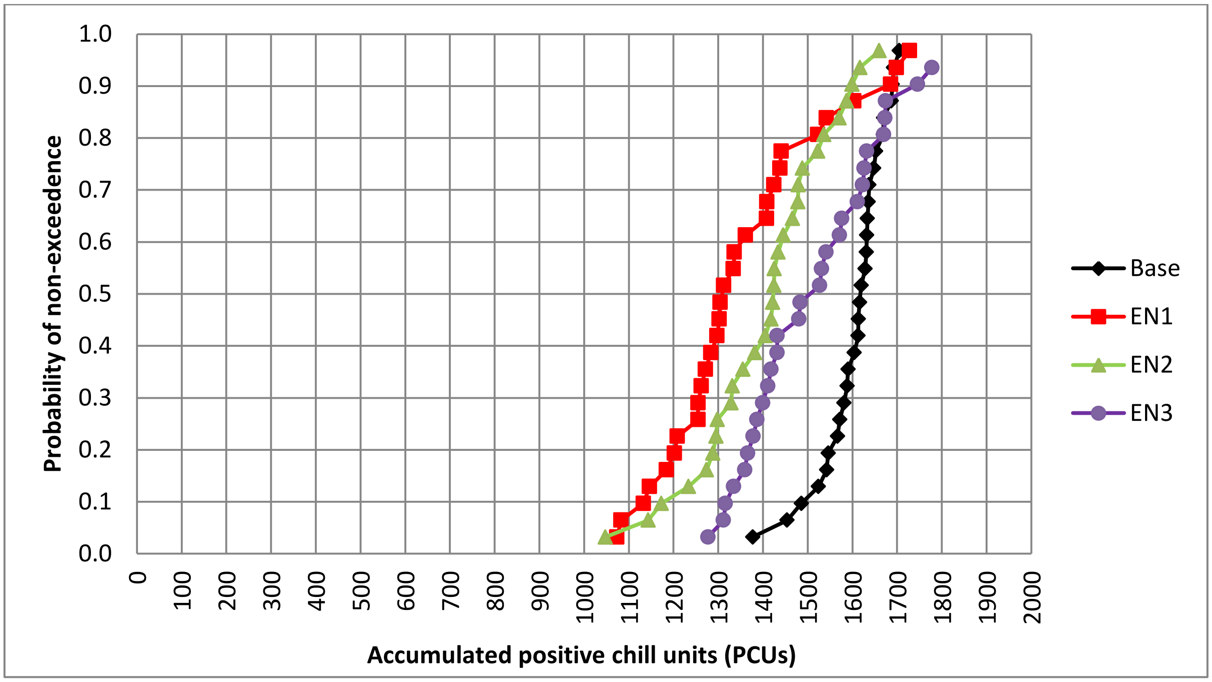

Figure 4.28 Cumulative distribution functions for accumulated positive chill units for Ceres for the period 2041 – 2070.

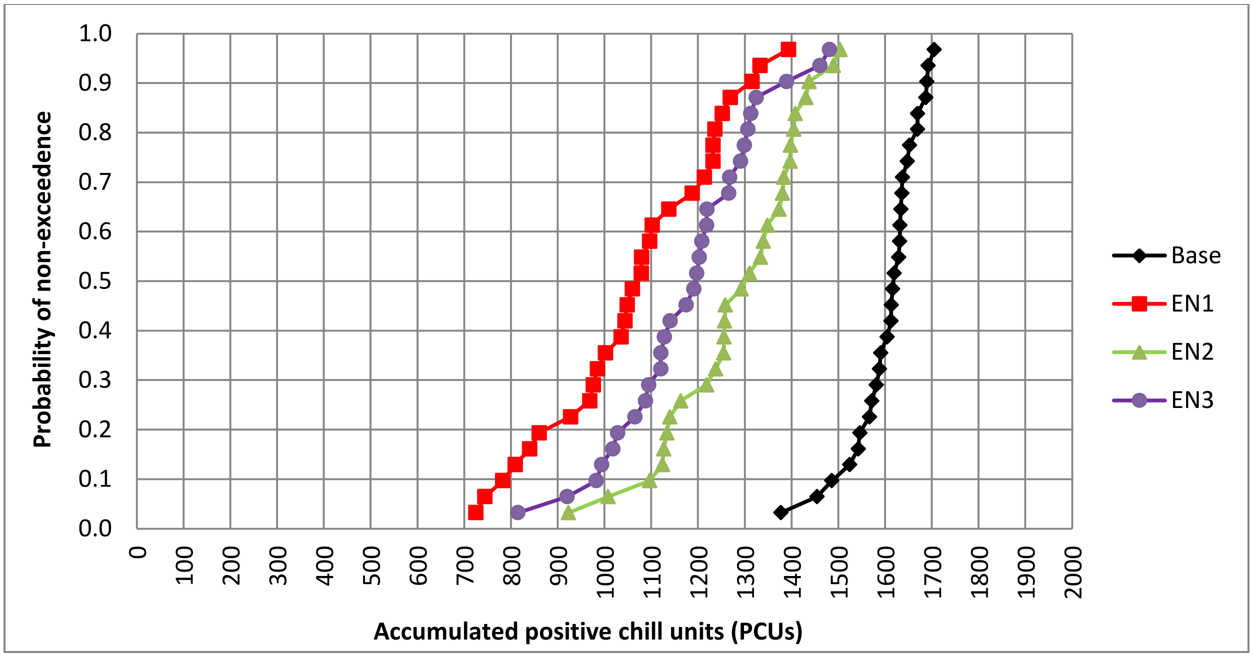

Figure 4.29 **Cumulative distribution functions for accumulated positive chill units for Ceres for the period 2071 – 2100.**

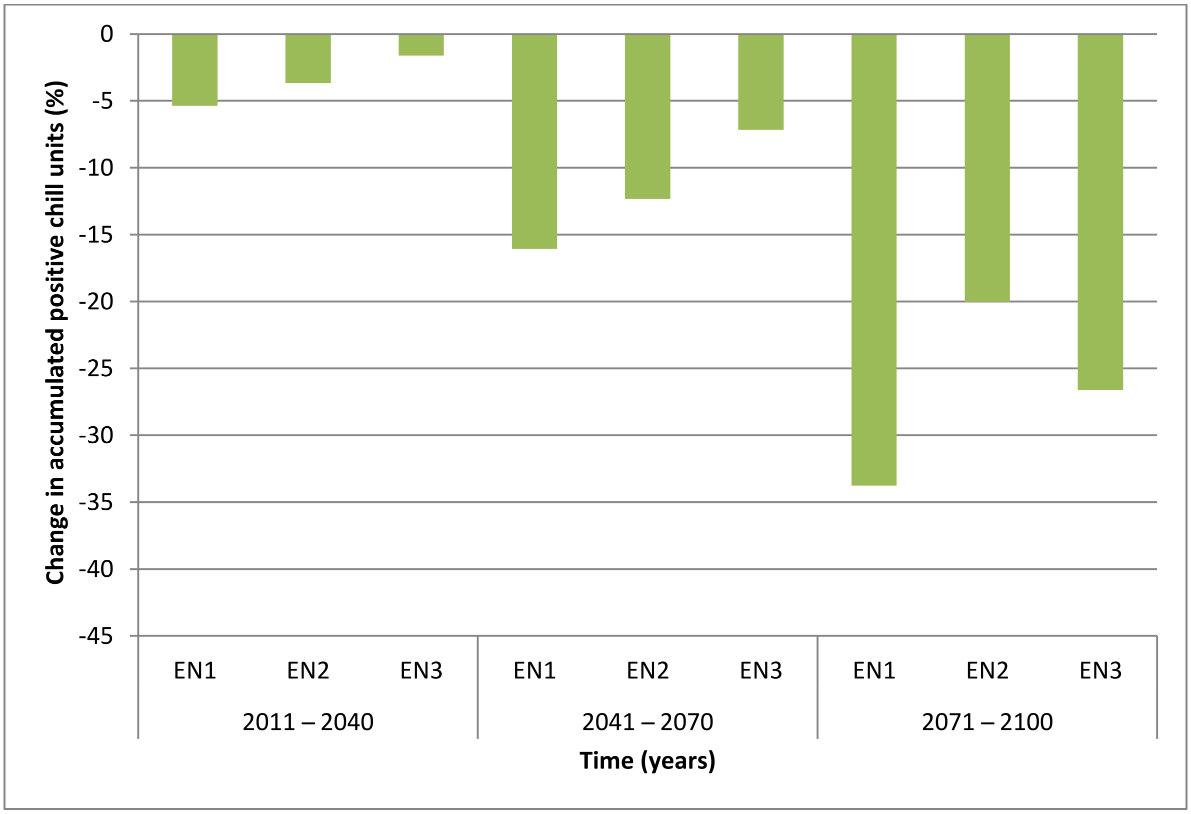

Figure 4.30 **Projected changes in accumulated positive chill units for Ceres (2011 – 2100).**

Table 4.8 Mean accumulated positive chill units (PCUs) for Ceres for the period 1981 – 2100.

Probability of non-exceedence (%)	Base (1981 – 2010)			2011 – 2040			2041 – 2070			2071 – 2100		
	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3
	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU
33.3	1589	1589	1589	1475	1470	1517	1265	1339	1413	991	1243	1121
66.6	1635	1635	1635	1605	1556	1637	1409	1474	1599	1170	1378	1250

4.6.3 Upington

In Section 4.5 it was already mentioned that only low chill requiring fruit types could be cultivated in this area. Any further reductions in accumulated PCUs will affect the viability of even these fruit types.

From the CDFs presented in Figures 4.31 – 4.33 and the corresponding summary in Table 4.9, it is evident that the below-normal and above-normal thresholds for the 2020s were respectively 95 and 27 PCUs lower than for the base period. These same thresholds decreased by 247 and 214 PCUs during the 2050s and with 435 and 378 PCUs by the 2080s. This constituted a decrease in accumulated PCUs of between 36% to 41% towards the end of the century (Figure 4.34).This implies that cultivating any deciduous fruit that require winter chill may eventually become unviable in this area.

Table 4.9 Mean accumulated positive chill units (PCUs) for Upington for the period 1981 – 2100.

Probability of non-exceedence (%)	Base (1981 – 2010)			2011 – 2040			2041 – 2070			2071 – 2100		
	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3	EN1	EN2	EN3
	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU	ΣPCU
33.3	1032	1032	1032	863	1064	884	774	795	785	543	683	564
66.6	1097	1097	1097	999	1190	1020	883	887	879	680	813	664

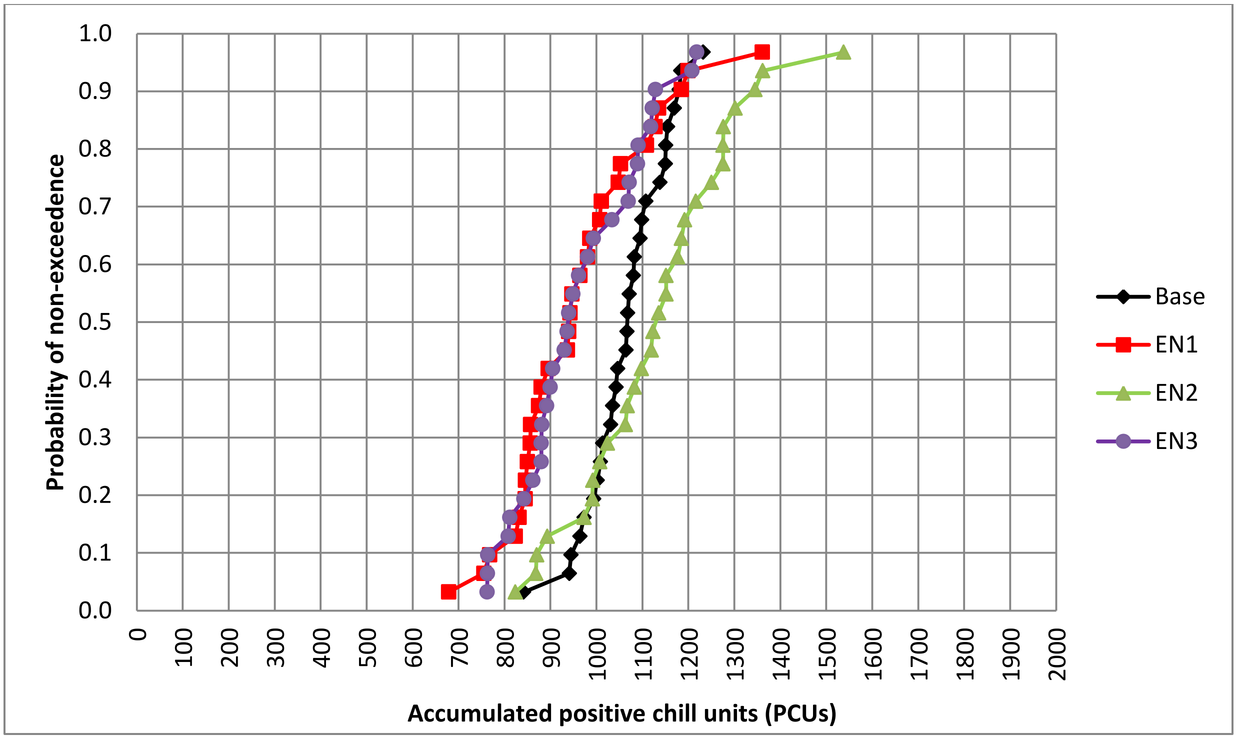

Figure 4.31 **Cumulative distribution functions for accumulated positive chill units for Upington for the period 2011 – 2040.**

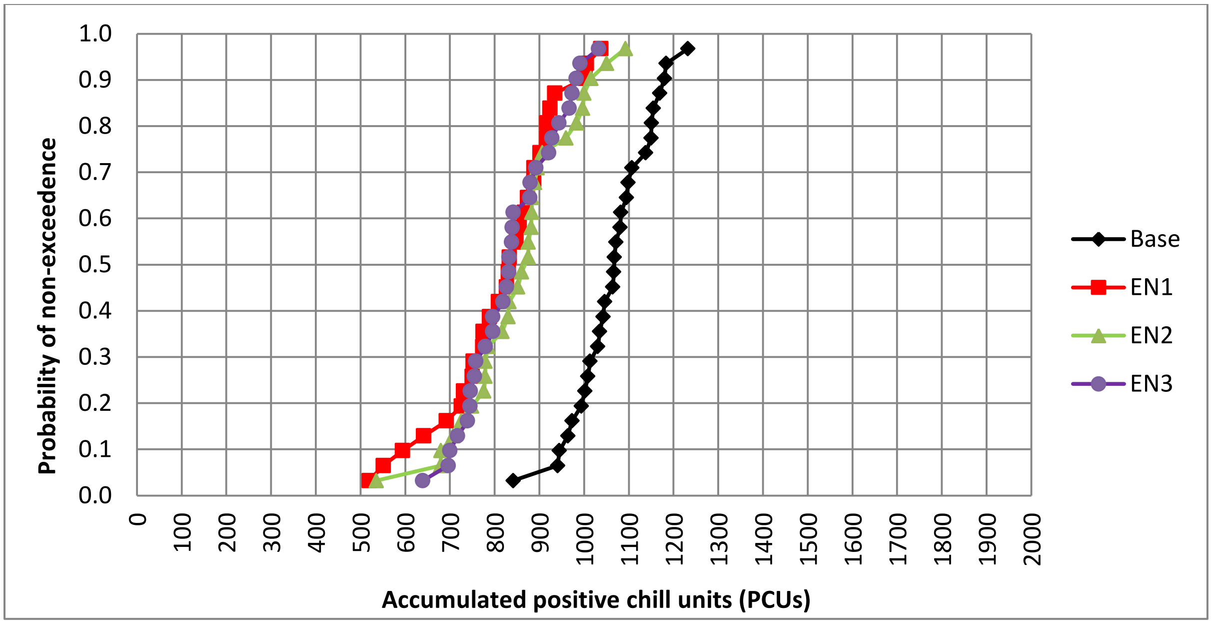

Figure 4.32 **Cumulative distribution functions for accumulated positive chill units for Upington for the period 2041 – 2071.**

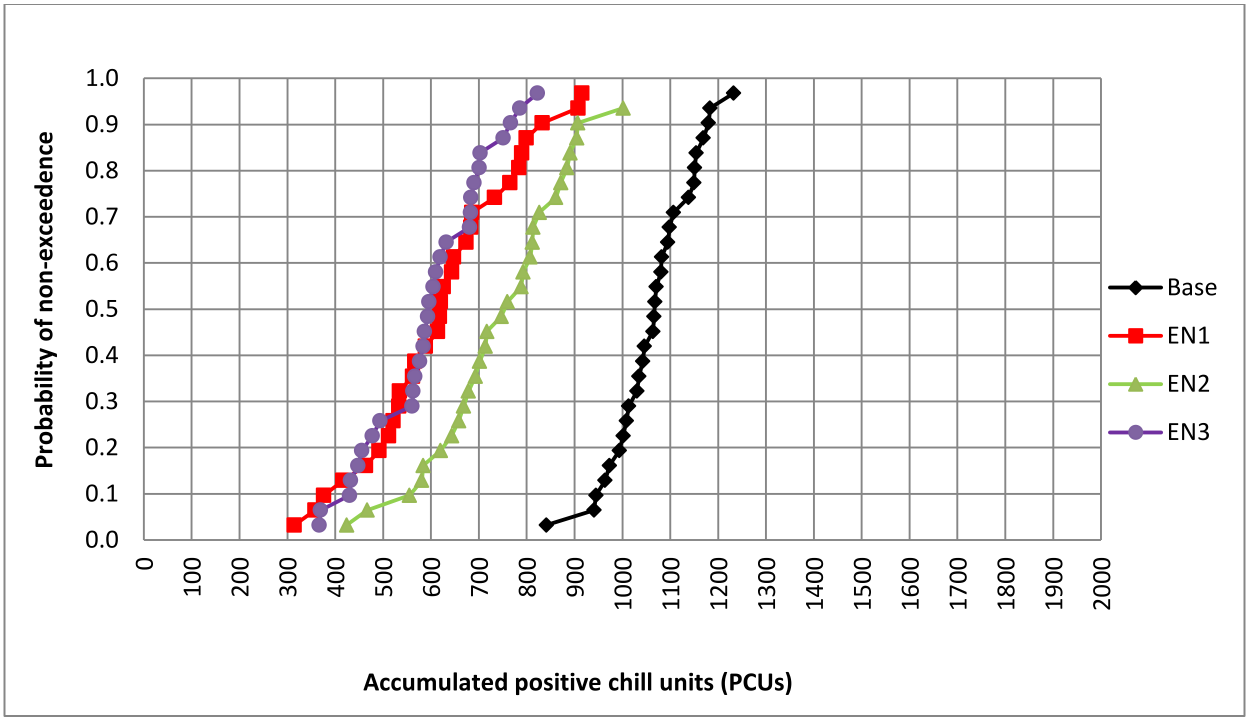

Figure 4.33 Cumulative distribution functions for accumulated positive chill units for Upington for the period 2071 – 2100.

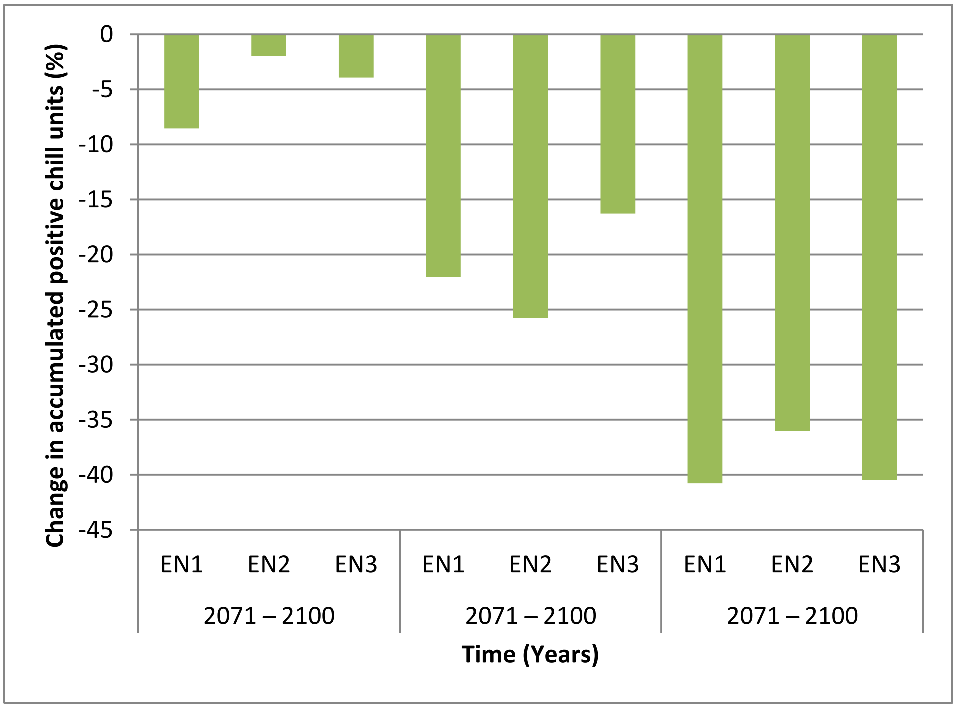

Figure 4.34 Projected changes in accumulated positive chill units for Upington (2011 – 2100).

4.7 GENERAL DISCUSSION

From the results provided in the foregoing sections, it became evident that climate impacts differ regionally and that a single generalised statement cannot hold for all three study areas. It was also clear that the impacts of climate change on accumulated PCUs are not always negative.

The projections indicate that Upington will experience severe declines in accumulated PCUs in future, while Ceres exhibited smaller reductions. It can be argued that this is a direct result of increasing temperatures. In contrast to this, the projections indicated a slight increase in accumulated PCUs for Bethlehem. Here it can be speculated that reductions in accumulated PCUs due to increasing maximum temperatures are offset by chilling gains caused by less frequent frosty conditions. As the century progresses, it is anticipated that Bethlehem will not experience any significant threads in terms of winter chill and deciduous fruit production. Moderate chill requiring fruit types in Ceres will start to experience problems in terms of winter chilling towards 2100. Meanwhile, any deciduous fruit production seems likely to become problematic in Upington over time.

It is important to remember that the number of PCUs received is not the only factor involved in bud break in deciduous fruit trees. The reserves in the tree, post-harvest care and fertilization of the orchard, light interception and temperatures during spring all play an important role in the development of both vegetative and reproductive buds. The efficiency of rest-breaking chemicals and the length of the flowering period are strongly influenced by how quickly temperatures increase during spring and the prevailing conditions prior to and during application. However, other manifestations of climate change not discussed here are also likely to affect deciduous fruit production within these study areas.

CHAPTER 5

CONCLUSIONS AND POTENTIAL ADAPTATION STRATEGIES

South Africa has been exporting deciduous fruit to the Northern Hemisphere for centuries and is regarded as a major supplier during the months of October to August (Huysamer, 1997). Worldwide economic volatility and oversupply of fruit, coupled with an ever changing political climate has created a financial strain to fruit growers in South Africa (Huysamer, 1997). With deciduous fruit production already marginal today (Midgley *et al*., 2005; Sheard, 2008), anticipated problems related to climate change will add more strain to deciduous fruit growers. After establishing a deciduous fruit orchard, trees need to produce fruit for the next 15 – 20 years. For most fruit trees to come into full production can take 2 – 4 years depending on the planting systems. For this reason it is even more important for fruit producers to anticipate and adapt to climate change than producers of annual crops. This study only focused on the impacts of climate change on accumulated chill at selected deciduous fruit production sites in South Africa.

Before proceeding to summarise the main results of the study, it is perhaps prudent to remind the reader of the following limitations:

a) It should be noted that global climate model GCMs cannot be expected to predict the day to day weather accurately for extended periods into the future. Their usefulness lies rather in predicting relative changes in the climatic attributes.
b) The temporal downscaling model was designed to simulate the diurnal variation in temperature under normal conditions and failed to replicate sudden changes associated with frontal passages.
c) The scientific understanding of the complex processes involved in tree physiology still lags far behind knowledge about processes in annual crops (Luedeling, 2012). While winter chill has received a fair amount of research attention, all existing modelling approaches are purely empirical, and there is little reason to believe that their mathematical equations are related in a

biologically meaningful way to tree physiology. The accuracy of existing chill estimation models differs substantially, as indicated by the comparison studies done by Luedeling (2012).

d) Consideration was not given to small-scale climatic differences that exist within the study areas due to topography (e.g. temperatures influenced by altitude, aspect and frost pockets).

e) It should be noted that other manifestations of climate change (e.g. decreasing rainfall, increasing dry spells, enhanced evapotranspiration, more frequent destructive winds, etc.) could also influence deciduous fruit production.

5.1 SUMMARY OF RESULTS

The output from the GCM model was verified against the observed temperature data measured from the weather stations in the study areas. The model exhibited the cold bias across all three study areas. The minimum temperature was under-predicted by less than 1°C in Bethlehem, 4.5°C in Ceres and 4ºC in Upington. The maximum temperature was also under-predicted by about 7°C in Bethlehem, 4.5°C in Ceres and 6°C in Upington (Section 4.2).

The TDM for estimating hourly temperature data from the observed daily minimum and maximum temperatures performed very well with a correlation coefficient of about 0.95 for Bethlehem and 0.94 for Upington (Section 4.3). This model could therefore be applied without reservation to the projected temperatures supplied by the GCM.

Both historical changes in temperature and accumulated positive chill units (PCUs) were analysed (Section 4.4). The historical change in minimum temperatures showed no significant trend for Bethlehem and Ceres, while surprisingly Upington exhibited a decreasing trend. All three study areas revealed a warming trend in terms of maximum temperatures over the historical period (1981 – 2010). The historical change in accumulated PCUs showed no significant trend for Bethlehem, although a clear cyclic pattern was observed. Both Ceres and Upington exhibited a decreasing trend.

Consistent with Global Warming theory, the GCM projections indicated increasing trends in terms of minimum and maximum temperatures across all three study areas

(Section 4.5). Generally, average minimum and maximum temperatures are expected to increase between 2.5°C and 6°C across the study areas by the end of the 21st century.

The GCM projections indicated that Ceres and Upington will experience declines in accumulated PCUs over the course of the 21st century. For one of the ensemble members (EN3) the near-normal range of accumulated PCUs in Ceres shifted from 1 589 – 1 635 over the base period to 1 121 – 1 250 for the period 2071 – 2100. In Upington, one of the ensemble members (EN1) showed a shift in the near-normal range of accumulated PCUs from 1 032 – 1 097 over the base period to 543 – 680 for the period 2071 – 2100. In contrast, Bethlehem is not expected to experience much change, because reductions in winter chill due to warming are thought to result in chill unit gains due to less frequent frost.

5.2 POTENTIAL ADAPTATION STRATEGIES

Based on the literature (Allan & Burnett, 1995; Darbyshire *et al.,* 2011; Luedeling, 2012), the need to expect and adapt to climatic changes is relatively urgent for fruit producers. Strategies that have been used to expand the range of temperate fruit types offer potential applications in adapting production to climate change. Based on the industry review conducted, it could be concluded that within deciduous fruit production there are three main adaptation strategies related to lack of winter chill in South Africa which are discussed below.

5.2.1 Cultivar and rootstock selection

In South Africa most deciduous fruit are produced in areas that are climatically marginal in terms of winter chilling resulting in delayed and uneven bud break. It is well known that each specie has its own chilling requirement, while different cultivars also have their own chill requirement. Aslamarz *et al.* (2009) classified walnut cultivars and genotypes in three groups (low, intermediate and high chill) according to their chilling requirement. This data can be used by producers to select a cultivar for a specific region so that the vegetative and reproductive growths of the cultivar selected are not negatively influenced. Growing a cultivar with low chilling requirements in a cold area will result in early flowering that can be damaged by early or late frost. In a study done by Hawerroth *et al.* (2013) on apple cultivars Royal Gala and Castel Gala grafted on M7 rootstock, it was reported that the two cultivars responded differently to temperature treatments during the winter period. The authors concluded that the buds of Castel Gala (low chilling requirement) will be capable to break even when subjected to higher temperatures, but this did not hold for Royal Gala (high chilling requirement). It is therefore important for any fruit producer to be able to select cultivars that can adapt to changing climatic conditions. Although the breeding and selection of new cultivars are mainly based on export market requirements such as fruit size and colour, the changing climate should also be taken in consideration in future.

Rootstocks is one of the biotic factors influencing fruit quality (Skrzynski & Gastol, 2007) and may influence the performance of a scion (cultivar) such as bud break, time of flowering, fruit size, flesh firmness and the soluble solids concentration of the fruit (Brown *et al.,* 1985; Autio *et al.,* 2001; Jacobs & Cook, 2003). One of the most critical decisions for any producer when establishing an orchard is the selection of the rootstock-cultivar combination. In South Africa the rootstock-cultivar combination has been used to enhance production, while the selection was based on environmental conditions. Due to the export market demand for the bi-colour apple cultivars such as Fuji, Braeburn, Royal Gala and Pink Lady, and pear cultivars such as Forelle, Rosemarie, Bon Rouge and Flamingo, the focus of cultivar selection has shifted away from environmental conditions (Huysamer, 1997).

Culltivar-rootstock combination may also improve bud break of fruit cultivars with a high chilling requirement growing in warm climates (Allan, 2004; Campbell, 2007). El-Sabagh *et al.* (2012) reported that the apple cultivar Anna was significantly influenced by the rootstocks when budded on MM106 and Malus. Anna budded on MM106 had a significant higher percentage of bud break and final fruit set than when budded on Malus rootstock.

A study by Jacobs and Cook (2003) on blushed pear cultivars (Forelle, Rosemarie and Flamingo) on different rootstocks (Quince A, QC51, BP1 and BP3) in three different production areas (Vyeboom, Ceres and Koue Bokkeveld) in the Western Cape did not reveal any trend in fruit maturity time. However, Stadler (1973) indicated that pear cultivars on quince rootstocks (dwarfing) ripens slightly earlier than those on seedling rootstocks. Tompson seedless grapes grafted on 110R had a more uniform and early bud break than when planted on its own roots or planted on Dogridge, 99R, 1103P and St George (Jogaiah *et al.,* 2012).

Anticipated climatic changes coupled with unstable financial systems can be addressed by intensifying interest in new cultivars and more precious and dwarfing rootstocks that are reproductive under low chill conditions (Huysamer, 1997). This is regarded as the most viable approach to adapt to climate change in the deciduous fruit and nut industries. Producers should now consider future agro-climate data, rather than historically observed data during selection for specific areas.

5.2.2 Microclimate management and manipulation

Since winter chill was shown to be a function of air temperature within the crop canopy (Section 2.3), any attempts to increase the accumulated PCUs must necessarily focus on:

- reducing daytime temperatures during warm days; and
- increasing night-time temperatures during frosty conditions.

The latter is however anticipated to become less of a problem under future climate conditions (Section 4.5).

Although the literature abounds with examples of microclimate manipulation in order to increase temperatures within the crop environment (mostly to accomplish frost protection), very little is documented in terms of management practices used to cool the plant environment down. One such example was from South Africa where sprinkler irrigation was applied to table grapes in the Upington and Blouputs areas (Allan & Hatting, 1998; Allan, 2004). The rationale was that the resultant evaporative cooling will ameliorate mild to warm daytime temperatures. From the trials conducted by Allan (2004) it was concluded that evaporative cooling should start when day temperatures rise above 16°C, provided night temperatures were below 12°C. Ideally, sprinkling cycles should be long enough to wet all the buds effectively, and the off time should be short enough to prevent bud temperatures rising too high. This practice brought about an earlier and improved bud break and an increase in the number of bunches produced during the early, high price period in November (Allan & Hatting, 1998). Allan (2004) also reported that the combination of evaporative cooling and chemical rest-breaking agents like Dormex raised bud break to over 80%, compared to 50% for Dormex alone and 0% without any treatment.

As an outcome of the good results achieved by Allan & Hatting (1998), evaporative cooling has been applied by farmers in the Northern Cape on a large scale since then. The industry review conducted by telephonic interviews supported this information (North[1] & Huysamer[2], 2015, Personal communication). It must be noted, however, that good results or increase in yields cannot be obtained every year and that evaporative cooling is merely used as a form of insurance in case of insufficient chilling during May and June.

In addition, future research could investigate the efficiency of the following microclimate management practices:

- Site selection

  Historically, many orchards in frost-prone areas have favoured sites along the middle of a hill slope as such areas are less prone to suffer from severe frost (Wolf & Boyer, 2001). Under a future warmer climate where frost may become a smaller problem in relation to reduced chill, orchards may be moved to locations further downhill where colder night-time temperatures are observed. South facing slopes may also become more popular as they are generally cooler due to lower levels of solar radiation.
- Row spacing and alignment

  This influences the amount of solar radiation reaching the lower canopy and surface due to shading. If rows are planted east-west the shading will be higher (HortResearch, 2015), which can be helpful in decreasing daytime temperatures.

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Increasing the spacing between trees may also result in less trapping of outgoing long wave radiation, thereby cooling night-time temperatures.

- Artificial shading

  Nets or shade cloth, similar to the ones currently used in Bethlehem to protect against hail damage, can be used to reduce the amount of solar radiation reaching the surface, which in turn should result in lower daytime temperatures. However, such nets will also lead to higher night-time temperatures due to them trapping the outgoing long-wave radiation. If the nets can be retracted by night it could be beneficial. Such a technique was employed by Tanny *et al*. (2009) over apple orchards in northern Israel.
- Albedo control

  The use of mulches with a high reflectivity could lower the absorption of incoming solar radiation, thereby cooling daytime temperatures.

It should be noted that apart from the use of evaporative cooling, the microclimate management practices listed above are purely speculative and should first be tested under field conditions.

5.2.3 Chemical rest-breaking

Due to the fact that delayed foliation is a common problem associated with uneven chilling in Bethlehem and Ceres, the problem is addressed by the use of rest-breaking agents such as dinitro-ortho-cresol or winter oil (Huysamer, 1997). There are other rest-breaking chemicals which are widely used to compensate for insufficient bud break in others parts of the world and for promotion of homogeneous fruit set. Rest-breaking agents can only compensate for a limited amount of chill. A number of chemicals have been found to promote bud break, for example mineral oil, giberellic acid (GA), potassium nitrate (KNO_3), Thiourea, hydrogen cyanamide (H_2CN_2) and fatty acids (North, 2003; Noppakoonwong *et al*., 2005; Erez *et al.,* 2008; Sheard, 2008). However, most of these chemicals used as rest-breaking agents may result in phytotoxic damage to fruit buds resulting in poor fruit set when applied at the wrong time, but some have been very successful in breaking dormancy, even when chilling requirements were not fulfilled (Erez *et al.,* 2008).

Sheard (2008) reported that insufficient winter chilling is a major factor limiting the production of high-chill stone fruits such as sweet cherries. Typical symptoms are delayed vegetative and floral bud breaking, floral abortion and bud drop resulting in poor flowering and fruit set (Sheard, 2008). Prolonged dormancy has become an obstacle to the economic production of sweet cherry cultivars such as Bing in Bethlehem (Faust, 1989). Sheard (2008) conducted experiments in four year old commercial cherry orchards over two seasons near Clarens and Reitz in the eastern Free State. The experiments were conducted in 2005 and 2006 on Bing trees grafted on Gisela rootstock. During this study the rest-breaking agents used were Dormex® (hydrogen cyanide 250 µmol L^{-1}), Lift® (thidiazuron 3 g L^{-1} in mineral oil) and Budbreak 5951 (869.3 g L^{-1} in mineral oil). During the trials period all the trees showed symptoms of delayed foliation due to lack of winter chilling caused by warm winters in the area (Sheard, 2008). All the rest breaking agents used improved bud break and all treatments showed increased fruit density and production efficiency as compared to the plots that was not treated with any rest breaking agent. Sheard (2008) concluded that the use of rest-breaking agents was effective in improving bud breaking and increasing yield of the sweet cherry cultivar Bing.

The production of table grapes in warm regions of South Africa such as Upington is associated with delayed and uneven bud break. Hydrogen cyanamide (H_2CN_2), a rest breaking agent is mainly used to overcome this problems in table grapes. In a study conducted by Avenant and Avenant (2014) on sultanina and sugarone in different table production regions of South Africa, it was found that hydrogen cyanamide can be used not only to improve bud break but also to ensure a more even bud break in regions receiving less than 400 chill units. It is clear from this data that although this practice will increase the production cost it can be used to overcome problems due to inadequate chill.

Most deciduous fruit such as apples and pears in South Africa is produced in areas which are climatically marginal in terms of winter chilling, resulting in delayed bud break. DNOC-winter oil was used with success in the past on apples and pears to overcome the problem of delayed bud break. DNOC is extremely toxic to man, harmful to the environment and was withdrawn from the market. The fruit industry was forced to search for more eco-friendly rest breaking agents that is cost efficient. Hydrogen cyanamide (Dormex®) at low concentrations and winter oil are used on apples. Thidiaxuron (Lift®) in an oil base can be used on apples, pears and cherries (Costa *et al.,* 2004).

It is clear from the above discussion that application of chemical bud breaking agents, when done correctly, can be very efficient in overcoming bud break problems. This is one of the main adaptation strategies currently used and its application will become more prevalent in future.

5.3 CONCLUDING REMARKS AND RECOMMENDATIONS

Based on the overall results of this research, it was clear that climate metrics such as winter chill units are influenced by climate change. Therefore, deciduous fruit production is anticipated to be influenced by potential changes in winter chill units in at least two of the study areas.

The economic cost of climate change, which is expected to be incurred by fruit farmers, could be substantial and devastating in Ceres and Upington. Producers in these two areas may be confronted with the decision either to abandon their production or adapt to altered climatic conditions. This is not good news for the local economies which rely heavily on agriculture, although some services may thrive in the face of adversity (e.g. providers of rest-breaking chemicals). Fortunately, adaptation strategies already exist and are successfully applied in South Africa. However, almost all of the adaptation strategies mentioned in the previous section are relatively expensive and could be economically unviable for some.

It is recommended that further research be conducted on climate change impacts on deciduous fruit production throughout the region. This includes not only the development of more refined modelling techniques, but also a focus on other climatic variables. The application of bias-correction could also be investigated with respect to Global Climate Model data.

A better understanding of the biological basis for chilling is needed in order to develop better models that relate environmental factors to the yield and phenology of fruit. A clear research drive towards viable adaptation strategies should also be embarked on. This includes investigations on microclimate manipulation of the plant environment, a renewed emphasis on breeding techniques and the development of environmental friendly rest-breaking agents. The future of the South African deciduous fruit industry will be guided by new plantings which will be more site-specific regarding fruit type, cultivar, rootstock and training systems, because marginal environmental conditions will have an increasingly severe impact on profitability. Close attention must be paid to growing the right trees in the right places, or equipping farmers with an arsenal of management tools to overcome slight mismatches of cultivar and climate.

The deciduous fruit farmers must be assisted to better prepare for the potential impacts of climate change. This can only be done with the assistance of Government in the form of well-informed extension personnel who can advise them accordingly. Information can be delivered to extension officers, farmers and other industry stakeholders by means of so-called “climate field schools” (Stigter & Govind, 2010) where scholars will have the opportunity to assess farmers’ vulnerabilities and convey pertinent information to the target groups concerned.

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