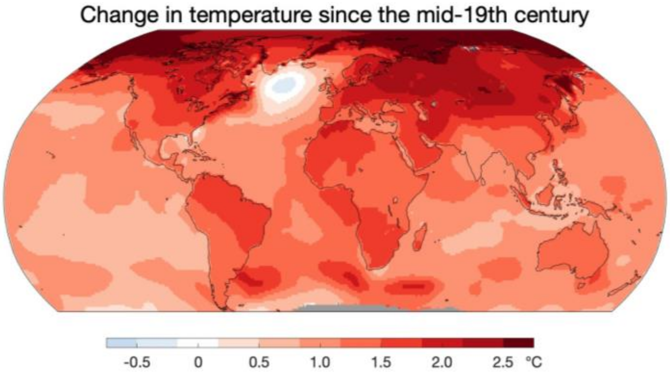
Scientific and Practical Guide to Climate Change and Pome/Stone Fruit Production in South Africa

Part 1: Atlas of Key Climate-Related Variables for Historical and Future Climate Conditions as Relevant to Pome and Stone Fruit Production

April 2021



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LIST OF FIGURES

LIST OF TABLES

LIST OF BOXES

Contents

CHAPTER 5

IMPACTS OF CLIMATE CHANGE ON FRUIT PRODUCTION AND FRUIT QUALITY

CHAPTER 1

INTRODUCTION, AIM AND SPATIAL SCOPE

1.1 Introduction

The year 2020 was tied with 2016 as the hottest years globally since measurements began. This is extremely worrying, since the five warmest years in the period 1880-2019 have all occurred since 2015, and 9 out of the 10 hottest years have occurred since 2005. The world's climate is changing fast because of human activities causing steady increases in atmospheric concentrations of greenhouse gases such as carbon dioxide, methane and nitrous oxide. The observed (and scientifically verified) changes can no longer be ignored and are set to continue over the next few decades. The questions for South African agriculture are: What does the climate of the foreseeable future look like? What aspects of climate are changing the fastest and pose the most risk to farming? What can farmers do about it?

Pome and stone fruit growers in South Africa are already experiencing the impacts of rising temperatures and increasingly unpredictable seasonal weather patterns. The recent evidence lies in more years with low rates of winter chill accumulation, a sequence of years with low fruit set in spring associated with erratic weather patterns, high sunburn incidence in summer, and poor red colour development in autumn. Shifts in rainfall patterns have been observed and the severe drought of 2015-2018 had significant negative impacts on the pome and stone fruit industries. More warm spells, and at times record heat, have caused more rapid soil drying and have increased the irrigation demand. These changes are depressing the commercial pome and stone fruit production potential and profitability. While climatic challenges have always existed, the scientific consensus is that climate change is a 'threat multiplier', i.e. it increases the likelihood and severity of such events. Over time, unless measures are taken, climate change could threaten the sustainability of the sector.

The pome and stone fruit industries need to overcome these climatic barriers and become more resilient by adapting to the changing climate. Timeous planning can also help growers to identify opportunities that climate change may offer. Effective adaptation can minimise the impacts on orchard operations, productivity and profitability; protect farm infrastructure, long-term investments and livelihoods; and help to grow the industry in the face of this and other threats. This requires a good understanding of the trends and future projections of key climatic variables and their impacts on fruit production.

1.2 Aim of the Guide

Although there is a large body of scientific knowledge on climate change available globally and in South Africa, it is not generally accessible to growers and technical advisors and is seldom useful for on-farm decision making. It is hoped that this Guide will become the 'go-to' source of spatial information on climate change risks, impacts and adaptation options for pome and stone fruit growers and technical advisors in South Africa. The aim is to provide a reliable science-based yet practical source of information to guide planning and adaptation for the next 30 years. Ideally, this should be seen as a 'living' document, with regular updating.

While the primary focus is on the farm and the production end of the value chain, the Guide can also be useful to input suppliers, packers, processors, marketers, retailers, regulators, water resource managers, researchers, and industry leaders.

The Guide can be used to:

- Collect baseline (present situation) climate information (e.g. to sense check current crop suitability in specific areas)
- Identify farm / business climate-related risks and opportunities
- Identify specific adaptation options for specific risks
- Inform a farm / business plan or strategy
- Inform investment decisions relating to the farm / business
- Inform strategic engagement between growers, their advisors, and the value chain
- Inform a fruit marketing strategy
- Inform applications made to Government as required by legislation e.g. (land use changes, water license applications)
- Inform a disaster risk reduction & management plan for a farm / business
- Inform industry-wide negotiations with export markets regarding fruit quality requirements (e.g. minimum red blush)
- Inform an industry-wide Climate Change Response Strategy
- Identify further impacts and adaptation related research needs for the industry
- Lobby politicians and financiers to better support an urgent response to dealing with climate change at local, national and international levels.

1.3 Spatial scope

This Guide is intended for pome and stone fruit growers and their technical advisors across South Africa. The section on observed (historical) trends in key climate parameters begins with results for the whole country. Equally, modelled projections of future temperature, rainfall and chill accumulation are provided at national scale. Nevertheless, for this first version, detailed modelling and mapping results focus on the Western Cape Province and the entire Langkloof valley. This region accounts for more than three-quarters of national pome and stone fruit production. Future versions of the Guide could extend the focus to other production regions across the country.

The Western Cape - Langkloof has a diversity of altitudes (from sea level to ~ 2 000 m above sea level, Fig. 1), complex mountain topography, a variety of soils, and strong oceanic influences of the Atlantic and Indian Oceans. Annual rainfall varies from around 120 mm/year in the semi-arid summer rainfall regime in the north-east Karoo, to more than 1500 mm/year in the Jonkershoek mountains of the south-western winter rainfall region (Fig. 2). Rainfall across the region is produced by three main weather processes: frontal systems, orographic rainfall (on windward mountain slopes) and convective thunderstorms. In the coastal plains and mountains, rainfall is associated primarily with cold fronts making landfall in the winter. The mountains act as a barrier to these frontal systems so that high rainfall is recorded on the west- and south-facing mountain slopes. Rain shadows form on the eastern and northern slopes, resulting in much lower rainfall in these areas (Fig. 2). Rainfall seasonality shifts from predominantly winter rainfall in the west to rainfall more evenly spread throughout the year in the coastal south-east. The higher-lying semi-arid interior experiences a continental climate and predominantly summer rainfall in the form of afternoon thunderstorms. This region is prone to frosts during the colder months. Together with wide-ranging temperature regimes and soils, the rainfall patterns give rise to a very diverse agricultural production potential.

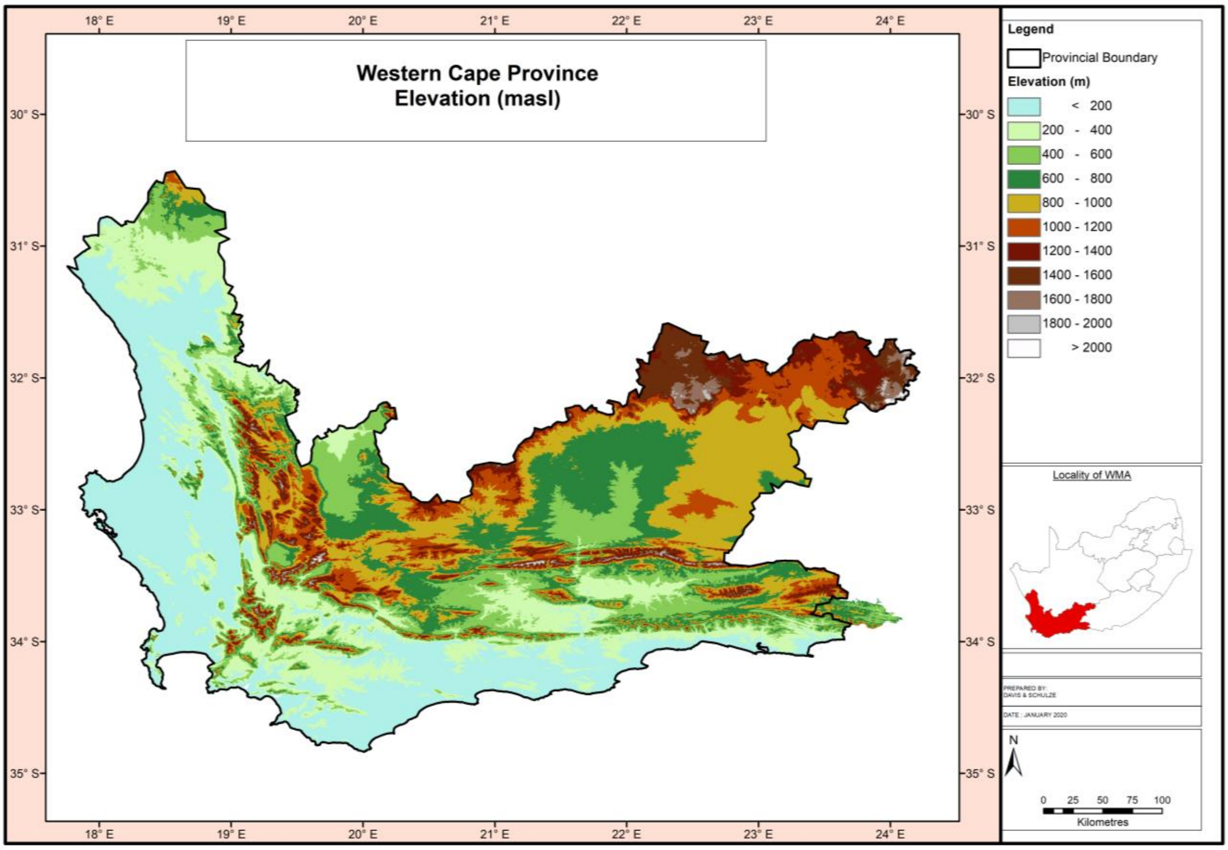

Figure 1. Location of the Western Cape Province – Langkloof region and its elevation.

All pome and almost all stone fruit orchards are irrigated. In the south-western production regions of the Western Cape (Berg River and Breede River catchments and the western Overberg), water for irrigation is provided by the large public dams connected to the Western Cape Water Supply System, private dams and the rivers and their tributaries. Other regions such as the Bokkeveld, Piketberg, Klein Karoo and Langkloof are reliant on local dams and sometimes groundwater. In most areas, assurance of water supply is a significant risk to agriculture.

The highly variable climate means that agricultural systems are already well adapted to the variability of the weather within and between seasons and years. Local climate is a vital criterium for the selection of appropriate fruit types and cultivars for a given locality. The more detailed the knowledge, the more intelligently the land use can be planned at the farm or orchard scale. Subtle microclimatic differences on farms result from differences in elevation and aspect, and the influence of water bodies and mountains. Together with different soil types, these are used to good effect by growers when making crop and cultivar planting decisions and can provide opportunities for adapting to climate change (interested readers are referred to the TerraClim tool[1]). Such micro scale variables are beyond the scope of this Guide, which will focus on larger land units as described in section 3.2.2, and projections of future climate changes.

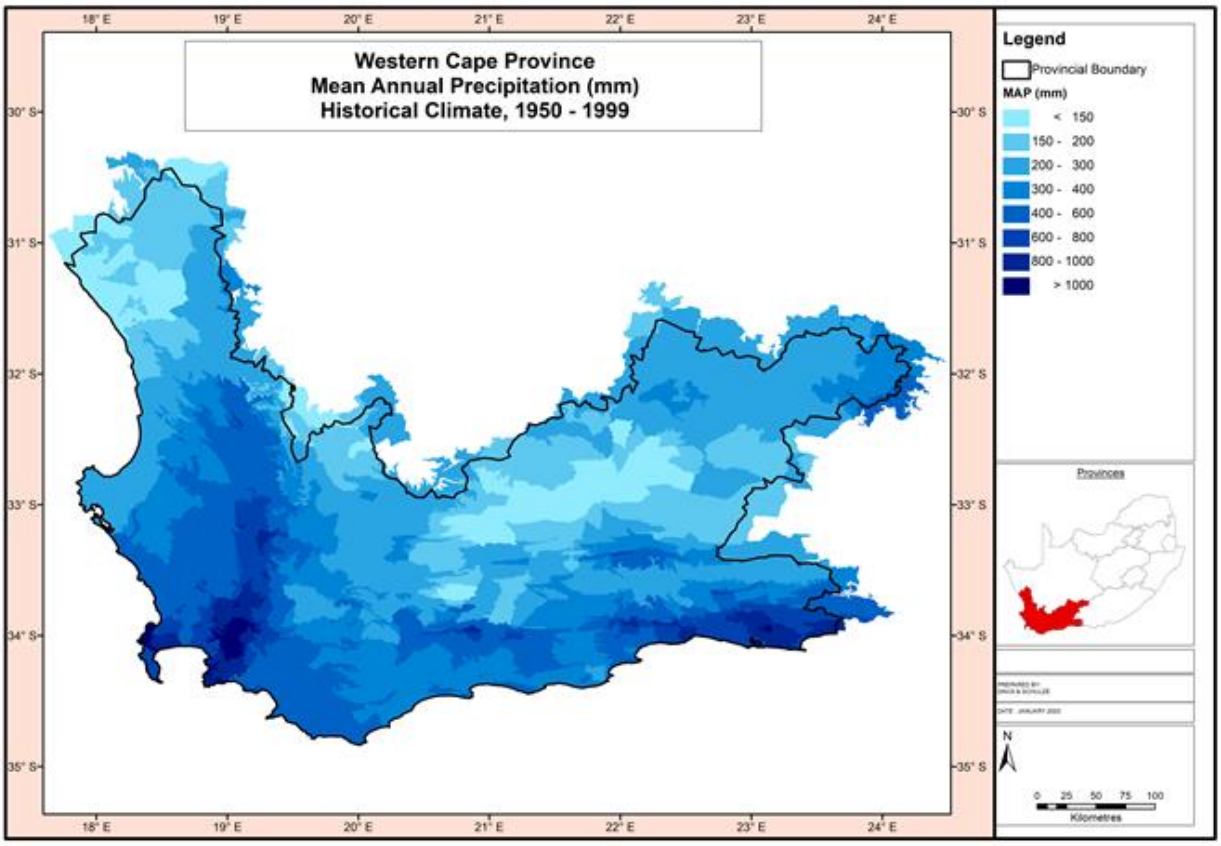

Figure 2. Mean annual precipitation (mm) of the Western Cape - Langkloof region under historical (1950-1999) climatic conditions.

Climate information is as important for longer-term agricultural planning (e.g. cultivar selection) as it is for day-to-day operational planning and decision making such as irrigation scheduling and the spraying of various chemicals including rest-breaking and fruit thinning agents. The influence exercised by climate on living organisms is, however, exceedingly complex, not only because the individual climatic variables play important roles, but also because of the constant interaction between the variables. This should be borne in mind by the users of this Guide.

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[1] https://terraclim.co.za

CHAPTER 2

THE POME AND STONE FRUIT INDUSTRY

2.1 Value of the pome and stone fruit industries

The growth potential of the agricultural sector in South Africa is well recognized. Between 2007 and 2017, the income from commercial agricultural production increased by 288% reaching R332,8 billion (Statistics South Africa, 2020). Nevertheless, several challenges facing the sector are significant and must be understood to aid planning and investment decision making for the next decade (BFAP, 2019) and beyond.

South Africa has a mature and profitable horticultural sector with a value of R70,5 billion in 2017 (24% income share within agriculture) at a national level (Statistics South Africa, 2020). Citrus, table grapes, pome and stone fruit form the backbone of the fruit sector. The focus of this guide is on pome and stone fruit production in South Africa, which has an annual turnover of R11,59 billion from just over 54 000 planted hectares (in 2018) across the country (Hortgro, 2019a). Pome fruits include apples and pears, whereas stone fruits include apricots, peaches, nectarines, plums, prunes and cherries. Apples (45% of hectares) and pears (23% of hectares) contribute R8,94 billion, whereas stone fruit (32% of hectares) contribute R2,64 billion of annual turnover. Both pome and stone fruit production are highly export-focused, with 45% of the total production exported (Hortgro, 2019a). Africa and Europe are the primary export markets for apples and pears, whereas stone fruit are exported mainly to the United Kingdom, Europe and the Middle East. Quality standards for export fruit are exceptionally high. The following sections summarise some of the key risk factors that contribute to reduced earnings.

The main apple cultivars grown include Golden Delicious (yellow), Royal Gala (blushed), Granny Smith (green), Cripps Pink/Pink Lady® (bi-colour), Topred/Starking (red) and Fuji (blushed). The high-value red, blushed and bi-coloured club cultivars (e.g. Pink Lady®, Cripps Red/Joya®, Big Bucks, Kanzi) are the fastest-growing. Sensitivity to poor red colour development under stressful climatic conditions varies widely but is one of the most important reasons (together with sunburn damage) for poor grading and low prices. Green and yellow apples are more prone to sunburn, but cultivars such as Fuji are also susceptible. The winter chilling requirement varies widely between cultivars but is generally high for apples. Insufficient chill leads to poor flower bud quality and weak and uneven bud break in spring.

The most commonly grown pear cultivars are Packham's Triumph (green), Forelle (blushed red) and Williams Bon Chretien (yellow). New high-value red/blushed cultivars such as Cheeky® are becoming popular. Pears also suffer from sunburn and poor red colour at harvest in some blushed cultivars. The chilling requirements of pears are slightly lower than for apples, but insufficient chill accumulation is a problem in some areas.

A very wide variety of stone fruit cultivars is grown in South Africa. These fruits suffer from many potential external and internal defects. While red colour development is not a general problem, sunburn damage is a problem for some cultivars, especially the yellow plums. Insufficient chill accumulation can be an issue for some cultivars (e.g. older cherry cultivars) and in some production regions.

2.2 Pome and stone fruit production regions of South Africa

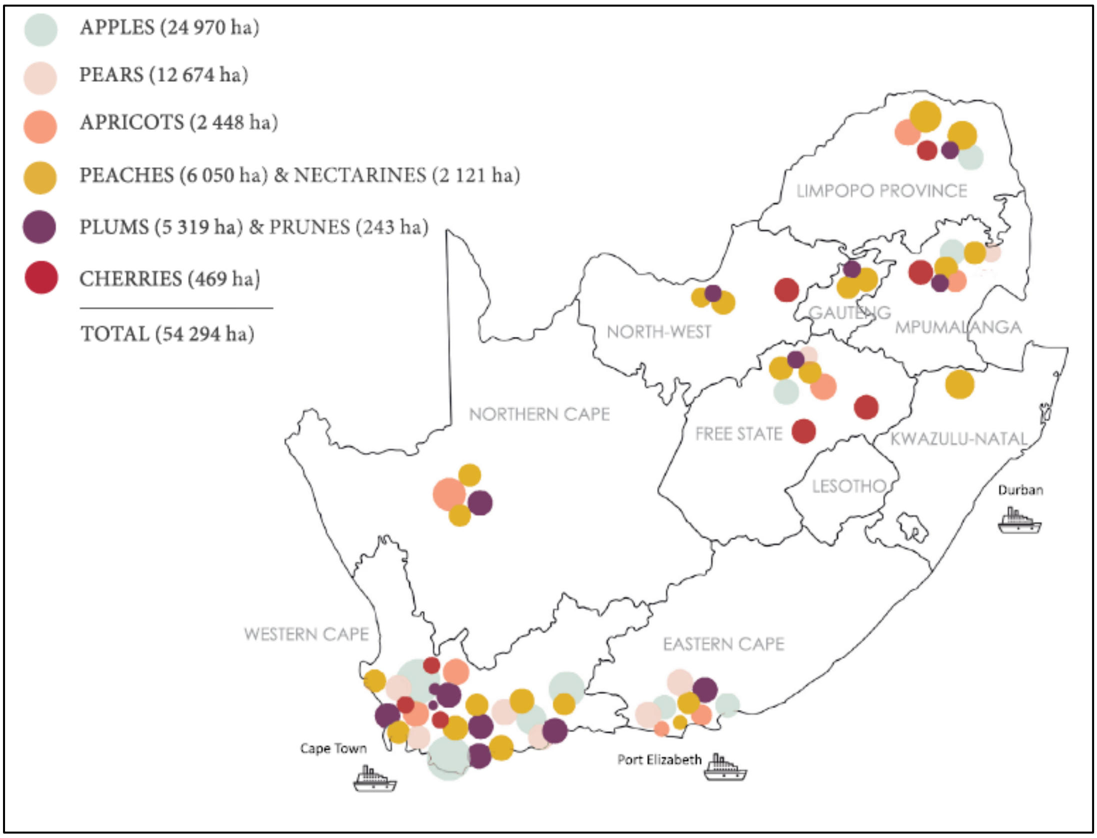


Figure 3. Stone and pome fruit production regions of South Africa. From Hortgro Key Deciduous Fruit Statistics (2019a).

The distribution (suitability) of tree fruit species is determined mostly by temperature regimes, as indicated by mean annual temperature, the maximum and minimum temperature at which growth can occur and injury is avoided, and the accumulated chilling requirement. For fruit species with a high chilling requirement, the mean daily minimum temperature of the coldest month can be a good indicator of climatic suitability. Air relative humidity, rainfall distribution, wind, and the incidence of solar radiation are also important climatic factors, together with soil type.

In South Africa, pome fruit is primarily grown in the Western Cape, Langkloof, eastern Free State, Mpumalanga and Limpopo (Fig. 3). The distribution of stone fruit orchards is wider, across all the provinces.

The first edition of this Guide focuses on the core southern production regions of the Western Cape Province and the Langkloof valley portion in the Eastern Cape Province. More than 96% of pome fruit and more than 70% of stone fruit are produced in these regions (Hortgro, 2019a).

Apple and pear production is concentrated in the regions marked "Pome" and "Mixed" in Fig. 4. These regions are characterised by colder winters, that are essential to fulfil the chilling requirements of pome fruit, and warm summers, and have sufficient water resources for irrigation.

For apples, the main production regions include the Koue and Warm Bokkeveld around the town of Ceres (region #3), the Elgin-Grabouw-Vyeboom-Villiersdorp (EGVV) region (#7), and the Langkloof valley (#6). Other production regions include Piketberg (#4), Somerset West (#8), Riviersonderend (#9) and the Klein Karoo East and West (#1,2). The Klein Karoo East is the area around Calitzdorp and Ladismith, whereas the Klein Karoo West is the area between Koo and Barrydale. The Koo valley has a higher altitude than Montagu-Barrydale and is cooler and milder in many respects, more similar to the Warm Bokkeveld in the southern part of the Ceres region.

Pears are grown primarily around Ceres (#3) and the adjacent Wolseley-Tulbagh area (#5), EGVV (#7), Langkloof (#6) and the Klein Karoo (#1,2). Pears also require colder winters (although generally less so than apples) but favour warmer daytime temperatures during the growing season. Smaller production regions include Piketberg (#4), Somerset West (#8) and Riviersonderend (#9).

Stone fruit production is concentrated in the warmer and drier parts of the country and the Western Cape – Langkloof region (Figure 3). A high proportion (>90%) of the country's apricots, cling peaches, nectarines and plums are grown in the Western Cape and Langkloof (Fig. 4). The specific areas include the Klein Karoo (#1,2), Ceres (#3), Piketberg (#4), Wolseley-Tulbagh (#5), Breede River valley (#11), the Berg River valley and adjacent Stellenbosch area (#10), and the Langkloof valley (#6).

Of the country's hectares planted to dessert peaches, about 70% are found in the Western Cape: Ceres (#3), Klein Karoo (#1,2), Piketberg (#4), Wolseley-Tulbagh (#5) and Berg (#10). Important production regions to the north (outside the scope of this guide) include the North-West, Free State, Gauteng, Limpopo and Mpumalanga Provinces (Fig. 3). Cherry plantings have grown strongly over the past decade, and whilst 60% of planted hectares are in the Western Cape - Ceres (#3) and Breede valley (#11) - significant plantings can also be found in the Free State, North-West, Gauteng, Mpumalanga and Limpopo. Modern cherry cultivars have a reduced chilling requirement compared to the older high chill cultivars previously available in South Africa. Many new production regions have opened up to this high value crop.

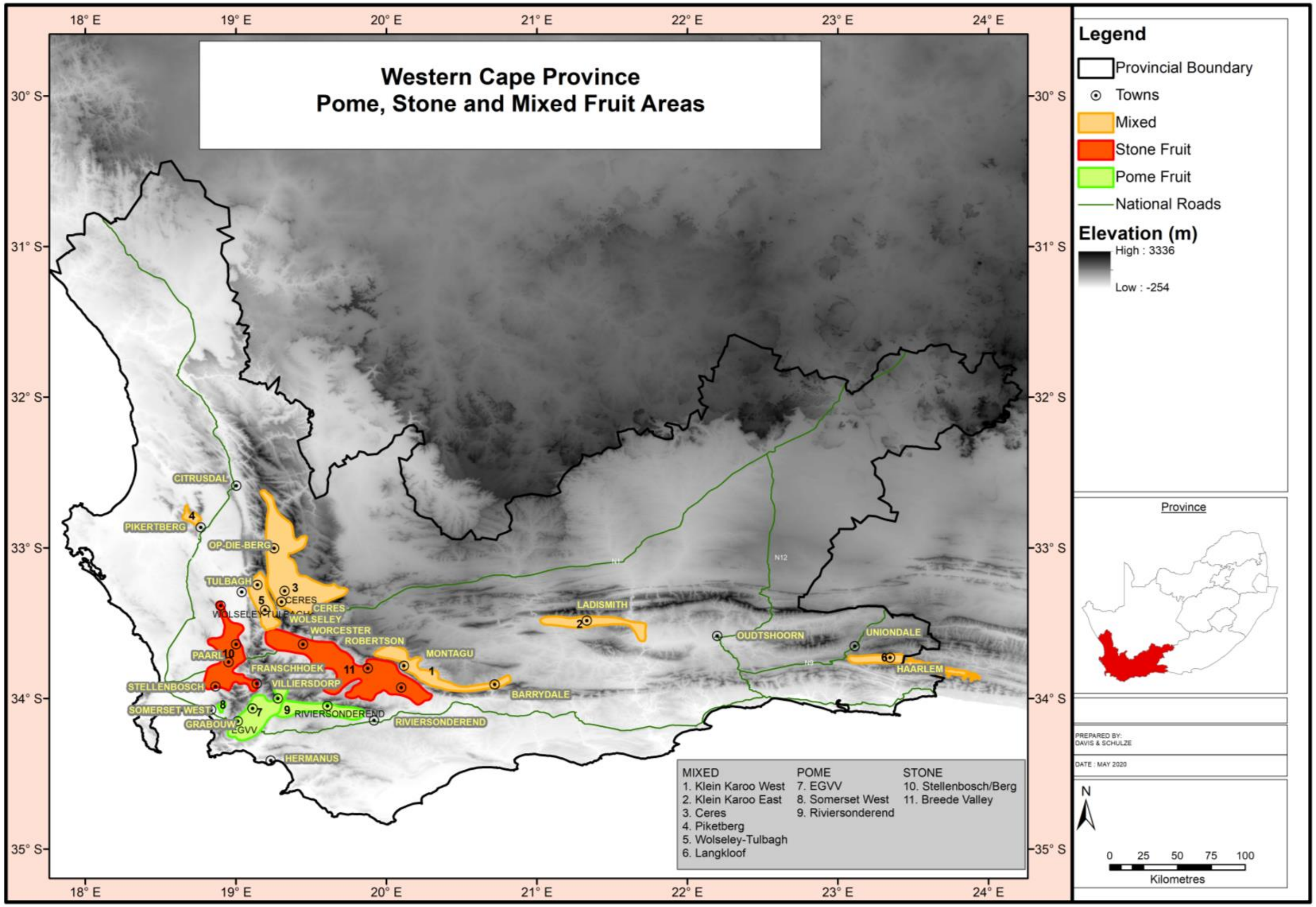


Figure 4. Pome and stone fruit production regions of the Western Cape and eastern Langkloof valley in the Eastern Cape. Based on data provided by the Western Cape Department of Agriculture (2018 fly-over database), and Google Earth (eastern Langkloof).

2.3 Production trends and setbacks, and production projections

Trends over the last few years indicate that pome fruit hectares and volumes have been under pressure (BFAP, 2019). Severe impacts of the prolonged drought in 2015-2018 led to decreases in hectares and volumes, especially in 2017/18. The apple and pear harvests declined by 11-12% in 2018. However, in both crops, the total value of production remained high in 2018 owing to good prices and a favourable exchange rate which compensated for the lower volumes (Hortgro, 2019a). While rainfall returned to more normal patterns in 2018/19, hot and windy conditions during the flowering period (October 2018) impacted negatively on pome fruit quality and, in some cultivars, yields were also affected.

Within the stone fruit sector, apricots and peaches are slowly declining in terms of hectares and volumes, a trend driven by market shifts as well as drought impacts. The drought resulted in a reduction of 25%, on average, of apricot export volumes in the period 2013/14-2017/18 compared to 2008/09-2012/13 (BFAP, 2019). Peaches and nectarines are increasingly marketed for export, fetching good prices, rather than for local sales which have decreased. Plum production has been expanding, with much of the planting replacing other fruit types such as apricots, peaches, and wine grapes. The drought led to a significant reduction in plum volumes in 2017/18. Nevertheless, plum production is expected to show strong future growth (BFAP, 2019). Cherry plantings have increased the area under production from 166 to 388 ha between 2013 and 2018 (Hortgro, 2019a), with a 30% increase in planting from 2017 to 2018. The drought had a strong impact on cherry volumes in both 2016/17 and 2017/18.

Even after more normal rainfall returned in 2018, “the knock-on effect of the drought had a huge impact on the quantity and quality of the 2018/19 crop” (Hortgro, 2019b). Moreover, the drought has not ended everywhere, with the Klein Karoo still experiencing severe impacts. These factors, combined with a heatwave during October 2018 resulted in a year-on-year decreases in export volumes in 2018/19 of 21% for apricots, 5% for nectarines, and 15% and 14% for peaches and plums, respectively (Hortgro, 2019b). To make things worse, especially for plum production, prolonged unseasonal warm spells during spring 2019 caused a severe reduction in fruit set and harvested volumes.

Climatic challenges are depressing the growth potential of large sections of the pome and stone fruit industries and are threatening sustainability over the longer term. Some of these challenges arise from a mismatch between the genetic potential of the current set of cultivars and rootstocks and the current climate of South Africa. Problems such as insufficient winter chill have always existed in certain warmer regions. On the other hand, increasingly variable weather patterns and unpredictability of the seasons, together with more frequent and more severe extreme weather events evident over the last 10-20 years, are exacerbating the existing climatic barriers. The scientific consensus is that climate change is a ‘threat multiplier’, i.e. it increases the likelihood of such events occurring. For example, the 2015-2018 drought in the Western Cape was three times more likely to occur because of the human influence on climate change (Otto et al., 2018). If the pome and stone fruit industries are to overcome these climatic barriers and adapt to the changing climate in order to remain profitable and competitive, a better understanding of the trends and future projections of key climatic factors and their impacts on pome and stone fruit production is needed.

CHAPTER 3

SETTING THE SCENE

In this chapter, some background information is provided on observed climate trends in South Africa and, more specifically, the Western Cape; on the approach used to model and map the future climate and some key impacts on pome and stone fruit production; and on key concepts used when assessing adaptations to climate change risks and impacts. This will provide the basis from which the following chapters will present specific climatic changes and their impacts, and how growers can respond.

3.1 Observed climate trends

3.1.1 Observed global climate trends

The effects of climate change resulting from steady increases in atmospheric concentrations of carbon dioxide (CO_2) (Fig. 5, top) and other greenhouse gases such as methane (CH_4) and nitrous oxide (NO_x) can no longer be ignored. Human emissions of these gases are unequivocally responsible for the steady increases in global temperature since the 19th century (Fig. 5, bottom). It is small wonder, therefore, that globally the five warmest years in the period 1880-2019 have all occurred since 2015, and 9 out of the 10 hottest years have occurred since 2005.

Moreover, across the globe, the annual numbers of cold days and nights have decreased, and the numbers of warm days and nights have increased since about 1950. Warming has also led to changes in temperature extremes and more frequent and prolonged heat waves. Although shifts in rainfall patterns are highly complex and vary by region, in many parts of the world the number of heavy precipitation events over land have increased.

3.1.2 Observed climate trends in South Africa and the Western Cape

The most recent national level analysis of climate trends (DEA, 2018) found that the largest warming trends have occurred over the drier western parts of the country (Northern Cape and Western Cape) and in the northeast (Limpopo and Mpumalanga, extending to the east coast of KwaZulu-Natal), as well as Gauteng (although this may have elements of an urban ‘heat island’ effect). The South African Weather Service (2016) stated that the countrywide trend in mean annual temperature from 1951 to 2015 was approximately 0.14°C per decade. For that period, the global trend was just under 0.1°C. More detailed information on the impacts and risks of climate change in Southern Africa can be found in the publication "Climate Risk and Vulnerability: A Handbook for Southern Africa" (Davis-Reddy and Vincent, 2017).

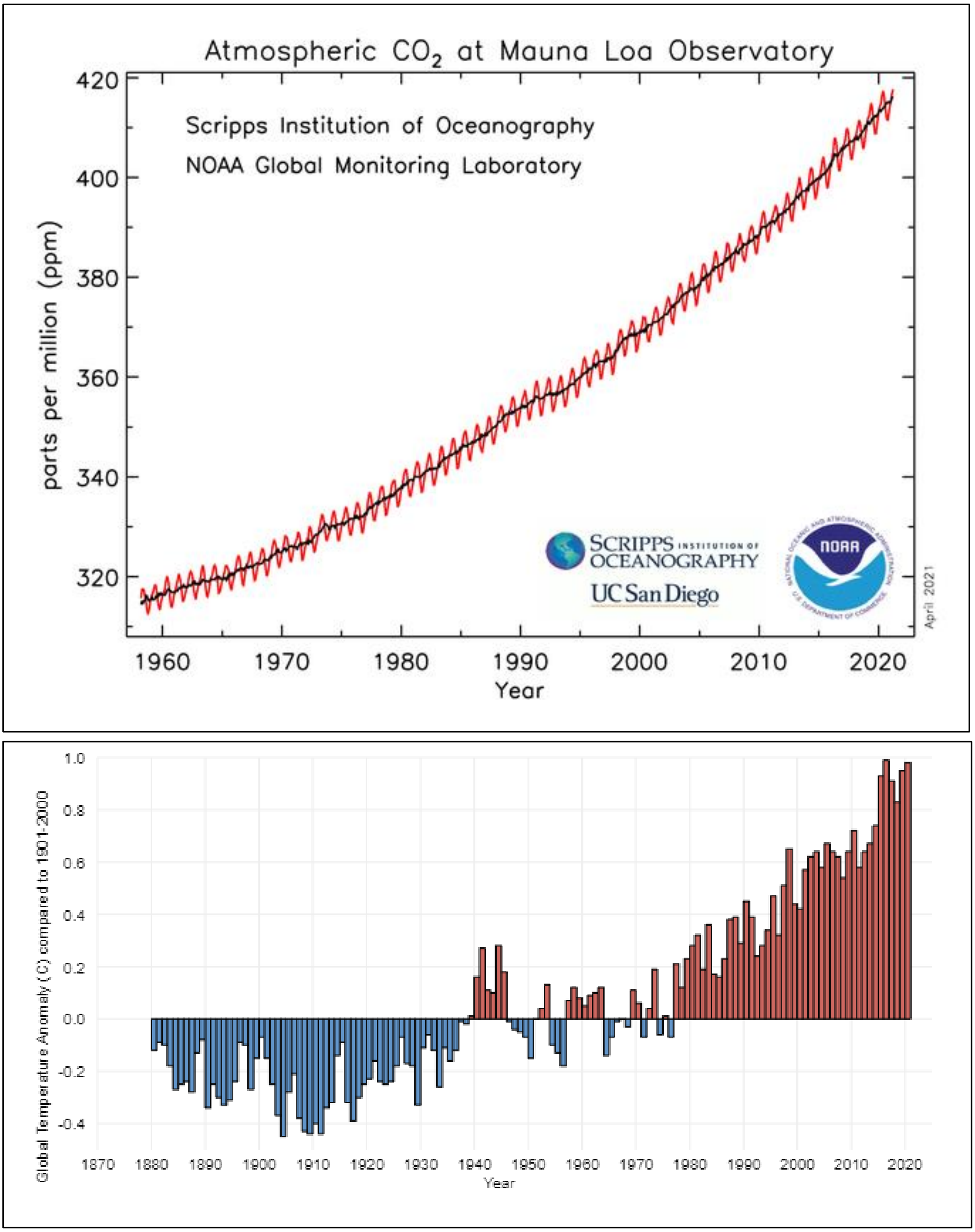


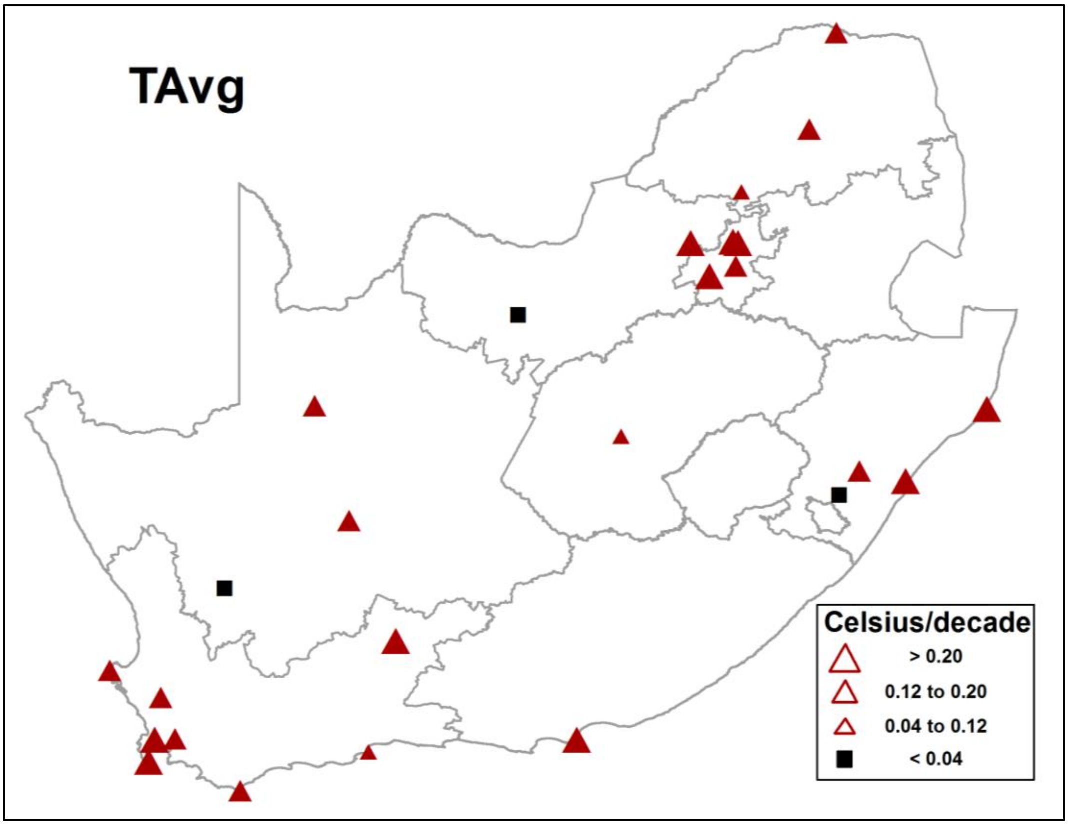
Figure 5. Measured changes in atmospheric CO_2 concentrations (in parts per million) in the recent past until April 2021 (top), and observed global temperature differences (anomalies) from 1880 until 2020 relative to the 20th century average (bottom). (Sources: https://www.esrl.noaa.gov/gmd/ccgg/trends/ and https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature)

The Western Cape has experienced a substantial rate of temperature increase at approximately 0.2°C per decade at several locations (Fig. 6, top), as recorded over the 1931-2015 period. Daytime maximum temperatures have increased steadily. Extreme warm events have also increased, such that the number of hot days has risen at a rate of about one day per decade. What is equally significant for pome and stone fruit production is that the mean annual minimum temperature has increased by approximately 0.15°C per decade (Midgley et al., 2016a) and the number of cold nights has decreased at approximately 1.5 to 2.5 days per decade (Fig. 6, bottom).

Annual rainfall totals show statistically significant increases over the central southern interior of South Africa during the period 1921-2015, with the rate of increase as high as 10 mm/decade or more (Fig. 7, top). Associated increases in the number of days with extreme rainfall (daily rainfall above the 95th percentile threshold) have also occurred in this region as well as several other regions of South Africa, at a rate of more than 2 days per decade in some places (Fig. 7, bottom). Significant decreasing trends in annual rainfall have been recorded over the northern parts of Limpopo.

The analysis also confirmed (results not shown) that the positive trends in annual rainfall totals and extreme rainfall over the southern interior (including the eastern parts of the Western Cape and the western parts of the Eastern Cape) are related mostly to increases in summer rainfall. This type of rainfall is associated with thunderstorm activity, which is projected to increase under climate change.

For the Western Cape, the mean number of rain days per annum has decreased by approximately 2 days per decade, especially along the south coast. The reduction in rain days is most noticeable in late summer and autumn (Midgley et al., 2016a). Where no long term significant changes in rainfall are identifiable in the historical weather records, this does not mean that changes are not occurring, it only means that currently there is insufficient evidence to suggest that any changes identified are not an artefact of natural cycles (10-30-year cycles) and variability, rather than long term steady change. It is thus important to increase rainfall monitoring and analysis in the long term so that emerging trends can be identified.



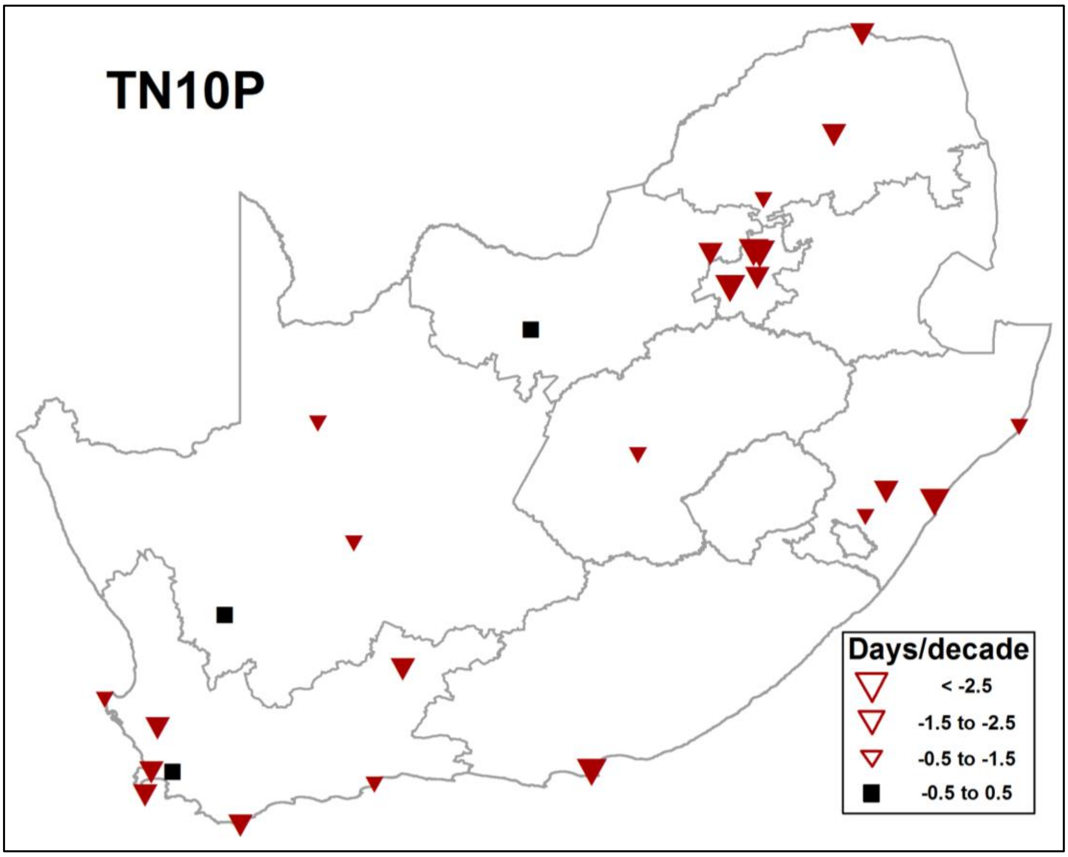


Figure 6. Trends in annual average temperatures (top) and in annual number of cold nights (bottom) over the period 1931-2015. Filled symbols indicate significance of trend at the 95% confidence level. (Source: SA TNC, 2016; adapted from Kruger and Nxumalo, 2016)

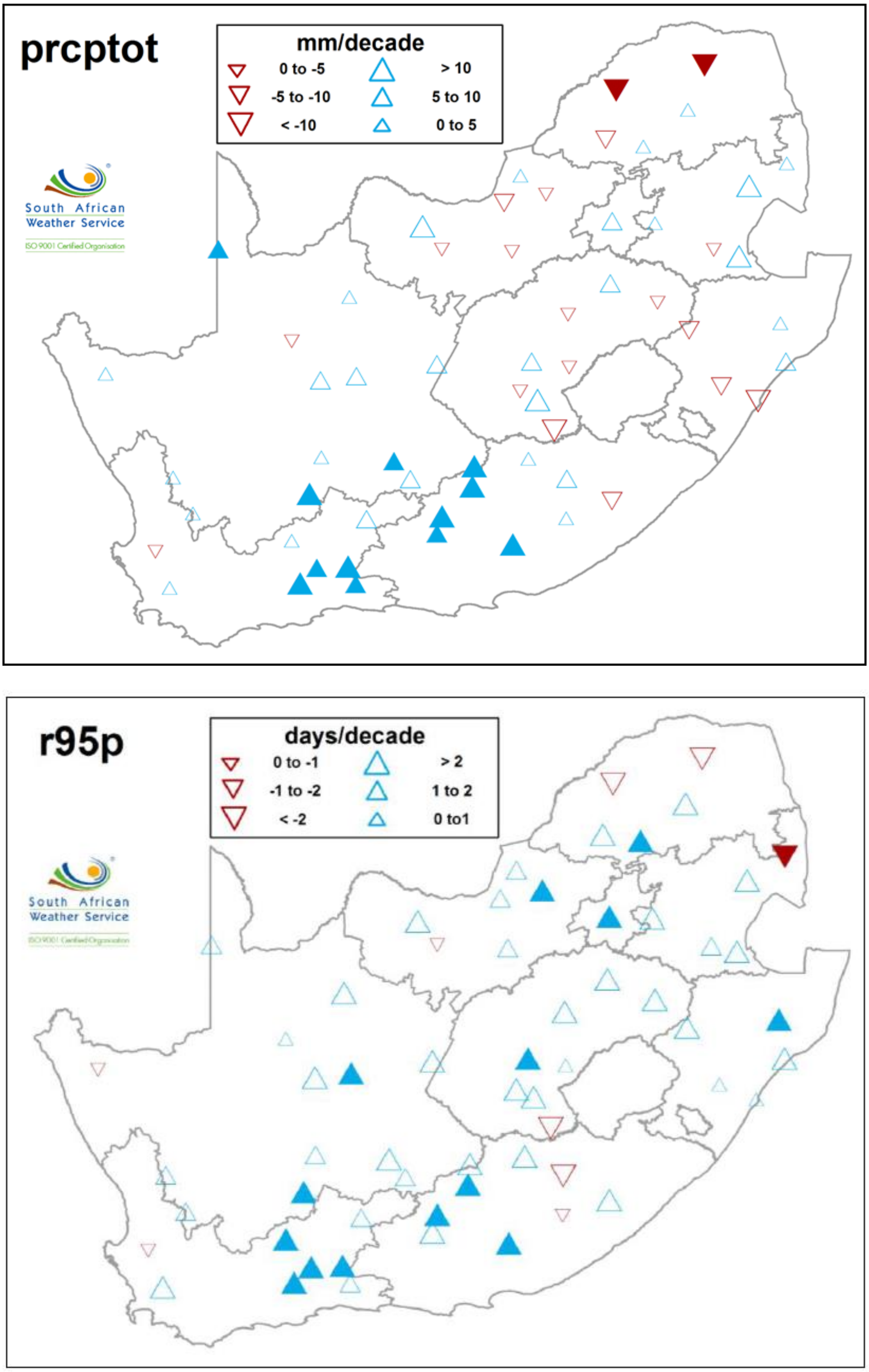


Figure 7. Trends in total annual rainfall for individual stations (top) and in the 95th percentile of precipitation (bottom) for the period 1921 – 2015. Filled symbols indicate significance of trend at the 95% confidence level. (Source: SA TNC, 2016; adapted from Kruger and Nxumalo, 2016)

3.1.2.1 Climate extremes

The Western Cape has in recent history experienced a high frequency of flooding events associated with intense winter frontal systems and/or cut-off low pressure systems. Ten significant flooding events were experienced in the period 2003-2008 (Holloway et al., 2010) followed by five high impact flooding events between 2011 and 2014 (Pharoah et al., 2016). The region has also experienced several droughts, some extending into multiple years. The devastating drought of 2015-2018 came on the back of droughts in 2002-2003 and 2009-2010 in some regions. In some parts of the Klein Karoo the drought has not yet been broken and has caused significant losses to stone fruit growers. Both flooding and drought events have had large impacts on the region ranging from loss of life and property damage, through to larger scale infrastructure damage, agricultural losses, costly response measures, and economic loss. Other extreme weather risks encountered include storms (strong wind), hail, extreme cold, snow, extreme heat, and severe humidity.

Hailstorms are relatively rare and localised in the Western Cape, but when they occur, they have the potential to inflict substantial physical and economic damages on fruit farms. In November 2006, a hailstorm in the Haarlem area (Langkloof) damaged almost 400 hectares of fruit trees and resulted in loss of employment and income for 354 farmworkers. Hail damage wiped out crops (apple, pears, stone fruit and onions) on scores of farms in the Ceres, Witzenberg and Koue Bokkeveld areas in November 2013 and caused significant damage to much of the remaining crop. The predictability of the occurrence of hail, and modelled projections of future risk, are quite poor because of the dynamic and chaotic nature of the weather systems giving rise to hail.

Scientific analysis cannot yet identify with high accuracy the contribution that climate change may be making to the frequency and severity of climate disasters in South Africa. As mentioned above, one study has shown that the probability of the 2015-2018 drought in the Western Cape was increased three times by human-induced climate change (Otto et al., 2018). Climate models are not yet sophisticated enough to model historical and future patterns of intense localised events such as hail and some storms. This Guide thus focuses mainly on gradual climate changes, although extreme patterns of rainfall (dry and wet spells and long duration design of rainfall) and risk of frost (extreme low temperature) and sunburn (extreme high temperature) are included where the modelling can be conducted with sufficient confidence.

3.2 Approach adopted to modelling and mapping future climate

3.2.1 Climate variables covered

The climate variables presented in this Guide are primarily based on temperature and rainfall and some of their derivative variables. We included several derivative variables that are particularly important in pome and stone fruit production, namely, climatic conditions conducive to frost, chill accumulation, heat accumulation, sunburn, red colour development, and insect pest life cycles.

Readers may question why agriculturally significant climatic variables such as hail and strong winds are not covered in this document. The reason is that current Global Climate Models (GCMs) remain weak at modelling these variables in space and time, and the climate database for these variables is poor. Nevertheless, recent modelling conducted at national level (DEA, 2018) has come to some conclusions on strong winds that are presented in the summary narratives of future climates in section 4.1.

3.2.2 Spatial resolution of mapping: Quinary Catchments

Maps shown in this Guide have been prepared at a spatial resolution of so-called Quinary Catchments (QCs, or Quinaries; Schulze and Horan, 2010), which are relatively homogeneous agricultural and hydrological spatial units regarding climate, topography and soils. The Western Cape Province is comprised of 1 401 such Quinaries. An example of the spatial detail provided by the Quinaries is given in Fig. 8 for the southern areas of the Western Cape.

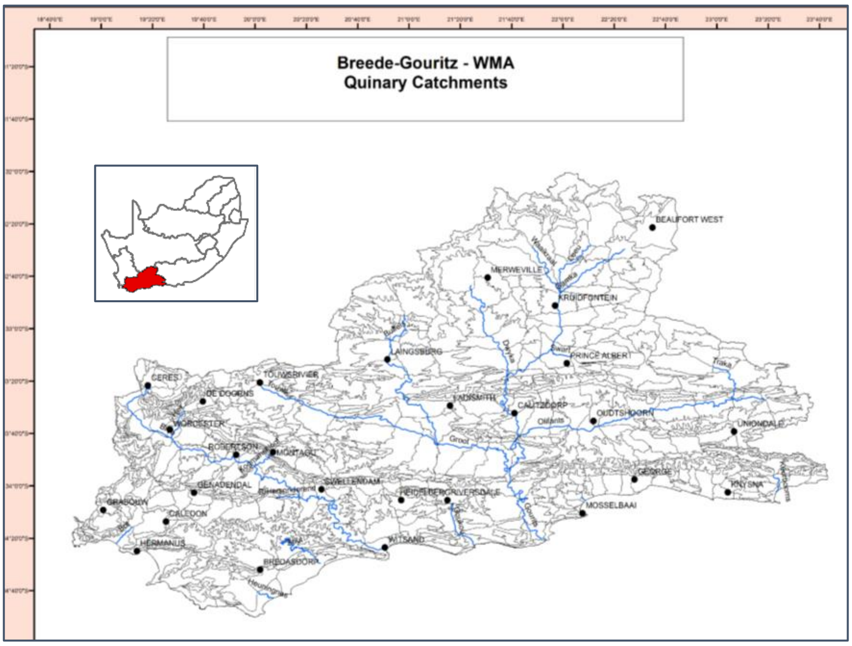


Figure 8. The spatial detail of mapping provided by the Quinary catchments: Example from the Breede-Gouritz Water Management Area within the Western Cape.

3.2.3 Historical climate of South Africa and the Western Cape

The historical climate of the Western Cape for the 50-year period 1950-1999 provides the reference, or baseline, against which projected impacts of climate change can be evaluated.

3.2.3.1 Rainfall and rainfall derivatives

In South Africa as a whole, rainfall is considered the most important input into any agricultural and hydrological assessment model. A comprehensive database (1950-1999) of quality-controlled rainfall data in southern Africa was compiled by Lynch (2004). From that database, a rainfall station, termed the 'driver' station, was selected for each QC, with that station's data considered representative of the daily rainfall of that Quinary (Schulze et al., 2010). Each driver station contained a 50-year record of daily rainfall from 1950 to 1999. The selection of driver stations was followed by the determination of multiplicative month-by-month rainfall adjustment factors (from the 1 arc minute raster of median monthly rainfalls created by Lynch, 2004) for each Quinary and these were then applied to the driver station's daily records in order to render its daily rainfall more representative of that of the Quinary. This resulted in a unique 50-year daily rainfall record for each of the Quinaries covering the region.

3.2.3.2 Temperature and temperature derivatives

Daily maximum and minimum temperature values facilitate estimations to be made, either directly or indirectly, of solar radiation, vapour pressure deficit and potential evaporation (Schulze, 2008). Procedures outlined by Schulze and Maharaj (2004) enabled the generation of a 50-year quality-controlled historical time series (1950-1999) of daily maximum and minimum temperatures at any unmeasured location in the Western Cape at a spatial resolution of one arc minute of latitude / longitude (~1.7 x 1.7 km). At each of these grid points the maximum and minimum temperatures were computed for each day of the 50-year data period by methods described Schulze and Maharaj (2004), who also achieved excellent verifications of results from this methodology. From the study of Schulze and Maharaj (2004) representative grid points were determined for each of the Quinaries covering the Western Cape, using techniques outlined in Schulze et al. (2010). The resulting 50-year series of daily maximum and minimum temperatures for each Quinary was then used to generate daily estimates of solar radiation and vapour pressure deficit and from these, daily values of reference potential evaporation were computed.

3.2.4 General Circulation Models (GCMs) and scenarios used in this study

Future climate *projections* (which are NOT forecasts nor predictions) are scenario descriptions of possible future conditions based on the current understanding of the physics of the atmosphere, on assumptions about changing greenhouse gas emissions and their atmospheric concentrations, as well as on assumptions of future technological, economic and demographic trends. The skill of projections (i.e. their accuracy) depends strongly on how far into the future projections are made, which of a number of possible future greenhouse gas emissions pathways is considered (the thicker lines in Fig. 9), and on the climate variable considered (e.g. temperature projections are generally more skilful than rainfall projections). Deriving key regional messages about future potential change thus requires assessing multiple lines of evidence. Climate projections are therefore assessed in this Guide from a range of climate models generically termed GCMs, i.e. General Circulation Models, as it is not possible to identify a 'best' model for all relevant climate variables for South Africa. This range of outcomes from different GCMs for a specific future pathway is shown by the different thin coloured lines in Fig. 9 for each of the thicker coloured lines of an emissions pathway.

Projections of impacts on the agricultural sector in South Africa (and other sectors as well) are often complicated by different scientists applying different sets of climate scenarios and using different modelling approaches. The various climate projections used in the impact studies presented in this Guide have been based on certain case studies of the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emission Scenarios (SRES) so-called A2 emission scenario. This is essentially a 'business as usual' scenario representing CO_2 equivalent levels of above 500 ppm by 2050. Other case studies have used outputs from GCMs driven by the various so-called RCPs, or Representative Concentration Pathways (thick lines in Fig. 9) (see Box 1).

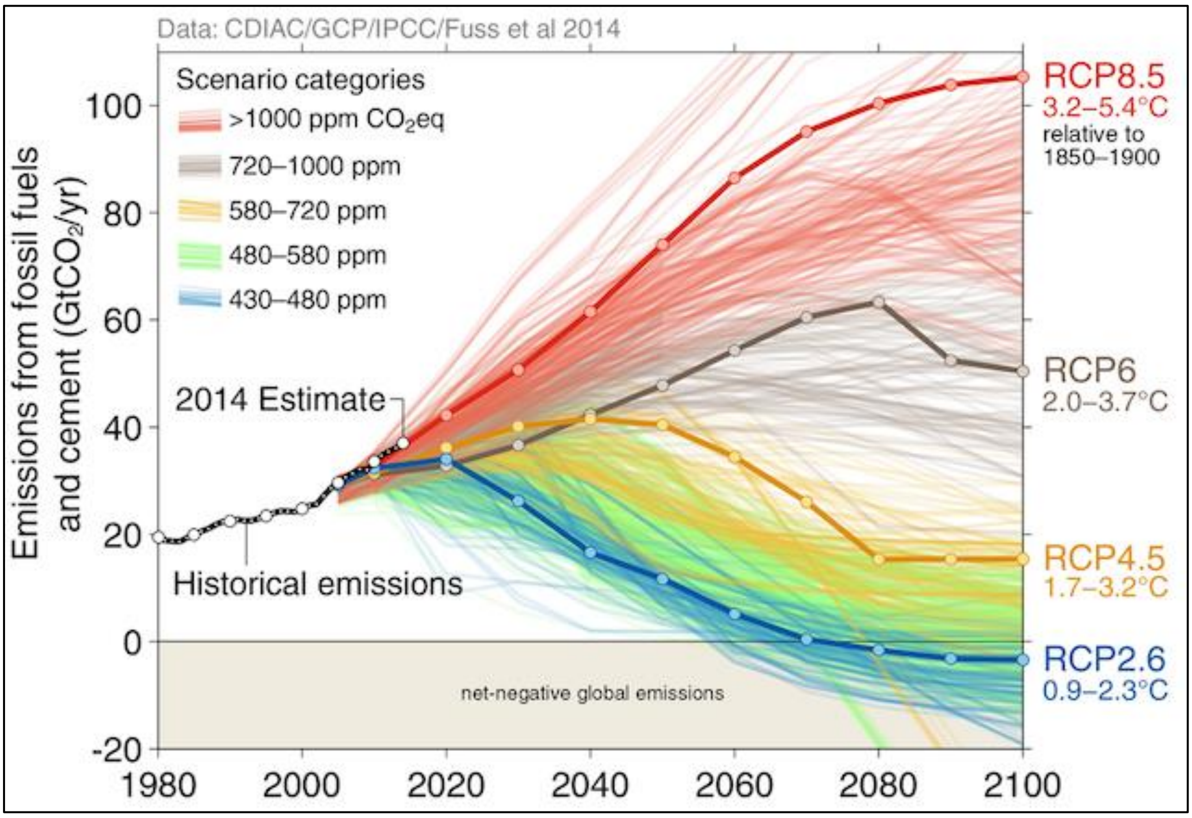


Figure 9. Emissions from fossil fuels and cement measured (until the present) and modelled using ~ 1200 scenarios and four Representative Concentration Pathways (RCPs) showing the range of modelled outcomes by 2100. (Photo: Global Carbon Project)

Box 1. Explanation of 'Representative Concentration Pathway' (RCP)

The Representative Concentration Pathway (RCP)

A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC. Four pathways were used for climate modelling and research for the IPCC Fifth Assessment Report (AR5) in 2014. The pathways describe different climate futures, all of which are considered possible depending on the volume of greenhouse gases (GHG) emitted in the years to come. Four pathways (RCPs) were developed and labelled after their end-of-century radiative forcing: RCP2.6, RCP4.5, RCP6, and RCP8.5 (forcing of 2.6, 4.5, 6, and 8.5 W/m^2, respectively).

The word 'representative' signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasises that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome. RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models produced corresponding emission scenarios.

In this Guide, the climate modelling is based on RCP8.5. This is a 'high baseline emission scenario' for which radiative forcing reaches greater than 8.5 W m^{-2} by 2100 and continues to rise for some amount of time. There is no reason to consider RCP8.5 a more likely outcome than, say, RCP6.0. It is built on certain assumptions, including high population growth and continued use of coal (original version), or high economic growth and a strong reliance on fossil fuels (in the updated version).

Until 2014, the measured carbon emissions corresponded well with the RCP8.5 trajectory (thick red line) in Fig. 9. In 2019, the annual emissions from fossil fuels and cement stood at around 37 GtCO$_2$/year, placing closer to the RCP4.5 trajectory (thick yellow line) for 2020. This can be ascribed to a recent reduction in emissions growth, especially from coal. However, in 2020 the evidence again points to an outcome aligned with RCP8.5.

The results presented in this Guide thus make certain assumptions of one possible future and are indicative only. Caution is advised in over-interpretation, and the reader is advised to rather look out for general trends in direction and spatial patterns across the fruit growing regions.

Irrespective of the sets of GCMs used, future rainfall projections remain challenging. This is because:

- First, rainfall is a derived rather than a direct output from GCMs.
- Second, complex rainfall-generating processes such as cloud formation and land surface-atmosphere interactions are not yet fully understood and resolved in climate models.
- Third, rainfall is an event based variable, and not continuous, as is temperature.

The two sets of GCMs that were used in various sections of this Guide are listed below, and on the relevant maps the set of multiple GCMs which were used in a specific analysis are referred to. All the GCMs used were accredited by the South African Long-Term Adaptation Scenarios initiative of the South African National Department of Environmental Affairs.

The first set of GCMs used were CMIP3 GCMs which were downscaled / distributed by the Climate Systems Analysis Group (CSAG) of the University of Cape Town and derived from global scenarios produced by five IPCC AR4 approved GCMs. All these GCMs were statistically downscaled to over 2 000 climate stations in South Africa and then further bias corrected for the 1 401 Quinary Catchments covering the Western Cape Province by techniques described in Schulze et al. (2010).

In all cases the future scenario A2 was used together with the following GCMs:

- CGCM3.1(T47)
- CNRM-CM3
- ECHAM/MPI-OM
- GISS-ER and
- IPSL-CM4

In each case, daily values of rainfall, maximum and minimum temperatures, and computed daily values of solar radiation, maximum and minimum relative humidity and reference potential evaporation (using methods given in Schulze, 2008) were generated for three 20-year time periods:

- the present (1971-1990),
- the intermediate future (2046-2065), and
- the more distant future (2081-2100).

The first two time periods were used in this Guide.

The second set of climate scenarios used were from the World Climate Research Programme sponsored Coordinated Regional Climate Downscaling Experiment CORDEX, in each case with daily rainfall and maximum / minimum temperature (again with derived daily values of solar radiation, relative humidity and potential evaporation). For these climate scenarios two 30-year periods were used:

- 1976-2005 (termed the historical, or present, climate), and
- 2016-2045 (termed the immediate future).

The modelling was conducted for the immediate future scenario, together with the RCP8.5 scenario. Again, the GCMs were downscaled to the 1 401 Quinary Catchments and then bias corrected for local topography by methods described in Schulze et al. (2014).

The GCMs used were:

- CCCma-CanESM2_historical_RCA5_1976
- CCCma-CanESM2_rcp85_RCA5_2016
- CNRM-CERFACS-CNRM-CM5_historical_RCA5_1976
- CNRM-CERFACS-CNRM-CM5_rcp85_RCA5_2016
- ICHEC-EC-EARTH_historical_RCA5_1976
- ICHEC-EC-EARTH_rcp85_RCA5_2016
- NCC-NorESM1-M_historical_RCA5_1976
- NCC-NorESM1-M_rcp85_RCA5_2016
- NOAA-GFDL-GFDL-ESM2M_historical_RCA5_1976
- NOAA-GFDL-GFDL-ESM2M_rcp85_RCA5_2016

These climate models are referred to on the maps as the CMIP5 GCMs. It is important to remember that all maps for the projected future, and change from present to future, are means of four or five different GCMs, except for red colouring where only one GCM was used. The variance between the model outcomes is not shown; rather, the mean or median of the different outcomes is shown.

Mean annual precipitation, median annual runoff and mean annual accumulated streamflows were simulated with the ACRU model using daily climate inputs from present (mid-1990s) and projected immediate future (mid-2030s) climatic conditions derived from 6 bias-corrected CMIP5 GCMs used in a current (as yet unpublished) Water Research Commission project at the Centre for Water Resources Research at the University of KwaZulu-Natal.

The GCMs used were:

- ACCESS1-0
- CCSM4
- CNRM-CM5
- GFDL-CM3
- MPI-ESM-LR
- NorESM1-M

A new set of GCMs (CMIP6) is now becoming available. Over the last two decades of model development, there has been very little change in the projections for temperature and temperature-derived variables. We thus have high confidence that the GCMs used in this study provide a reliable picture of the future that will not be altered substantially as the new GCMs begin to be used. However, for reasons given above, projections for rainfall and rainfall-derived variables remain challenging. As the model developers address the weaknesses and inconsistencies in the older GCMs, the new set of GCMs can alter the picture somewhat. We thus have lower confidence in the rainfall and rainfall-derived variables, and have decided to place these in an Appendix to this Guide. The user is advised to be cautious when engaging with the results. We have included the results for dry and wet spells in the Extended Executive Summary since the science shows better agreement around increasing variability of rainfall. We recommend that the analyses are updated once the new GCMs have become available.

CHAPTER 4

CLIMATE AND CLIMATE CHANGE PROJECTIONS

In this Chapter, modelling results for historical and projected future solar radiation, temperature and reference potential evaporation over the Western Cape - Langkloof region are presented. However, to set the scene, summary scenarios compiled during the most recent assessment completed at national and provincial levels (DEA, 2018) are first included. In the case of rainfall, in particular, different modelling approaches and assumptions can lead to different outcomes, and climatologists use a multi-model and multi-method approach based on the understanding that “all models are wrong, but some models are useful”. It is important to provide the reader with a broad consensus view that includes all the main (and validated) modelling approaches used in South Africa. Together, they inform an emerging picture of ‘plausible futures’ that avoid the pitfalls of misrepresenting the uncertainties.

4.1 Summary perspective

The following two narratives for the Western Cape Province are taken from South Africa’s Third National Communication under the United Nations Framework Convention on Climate Change (DEA, 2018). They are based on the full set of analyses presented in that report.

Narrative 1: A drier, hotter, windier future

“In this narrative, the climate of the Western Cape will continue to be characterised by cycles of drier years and wetter years for the next 20 to 30 years. At the same time, average temperatures rise at around 0.5°C per decade so the average temperatures will reach 1.5°C higher than recent historical averages somewhere between 2040 and 2060. The impact of these higher temperatures will increase the frequency and length of hot spells in summer, as well as decrease the frequency and duration of cold spells in winter. The increasing effect of the sub-tropical high-pressure systems combined with more intense inland heating will result in stronger summer south-easterly winds. Higher wind speeds combined with higher temperatures will strongly influence evaporation and evapotranspiration either resulting in drier soils and crops or increasing demand for irrigation, particularly of summer crops. Higher evaporation from dams, combined with competing demands from agriculture and rapidly growing urban populations will place significant strain urban water supply systems.

Moving towards the middle of the 21st century, natural cycles of rainfall begin to shift towards more frequent dry years and consecutive dry years (such as the 2014-2015 years). Temperatures will continue to rise along with summer wind speeds which enhance evaporation, so reduced rainfall will only exacerbate the challenge of increased evaporation from agricultural land, natural ecosystems, and water storage dams. Competition for water between agriculture, industry and urban water supply could become critical with water cuts becoming the only viable solution during extreme dry years.

With average temperatures now reaching 2°C higher than the recent past, agricultural activities will become unviable, including some fruit farming which requires low temperatures to develop and possibly certain livestock that are unable to cope with sustained higher temperatures. Added to these summer stresses, winter storm intensity begins to increase resulting in more frequent heavy rainfall events in winter which produce flooding and related damage."

Narrative 2: A warmer wetter future

The narrative for the first 20-30 years is like that presented for the first narrative. "Moving towards the middle of the 21st century, natural cycles of rainfall will continue, but changes in average rainfall begin to emerge. Rainfall in the mountains increases as a result of more moist and energetic winter storms, as well as increased moist warm southerly flow off the ocean in the summer months. While coastal and inland plains do not experience these changes directly, they have important impacts on water supply and irrigation as river flows increase and runoff into dams increase.

However, increased rainfall is offset by increased evaporation due to higher temperatures (reaching 2°C higher than current) and stronger winds. This results in increasing demand for irrigation and higher losses from dams. Higher urban populations also place ever increasing demands on water supply systems. Therefore, while the relatively small increases in rainfall may partly delay the need for adaptation measures, adaption to reduce water demands is still required. Higher temperatures will still result in some agricultural activities being unviable, regardless of changes in rainfall. Inland plains do not receive increased rainfall, and so follow very similar story lines to the dry narrative above."

The remainder of this chapter presents the results of the modelling conducted as described in section 3.2.

4.2 Solar radiation

4.2.1 Background

Crop plants utilise the visible portion of the solar radiation spectrum to produce carbohydrates out of water and CO_2 through the reactions of photosynthesis. These carbohydrates (in the form of starch, sugar, and cellulose) form the building blocks for growth and reproduction. Solar radiation is thus a major determinant of crop development and yield. Approximately 1.4 g of dry matter is produced per megajoule (MJ) of solar radiation intercepted by the leaves. It is, therefore, a major input variable in commonly used crop yield models as well as being the major driver of reference potential evaporation (see section 4.4).

The estimation of daily solar radiation is a complex one, and is at any given location and time of year and day influenced by five sets of factors:

- astronomical;
- geographical (latitude and altitude);
- physical (scattering of solar radiation by atmospheric pollutants/aerosols and absorption mainly by water vapour);
- geometric (solar altitude and azimuth as well as slope steepness and aspect); and
- meteorological (cloudiness, type and thickness of the cloud, reflectivity).

From these five sets of factors, daily estimates of solar radiation for 50 years were calculated at a 1.7 km resolution by a series of relatively complex equations developed and verified for South Africa (Schulze, 2008; Schulze and Chapman, 2008).

4.2.2 Results

Means of historical daily solar radiation are presented for October (representing spring), January (summer), April (autumn) and July (winter) in the left column of Fig. 10, while projected percentage changes to the 2050s (intermediate future) are presented in the right hand column of Fig. 10. The highest changes of the order of 3 MJ/m^2 per day are projected for the transitional spring and autumn seasons as well as for winter (indicative of fewer cloudy days) while in the already sunny summer the projected changes are only ~ 1.5 MJ/m^2 per day. The range of increases of ~ 1-4% is small to modest.

4.2.3 Implications

The high values of solar radiation across the region, and generally low variability from year to year, mean that solar radiation *per se* is seldom considered a limiting factor to crop growth and yield on a broad scale. Agro-climatically, it is probably more meaningful to view solar radiation receipt in conjunction with other climatic indices, and on a meso- or farm scale, especially in relation to the effects of varying slope and aspect (e.g. north- or south-facing). These factors could be a major influence in hilly and mountainous areas and need to be considered for future orchard planning. Another possible effect of slightly increased solar radiation is its contribution to higher potential evaporation (section 4.4) and thus higher irrigation water demands.

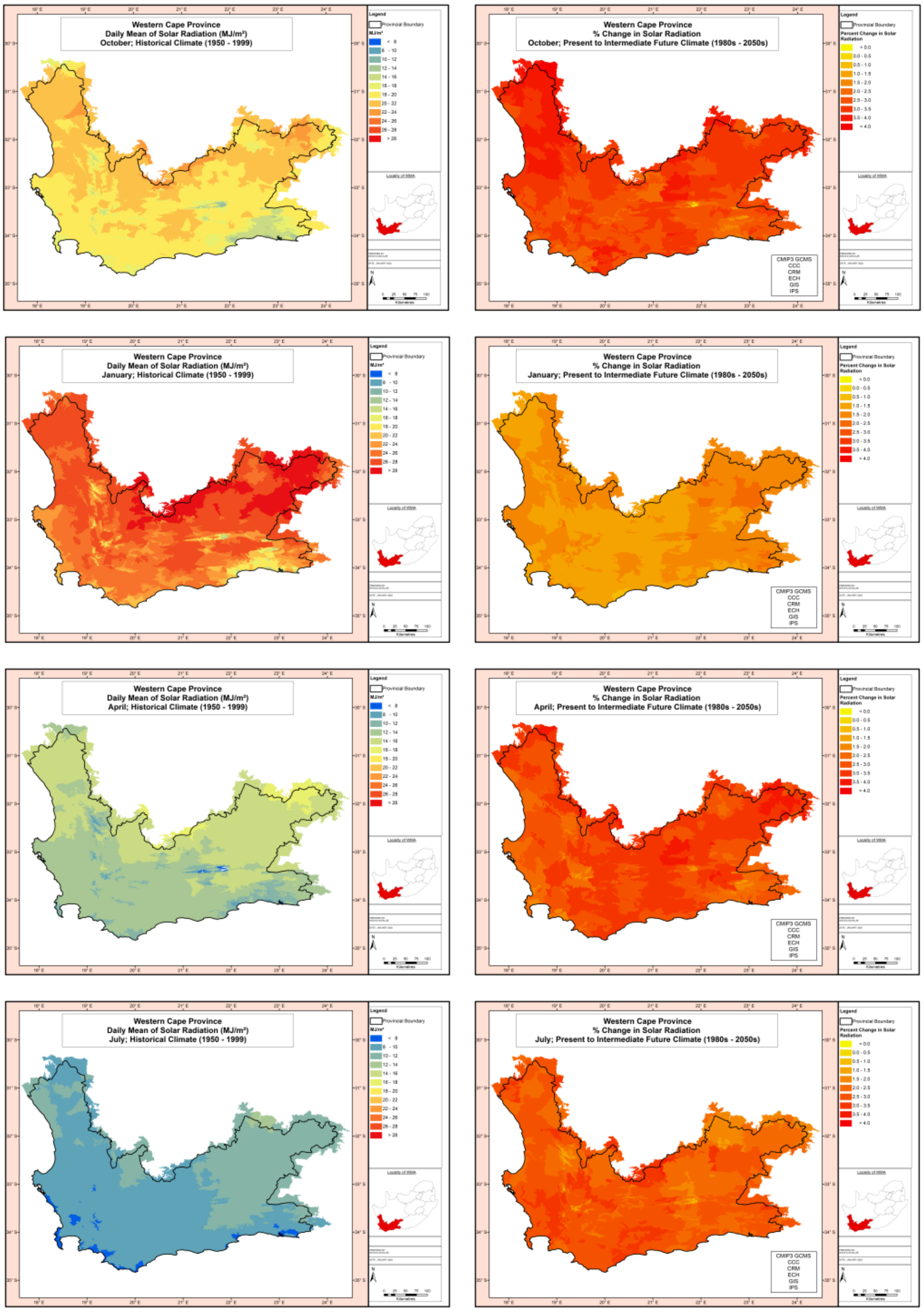


Figure 10. Daily means of solar radiation in MJ/m^2 under historical climate conditions (left column) and their respective percentage changes from the present climatic conditions into the intermediate future. In each column, results are presented from top to bottom for October (representing spring), January (summer), April (autumn) and July (winter). The modelling was conducted using multiple CMIP3 GCMs (original research: Schulze et al. 2016).

4.3 Temperature

4.3.1 Temperature and its importance to agriculture

Temperature is a basic climatological parameter used frequently as an index of the energy status of the environment. Consequently, temperature parameters such as daily and seasonal means, maxima and minima, and optimal and diurnal ranges of temperature are vital determinants of the distribution of plant species and provide boundaries for the suitability of various crop types. Note that by the term temperature the *air temperature* at Stevenson screen height is usually inferred, and this is taken as being representative of the surrounding area.

The factors which generally influence the distribution of temperatures over a region are:

- *Latitude*, with temperatures generally decreasing with increasing latitude (i.e. pole-wards, in South Africa this is southwards), all else being equal.
- *Altitude*, with generally, the higher the altitude, the lower the temperature. However, the rate of decrease of temperature with altitude (i.e. the 'standard adiabatic lapse rate') is not constant, but varies month-by-month, by four different lapse rate regions within the region, by proximity to oceans (including the local effect of the cold Benguela current off the west coast), and between maximum and minimum temperatures (see Schulze and Maharaj, 2004).
- *Continentality* (i.e. distance from the ocean), with oceans have a moderating influence on temperature. The temperature variations are relatively smaller near the sea, giving way rapidly as one moves inland to increases in daytime temperatures and decreases in night-time temperatures. In inland regions, less humid conditions favour strong day-time incoming and night-time outgoing radiation losses.
- *Local topography*, where especially during winter nights, it is colder in valleys than on crests because night-time cold (and thus denser) air drains into valley bottoms. This is of great importance for fruit growers in hilly inland areas and other settings where orchards are planted in the valley bottoms.

4.3.2 Mean annual temperature and projected changes

4.3.2.1 Background

Mean annual temperature (*MAT,* in °C) represents the very broadest of indices of the environmental status of a location, and while in itself not a particularly useful statistic because it has integrated and smoothed the effects of diurnal, monthly and seasonal patterns of maximum and minimum temperatures, it is nevertheless a commonly requested statistic which is used as a general first guide to determine the suitability of a location for specific crops.

4.3.2.2 Results

Under historical climatic conditions, *MAT* ranges from < 8°C in the mountain peaks to 18-20°C in the arid north-west, with most of the region experiencing a *MAT* of 14-18°C (Fig. 11, top left). Model projections from multiple CMIP3 GCMs for the intermediate future (mid-century) display marked increases in *MAT* (Fig. 11, top right). The changes from historical to intermediate future (Fig. 11, bottom) are of the order up to 2.0°C along the southern coast (under the modifying influence of the warm Mozambique current) to approximately 2.6°C in the northern interior and north-east.

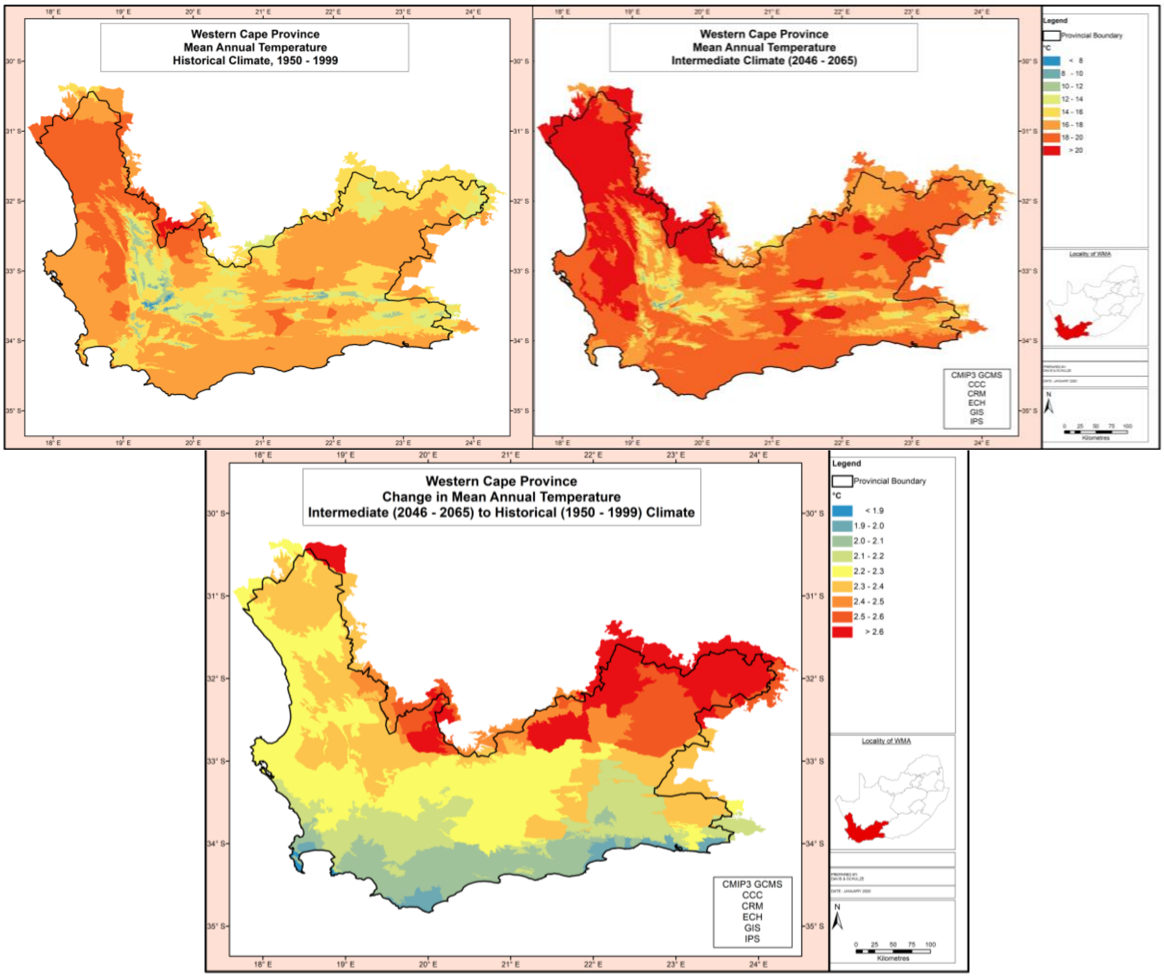


Figure 11. Mean annual temperatures (°C) under historical climatic conditions (top left) and projected intermediate future climatic conditions (top right), and (bottom) projected changes (in °C) from the historical climatic conditions to the intermediate future of mean annual temperatures. The latter two are derived from multiple CMIP3 GCMs (Original Research: Schulze, 2011)

4.3.2.3 Implications

Mean annual temperature is the integrator of both diurnal and seasonal temperature differences and serves as a very broad indicator of agricultural potential and crop suitability. It stands to reason that the anticipated increase in *MAT* becomes a major concern for pome and stone fruit growers. It will likely lead to spatial shifts in production areas and shifts in the fruit types and cultivars that are suited to specific regions. In broad terms, such shifts could see the warmer parts of EGVV and Piketberg becoming unsuited to pome fruit production, and core cooler apple regions becoming more like present day core pear regions. Pear production in the warmer parts of the Klein Karoo is likely to become more marginal, if not unsuited. More detailed analyses of some of the mechanisms by which warming will influence fruit production are dealt with in Chapter 5.

Stone fruit production should not become limited by *MAT* in the north-western high-lying regions or the Stellenbosch-southern Berg region, but could become marginal in the warmest parts of the Klein Karoo production regions, the northern Berg, and parts of the Breede River valleys.

4.3.3 Monthly means of January maximum and July minimum temperatures and projected changes

4.3.3.1 Background

This section first assesses mean monthly day-time maximum temperature in mid-summer (January). During the fruit growth period, rates of physiological and growth processes generally show positive responses as temperature increases up to an optimum temperature which is often in the region of 28-30°C. As daytime temperature continues to rise, the rate of these processes begins to decrease, and this is frequently measurable above 35°C. Above 40°C, rapid decreases occur and at 45°C these processes come to a halt and damage (e.g. bleaching, sunburn) can start to occur in exposed tissues. Increasing heat, especially when experienced over several days to weeks, alters the balance between carbon gain (photosynthesis in leaves) and carbon loss (respiration in all cells, which is very sensitive to temperature increase) and thus lowers the carbon balance of the whole tree and its productive capacity. Hot mid-summer periods also increase the likelihood of sunburn and poor red colour development in susceptible cultivars.

The second part of this section assesses mean monthly night-time minimum temperature in mid-winter (July). Both low and high night-time minimum temperatures in winter can limit fruit crop productive potential. Since deciduous fruit trees experience a period of dormancy in winter, they are in this phase well protected from chilling injury even at very low temperatures. However, this is only true for the endo-dormancy phase and before the buds start to become active at the end of winter. In South Africa, pome fruit generally start to flower towards the end of September, while some stone fruit cultivars already start to flower in July. Extended cold weather in this sensitive reproductive period can be detrimental to fruit set and yield, especially where it is accompanied by the risk of frost. An extended period of very warm winter nights, on the other hand, can interfere with the normal accumulation of chill units and result in trees not reaching the dormant state before spring, as well as triggering early flowering. Once trees become physiologically active (as for some early apricot and peach cultivars in July already), hot nights can accelerate and potentially damage processes occurring during pollination and can lead to low fruit set. High night-time temperatures will also increase respiration rates of emerging leaves and create a carbon deficit in this early growth stage.

4.3.3.2 Results

Under historical climatic conditions, high mid-summer temperature maxima are a feature of the semi-arid north-east interior, the inter-montane areas, and the arid north-west (Fig. 12, top left), with mean monthly maxima averaging > 30°C in January. In the higher-lying mountainous areas and the coastal zone, mean monthly maxima are < 28°C (Fig. 12, top left). With projected climate change in the intermediate future (mid-century) it is particularly the east and north-east that display the highest increases at >2.5°C, with maxima in the southern areas projected to generally increase at < 2.2°C (Fig. 12, top right).

July mean minima are, historically, highest along the south and west coast areas at 6-12°C. In the interior, July mean minima are often in the range 0-4°C, with the lowest minima in the mountainous regions (Fig. 12, bottom left). Overall, projected July minimum temperature by mid-century increases by around 2°C, but in the north-east by up to 2.5°C (Fig. 12, bottom right).

Note that, overall, the CMIP3 GCMs used in this analysis display lower, more benign, mid-winter minimum temperature increases than the projected increases of mid-summer maxima.

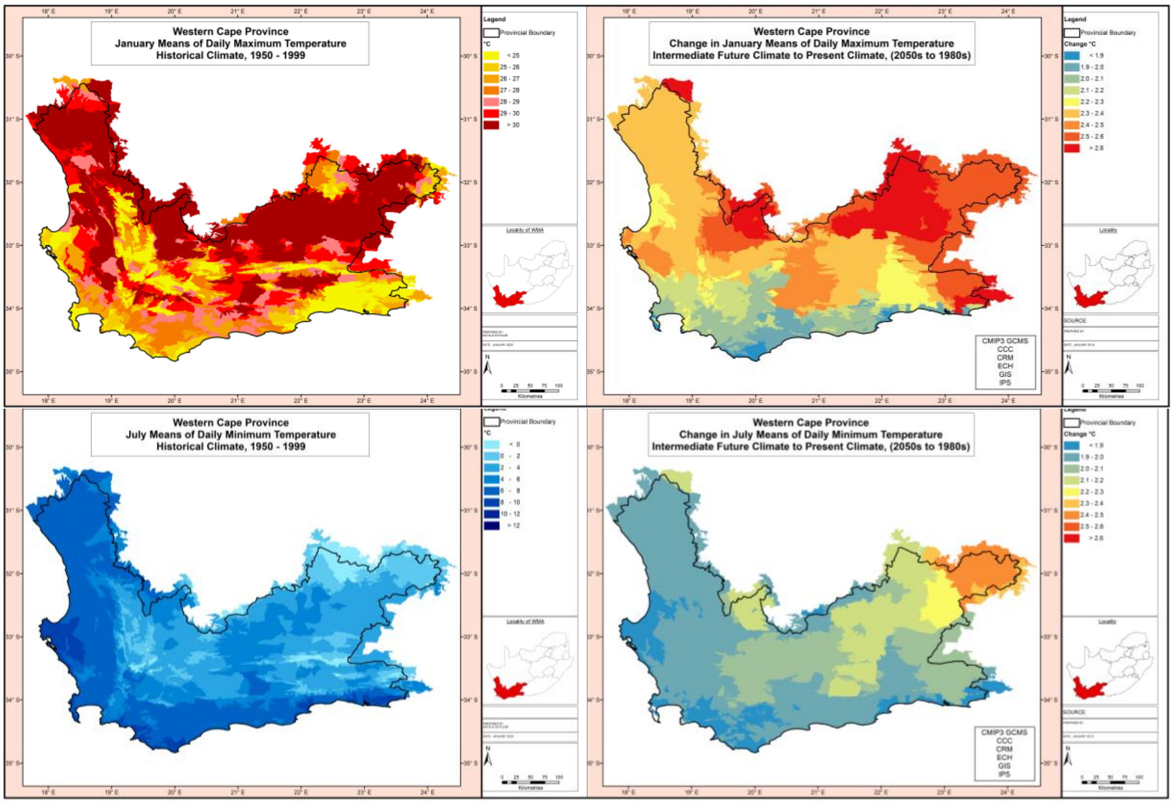


Figure 12. January means of daily maximum temperatures (top left) and July means of daily minimum temperatures (bottom left) under historical climatic conditions, and respective projected changes (in °C, top and bottom right) between present and intermediate future climates. Futures mapping was based on the means of outputs from multiple CMIP3 GCMs (Original research: Schulze, 2011)

4.3.3.3 Implications

The projected changes in summer mean monthly maxima will affect the pome and stone fruit sector throughout the region. However, parts of the region e.g. northern Berg River valley, Wolseley-Tulbagh and Klein Karoo, will likely experience the 'double whammy' in already being hot and then having the highest projected increases in temperatures in mid-summer. Impacts will be wide-ranging, from sunburn to increased irrigation water demand resulting from high evapotranspiration rates.

The increase in winter mean monthly minima holds both positives and negatives. Less frost damage could be one outcome (see section 5.1). However, dormancy could be disrupted, with trees beginning to flower earlier, which may even increase the risk of frost damage during the early season. Insufficient accumulated chilling would have significant impacts on pome (and some stone) fruit production in already warmer production regions (see section 5.2). Many pests and diseases would be able to over-winter in the warmer conditions, thus changing the timing and severity of early season impacts on orchards (see section 5.6).

4.3.4 High and low temperature thresholds and projected change

4.3.4.1 Background

Crops have critical upper and lower temperature and relative humidity thresholds which, when they are exceeded even for a short time, can affect yield or the quality of the crop. These thresholds can be:

- maximum values which should not be exceeded at certain growth stages of the crop
- minimum values which should not be breached at critical times.

The thresholds differ from crop to crop and even between cultivars, with different penalties regarding yields or quality, depending on which threshold is exceeded. Not all critical threshold temperatures that exist for different fruit crops at different points in their annual cycle can be mapped in this Guide, and only two examples will be presented for historical and projected future (mid-century) climates:

- number of days per annum when the maximum temperature exceeds 35°C
- number of days per annum when the minimum temperature is below 6°C.

The determination of exact threshold temperatures for specific processes is complex and only understood to some degree for pome and stone fruit. Plant physiological processes (e.g. stomatal opening and thus photosynthesis) often decline above 35°C, certain metabolites (e.g. red pigment) begin to be destroyed, and tissue damage can result at temperatures approaching 40°C when oxidative processes become toxic. In related analyses and mapping, the potential risks of future high temperatures on sunburn (section 5.4) and poor red colour development (section 5.5) in susceptible cultivars are presented, based on known thresholds. In the period before harvest of pome and stone fruit, cold nights provide the signal for the induction of red pigment biochemical pathways. As deciduous plants enter dormancy, they become more cold hardy and low temperature thresholds shift downwards. However, frost remains a risk especially in spring (section 5.1).

4.3.4.2 Results

The average number of days per annum with a maximum temperature exceeding 35°C is, for the most part, less than 20 over most of the region (Fig. 13, top left). Along the north-west border this can be 30-40 days, and in places even up to 50 days per annum under historical climate conditions. Under the projections for the 2050s (Fig. 13, top right), much of the region will experience up to 20 additional days exceeding 35°C (Fig. 13, bottom). In the worst affected regions of the north-west coast, the northern border and the north-east (Karoo), 30 to 50 additional hot days could be experienced per annum.

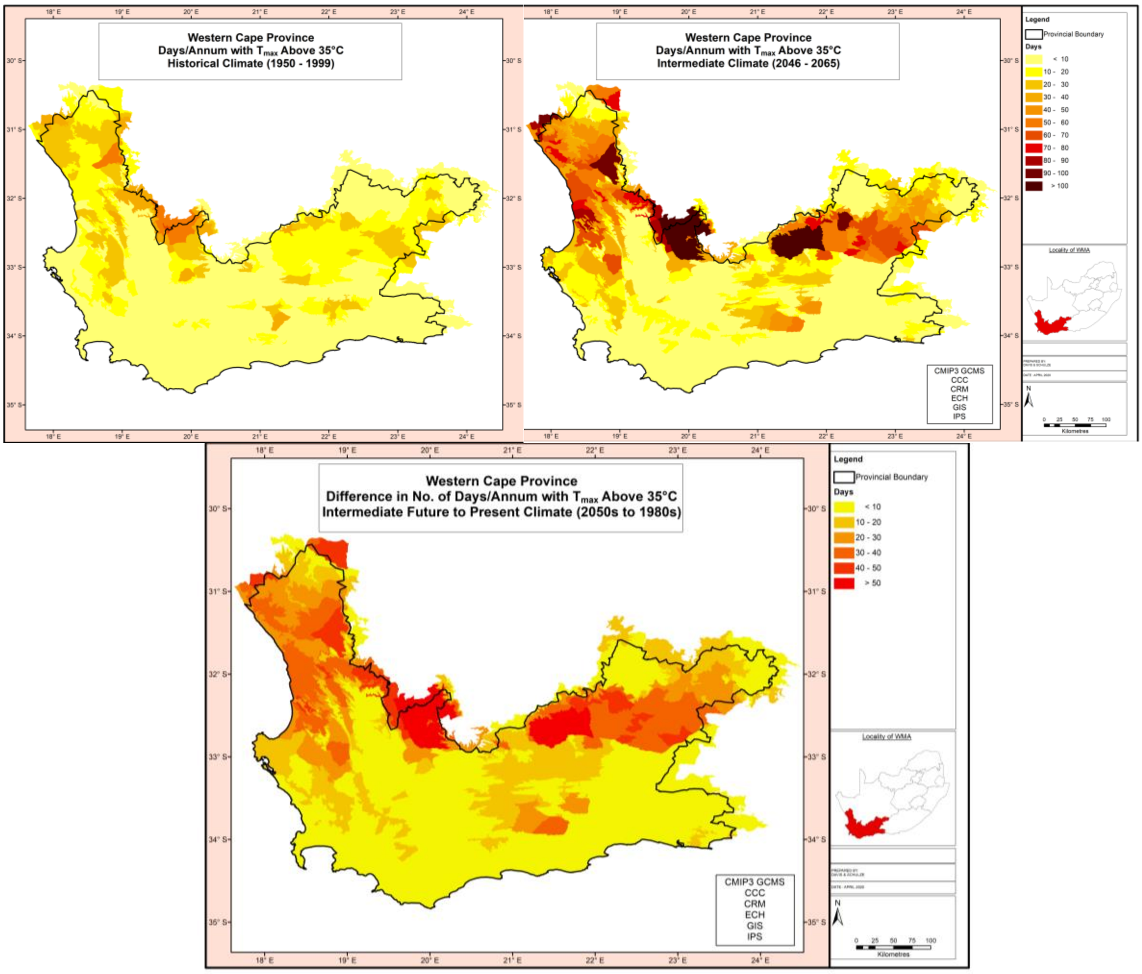
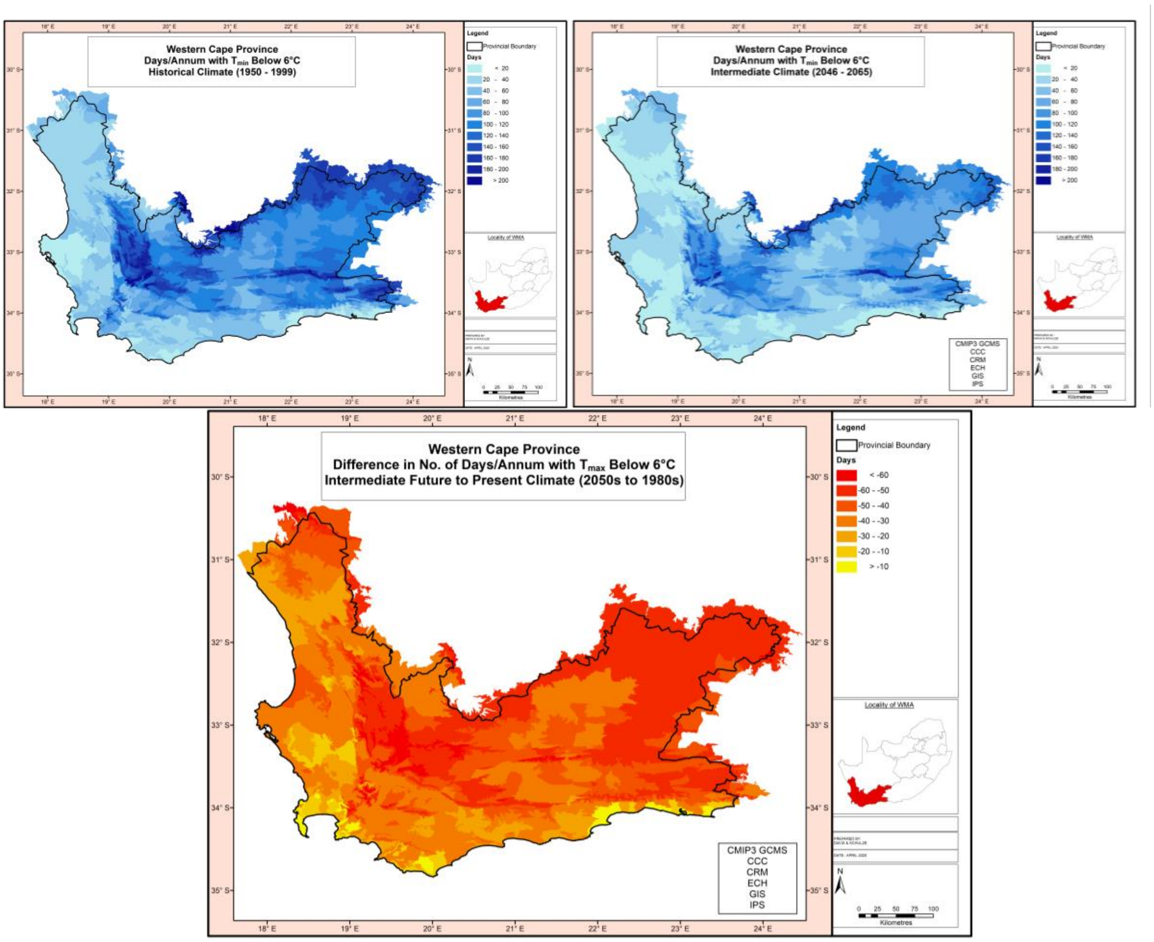


Figure 13. Average days per annum on which daily maximum temperatures exceed 35°C under historical climatic conditions (top left) and projected intermediate future (top right) climates. The figure at the bottom shows the changes (in days per annum) between present and intermediate future climates. Futures mapping was based on the means of outputs from multiple CMIP3 GCMs.

Fig. 14 shows the results for the average number of days per annum with a minimum temperature below 6°C for the historical period (Fig. 14, top left) and for the intermediate future period (Fig. 14, top right). The pattern is strongly related to elevation, with mountainous and other high-lying areas experiencing more than 120 such days per annum. The intermediate future shows a reduction of up to 20 days in the coastal southern regions and a reduction of more than 50 days in mountainous and high-lying interior areas (Fig. 14, bottom).



Western Cape Province
Days/Annum with T_{min} Below 6°C
Historical Climate (1950 - 1999)

Western Cape Province
Days/Annum with T_{min} Below 6°C
Intermediate Climate (2046 - 2065)

Western Cape Province
Difference in No. of Days/Annum with T_{max} Below 6°C
Intermediate Future to Present Climate (2050s to 1980s)

Figure 14. Average days per annum on which daily minimum temperatures are below 6°C under historical climatic conditions (top left) and projected intermediate future (top right) climates, The figure at the bottom shows the changes (in days per annum) between present and intermediate future climates. Futures mapping was based on the means of outputs from multiple CMIP3 GCMs.

4.3.4.3 Implications

The significant projected increases in hot and very hot days in the intermediate future (~ 30 years hence) does not bode well for pome and stone fruit growers in regions that today are already hot. Heat stress will affect fruit trees and humans working outside in many ways. Such conditions also result in high evaporative water losses from soil and water bodies (see section 4.4) and through transpiration. Irrigation demand will thus increase. At the lower temperature end, the reductions in numbers of days having nights below 6°C is likely to lead to a higher incidence of pests and diseases (see section 5.6).

4.4 Reference potential evaporation and projected changes

4.4.1 Background

The accurate estimation of evaporation from natural vegetation or agricultural crops is vital. Evaporation is the driving force of the total amount of water which can be 'consumed' by a plant system through evaporation and transpiration processes (together termed 'evapotranspiration'). Similarly, evaporation from storage reservoirs, wetlands and rivers can constitute a major loss of water to water resource managers, irrigators, and downstream users.

Evaporation is controlled by three atmospheric conditions:

- The capacity of air to take up water vapour. This capacity increases rapidly at higher temperatures and at lower relative humidity (*RH)* of the air.
- The amount of energy available for the process of evaporation. This energy is provided mainly by solar radiation.
- The degree of turbulence (related to wind) in the lower atmosphere. Turbulence is necessary to replace the moist air layers above the evaporating surface with drier air from higher levels or from different air masses.

These three factors create an atmospheric demand, and when this demand can be met fully, e.g. when soils are wet and actively growing vegetation covers the ground completely, then *potential evaporation* (E_p) takes place. All three these factors change with climate change.

The actual amount of water 'consumed' by a vegetated surface is termed *total evaporation* (E), and E may be taking place at the potential evaporation rate (i.e. wet soil conditions) or at an *actual evaporation* rate which can either be equal to E_p or lower (i.e. when soils dry out and plants become water stressed).

4.4.2 Estimating potential evaporation

There are many methods of estimating potential evaporation (E_p) ranging from complex equations to measurements from evaporation pans and simple equations based on temperature. These methods all give slightly different answers under different climatic conditions, and a *reference potential evaporation* (E_r) must therefore be selected. This reference is that evaporation against which results from other methods must be adjusted appropriately. The choice of E_r has inherent advantages and defects and these should be understood.

In this Guide, the Penman-Monteith method of estimating evaporation (E_{pm}) is used as the point of departure in computations (Penman, 1948; Monteith, 1981). The Penman-Monteith equation uses solar radiation, humidity, temperature and wind as its climate inputs. A version for South Africa can be found in Schulze (2012). Daily values of E_{pm} were then multiplied by a local factor varying from 1.19 (summer) to 1.27 (winter) to convert E_{pm} to an A-pan equivalent reference potential evaporation. The rationale is that the expression of water use of crops and natural vegetation in South Africa is to this day still largely based on an A-pan equivalent.

4.4.3 Results

Under historical conditions (1950-1999), mean annual A-pan equivalent reference potential evaporation ranges from ~ 800 mm along the cool moist mountain ranges to > 2 000 mm in the arid and hot north-west to north-east (Fig. 15, left). Climate projections from the present into the immediate future of the 2030s show annual increases from as little as 20 mm in the eastern mountains to > 140 mm in the eastern Karoo (Fig. 15, right). Over the pome and stone fruit production regions the historical annual values are in the range 1200-1900 mm, and the projected annual increases in the immediate future are in the range 70-120 mm.

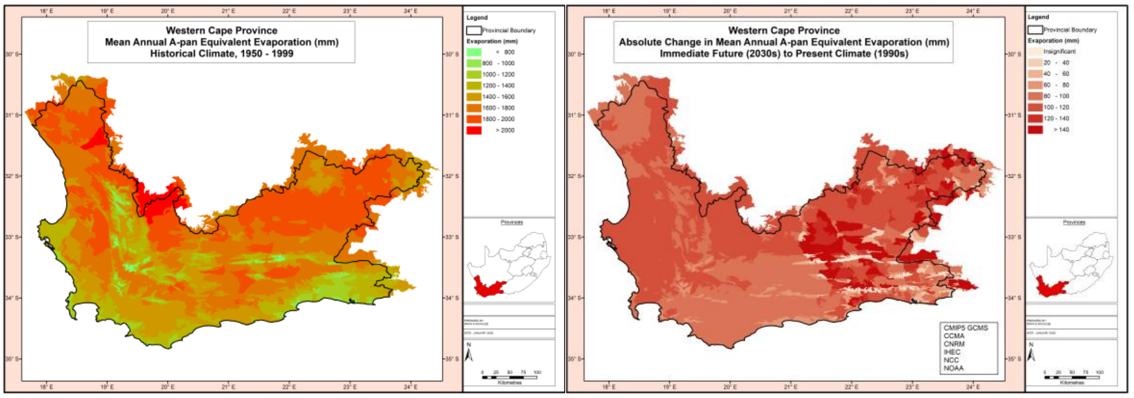


Figure 15. Mean annual A-pan equivalent reference potential evaporation under historical climatic conditions (left) and projected increases (mm) from the present to immediate future climates (right). The latter is derived from multiple CMIP5 GCMs.

Reference potential evaporation is a highly seasonal phenomenon. Fig. 16 (left column, from top to bottom) shows historical climate values in the range of 250-600 mm in spring, 300-700 mm in summer, dropping to 300-400 mm in autumn, and 150-300 in winter. Mountainous and south-eastern areas generally display the lowest values and the semi-arid north-west and the Karoo display the highest values.

Projected changes into the immediate future of the 2030s, shown in the right-hand column of Fig. 16, display the largest increases in spring and summer at 30-40 mm. The projected increases are 10-30 mm in autumn and only 10-20 mm in winter. However, each season shows insignificant increases in some of the high-lying areas (mainly in the east) and hotspots of large increases in the semi-arid zones of the east.

4.4.4 Implications

Historical annual reference potential evaporation is already high in the region at up to around 2 000 mm, and projected increases into the 2030s of up to 120 mm, mostly in spring and summer, will impact on water availability. Higher potential evaporation from dams, wetlands and riparian zones will constitute an unavoidable loss to the region's water, ecology, and agriculture sectors. Additionally, all else remaining the same, soils are anticipated to dry out more rapidly in future, leading to potential negative implications for runoff production. Irrigation water demands will be higher than at present, leading to both increased abstractions from dams and reduction in river flows where irrigation is from run-of-river.

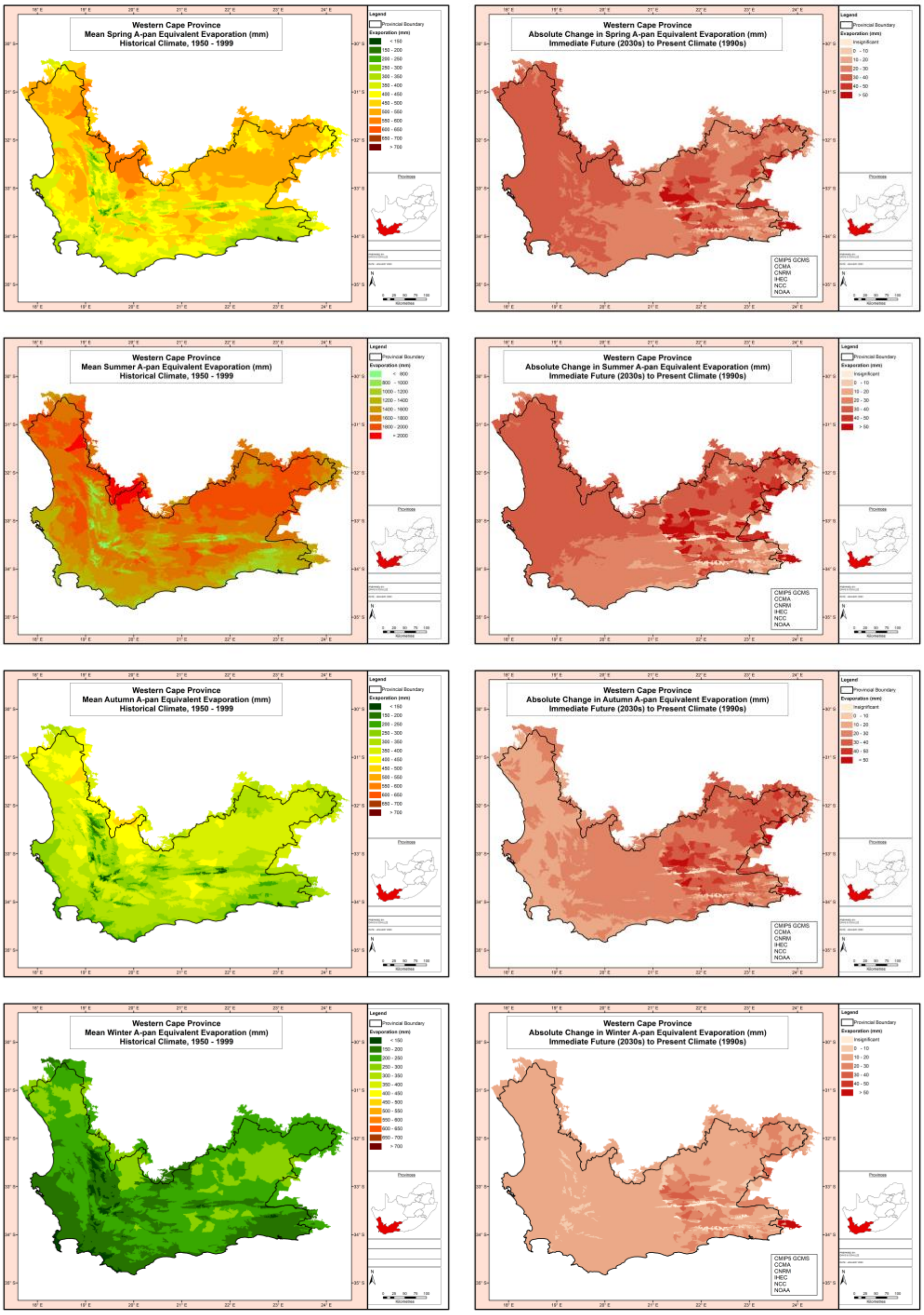


Figure 16. Mean spring (September-November), summer (December-February), autumn (March-May) and winter (June-August) A-pan equivalent reference potential evaporation under historical climatic conditions (left column, top to bottom), and corresponding projections of absolute changes to the immediate future (right column, top to bottom). The latter are derived from multiple CMIP5 GCMs.

CHAPTER 5

IMPACTS OF CLIMATE CHANGE ON FRUIT PRODUCTION AND FRUIT QUALITY

5.1 Frost and projected changes

Frost is a component of climate which is both an asset (e.g. in that it can kill pests and diseases) and a liability (when it kills or injures crops).

5.1.1 Some definitions related to frost

- A *frost* is defined as the occurrence of an air temperature of 0°C or lower, measured at a height of between 1.25 and 2.0 m above soil level, inside an appropriate weather shelter such as a Stevenson screen. Water within plants may or may not freeze during a frost event, depending on several avoidance factors characterising a specific plant (e.g. supercooling and concentration of ice nucleating bacteria).
- A *freeze* occurs when extra-cellular water within the plant freezes (i.e. changes from liquid to ice). This may or may not lead to damage of the plant tissue, depending on tolerance factors (e.g. solute content of the cells). A frost event therefore becomes a freeze event when extra-cellular ice forms inside of the plant.
- *Freeze injury* occurs when the plant tissue temperature falls below a critical value, thus inducing an irreversible physiological condition that leads to death or malfunction of the tissue. This temperature is correlated with air temperatures ('critical temperatures') measured in standard instrument shelters.

5.1.2 Conditions conducive to frost occurrence

Conditions that are most favourable for frost occurrence are:

- Surface temperatures must be below freezing, otherwise dew rather than frost may form;
- Surface temperatures must be below the dew point temperature, to ensure that the air near the tissue surface contains more moisture than it can hold at the surface temperature (for rapid frost formation);
- Dew point temperatures must be near (even above) freezing, to ensure a large amount of moisture in the air for possible deposit on the surface as frost.

5.1.3 Factors influencing frost occurrence

The following four factors are important regarding frost occurrence over South Africa:

- *Altitude:* in general, the higher the altitude, the lower temperature and hence a greater likelihood of frost occurrence
- *Latitude:* in general, the further from the equator, the lower the temperature and the higher the likelihood of frost occurrence
- *Distance from sea, or continentality:* the further a location is from the moderating influence of the ocean (irrespective of altitude or latitude), the greater the likelihood of freezing temperatures being reached

- *Local topography:* a valley location surrounded by higher altitudes experiences cold air drainage resulting from radiative cooling on the upper slopes; this causes the denser cold air to 'sink' into the valleys; thus the intensity of valley frost occurrence depends on the steepness of the surrounding topography.

5.1.4 Types of frosts

Types of frosts fall into two broad categories:

- *Advective frosts* are those associated with large-scale inflows of cold air masses that replace warmer air that was there before the weather change. They occur with a well-mixed and usually moderate to strong windy atmosphere under cloudy conditions and relatively low humidity, with temperatures that are often < 0°C, even during the daytime.
- *Radiative frosts* are associated with a cooling due to energy loss through radiant exchange. In summary, for radiative frost to occur, the requirements are, ideally, *long clear nights*, which often occur in the relatively dry winter months in the more arid regions, during which the loss of heat from the earth's surface by outgoing longwave radiation is rapid; *little wind*, so that little mixing of air occurs and the surface layers can thus quickly cool, and *relatively dry air*, so that little of the outgoing radiation is absorbed by atmospheric water vapour and re-radiated back. Temperatures then rise to >0° again during the daytime.

5.1.5 Effects of freezing temperatures and plant responses

While plants possess a number of physical and biological mechanisms to avoid freezing (e.g. solute accumulation within the cell serving to depress freezing points by 2 to 3°C; or supercooling of water; or the facilitation of extra-cellular freezing), none of these provides complete protection from below zero temperatures. Frost can cause formation of ice within the plant cell and outside the cell. Fundamental biological changes can then take place under conditions. Some plants are killed outright by frost while others suffer damage, such as complete defoliation, from which they can recover. Frost damage varies with the type of plant and between tissue types, and the season and growth stage of the plant, and depends on the way temperature changes. For example, if freezing is rapid, then the tissue or plant can be killed at higher temperatures than if freezing is gradual. Furthermore, greater injury to the plant or tissue is likely to occur during a period of continued freezing than during a short freeze. In deciduous fruit trees, the tree is seldom killed by frost, but frost can kill sensitive buds and other actively growing tissues. The dangerous periods are generally in late winter and spring, when frost can cause sufficient damage to emerging buds and flowers, especially in early stone fruit such as apricots and some peach cultivars. Late frosts can also lead to significant damage in later cultivars.

5.1.6 Results – days per annum

Frost occurrence (T_{min} < 0°C) under historical climatic conditions is most prevalent in the high-lying inland areas, including the north-east and the mountainous areas in the central east and west (Fig. 17, top left). Up to ~ 40 or more frost occurrences per annum can occur in these areas. The coastal areas are either frost free or experience fewer than 5 frost days per annum. The historical patterns for severe frost (T_{min} < -1°C; Fig. 17, middle left) are similar, but shrunk, while for very severe frosts (T_{min} < -2°C; Fig. 17, bottom left) there is further spatial shrinkage and a reduction in numbers per annum of such frosts.

Into the intermediate future of the 2050s the middle column of maps in Fig. 17 shows severe shrinkage when compared to the historical maps (left column). When reductions in frost occurrences from the present to intermediate future climates are mapped (right column, in days per annum), the biggest reductions are in the mountainous and high-altitude areas at between 5-40 frost days (top right), 5-30 severe frost days (middle right) and 5-20 very severe frost days (bottom right).

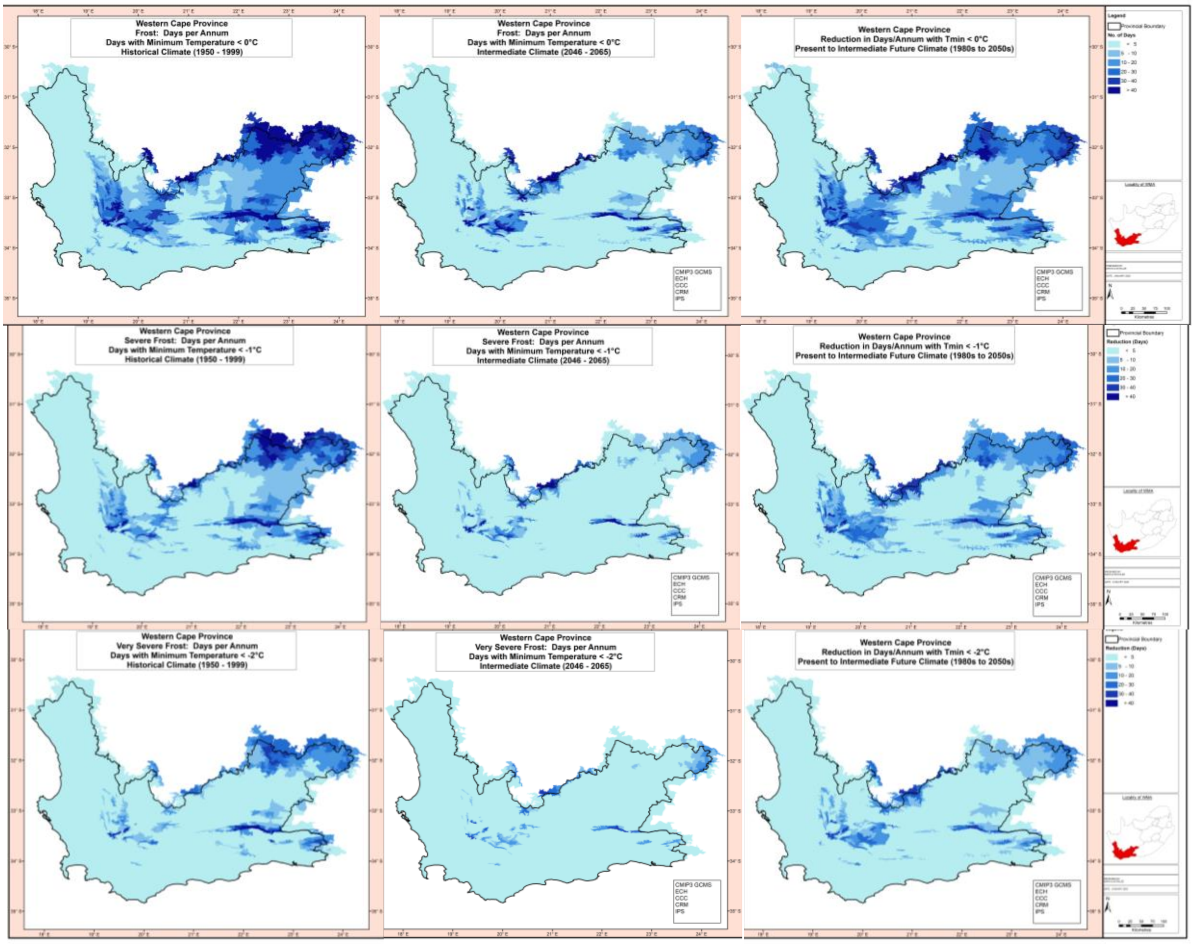


Figure 17. Number of days per annum with frost (T_{min} < 0°C), severe frost (T_{min} < -1°C) and very severe frost (T_{min} < -2°C) risk under historical climatic conditions (left column, top to bottom). The maps in the middle column show the respective days under projected intermediate future conditions. The maps in the right column show changes (in reduction of days per annum) between the present and intermediate future. Future and future change maps were derived from multiple CMIP3 GCMs (original research: Schulze, 2011).

5.1.7 Results – days per month in spring

The highest risk of frost to deciduous fruit production is in the late winter and spring months (July to November). Fig. 18 shows the present (left column) and projected intermediate future (right column) patterns for frost (T_{min} < 0°C) for these months. In July and August the present frost risk is highest with many inland areas experiencing more than 4 frost days per month. Into the intermediate future of the 2050s this level of risk is reduced to the interior and high-lying areas. Other areas in the interior and along the coast essentially become frost free or experience fewer than 1 frost day during these months. The present frost risk is reduced in September but still widespread, including some coastal areas, while in October and November it is mostly limited to the interior and high-lying areas. The maps for the projected intermediate future indicate strong shrinkage in the high risk areas, and the November of the future could become almost entirely frost free.

The present patterns for severe frost (T_{min} < -1°C; Fig. 19, left column) and very severe frosts (T_{min} < -2°C; Fig. 20, left column) show a similar higher risk in July and August compared to later months, but spatially shrunk compared to frost (Fig. 18). Into the intermediate future (Figs 19 and 20, right column), some risk of severe and very severe frost remains in small areas from July until September, but in October and November the risk becomes negligibly small everywhere.

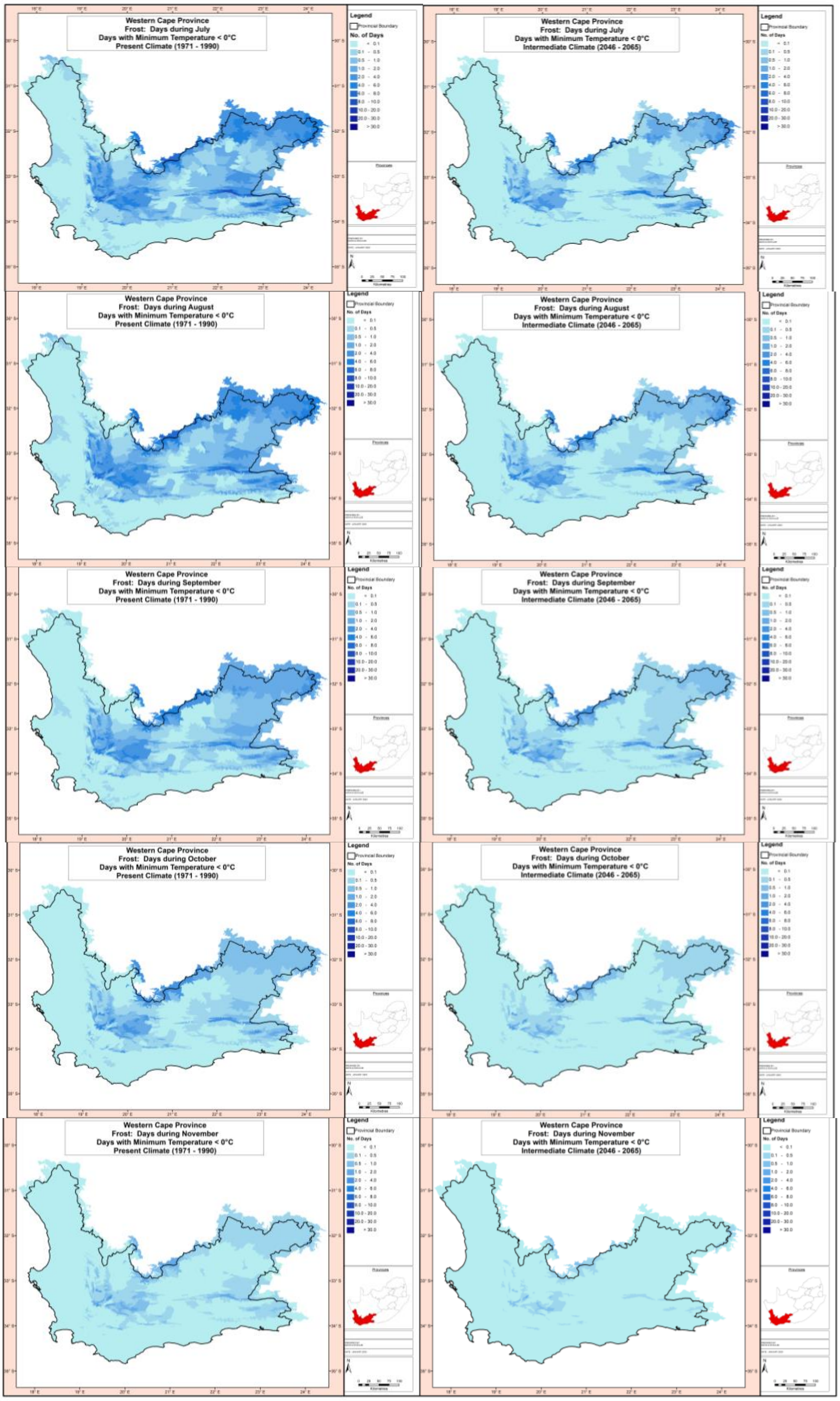


Figure 18. Number of days per month in spring with frost ($T_{min} < 0°C$) risk under present climatic conditions (left column) and projected intermediate future conditions (right column). Results are presented monthly from July (top) to November (bottom) in each column. Future maps were derived from multiple CMIP3 GCMs (original research: Schulze, 2011).

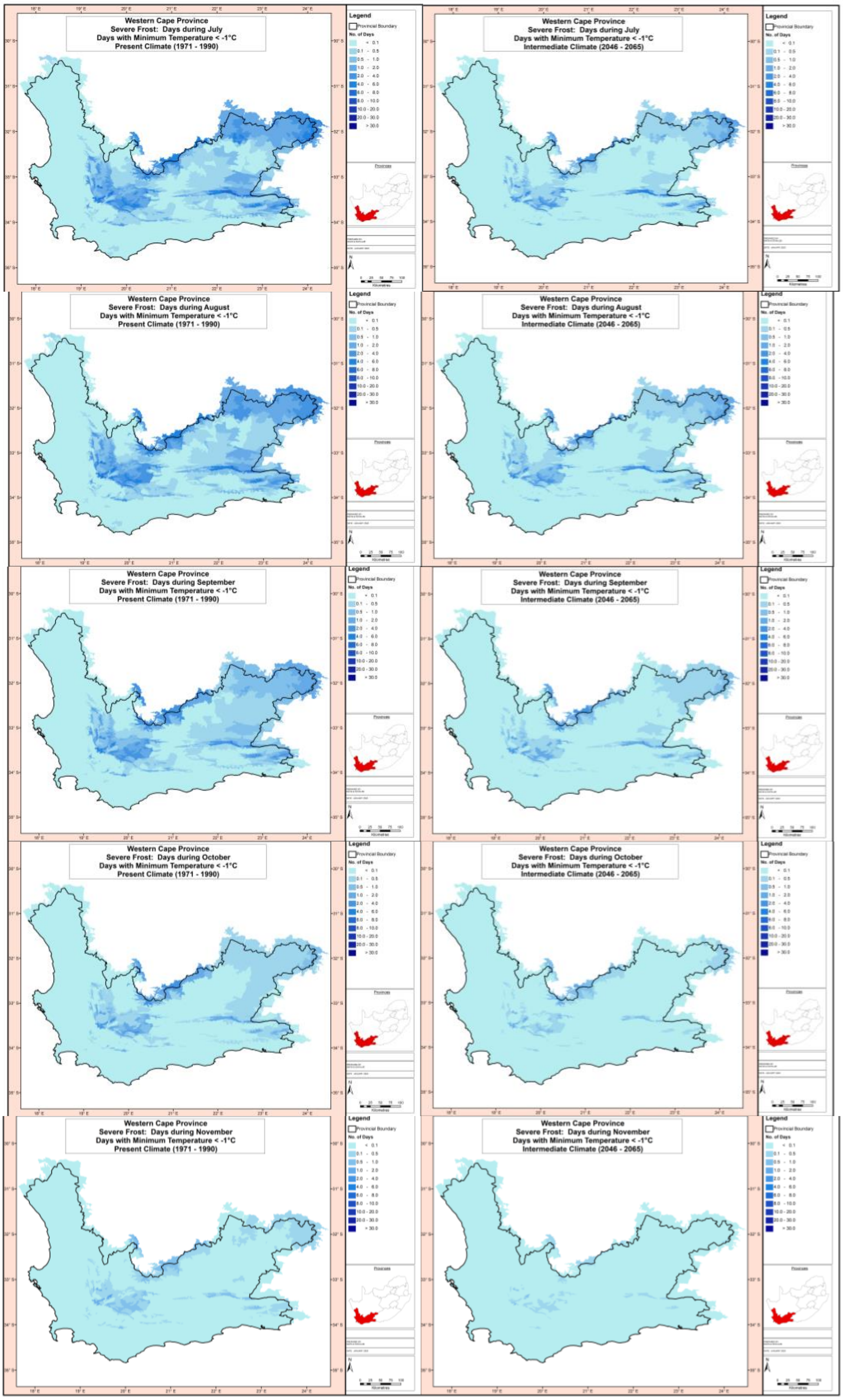


Figure 19. Number of days per month in spring with severe frost ($T_{min} < -1°C$) risk under present climatic conditions (left column) and projected intermediate future conditions (right column). Results are presented monthly from July (top) to November (bottom) in each column. Future maps were derived from multiple CMIP3 GCMs (original research: Schulze, 2011).

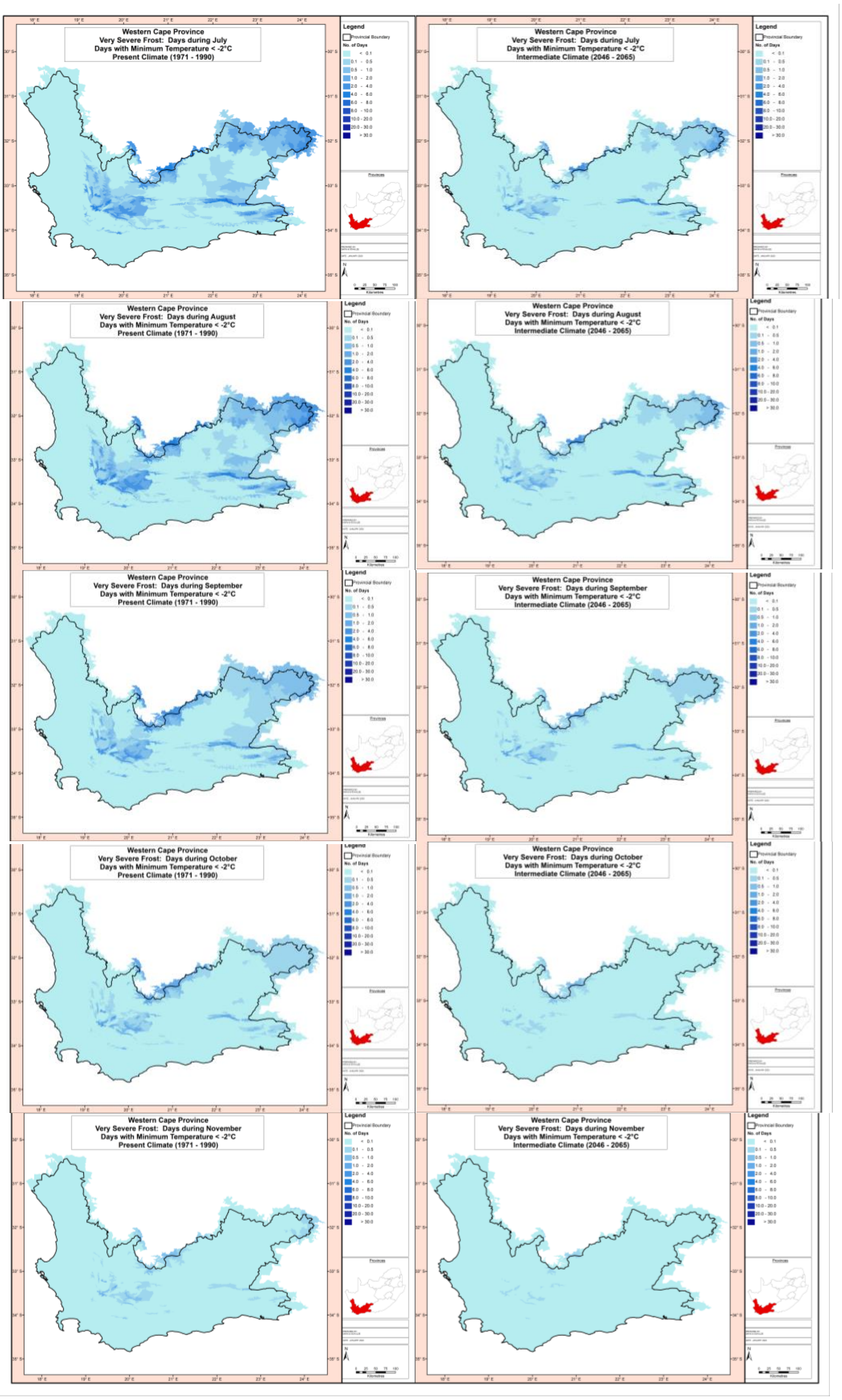


Figure 20. Number of days per month with very severe frost (T$_{min}$ *< -2°C) risk under present climatic conditions (left column) and projected intermediate future conditions (right column). Results are presented monthly from July (top) to November (bottom) in each column. Future maps were derived from multiple CMIP3 GCMs (original research: Schulze, 2011).*

5.1.8 Implications

At first glance, the projected reductions in frost, severe frost and very severe frost days could release certain areas for pome and stone fruit production which are currently subject to damaging frost events, and extend the length of the growing season by a generally later start to the frost season and an earlier finish. Potential frost damage to fruit trees early in the growing season depends on the timing of flowering, and damage to buds depends on the bud developmental stage. In general, the risk to buds is increased in pome fruit trees from the green/white tip stage until the flower clusters open, and maximum damage through frost is experienced at full bloom and post-bloom. However, stone fruit are most susceptible even before full bloom, and since some stone fruit types and cultivars bloom as early as July and early August, frost damage is most often experienced in stone fruit orchards, especially in parts of the Klein Karoo and other areas with a high frost risk. Even where flowering occurs later in spring, late frost can inflict devastating losses. The timing of the last frost is thus critical.

The results must be interpreted together with the projections for future winter and spring daytime temperature and chill accumulation trends. Bud break is determined both by conditions leading to the breaking of dormancy, and by temperatures thereafter ("forcing" conditions). An earlier and more rapid start to flowering once dormancy has been broken (linked to more rapid accumulation of heat units as winter and spring temperatures rise) can increase the risk of frost damage. Even if the frost risk (number of events expected per month) is reduced in future, it takes only one night of heavy frost to inflict the damage, therefore a reduction in mean frost days is of little comfort. The results suggest that late frost could become less frequent, and eventually not occur during flowering periods and thereafter. However, it is impossible to project when this will occur and there is a danger in becoming complacent too quickly. There is also a danger that greater use of low chill cultivars (as an adaptation to reduced winter chilling) can cause very early flowering after a warm winter spell, and then expose the buds and flowers to frost. The combined and interacting risks from all these factors will be highly cultivar- and area-specific. Further research is needed in this area.

Changing patterns of frost have implications for certain pests and diseases which are killed by frosts. These are likely to proliferate where winter morning temperatures are more benign.

5.2 Chill units and projected changes

5.2.1 The concept of chill units

In autumn, deciduous fruit trees lose their leaves and enter a dormant phase to survive the winter. To end this dormancy, they require a certain amount of winter cold (their ‘chilling requirement’) followed by a certain amount of heat. This winter cold is, broadly speaking, a period of accumulated minimum temperatures below a threshold. Insufficient winter chilling may result in poor and prolonged flowering, delayed foliation, reduced fruit set and yield, and reduced fruit quality. The required amount of chilling for completion of the rest period varies between species and cultivars.

The period of dormancy is a progression involving up to three types of dormancy. In the context of climate and climate change, two are of most importance: (i) Ecodormancy, which can occur at the beginning or end of the dormant period and is controlled by growth limitations imposed by external environmental conditions, e.g. temperature. The lifting of the environmental limitation, e.g. a warm spell, can lead to renewed metabolic activity and growth. (ii) Endodormancy, a period of "deep" rest controlled by the buds themselves. Growth of the buds can only begin when they release certain biochemical compounds following a period of sufficient chilling of the buds.

5.2.2 Estimating chill units

Many chill accumulation models have been formulated, most of them requiring observed or estimated hourly temperatures. The application of chill unit models enables growers to, for example:

- predict the time of dormancy completion and bud break,
- determine the time when chemical rest-breaking sprays should be performed, where these are used,
- determine the time when other cultural practices should begin, or
- identify potential growing locations with sufficient chilling for various fruit types and cultivars.

For this study, the Utah Chill Unit model, with its South African modification to the Daily Positive Chill Unit (or *PCU*) model by Linsley-Noakes et al. (1995) was used to produce maps of mean seasonal or monthly chill units. This model is also known as the Infruitec model, or the Modified Utah Chill Unit model, and is more suited to the warm South African climate. The optimum temperature range for chilling accumulation is between 7.2 and 9.1°C, with temperatures >15°C negating chilling. In contrast to the Utah model, the PCU model assumes that high temperatures can only negate the chilling received on the day of occurrence and do not affect the chill units accumulated previously.

The techniques by which *PCU*s are computed from hourly temperature values is outlined in detail in Schulze (2011). From the hourly *PCU* calculations, daily *PCU*s are accumulated, from which monthly and seasonal totals of *PCU*s can be computed for the period April to August. The accumulation of chill units in June and July is considered the most important indicator of whether sufficient chilling is received in a specific area.

Different deciduous fruit species and cultivars require different numbers of *PCU*s. Broadly speaking:

- *Low chill cultivars* require up to ~ 450 *PCU*s and are generally grown in warmer climates;
- *Medium chill cultivars* require between 450 and 650 *PCU*s, and in areas with this range of *PCU*s one can grow both medium and low chill cultivars, providing the low chill plants are protected from late spring frosts; while
- *High chill cultivars* require > 650 *PCU*s, and in areas with this level of chilling one needs later blooming and frost hardy cultivars, but one can also grow low and medium chill cultivars, again providing that these plants are protected from late spring frosts.

As a group, pome fruit species generally have a higher chilling requirement than stone fruit species, but there is variation within species. There is a wide range between apple cultivars that are suited to temperate climates with cold winters (high chill) and those more suited to warmer production regions. Cultivars with a high chilling requirement include Braeburn, Fuji, Golden Delicious, Royal Gala and Starking. Cripps Pink (Pink Lady®) has a medium chilling requirement and Granny Smith has a medium to low chilling requirement.

Divergent chilling requirements are also found in pears. The highest chill requirement is found in the cultivars Doyenné du Comice, Bon Chrétien and Beurré Bosc, followed by Abate Fatel, Bon Rouge and Cheeky^{TM} (SA) with a medium chilling requirement. Medium to low chilling requirements are found in Packham's Triumph, Rosemarie, Forelle and Early Bon Chrétien.

Apple growers in the warmer production regions of South Africa routinely make use of chemical rest-breaking agents, such as Dormex® (active ingredient: hydrogen cyanamide, often applied with mineral oil), to regulate flowering and fruit set under conditions of sub-optimal chilling. These are sprayed in the first two weeks of September, 4-6 weeks before the expected start of flowering. Most pear farmers use only mineral oil applications for rest-breaking.

For the stone fruit species, sweet cherry cultivars have until recently had a high chilling requirement, but new cultivars have now become available in South Africa with much lower requirements. Most apricots have a medium to low chilling requirement, nectarines range from medium-high to low, peaches range from medium to low, and plums range from medium to low chilling requirements. South Africa currently has a very wide range of stone fruit cultivars available with highly divergent climatic preferences within the medium-high to low band. Rest-breaking sprays can be applied in some cultivars (apricots, cherries, plums) where chilling is insufficient.

5.2.3 Results – seasonal and monthly chill units

We begin by presenting the number of chill units that are accumulated across South Africa on a monthly basis from April to August (Fig. 21), with the left column showing the units under the historical climate, and the right column showing the units projected for the climate of the intermediate future. Historically, chill unit accumulation begins slowly in April, but the rate increases rapidly in May and June, reaching a peak in July, and thereafter (August) decreasing. Areas receiving the highest chill units include the mountains of the south-western and southern interior, the mountains and high-lying parts of the Eastern Cape and the Drakensberg foothills. Significant chilling is also experienced on the central plateau, the Highveld and the eastern Escarpment.

The projections into the intermediate future indicate a later start to significant chilling, with reductions in chill units in all the months and a contraction of the areas receiving high levels of chilling (Fig. 21, right column).

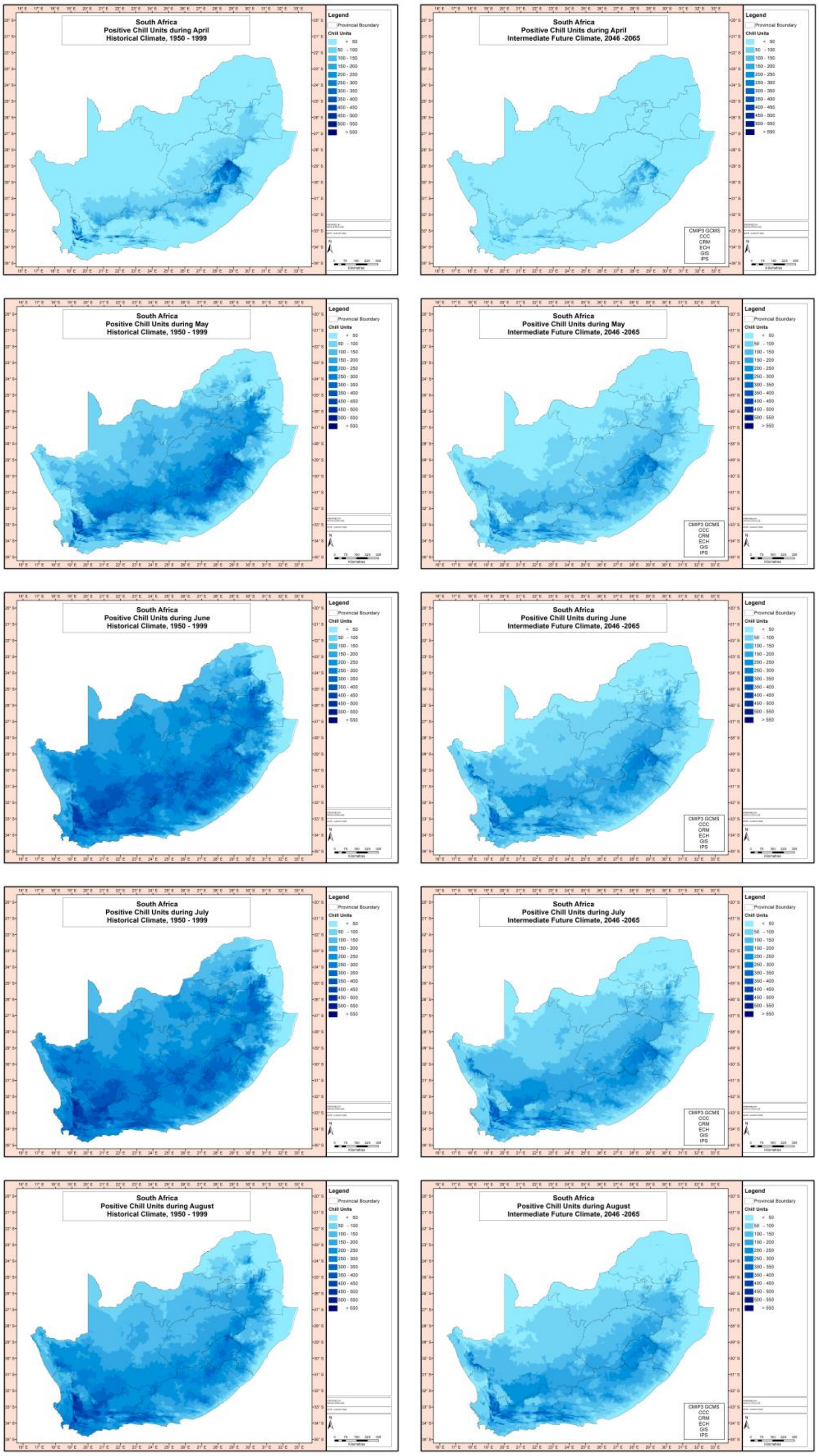


Figure 21 Mean monthly PCUs *in South Africa under historical climatic conditions from April (top left) to August (bottom left) and corresponding projections under intermediate future climatic conditions (right column of maps) derived from multiple CMIP3 GCMs.*

For the Western Cape and Langkloof, the means of accumulated *PCU*s from April to August under historical climatic conditions are shown in Fig. 22 (top), with *PCU*s for that part of the year ranging from < 600 in the north-west, to > 2 000 *PCU*s in the high-altitude mountain areas. *PCU* values of 800-2000 are seen in the pome fruit production regions, with values of 600-800 also common in the stone fruit production regions.

For the intermediate future of the mid-century, a sharp decline in *PCUs* is very clear (Fig. 22, bottom). Reductions of 250 to 500 or more *PCU*s are likely to be experienced across large areas. Accumulated seasonal *PCU*s are projected to range between < 200 and 2000 across the region. In the pome fruit regions, the *PCU*s are projected to be between 200 and 1600, while values of 200-600 could become common in the stone fruit regions.

Fig. 23 (left column, from top to bottom) presents *PCU*s on a month-by-month basis from April to August for historical climatic conditions. Spatial patterns across the region are preserved under historical climatic conditions in the monthly maps of Fig. 23 (left column) compared to Fig. 22 (seasonal). *PCU* accumulation starts very slowly in April and increases through May to reach maximum levels in June, July and August. The right column of maps in Fig. 23 shows the projections into the intermediate future of the 2050s for the same set of months, derived from multiple GCMs and the RCP8.5 scenario. The maps indicate significant losses of *PCU*s in April and May, especially in the warmer production regions of the south. In future, most *PCU*s in these regions could be accumulated in the core months of June, July and August compared to the longer period of accumulation in the cooler regions. In some regions this will leave chill accumulation too late to reach medium or higher *PCU* thresholds.

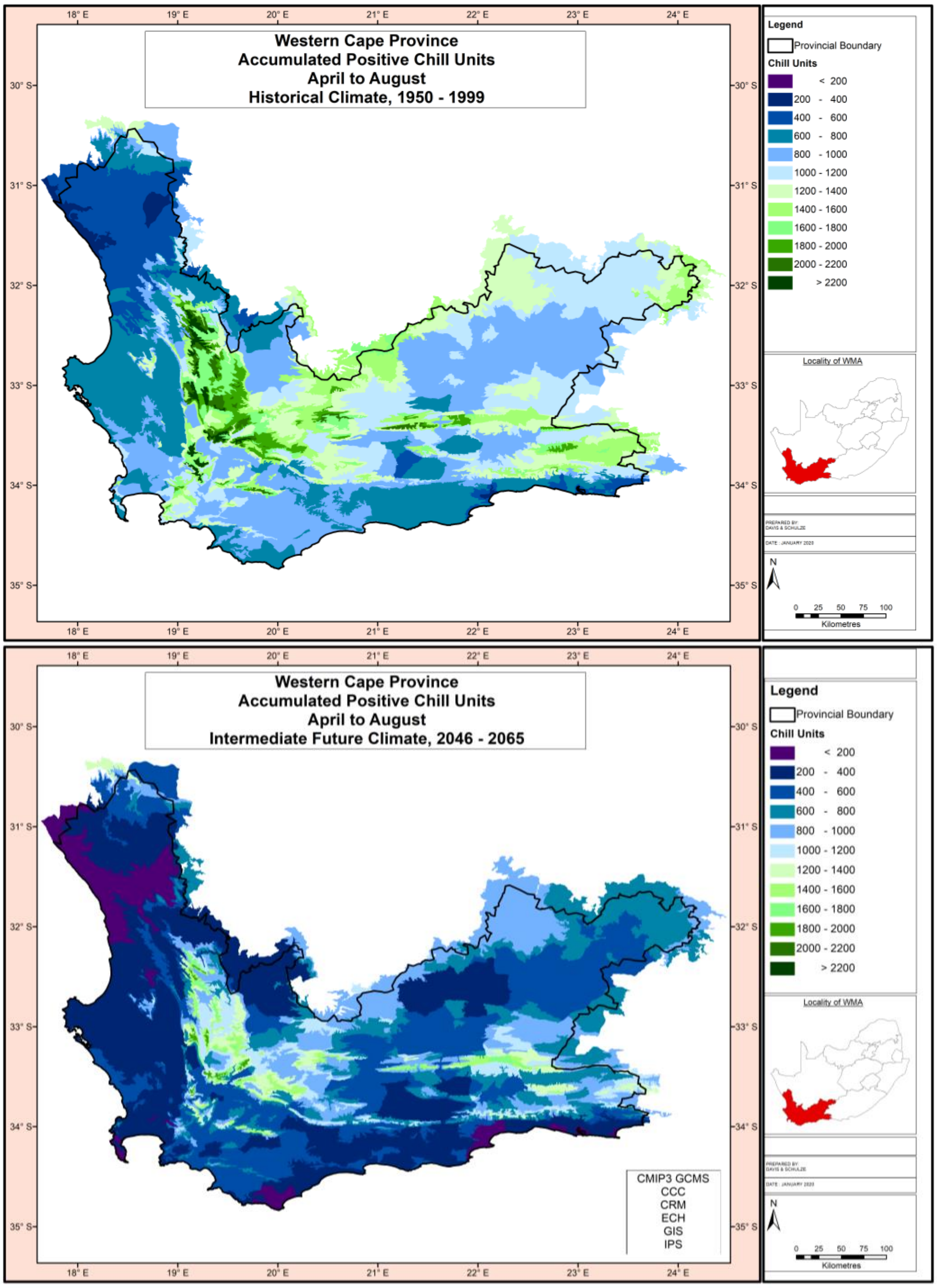


Figure 22. Mean of accumulated positive chill units in the Western Cape Province from April to August under historical climatic conditions (top) and the corresponding projected under intermediate future climate conditions (bottom). The latter was derived from multiple CMIP3 GCMs.

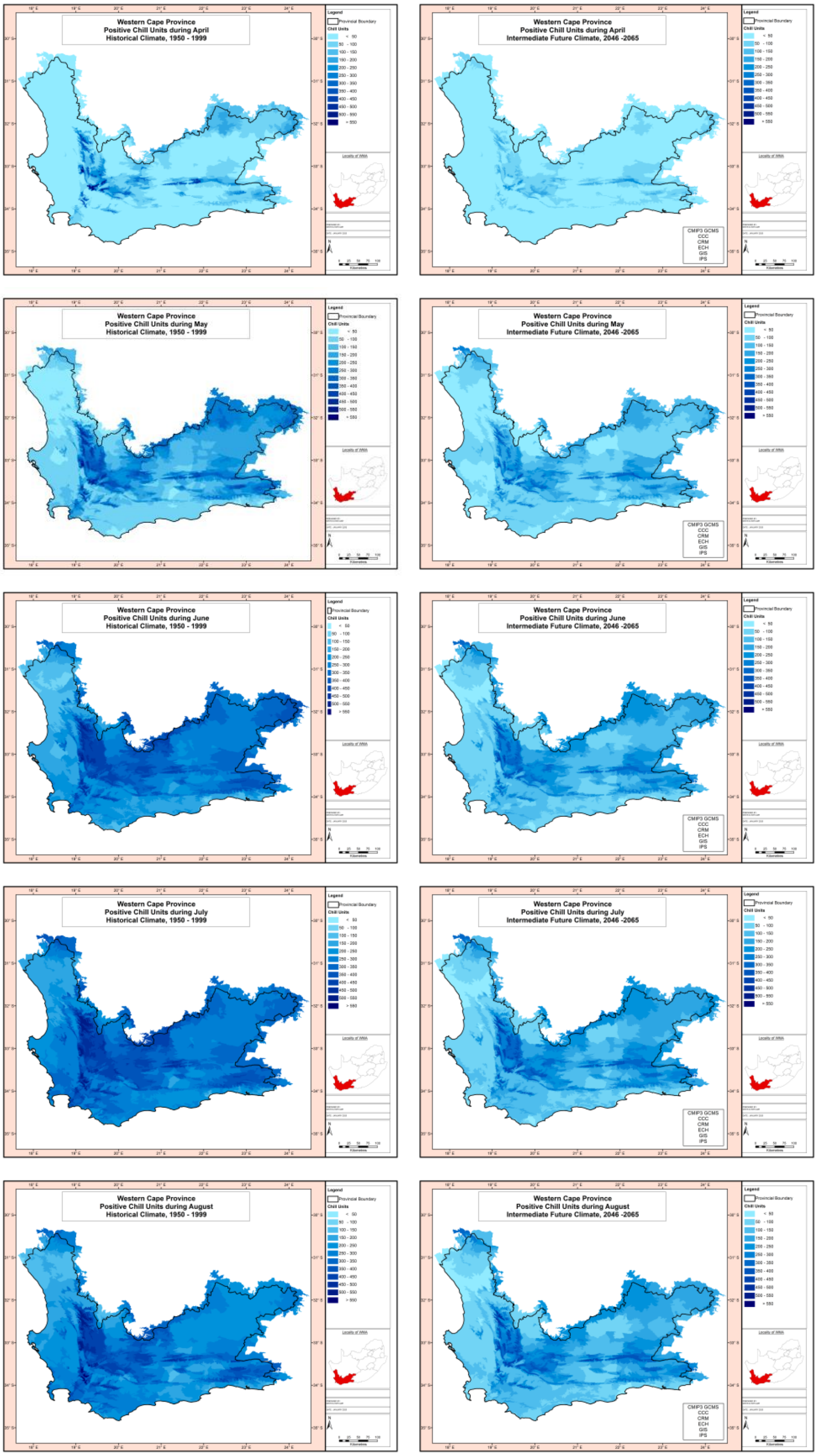


Figure 23. Mean monthly PCUs *in the Western Cape Province under historical climatic conditions from April (top left) to August (bottom left) and corresponding projections under intermediate future climatic conditions (right column of maps) derived from multiple CMIP3 GCMs.*

The next set of maps present the historical and projected future chilling accumulation on a monthly basis for the provinces Free State (Fig. 24), KwaZulu-Natal (Fig. 25) and Mpumalanga (Fig. 26).

The fruit-growing area of the eastern Free State, in the foothills of the Drakensberg Mountains, has historically received high levels of winter chilling in the period May to August (Fig. 24, left column). The projection for the intermediate future show a later start to chilling, with significant chilling shown for the period June to August (Fig. 24, right column). Although the *PCU*s are strongly reduced by the mid-century, they should still be sufficient for the production of fruit with a higher chilling requirement. However, the reduction in chilling in the warmer areas of the province could be of greater significance for higher chilling pome and stone fruit production.

In KwaZulu-Natal, stone fruit (cling peaches) are produced in a small area of the colder northern interior. Here, historically, chilling accumulates mainly from May to August (Fig. 25, left column). While peaches do not require high chilling, the loss of chill units into the intermediate future (Fig. 25, right column) could be of concern to growers in this area.

Similarly, the high-lying escarpment and Highveld regions of Mpumalanga have historically accumulated chill units from May, and peaking in July (Fig. 26, left column). In the intermediate future, the area receiving high chilling is substantially reduced (Fig. 26, right column), which will influence where higher chilling pome and stone fruit cultivars can be grown. However, sufficient chilling should still be experienced for medium to low chill cultivars.

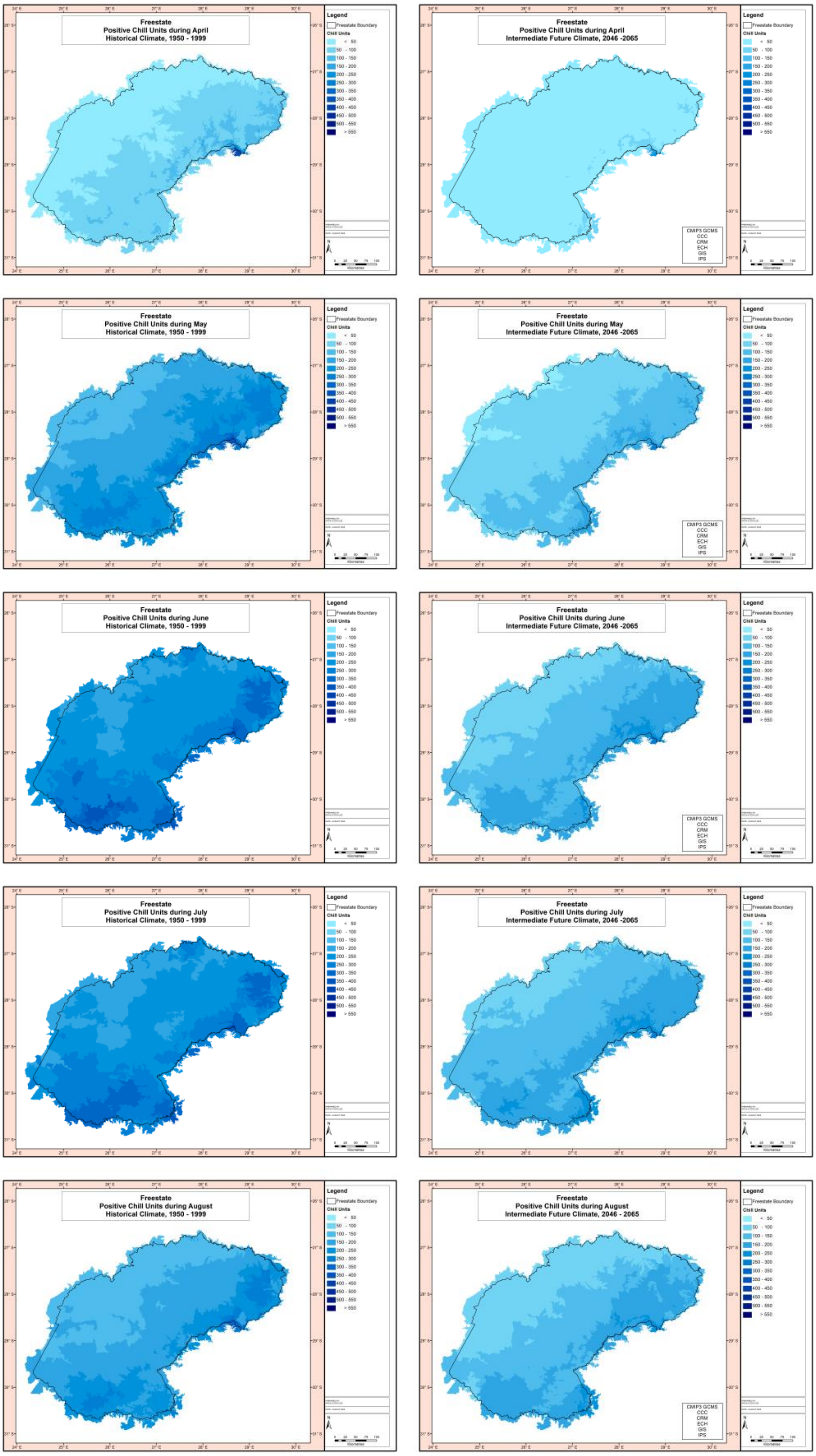


Figure 24. Mean monthly PCUs in the Free State Cape Province under historical climatic conditions from April (top left) to August (bottom left) and corresponding projections under intermediate future climatic conditions (right column of maps) derived from multiple CMIP3 GCMs.

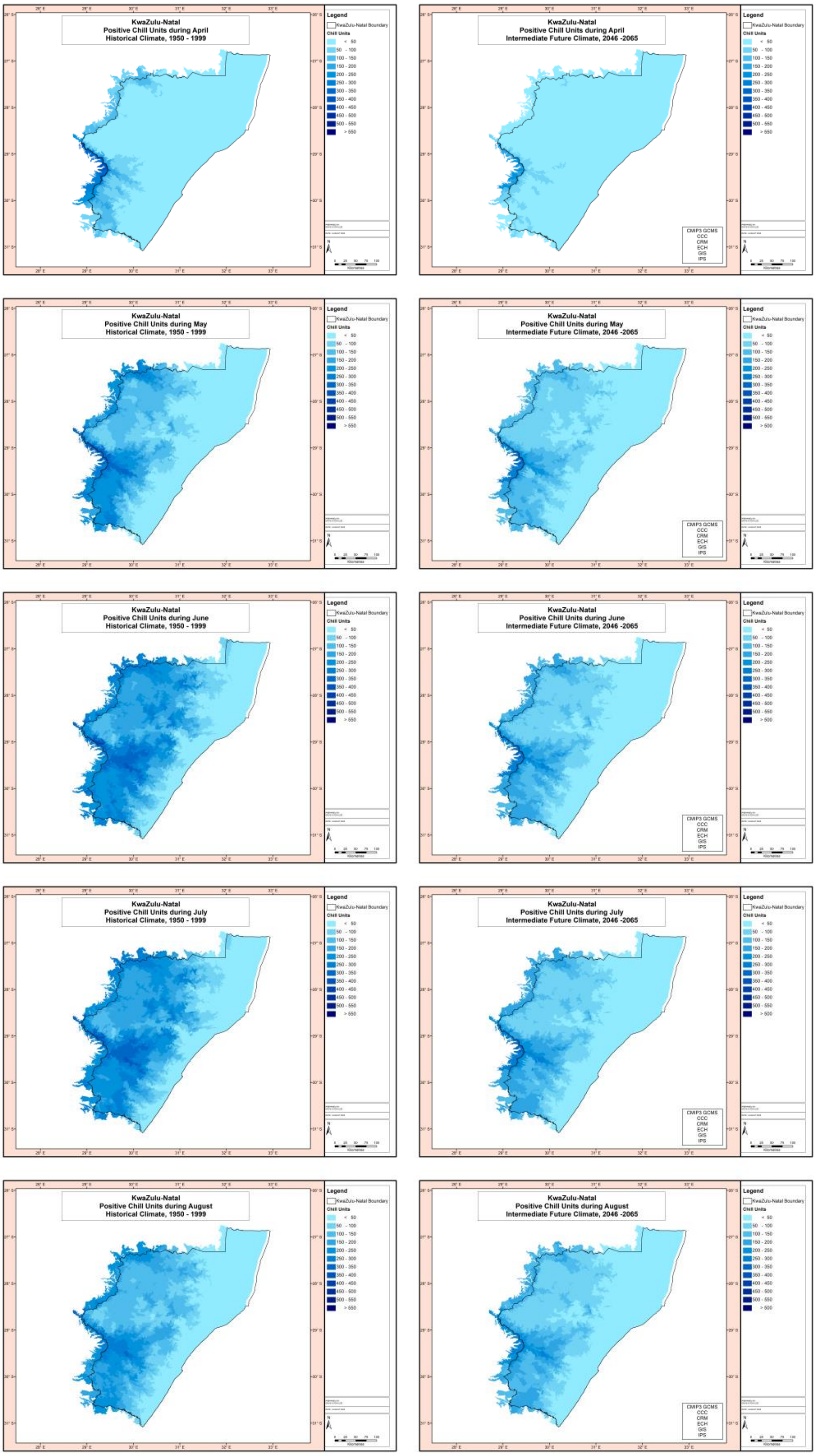


Figure 25. Mean monthly PCUs in the KwaZulu-Natal Province under historical climatic conditions from April (top left) to August (bottom left) and corresponding projections under intermediate future climatic conditions (right column of maps) derived from multiple CMIP3 GCMs.

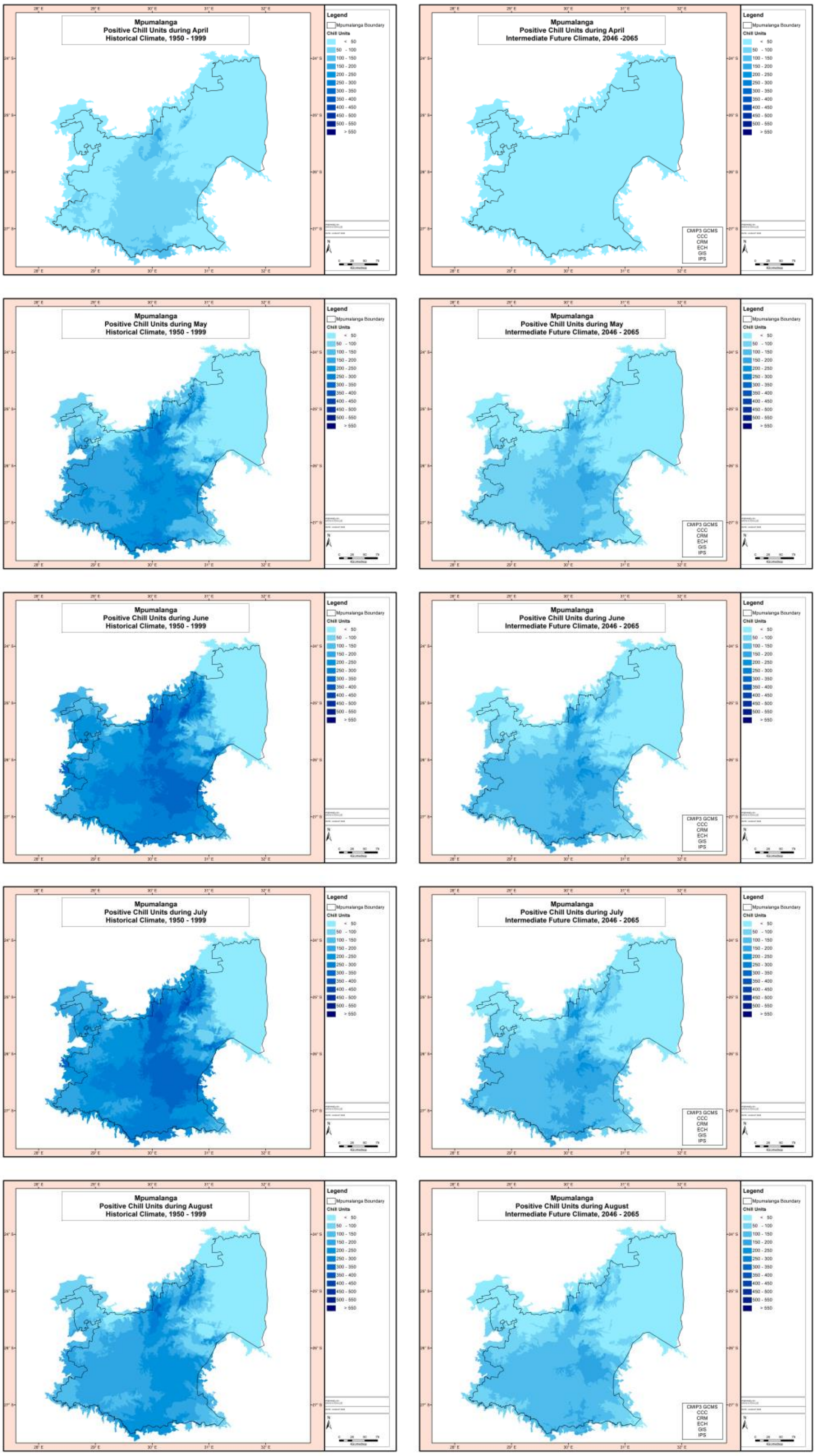


Figure 26. Mean monthly PCUs *in the Mpumalanga Province under historical climatic conditions from April (top left) to August (bottom left) and corresponding projections under intermediate future climatic conditions (right column of maps) derived from multiple CMIP3 GCMs.*

5.2.4 Results - month by which threshold accumulated chill units are achieved, and projected changes

For deciduous fruit cultivars with a given chill requirement, a key question is *when* (i.e. in which month) certain levels of chill accumulation are met at a specific location. For the purposes of this study, a low chill requirement is represented by 250 *PCU*s, a medium chill requirement is represented by 500 *PCU*s, and a high chill requirement is represented by 700 *PCU*s. Results for South Africa are illustrated by way of maps in Fig. 27, with the left column showing the historical climate and the right column showing the intermediate future climate.

Historically, low *PCU*s (250) are reached by May in the mountains of the Western Cape, along the Escarpment, the Drakensberg Mountains and their foothills, and parts of the high-lying interior (Fig. 27, top left). This covers most of the deciduous fruit production regions, with some regions reaching this threshold in June. My mid-century (Fig. 27, top right) the areas still reaching this threshold by May are expected to contract to only the highest mountainous areas, with most of the fruit production regions reaching 250 PCUs by June or July.

The medium *PCU* threshold of 500 units has historically been reached between May (mountains) and July (Fig. 27, middle left), whereas in the intermediate future (Fig. 27, middle right) this shifts to a patchwork of June (mountains), July, August, and in some areas September.

High *PCU*s (700) have historically been reached by June or July in most of the pome and stone fruit regions, and sometimes August in stone fruit regions (Fig. 27, bottom left). The projected changes by mid-century (Fig. 27, bottom right) suggest that only the coldest areas will achieve 700 *PCU*s by July, with other production regions reaching this threshold by August, September and October (or never, in the warmest regions).

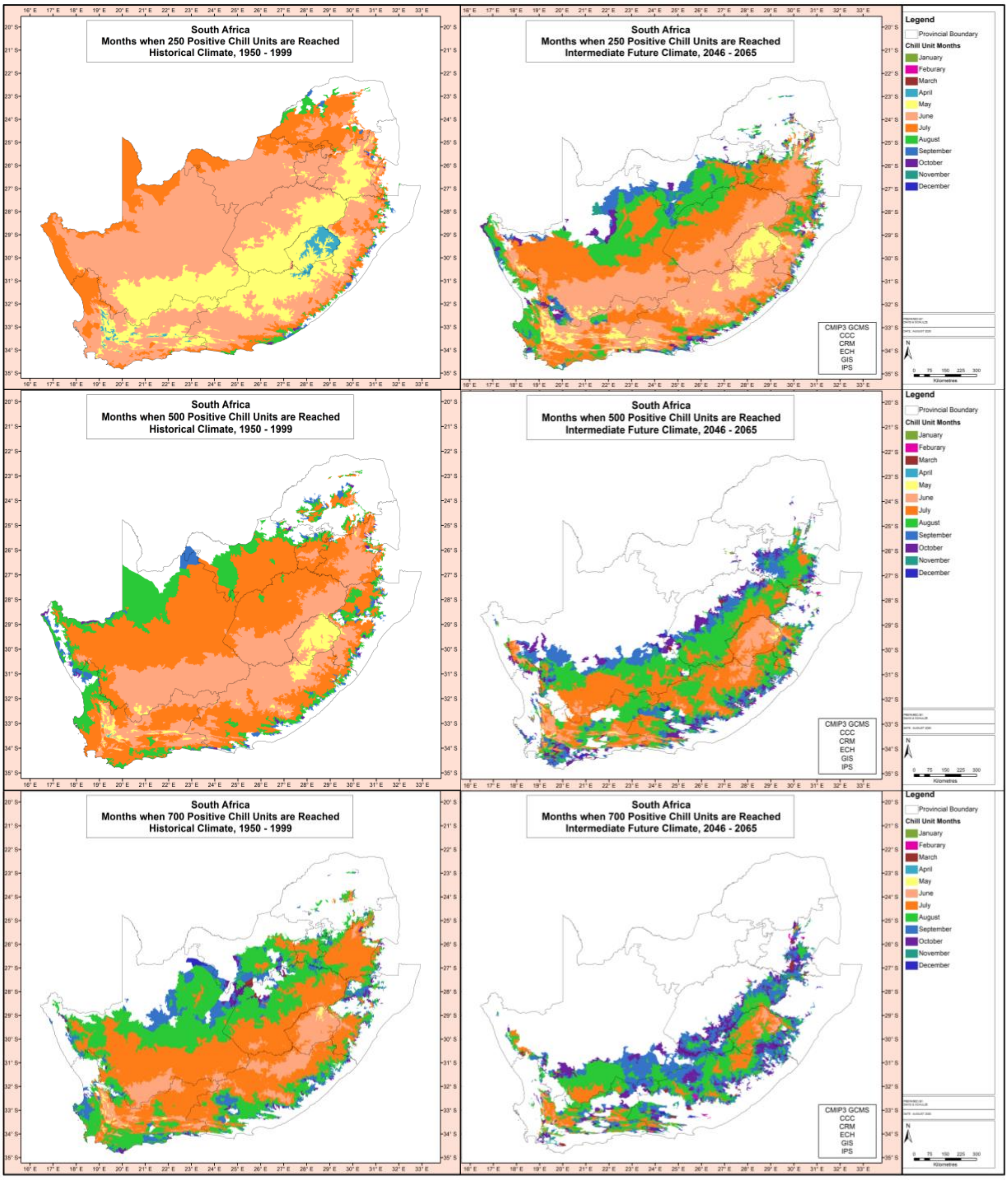


Figure 27. Month by which 250 (top left), 500 (middle left) and 700 (bottom left) PCUs are reached in South Africa under historical climatic conditions, as well as under intermediate future climatic conditions in the corresponding right-hand maps (original source: Schulze and Schütte, 2016).

In the next set of maps, the results are presented for four provinces: Western Cape, Free State, KwaZulu-Natal and Mpumalanga.

In the Western Cape, low *PCU*s (250) have historically been reached by May in the cooler parts, and by June in the remainder of the fruit production areas (Fig. 28, top left). By the projected intermediate future of the 2050s, 250 *PCU*s are generally reached one month later, but in some areas up to two months later (Fig. 28, top right). On the other hand, 500 *PCU*s are achieved historically largely by May-June (cooler areas) or July (warmer areas) in the fruit growing areas (Fig. 28, middle left). By the intermediate future of the 2050s (Fig. 28, middle right), the southern parts of the fruit growing areas only achieve 500 *PCU*s by August or September or later, whereas the cooler northern regions (with the exception of Wolseley-Tulbagh) and Langkloof mostly still achieve 500 *PCU*s by June or July. Under historical climatic conditions, high *PCU*s (700) are reached by June-July (cooler northern fruit areas and western Langkloof) or July-August (warmer southern areas and Little Karoo) (Fig. 28, bottom left). Into the intermediate future (Fig. 28, bottom right), this shifts to mostly July in the north and western Langkloof, and to September to October (cooler south) or never (warmer south e.g. Berg and Breede River valleys).

In the Free State, 250 *PCU*s have historically been reached by May in the south-eastern half, and by June in the north-western half (Fig. 29, top left), while in the intermediate future this is expected to shift to June and July, respectively (Fig. 29, top right). Historically, the 500 *PCU* threshold has been achieved by June (south-east) or July (north-west) (Fig. 29, middle left), but by the mid-century (Fig. 29, middle right) this threshold may only be reached in July (in the coldest areas), August (other parts of the south-east), or September-October or not at all (north-west). Large parts of the province historically achieved 700 *PCU*s by July (Fig. 29, bottom left) but into the intermediate future (Fig. 29, bottom right) only a small area could achieve this threshold by August, with other parts of the south-east reaching 700 *PCU*s by September or October.

Large parts of the KwaZulu-Natal interior have historically reached 250 *PCU*s by May (Drakensberg and Escarpment) or June (Fig. 30, top left), but this area contracts significantly into the intermediate future (Fig. 30, top right), mostly to the Drakensberg foothills / Midlands and the Escarpment. The remainder of the interior achieves this threshold by July or August. The medium chilling threshold (500 *PCU*s) has been historically reached by June or July (Fig. 30, middle left), shifting to July, August or later in the Drakensberg foothills / Midlands, while the northern interior does not reach this threshold except on the Escarpment. Only small areas of this province are cold enough to receive 700 *PCU*s by June or July, historically (Fig. 30, bottom left). By the mid-century (Fig. 30, bottom right) a very small colder area south of Estcourt-Greytown reaches this threshold by July-August, with the remainder of the Midlands and Escarpment areas achieving 700 *PCU*s only by September or October, or never.

The coldest areas of Mpumalanga, suitable for deciduous fruit production, are the high-lying areas west of the Escarpment. Historically, this area has achieved 250 *PCU*s by May-June (Fig. 31, top left), but this shifts to June-July into the intermediate future (Fig. 31, top right), similar to the map for the historical achievement of 500 *PCU*s (Fig. 31, middle left). By mid-century, 500 *PCU*s are expected to be reached by July in the coldest areas, and by August or September over most of the remaining area (Fig. 31, middle right). Most of the area has historically reached 700 *PCU*s by July (Fig. 31, bottom left), but into the intermediate future this threshold may only be reached by August (coldest area), September or October (other cooler areas) or not at all (Fig. 31, bottom right).

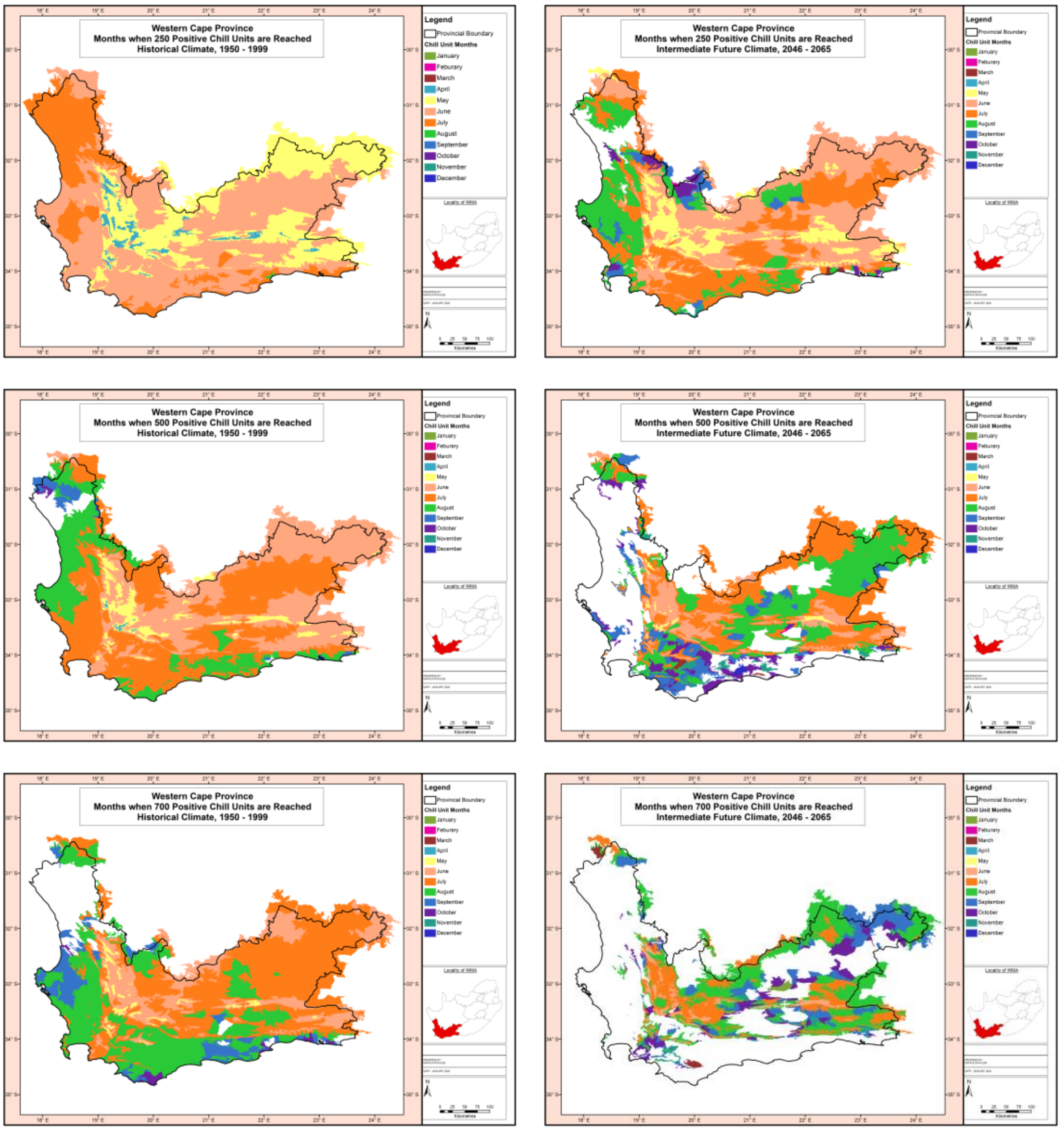


Figure 28. Month by which 250 (top left), 500 (middle left) and 700 (bottom left) PCUs are reached in the Western Cape Province under historical climatic conditions, as well as under intermediate future climatic conditions in the corresponding right-hand maps (original source: Schulze and Schütte, 2016).

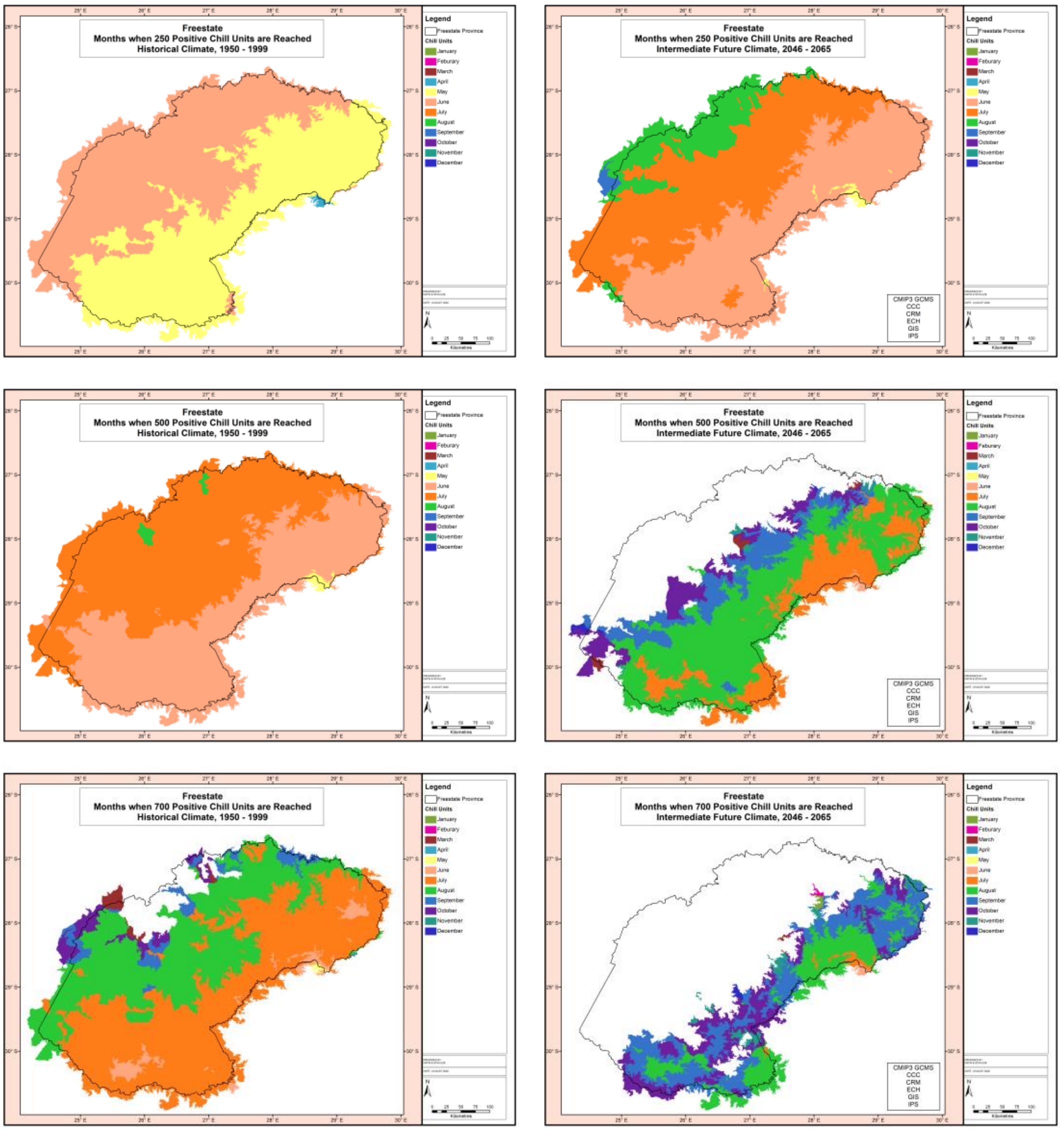


Figure 29. Month by which 250 (top left), 500 (middle left) and 700 (bottom left) PCUs are reached in the Free State Province under historical climatic conditions, as well as under intermediate future climatic conditions in the corresponding right-hand maps (original source: Schulze and Schütte, 2016).

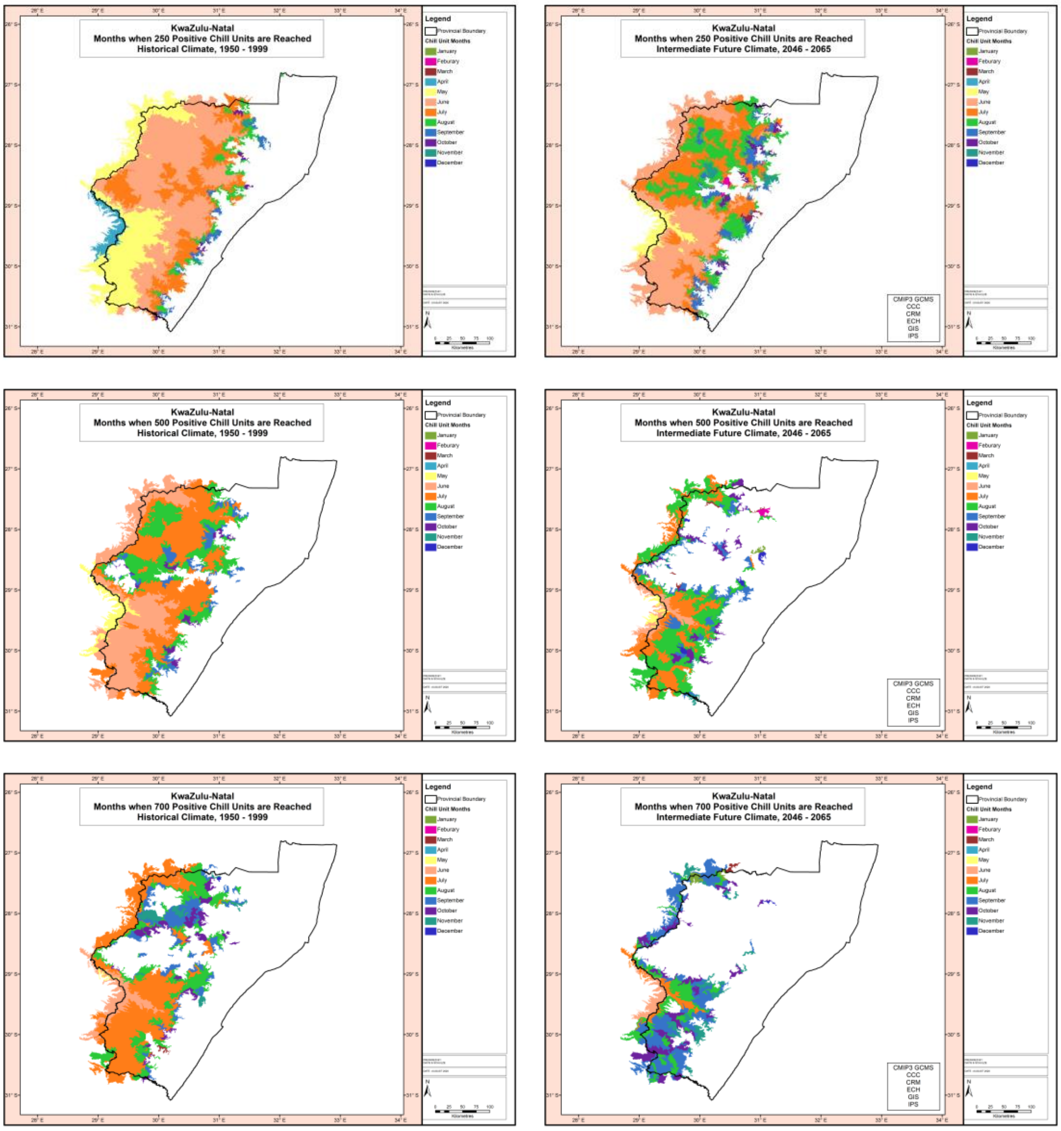


Figure 30. Month by which 250 (top left), 500 (middle left) and 700 (bottom left) PCUs are reached in the KwaZulu-Natal Province under historical climatic conditions, as well as under intermediate future climatic conditions in the corresponding right-hand maps (original source: Schulze and Schütte, 2016).

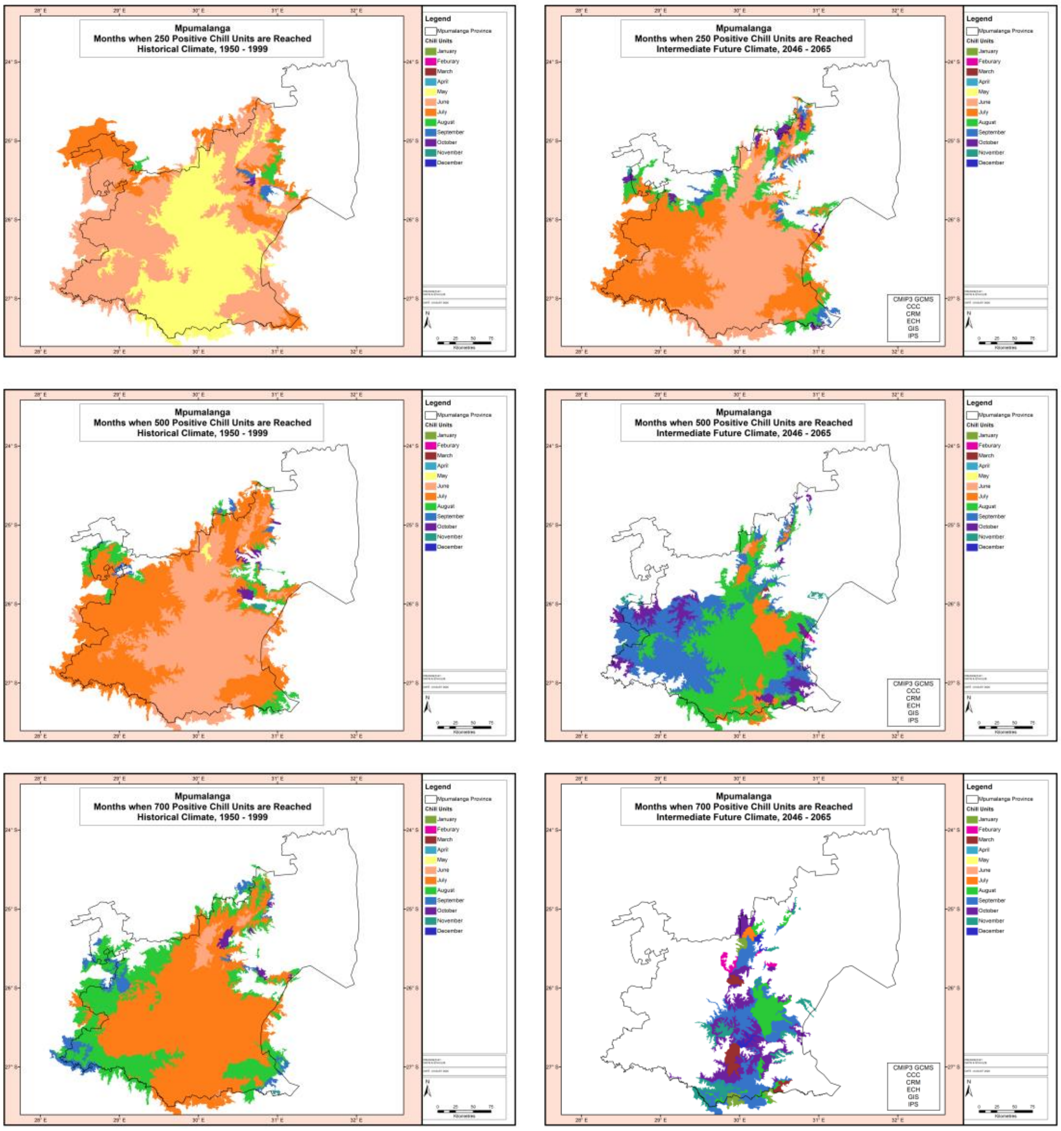


Figure 31. Month by which 250 (top left), 500 (middle left) and 700 (bottom left) PCUs are reached in the Mpumalanga Province under historical climatic conditions, as well as under intermediate future climatic conditions in the corresponding right-hand maps (original source: Schulze and Schütte, 2016).

5.2.5 Results - shifts in “chill regions”

From Fig. 32 (top) it can be seen that the eleven pome and stone fruit regions of the Western Cape – Langkloof have historically distinctive seasonal (April to August) accumulated chill units. These have played a large role in determining the current distribution and dominance of fruit species and cultivars between and within specific regions. With climate change, chill units are projected to shift to a lower seasonal total (Fig. 32, bottom).

The range of mean seasonal *PCU*s experienced historically within each of the production regions (sometimes divided into sub-regions), together with the projected intermediate future seasonal *PCU*s, are listed in Table 1. As regions become warmer and seasonal PCUs are reduced, they become more like currently other warmer production regions, or they may accumulate fewer PCUs than any current production region. In Table 1, the ticks indicate current and projected future suitability for pome and stone fruit production. The absence of a tick for future suitability indicates that current cultivars and production methods may not allow for production in future, but that with additional adaptation e.g. low chill cultivars, this may still remain possible. The results are specific to the set of GCMs used for the modelling (CMIP3), together with the future scenario (A2), and slightly different results may be expected with other GCMs and scenarios.

From this, estimates can be made of what each region / sub-region could in future resemble, in comparison with the historical situation in other regions. The coldest region, the Koue Bokkeveld / Witzenberg, could in future experience chilling currently experienced in parts of EGVV, Franschhoek and the colder areas of the Klein Karoo. The modelling also suggests that the Koo valley will in future experience similar chilling to the Koue Bokkeveld / Witzenberg. The Warm Bokkeveld, on the other hand, together with Piketberg and the western Langkloof, could become like Stellenbosch, Paarl, the Breede River valley, and warmer areas of the Klein Karoo, in terms of chilling. It is likely that all these regions will remain suitable for apple and/or pear production, especially with the adoption of medium to low chill cultivars. Stone fruit production will also remain viable in these regions.

The modelling methods used in this study suggest that the historically warmer regions for pome fruit production (most of the Klein Karoo, the eastern Langkloof, Grabouw and Vyeboom) could by the mid-century become like the current stone fruit regions of the central Berg River (Wellington, Riebeeck Kasteel) and the Breede River valley (Robertson, Ashton). It is thus likely that pome fruit production will become increasingly less viable, and stone fruit production will become more viable in these regions. It is important to note that other requirements for stone fruit production (e.g. well-drained soils) must be met, and this discussion deals only with the chilling requirement. Of great concern is the apparent significant shift in chilling projected for Wolseley, currently a core pear production region. The future seasonal chill unit range is lower than that of current stone fruit regions and does not resemble any current deciduous fruit production region. However, it is likely that with the correct cultivar choices, stone fruit production will be viable. Similarly, the warming projected for Elgin, Villiersdorp, Somerset West and Riviersonderend, all current pome fruit production regions, makes these regions suitable only for stone fruit production in future (but possibly not Somerset West which may lose too many *PCU*s).

Most of the Breede River valley is likely to continue to receive sufficient chilling for stone fruit production, even though the future seasonal totals are projected to be lower than current stone fruit regions. The Bonnievale region may be the exception (high loss of *PCU*s), but we caution that further modelling should be conducted to increase the confidence in this outcome. Similarly, further research is needed on the shifts in seasonal chilling in the Berg River region (except Franschhoek) and Tulbagh, where chilling may become too low for most stone fruit.

We caution that these results should be interpreted broadly, giving only an indication of a possible future. Further modelling with new sets of GCMs and scenarios, and long-term instrumental on-farm observations, are required to confirm the projections and trends, and to guide possible responses at farm level.

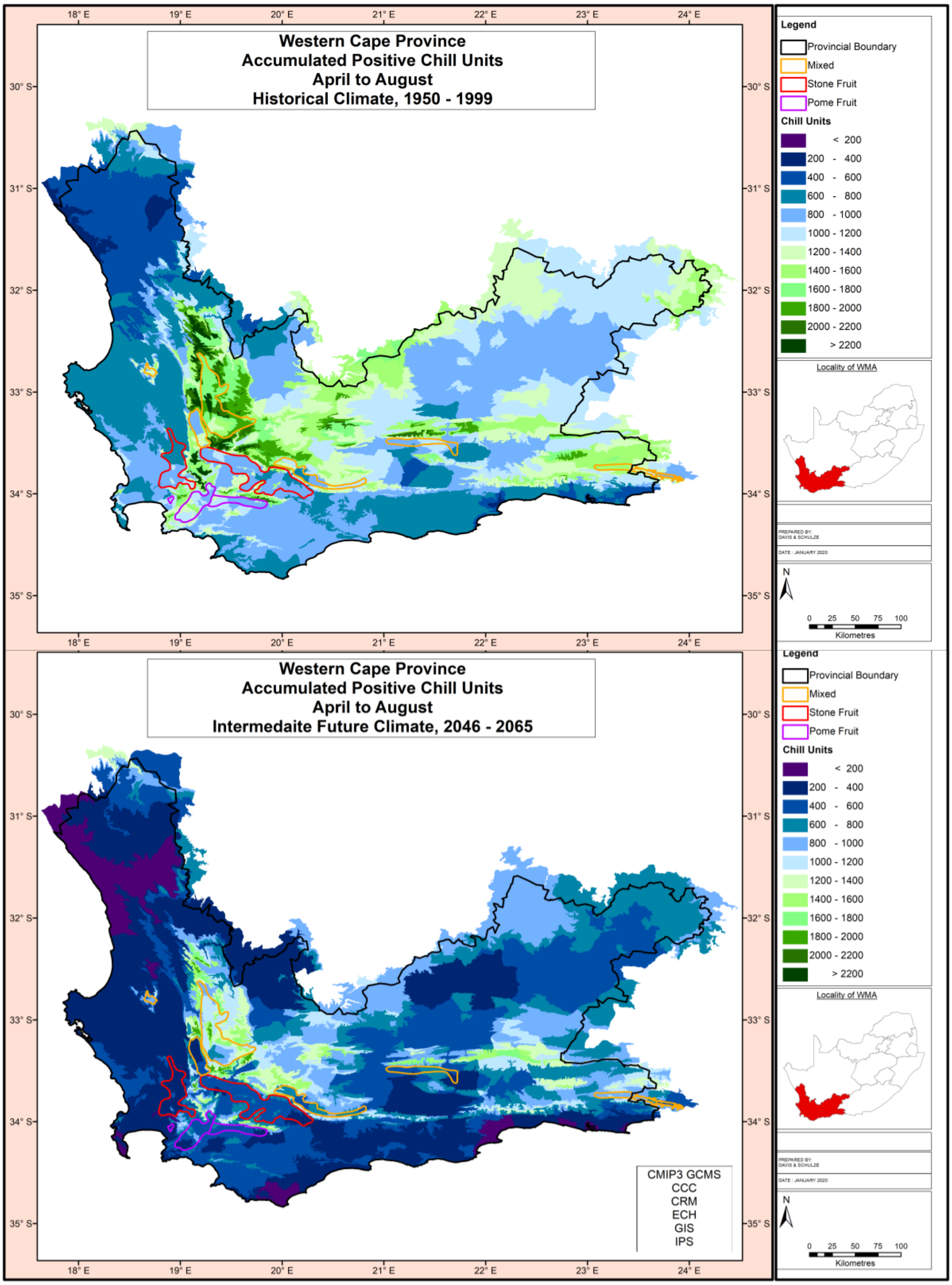


Figure 32 Mean of accumulated positive chill units in the Western Cape Province in April-August under historical climatic conditions (top) and the corresponding projected under intermediate future climate conditions (bottom). The latter was derived from multiple CMIP3 GCMs. The borders of eleven fruit production regions are overlaid (see Fig. 4) with purple denoting pome fruit regions, red denoting stone fruit regions, and orange denoting regions with both.

Table 1. Historical and projected intermediate future (ca. 2050) seasonal PCUs for regions and sub-regions where pome and stone fruit are currently produced.

No.	**Region**	**Sub-region**	**Historical seasonal PCUs**	**Intermediate future seasonal PCUs**	**Intermediate future becomes more like**	**Historical suitability pome**	**Historical suitability stone**	**Future suitability pome**	**Future suitability stone**
1	Klein Karoo West	Koo	1200-1400	1000-1200	Barrydale, Ladismith, Elgin, Villiersdorp, Franschhoek, Langkloof east, Somerset West, Riviersonderend west	√	√	√	√
		Montagu	600-1000	400-800	Wellington, Riebeeck Kasteel, Robertson, Ashton	√	√		√
		Barrydale	1000-1200	400-800	Wellington, Riebeeck Kasteel, Robertson, Ashton	√	√		√
2	Klein Karoo East	Ladismith	1000-1200	600-800	Wellington, Riebeeck Kasteel, Robertson, Ashton	√	√		√
		Calitzdorp, Ladismith west	600-1000	200-600	No current region	√	√		√
3	Ceres	Warm Bokkeveld	1200-1600	600-1000	Montagu, Calitzdorp, Tulbagh, Riviersonderend east, Stellenbosch, Paarl, Breede valley	√	√	√	√
		Koue Bokkeveld, Witzenberg	1600-1800	800-1200	Barrydale, Ladismith, Langkloof east, Elgin, Villiersdorp, Somerset West, Riviersonderend west, Franschhoek	√	√	√	√
4	Piketberg		1200-1400	800-1000	Montagu, Calitzdorp, Tulbagh, Riviersonderend east, Stellenbosch, Paarl, Breede valley	√	√	√	√
5	Wolseley-Tulbagh	Wolseley	1200-1400	400-600	No current region	√	√		√
		Tulbagh	800-1000	200-400	No current region	√	√		
6	Langkloof	Langkloof east	800-1200	400-800	Wellington, Riebeeck Kasteel, Robertson, Ashton	√	√		√

No.	Region	Sub-region	Historical seasonal PCUs	Intermediate future seasonal PCUs	Intermediate future becomes more like	Historical suitability pome	Historical suitability stone	Future suitability pome	Future suitability stone
		Langkloof west	1200-1600	800-1000	Montagu, Calitzdorp, Tulbagh, Riviersonderend east, Stellenbosch, Paarl, Breede valley	√	√	√	√
7	EGVV	Grabouw, Vyeboom	1200-1400	400-800	Wellington, Riebeeck Kasteel, Robertson, Ashton	√	√		√
		Elgin, Villiersdorp	800-1200	200-600	No current region	√	√		√
8	Somerset West		1000-1200	200-400	No current region	√	√		
9	Riviersonder-end	Riviersonderend west	1000-1200	400-600	No current region	√	√		√
		Riviersonderend east	800-1000	200-600	No current region	√	√		√
10	Stellenbosch-Berg	Franschhoek	1000-1200	400-600	No current region	√	√		√
		Stellenbosch, Paarl	800-1000	200-400	No current region	√	√		
		Wellington, Riebeeck-Kasteel	600-800	200-400	No current region		√		
11	Breede valley	Most of the region	800-1000	400-600	No current region	√	√		√
		Robertson, Ashton	600-800	400-600	No current region		√		√
		Bonnievale	800-1000	200-400	No current region	√	√		

Not only the seasonal historical and future PCU totals are important, but also the timing of the expected shifts. Figs 33-37 present the maps of monthly PCUs with the 11 pome and stone fruit regions overlaid. The later start to PCU accumulation is clearly seen in the maps for April (Fig. 33), particularly in the pome fruit regions EGVV, Ceres, Wolseley and western Langkloof. In May (Fig. 34), the loss of chilling is evident everywhere, noticeably in the Elgin and Berg River regions. Losses in PCUs in June (Fig. 35) and July (Fig. 36) affect the south-western coastal and river valley regions the most. Chilling continues to accumulate everywhere in August (Fig. 37), albeit with reductions in the monthly total PCUs.

5.2.6 Implications

If climate change continues as projected under the emissions scenario used in the modelling (RCP8.5), this will present severe challenges regarding the loss of chill accumulation. The regions at most risk regarding production of high and medium chill requiring pome fruit cultivars include the whole south-western coastal region, Wolseley, and possibly the eastern Langkloof. Chilling could become insufficient for pear production in the Klein Karoo. There is a wide range of stone fruit cultivars available with differing chill requirements, so the situation for this industry will depend on whether new climates can be matched with suitable cultivars. Challenges could arise around Tulbagh, the central Berg River region, and the warmest parts of the Klein Karoo.

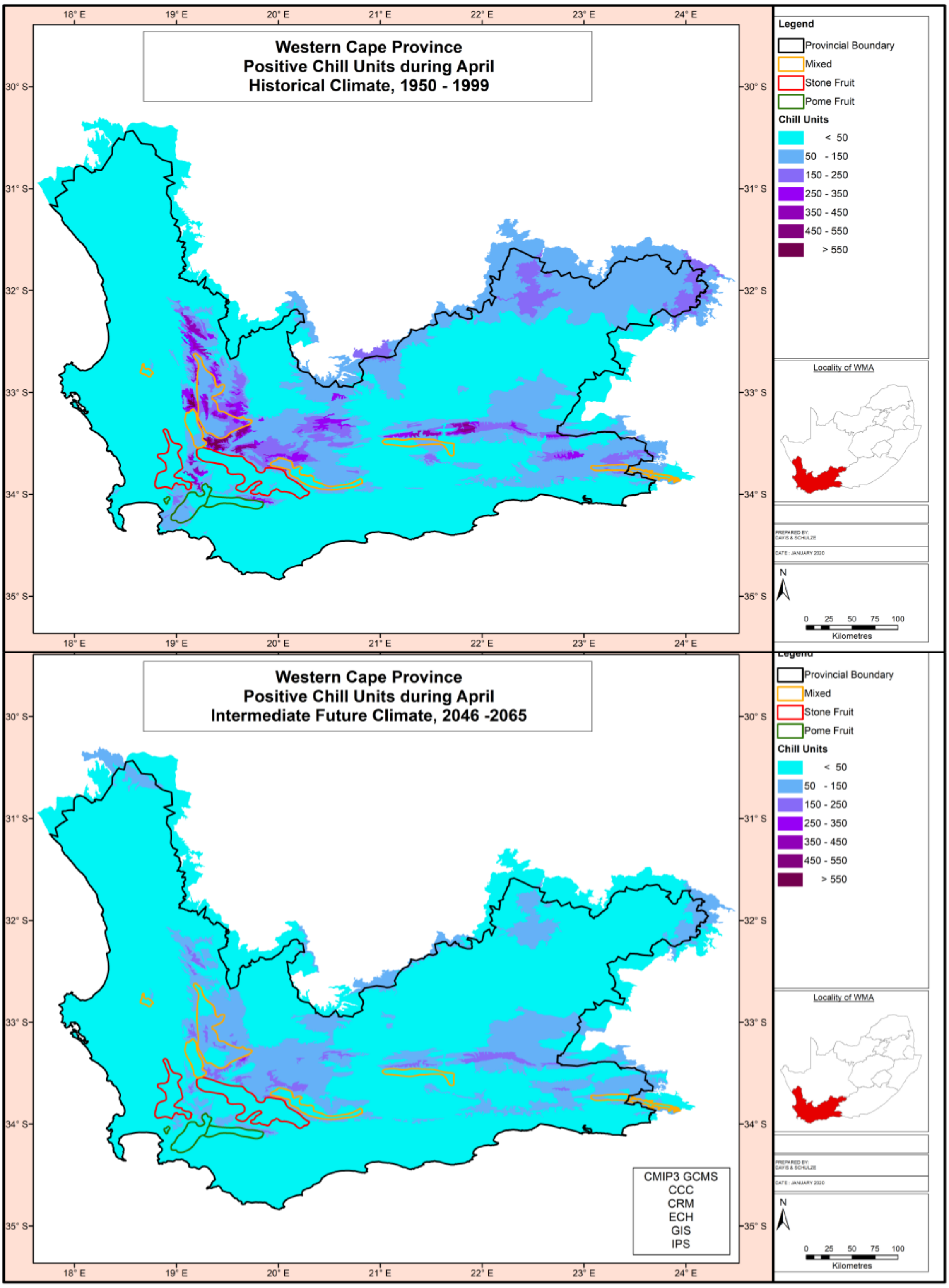


Figure 33 Mean of accumulated positive chill units in the Western Cape Province in April under historical climatic conditions (top) and the corresponding projected under intermediate future climate conditions (bottom). The latter was derived from multiple CMIP3 GCMs. The borders of eleven fruit production regions are overlaid (see Fig. 4) with green denoting pome fruit regions, red denoting stone fruit regions, and orange denoting regions with both.

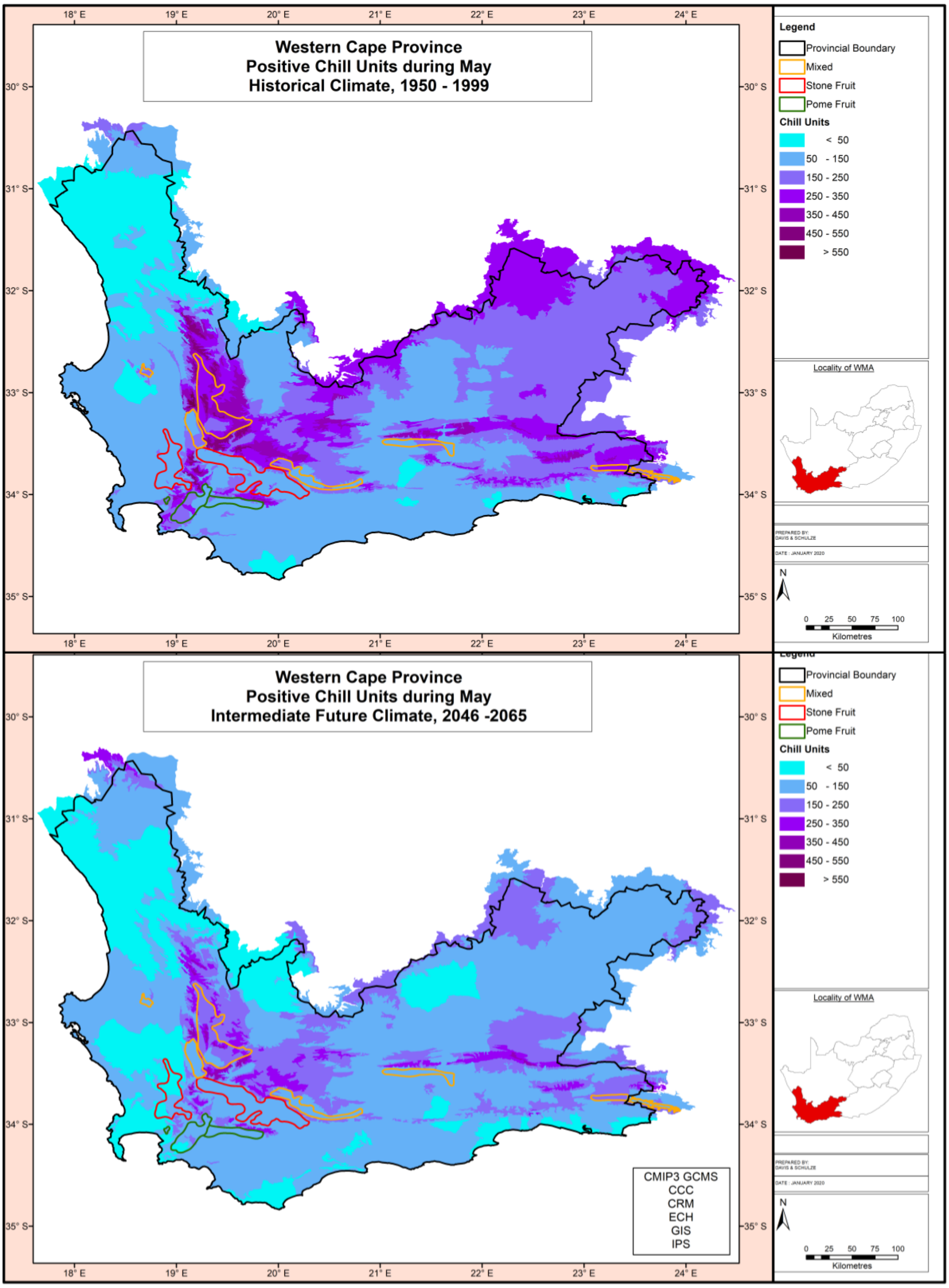


Figure 34 Mean of accumulated positive chill units in the Western Cape Province in May under historical climatic conditions (top) and the corresponding projected under intermediate future climate conditions (bottom). The latter was derived from multiple CMIP3 GCMs. The borders of eleven fruit production regions are overlaid (see Fig. 4) with green denoting pome fruit regions, red denoting stone fruit regions, and orange denoting regions with both.

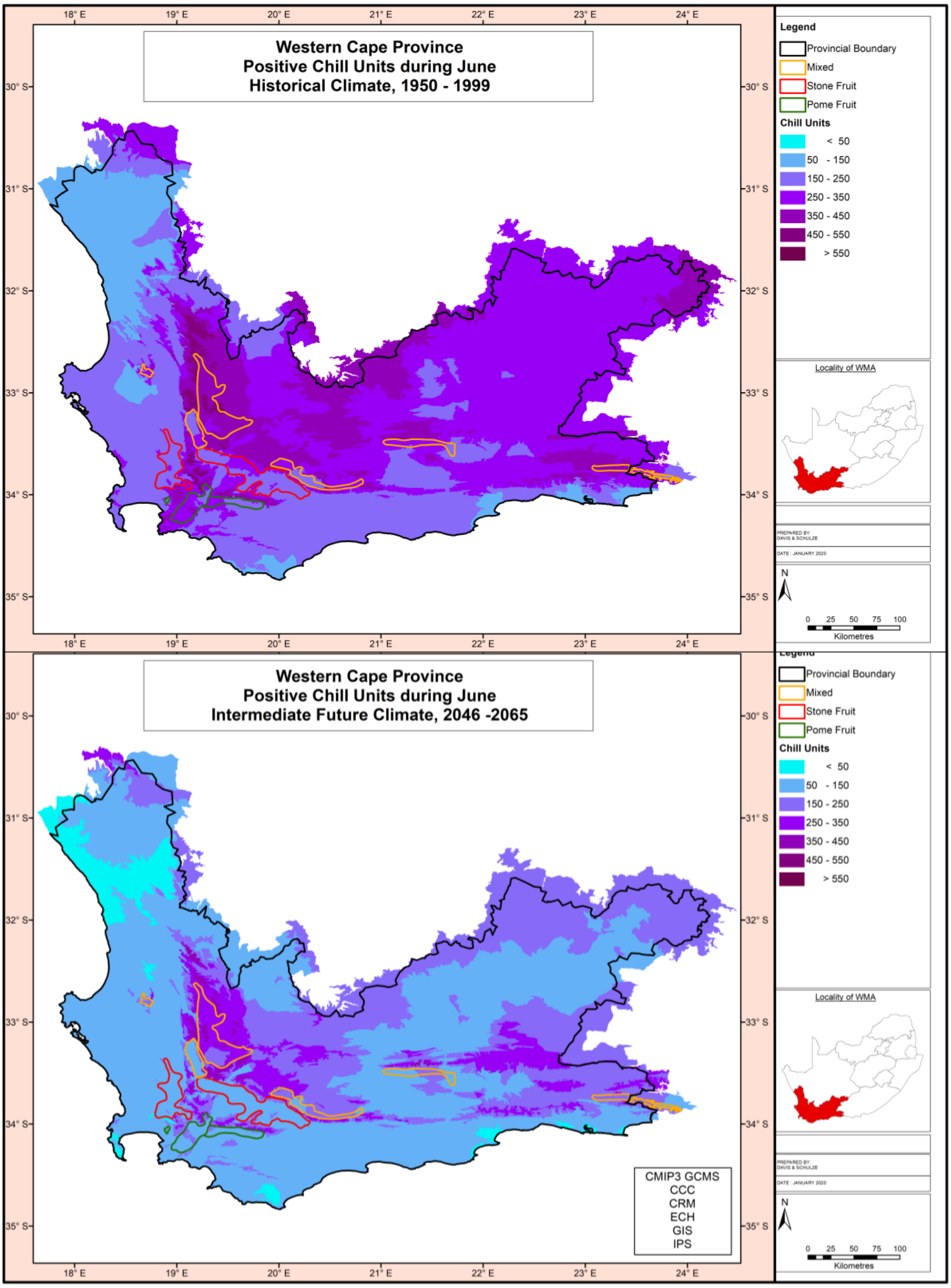


Figure 35 Mean of accumulated positive chill units in the Western Cape Province in June under historical climatic conditions (top) and the corresponding projected under intermediate future climate conditions (bottom). The latter was derived from multiple CMIP3 GCMs. The borders of eleven fruit production regions are overlaid (see Fig. 4) with green denoting pome fruit regions, red denoting stone fruit regions, and orange denoting regions with both.

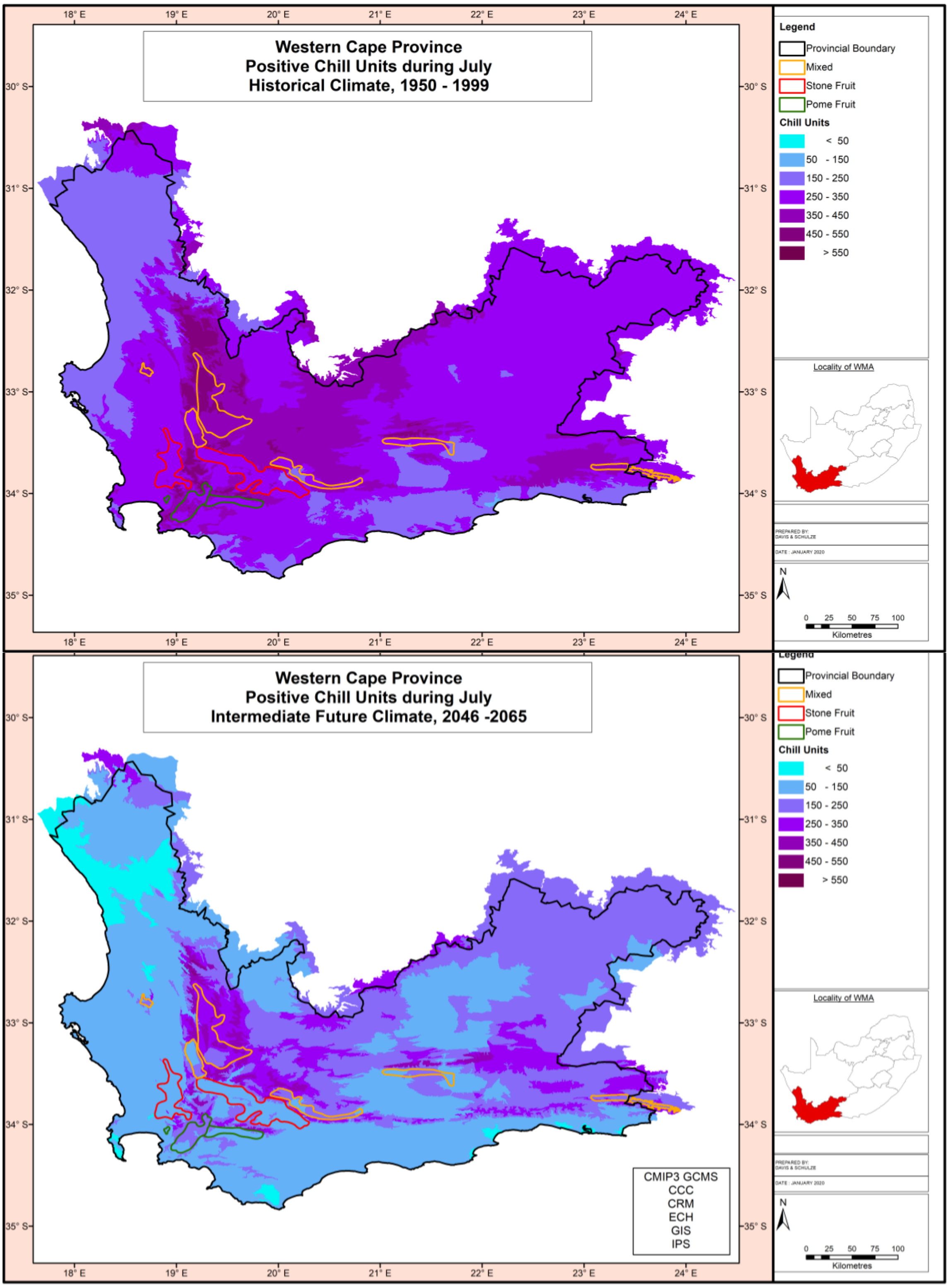


Figure 36 Mean of accumulated positive chill units in the Western Cape Province in July under historical climatic conditions (top) and the corresponding projected under intermediate future climate conditions (bottom). The latter was derived from multiple CMIP3 GCMs. The borders of eleven fruit production regions are overlaid (see Fig. 4) with green denoting pome fruit regions, red denoting stone fruit regions, and orange denoting regions with both.

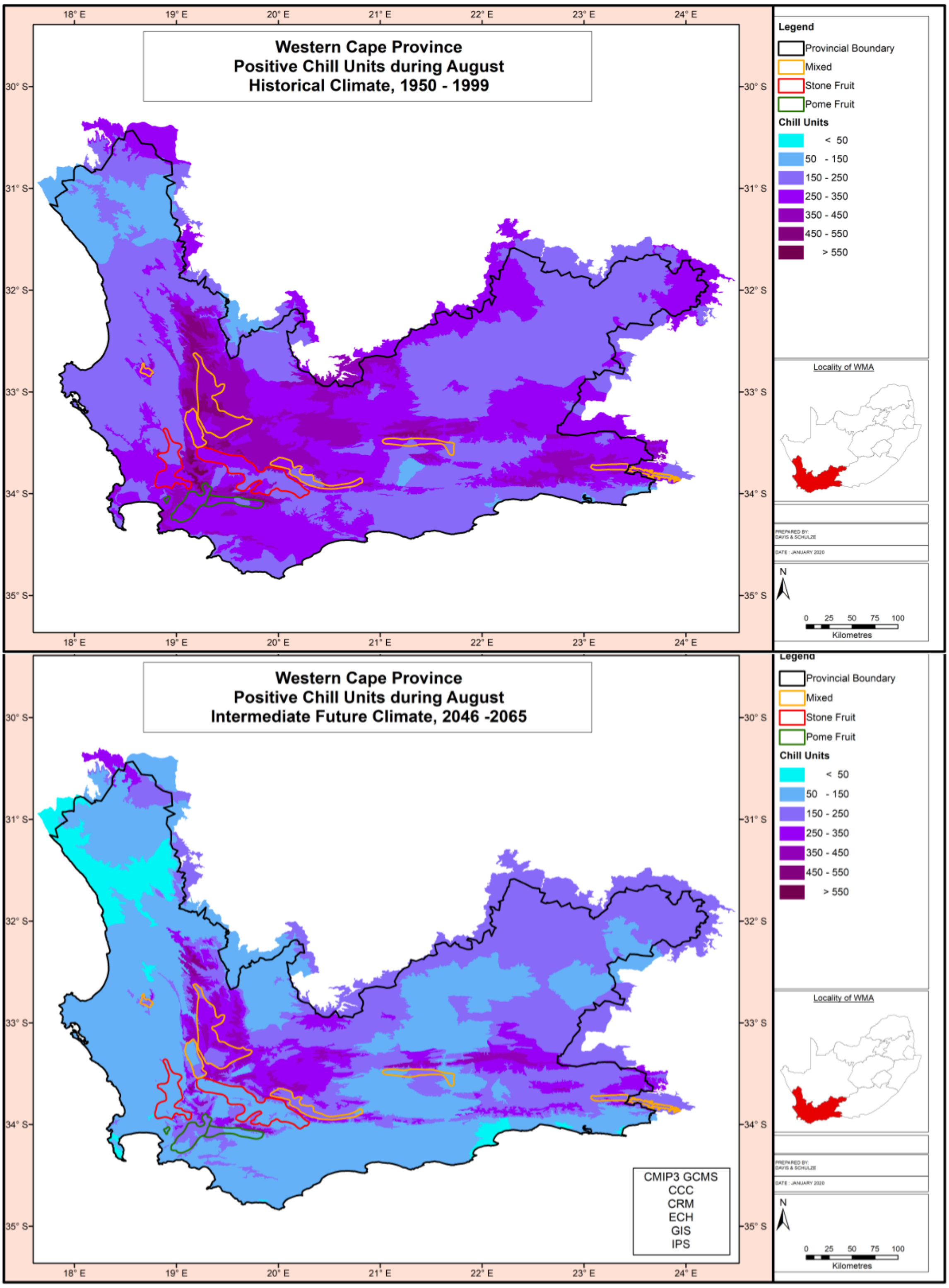


Figure 37 Mean of accumulated positive chill units in the Western Cape Province in August under historical climatic conditions (top) and the corresponding projected under intermediate future climate conditions (bottom). The latter was derived from multiple CMIP3 GCMs. The borders of eleven fruit production regions are overlaid (see Fig. 4) with green denoting pome fruit regions, red denoting stone fruit regions, and orange denoting regions with both.

5.3 Heat units and projected changes

5.3.1 Concepts and applications of heat units in agriculture

The concept of heat units (*HU*s, also known as growing degree days, *GDD*s) is based on the fact that plant development stages depend on the accumulated heat experienced prior to a critical phenological milestone. In general, it holds that the lower the temperature and thus accumulated heat, the slower the rate of growth and development of plants and their organs. Also, the amount of accumulated heat required to complete a given developmental stage does not vary substantially from year to year.

*HU*s are an accumulation of mean temperatures above a certain *lower threshold value* (below which active development is considered not to take place), and below an *upper threshold value* (above which growth is considered to remain static or even decline), over a period of time. Different crops have different lower threshold limits (base), and for temperate fruit this is generally taken as 10°C. *HU*s are accumulated from a starting date known as the *biofix*, which varies from crop to crop. They can be applied, in the context of pome and stone fruit production, for:

- designating the switch from one phenological stage to the next, with different values applicable to different crop types and cultivars
- the prediction of harvest dates
- the prediction of the length of the season (both vegetative and reproductive) for different crop types and cultivars
- modelling the development of a crop canopy or an organism (e.g. one generation of codling moth is 572° days above its temperature threshold)
- estimating when to spray against pests, since degree days predict the stage of development of a pest

*HU*s can thus be used to distinguish between crop or organism development at different locations, or alternatively in different years (cool vs. hot) at the same location, or under present vs. future climatic conditions. For this study, a low temperature threshold (base) of 10.0°C was used.

5.3.2 Results – annual and seasonal

Mean annual *HU*s under historical climatic conditions are shown in Fig. 38 (top left). They range from < 400 *HU*s in the high-altitude colder mountain areas to > 3 500 *HU*s in the north-west. Over most of the fruit production regions they are in the range 800-2500, but up to 3500 *HU*s are received in some stone fruit production regions. Heat units are essentially a summer season phenomenon, and the *HU* range in summer in the fruit regions is mostly 600-2500 (Fig. 38, middle left). Winter *HU*s are less than 800 in the fruit regions (Fig. 38, bottom left).

The projected absolute changes in *HU*s from the present into the intermediate future, mapped on a monthly basis, are shown in Fig. 39 (January to June) and Fig. 40 (July to December).

The impact of climate change on *HU*s is expressed in Fig. 38 as a ratio change between the intermediate future and the present. For the mean annual scenario (Fig. 38, top right), the ratios are generally up to 1.4 in the fruit areas, implying a 40% increase with climate change. Higher ratios of up to 1.5 are projected for the north-western and Langkloof production areas.

The colder high-lying areas are more responsive to climate change, displaying ratios up to 1.8, or a projected 80% increase (Fig. 38, top right). Regarding projected seasonal *HU* changes, these are generally < 1.3 (30%) in summer in the southern production areas, and up to 1.5 (50%) in the north-western and Langkloof production areas (Fig. 38, middle right). The greatest changes by mid-century are seen in winter, with projected ratio changes of 1.3-1.5 in the southern areas and up to 1.8 in the Langkloof and the higher altitude areas of the north-west (Fig. 38, bottom right).

5.3.3 Implications

The projected increases in heat units have major repercussions for fruit production ranging from changes in growth rates, shortening of heat unit dependent phenological periods, negative impacts on fruit maturation processes and fruit quality, overlapping harvesting of different crops/cultivars, and increases in the number of life cycles per year of certain pests and diseases, causing disruption of spray schedules. The magnitude of anticipated changes in heat units again highlights the fact that so-called second order changes, based on derivatives of temperature, have far greater impacts than only the first order changes such as a temperature increase *per se*. Also, changes from the present to the future need to be expressed in both absolute units (e.g. in °days in this instance) or as percentage or ratio increases, because the results can be very different and both are needed for a more complete interpretation of findings.

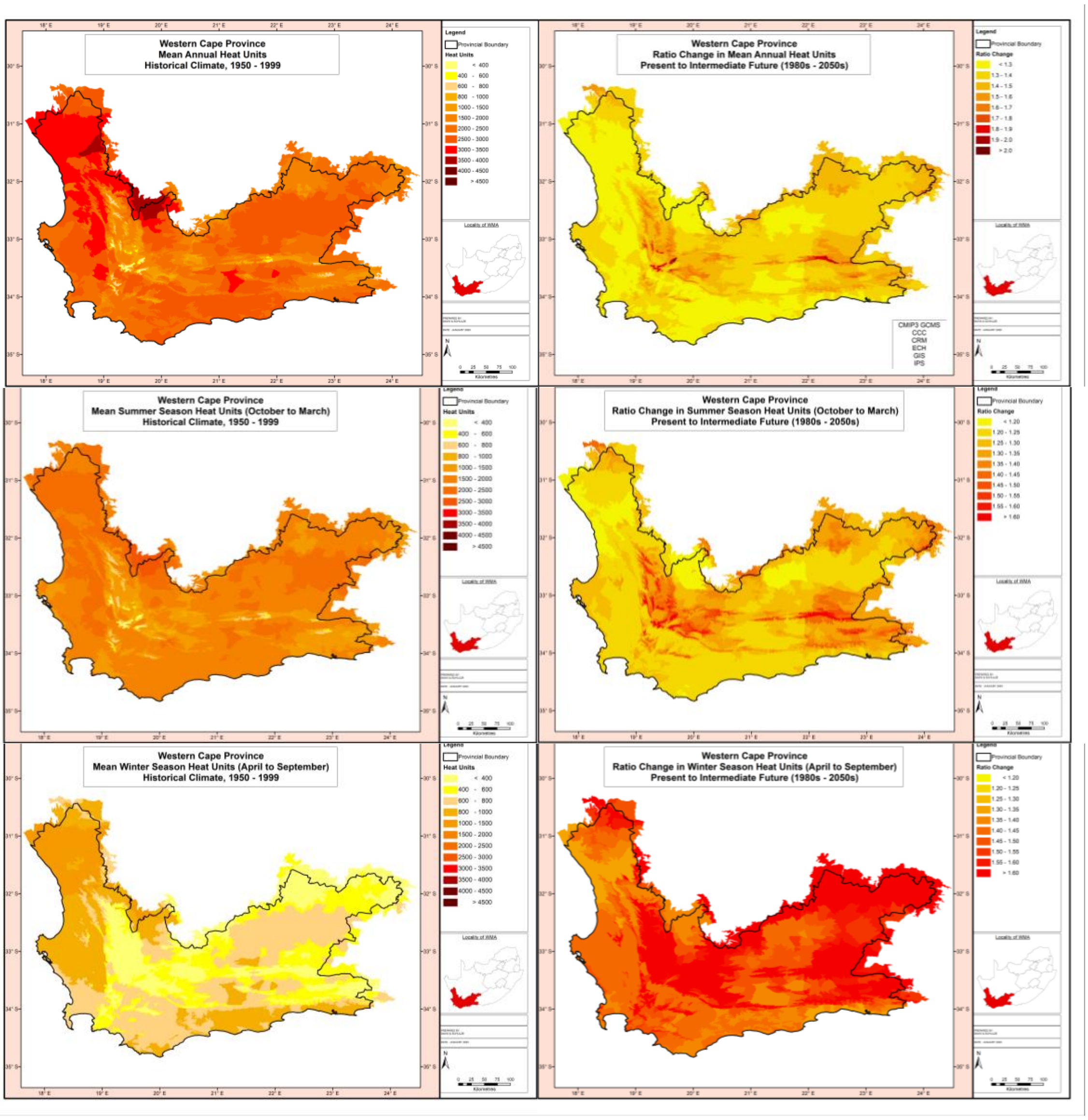


Figure 38. Mean annual heat units (base 10°C; top left) as well as mean summer season (October-March; middle left) and mean winter season (April-September; bottom left) heat units under historical climatic conditions, and corresponding ratio changes from the present to the intermediate future (right column of maps). The latter were projected from multiple CMIP3 GCMs.

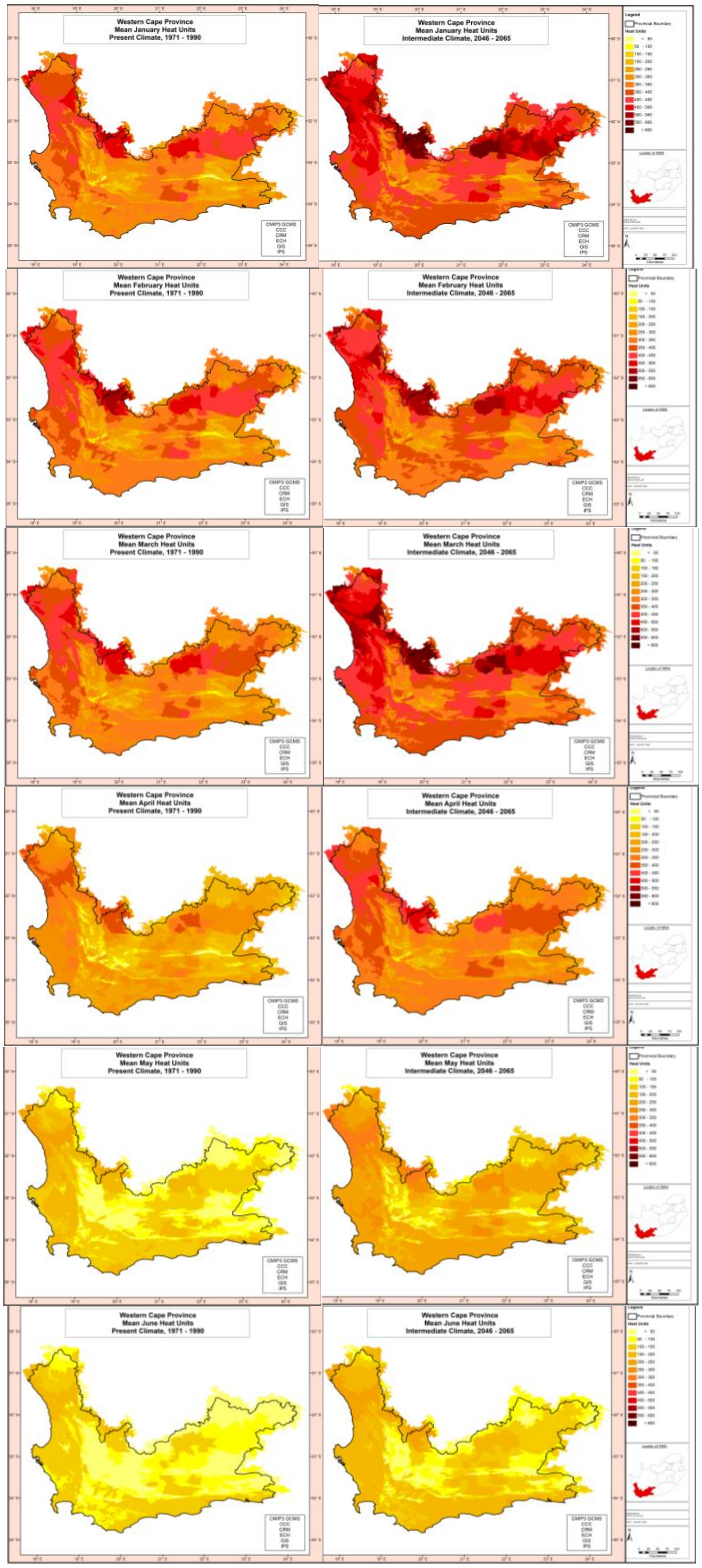


Figure 39. Mean monthly heat units (base 10°C) under present climate conditions (left column) and into the intermediate future (right column) for the months January (top) to June (bottom). The latter were projected from multiple CMIP3 GCMs.

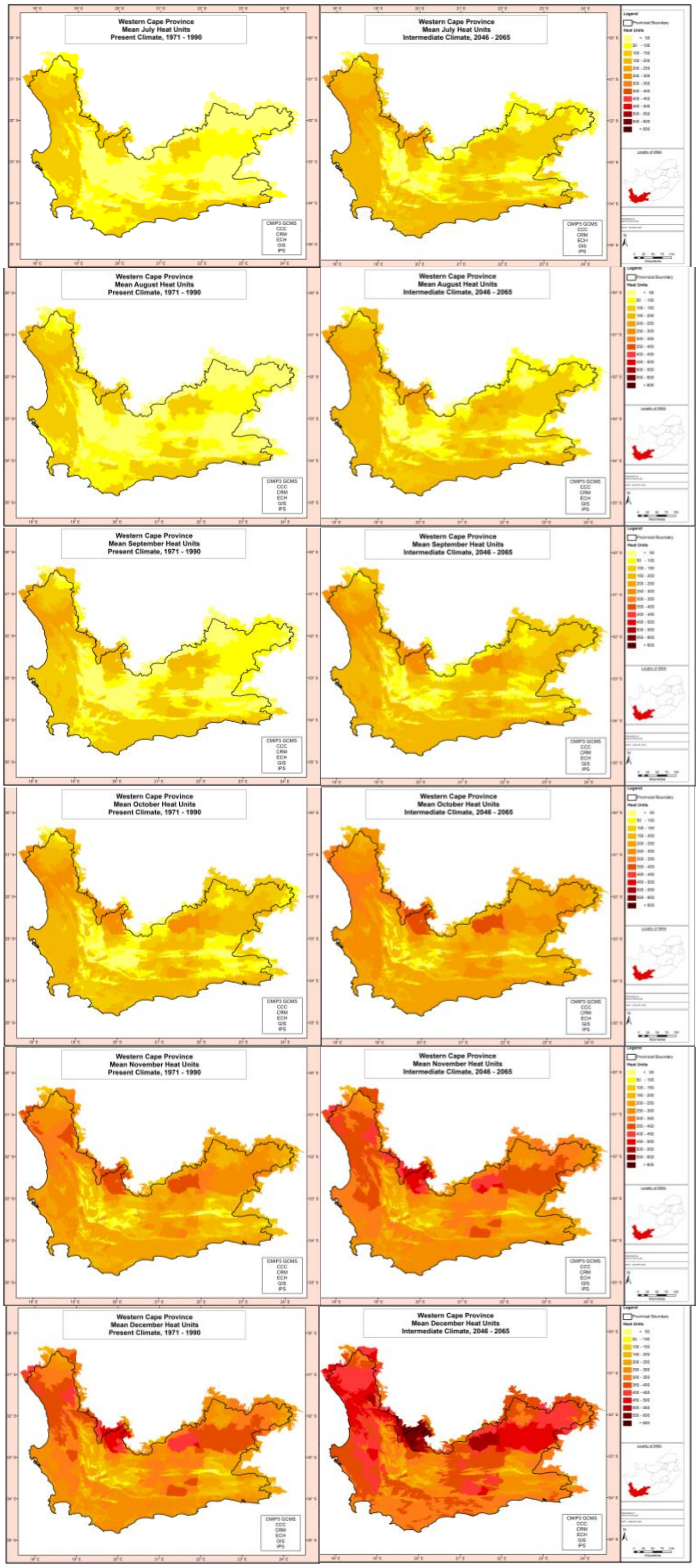


Figure 40. Mean monthly heat units (base 10°C) under present climate conditions (left column) and into the intermediate future (right column) for the months July (top) to December (bottom). The latter were projected from multiple CMIP3 GCMs.

5.4 Sunburn risk of apples and projected changes

5.4.1 Background

Temperature significantly affects fruit quality attributes such as fruit size, colour, sunburn damage, and sugar and acid content. The exposure of fruit surfaces to combined high levels of direct sunlight and high temperature can result in sunburn of the peel. Sunburn on pome and stone fruit causes significant economic losses in South Africa. It is a major problem in the production of key apple cultivars, but can also lead to severe losses in certain pear and plum cultivars in some years.

Sunburn in apples has been classified into three distinct categories (Schrader et al., 2001, 2008):

- *Sunburn browning*, the most prevalent and costly, results in a yellow, bronze, or brown spot on the sun-exposed side of an apple and occurs when the fruit surface temperature (FST) reaches 46 to 49°C in the presence of strong sunlight;
- *Sunburn necrosis* results in a necrotic spot (a dark brown or black area of dead surface tissue) on the sun-exposed side of the fruit when the FST reaches approximately 52°C for around ten minutes or longer; in this case, sunlight is not needed to cause the damage;
- *Photo-oxidative sunburn* occurs when non-acclimated apple fruit previously grown in shaded positions are suddenly exposed to full sunlight, causing a white spot on the affected side within 24 hours.

The appearance and severity of sunburn symptoms in apples vary from cultivar to cultivar under the same environmental conditions, with ‘Granny Smith’ being highly prone to sunburn, for example. Cultivar sensitivity to sunburn can relate to the colour of the fruit i.e. the presence and concentration of red pigment (anthocyanins) which provides protection against photo-oxidative stress caused by excessive light and temperature. Well-coloured red cultivars generally show fewer symptoms; however, this is partially ascribed to the masking of sunburn browning by the red pigment.

Although temperature and high irradiance are primarily responsible for the occurrence of sunburn, other indirect climatic factors and cultural practices can facilitate its occurrence. Sunburn prevalence and intensity is worse on the northern and north-western sides of the tree rows in the southern hemisphere. Although sunburn occurs on fruit exposed to full sunlight, not all fruit in such positions are sunburnt, and other internal and external factors are known to play a role. Air movement and wind lowers the fruit surface temperature (potentially by several degrees) by disturbing and dissipating the warm air of the boundary layer around the fruit, thus reducing the risk of sunburn. Sunburn is more prevalent on apple and plum trees experiencing water stress.

Sunburn can potentially occur in all apple growing regions of the world, but the severity and extent of damage varies from region to region. Regions such as South Africa that are characterised by clear summer skies with high light and temperatures experience higher levels of sunburn damage than, for example, the temperate production regions of central Europe, where maximum irradiance and temperature in summer are lower due to higher latitude, and summer rainfall and associated cloud cover reduce the risks. For further information on sunburn please refer to Hortgro (2020).

5.4.2 Climate criteria used to model the sunburn risk of apples

Because monitoring the temperature dynamics of all fruits throughout the entire growing season is challenging, models that simulate FST are developed and applied. One such experimentally based FST model (Li et al., 2014) calculates the maximum temperature of the fruit surface when facing directly to the sun at midday on a sunny day, without any shading of the fruit surface. It then calculates the difference between FST and air temperature, which is on average ~ 12°C. This value which corresponds well with experimentally obtained values in South African and Australian apple orchards.

Our first approach to modelling the risk of sunburn attempted to use the FST criteria for sunburn browning and sunburn necrosis. We assumed that browning (FST ≥ 48°C) would occur when daily maximum air temperature (T_{max}) was between 34.0 and 38.9°C, while necrosis (FST ≥ 52°C) would occur when daily T_{max} was ≥ 39°C. This was very similar to the air temperature thresholds used by Darbyshire et al. (2015) in Australia (34.1 and 38.7 °C, respectively, for browning and necrosis). We then analysed the total number of days per month (November to April) where daily T_{max} crossed the threshold for potential sunburn damage.

On assessing the results we decided that the modelling approach using daily T_{max} does not lend itself to distinguishing between the risks for sunburn browning and necrosis. This may be partially attributable to the fact that necrosis can occur within 10 minutes of the necessary conditions arising (which could then be relieved equally rapidly), and these short timescales cannot easily be captured using daily T_{max}. The known risks of sunburn necrosis across the study region were not reflected in the results. We thereafter focused only on analysing the risk of "sunburn" generically (excl. photo-oxidative sunburn).

Sunburn was then modelled for the study region using the following scenarios. We aimed to capture the risk of sunburn, where the minimum FST threshold of 48.0°C was crossed, but where this occurred under variable differences between FST and T_{max}. Such variability could, for example, be ascribed to peel characteristics (including through previous exposure), wind or water relations. The scenarios using lower T_{max} would clearly result in more days with sunburn risk than the scenarios using high T_{max}, but this would differ between fruit growing regions. On examining the results, we found that the fruit production regions so seldom experience T_{max} ≥ 37.0°C, that scenarios 2 and 4 do not provide useful information (see also section 4.3.4.2 and Fig. 13 for the analysis of average days per annum on which daily maximum temperatures exceed 35°C). This methodology remains explorative and should be followed up with further research.

1. Number of days with FST ≥48.0°C and daily T_{max} 34.0 – 36.9°C
2. Number of days with FST ≥48.0°C and daily T_{max} > 37.0°C
3. Number of days with FST ≥48.0°C and daily T_{max} 34.0 – 38.9°C
4. Number of days with FST ≥48.0°C and daily T_{max} > 39.0°C

We present the results for scenario 3. The historical climate risk (days per month meeting the criteria), the projected intermediate future climate risk, and the difference (days per month) between the two were mapped using the average outcomes from four CMIP3 GCMs.

5.4.3 Results

The average number of days per month when the conditions were historically conducive to sunburn of apples for the months of November to April are presented in Fig. 41 (left column, months from top to bottom). The results for intermediate future conditions (2050s) are shown in the central column, and the differences between the two are shown in the right column.

The risk of sunburn browning in apples under historical climatic conditions is low in November, and the increased risk in future is small (up to two additional days) in the apple production regions (Fig. 41). Historical sunburn browning risk increases from December onwards, peaks in January/February and declines from March. In December and January, the risk in future (mid-century) increases by up to five days per month in the warmer production areas. The additional risk then decreases from February onwards, with the exception of parts of the Berg River valley which could experience five additional risk days in March. The south-western coastal production regions e.g. EGVV, show a lower increase in risk (up to two additional days per month), with the risk increasing across a wider area until March. The Langkloof is projected to experience up to two additional risk days per month throughout the summer.

5.4.4 Implications

Since sunburn is already acknowledged as a major problem in the deciduous fruit industry, much is already being done to reduce the damages. The increased risk brought about by climate change underscores the need for a more rapid implementation of affordable and effective technologies to reduce strong direct sunlight and/or reduce orchard temperature. Cultivars that have high susceptibility to sunburn will remain viable if they produce well and fetch a high price for excellent quality fruit, so that protective technologies such as netting provide a viable return on investment. However, lower value sensitive cultivars may in some areas need to be replaced. Breeding and selection for sunburn resistance will become increasingly important, especially for apples. The climate of the future is, however, unlikely to substantially increase the sunburn risk in the southern coastal belt and Langkloof, so that low and medium chill apple cultivars can still do well here even if they have a higher sunburn sensitivity. The Berg River valley is an area of concern, especially for sensitive plum cultivars.

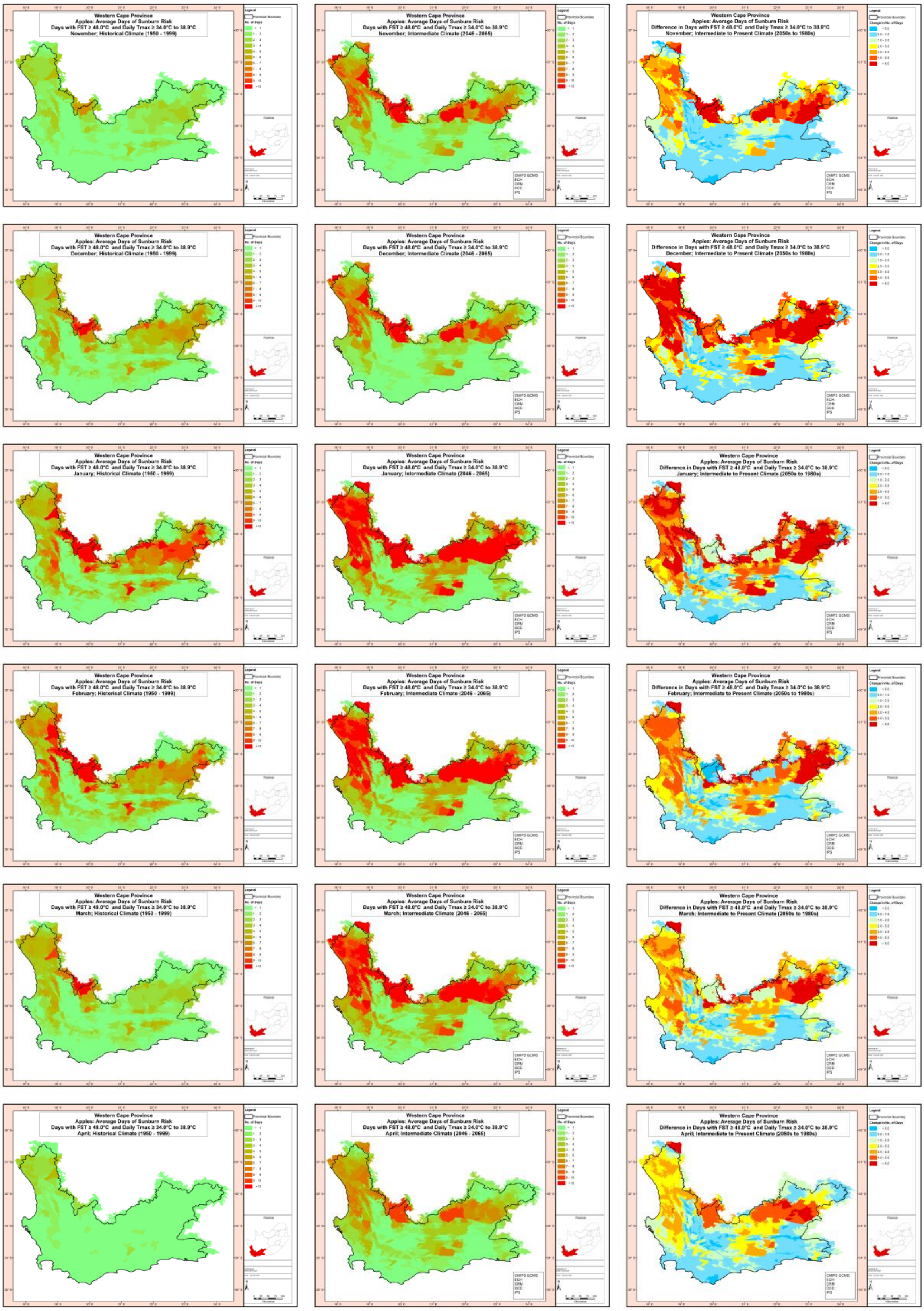


Figure 41. Average number of days per month when conditions are conducive to sunburn of apples (when FST is ≥48.0°C and daily T_{max} is 34.0-38.9°C) under historical climate conditions (left column), under projected intermediate future climates (middle), and the difference (days per month) between the two for October (top row) to April (bottom row). The maps in the latter two columns are averaged outcomes derived from four CMIP3 GCMs.

5.5 Red colour development in apples and projected changes

5.5.1 Background

Apple fruit peel colour is an important factor determining market acceptance, price and profitability. The pigment responsible for red colour in apple peel is anthocyanin. There is a strong genetic component to red colouring potential, and different cultivars can have either full red colour, blushed/striped red colour, or a bi-colour appearance. Although early season red-striped cultivars are widely grown in South Africa (e.g. ‘Royal Gala’ and its mutants), the mid and later season (March-April harvest) blushed and bi-colour apple cultivars (e.g. ‘Fuji’, ‘Cripps Pink’/'Rosy Glow'/Pink Lady®, ‘Cripps Red’/Sundowner®/Joya®) are potentially highly profitable and increasingly popular.

In addition to genetic potential, red colour development (both the presence and extent of red blush) is primarily driven by a combination of temperature and solar radiation in the weeks leading up to fruit maturation and harvest, although other factors such as water stress and nitrogen status can also play a role. As apple fruits develop, anthocyanin synthesis first peaks towards the end of fruit cell division, and peaks again in red cultivars as the fruits mature. At this time, the green pigment chlorophyll begins to be degraded, which results in the red colour becoming visible. Anthocyanin synthesis is induced by cool night-time temperatures in the pre-harvest period, generally below 15°C, with optimum synthesis occurring thereafter under warm (20-25°C) and sunny days (with slight variation between cultivars) (Curry, 1997). Sunlight is an essential requirement for pigment synthesis. Little synthesis occurs below 15°C or above 35°C. Temperatures exceeding 35°C inhibit anthocyanin synthesis and result in its degradation, which can lead to visible colour loss in cultivars with lower inherent pigment concentrations. For further information please refer to Hortgro (2018a).

5.5.2 Climate criteria used to model conditions for red colour development potential

For this study, the criteria used to determine conditions conducive to peel red colour development were broadly based on experimental research in South African apple orchards, and modelled for mid- to late-season blushed/bi-colour cultivars for the months March and April. The criteria used were one day of daily minimum temperature below 12°C (for the induction of anthocyanin synthesis), followed by daytime maximum temperatures in the range 20-28°C for three consecutive days (for strong anthocyanin synthesis), conditional upon solar radiation on the qualifying days being at least 60% of those days’ maximum solar radiation potential.

The number of occasions during March and April that the above conditions were met in each of the 1 401 Quinaries were counted for each year of the historical record (1950-1999), the average determined, and the outcome mapped separately for March, April, and the combined March-April period. Using daily outputs from the ECHAM GCM, considered to be a representative GCM for the region, the same criteria were isolated, and the results mapped separately for the intermediate future period of the 2050s. Finally, the differences (in days per month) between the historical and future climate conditions were calculated and mapped for these months.

5.5.3 Results

The number of days in March on which the climatic criteria are met for red colouring of mid- to late-season blushed or bi-colour apples under historical climatic conditions and into the intermediate future climates are shown Fig. 42, top left and top right, respectively. The climatic criteria are met more than 8 times, and in some areas more than 14 times in the pome fruit regions of the west and the Langkloof (Fig. 42, top left). In the intermediate future (Fig. 42, top right), projections show that much of the region could warm to the extent that climatic criteria for red colouring are met up to 6 times in the warmer southern areas and the western Langkloof, and up to ten times in the cooler northern areas. The greatest reductions (9-15 days less) are seen in the high-lying northern areas and the western Langkloof (Fig. 42, bottom), and the lowest reductions (0-9 days less) are seen in the coastal south-west.

Conditions for red colouring come into their own in April, when under the historical climatic regime the spatial patterns, although patchy, indicate that the apple production areas meet the red colouring criteria on 10 or more days, and in several areas more than 14 times (Fig. 43, top left). However, the April of the intermediate future (Fig. 43, top right) sees projected reductions in qualifying days to 2-4 days in the south and 2-8 days in the north and western Langkloof (Fig. 43, top right). This represents a reduction of up to 15 days in April in apple production regions (Fig. 43, bottom).

When March and April are combined (Fig. 44, and note the change in the legend), the southern production regions have 20-25 days that meet the colouring criteria under historical climate conditions, the western Langkloof has 25-30 days, and the northern regions have at least 25 days and in some areas over 30 suitable days (Fig. 44, top left). This decreases significantly into the intermediate future of the 2050s (Fig. 44, top right), with the reduction being 9 days or more, and some areas (Koue Bokkeveld, western Langkloof) showing a reduction of more than 15 days (Fig. 44, bottom).

5.5.4 Implications

With the growing consumer demand for, and profitability of red/blushed/bi-colour apples (and also red-coloured pears and stone fruit), researchers, breeders, growers and their technical advisors have for the last 20 years given considerable attention to the problem of poor red colour development of fruit associated with climatic variability in a warm region. The results presented here suggest that this problem will become greater, especially in cooler production regions that have historically not experienced losses comparable to the warmer regions. However, practical knowledge and technologies are available and can be applied in orchards across the region in future. Some of the approaches include the use of redder strains of existing cultivars, the appropriate matching of cultivars with microsites on farms (using cooler sites for red cultivars that colour up with difficulty), canopy management practices that optimise light distribution throughout the canopy, avoiding excess nitrogen fertilisation that leads to excess vegetative growth and shading of fruit, and avoiding over cropping.

The type of research results presented here need to be repeated using refined red colouring criteria for a larger range of apple and pear cultivars, as well as selected stone fruit cultivars, and using climatic outputs from more than a single GCM.

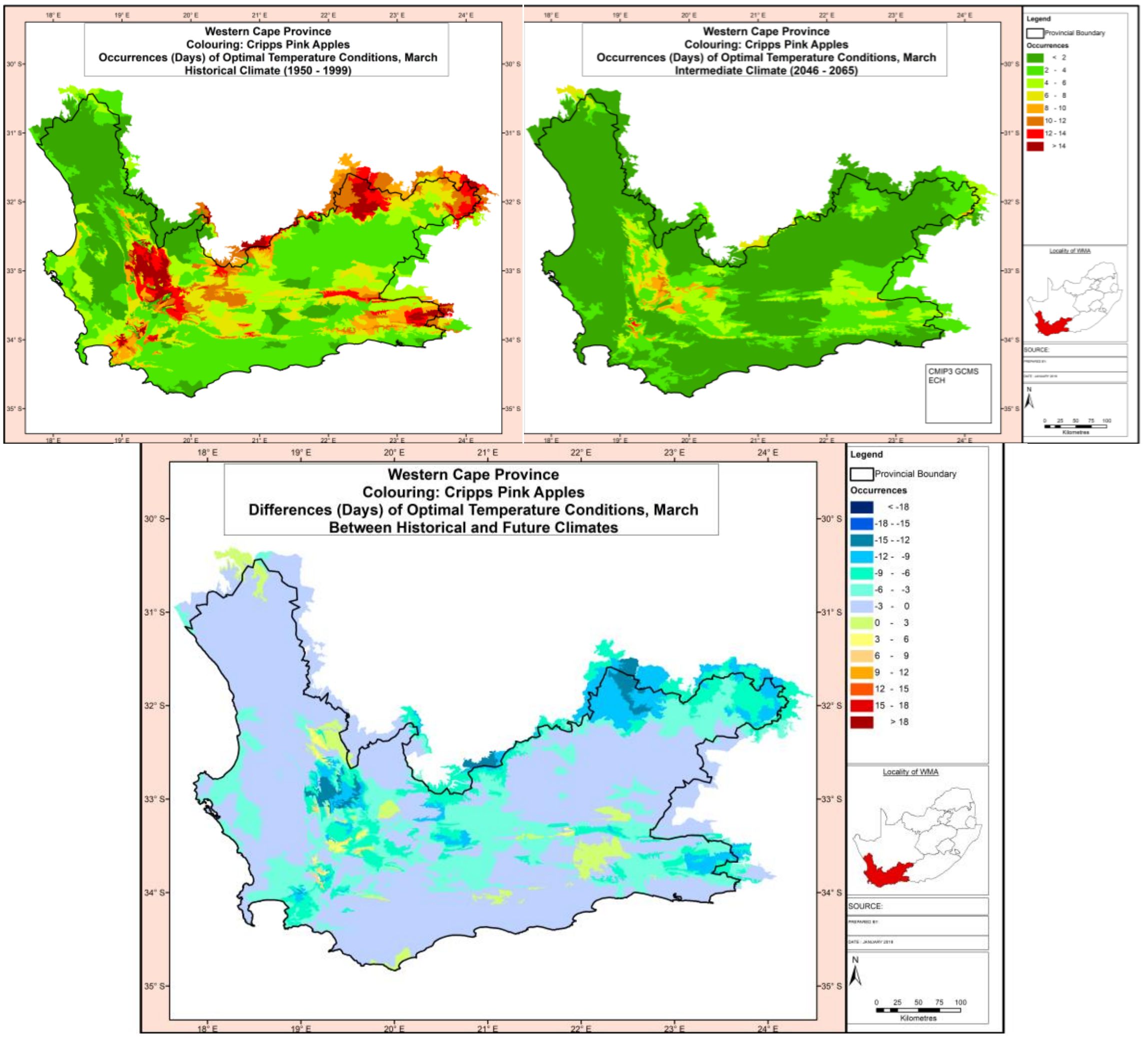


Figure 42. Number of days in March that climatic criteria are met for red colouring of mid- to late-season blushed or bi-colour apples under historical climatic conditions (top left) and into the intermediate future climates of the 2050s (top right), with the difference (in days) in optimal climatic conditions shown in the bottom map. The latter two are derived from the CMIP3 ECH GCM.

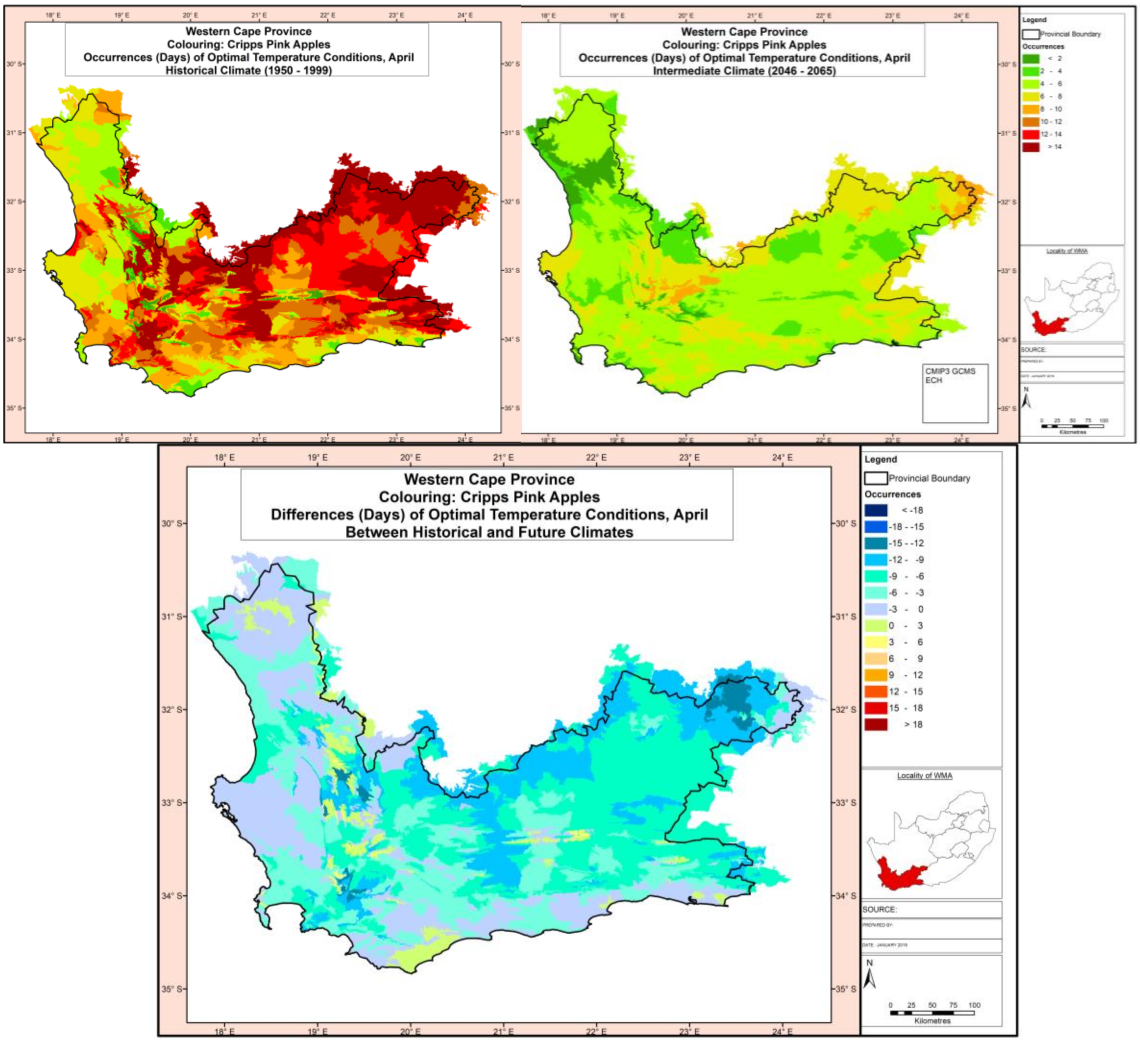


Figure 43. Number of days in April that climatic temperature criteria are met for red colouring of mid- to late-season blushed or bi-colour apples under historical climatic conditions (top left) and into the intermediate future climates of the 2050s (top right), with the difference (in days) in optimal conditions shown in the bottom map. The latter two are derived from the CMIP3 ECH GCM.

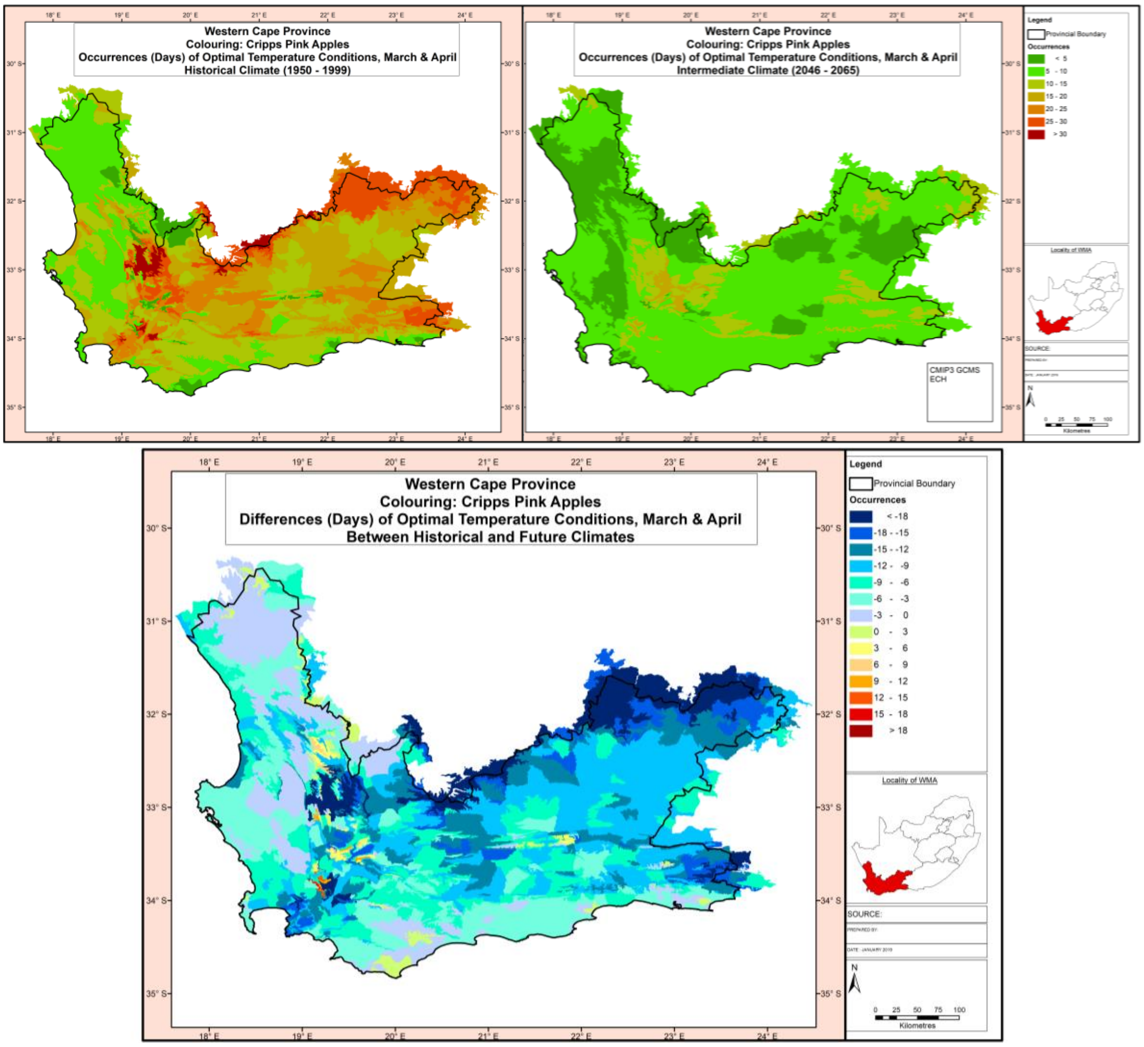


Figure 44. Number of days combined in March and in April that climatic criteria are met for red colouring of mid- to late-season blushed and bi-colour apples under historical climatic conditions (top left) and into the intermediate future climates of the 2050s (top right), with the difference in optimal climatic conditions shown in the bottom map. The latter two are derived from the CMIP3 ECH GCM.

5.6 Insect pests – moth life cycles and projected changes

5.6.1 Background

The spatial distribution of disease vectors, pests and species used in the biological control of exotic pests is temperature dependent and, hence, subject to shifts under conditions of climate change (Schulze and Kunz, 2010). Furthermore, specific species have defined lower and upper thresholds of temperature between which development and reproduction takes place. In pests, the rate of development to complete one life cycle is dependent on accumulated heat units. Life cycles are thus measured by 'physiological' time rather than by calendar time (Zalom et al., 1983). Such information is important for integrated pest management under future climates and requires the modelling of projected changes in pest life cycles of significant species.

The codling moth (*Cydia pomonella* L.*)* is a serious pest of apples in South Africa. The larvae also attack pears and other fruit, usually tunnelling to the core of the fruit and pushing out a mass of chewed material ('frass'). Such fruit are unmarketable and economic losses are high in infested orchards.

The oriental fruit moth (*Grapholita molesta* (Busck)) infests all stone fruit and is found in various stages of its life cycle during the entire growing season, this being the main reason for the necessity of season-long and repeated insecticide applications. Oriental fruit moth (OFM) larvae pupate in late winter to early spring, with multiple generations per season. Infested shoots and terminal leaves wilt and bend over, known as 'flagging', and leaves eventually dry up. Flagging stimulates lateral growth below the point of injury, providing wound sites for pathogens. More critical even than flagging is fruit injury, occurring either early in the season or later after pit hardening to final swell, with gum and frass often exuding from the wound area.

5.6.2 Codling Moth

5.6.2.1 Modelling life cycles of Codling Moth

Lower and upper temperature (°C) thresholds and accumulated heat units (degree days) for one life cycle of codling moth are, respectively, 11.1°C, 34.4°C and 603°days (Zalom et al., 1983). Life cycles per annum of codling moth were determined by computing degree days with a base temperature of 11.1°C and an upper limit of 34.4°C for historical climatic conditions, using 50 years of daily values of maximum and minimum temperatures (1950-1999). This was repeated for projected intermediate (mid-century) climate change conditions using multiple GCMs for the Quinaries making up the region. To calculate the number of life cycles per annum of codling moth, the degree days accumulated over one year were divided by the °days required for one life cycle to be completed by codling moths, i.e. by 603°days.

5.6.2.2 Results

The modelling assumed that no factors other than 603 accumulated degree days affect the life cycle of a codling moth, and that, in theory, codling moths can be found throughout the region and in all seasons. Fig. 45 (top left) shows that under historical climatic conditions the number of life cycles per annum ranges is generally up to 5 in the fruit production regions, with lower numbers in the mountain belts (up to 3) and higher numbers in the warmer areas. The map of codling moth life cycles per annum into the intermediate future (Fig. 45, top right) shows distinct increases. When mapped as changes, these are generally of the order of 0.5-1.5 additional life cycles per annum (Fig. 45, bottom left), with lower increases (< 1.0) in the core pome fruit regions. However, when expressed as percentage change, the northern and western Langkloof pome fruit regions show a higher relative increase of >40% increase (Fig. 45, bottom right).

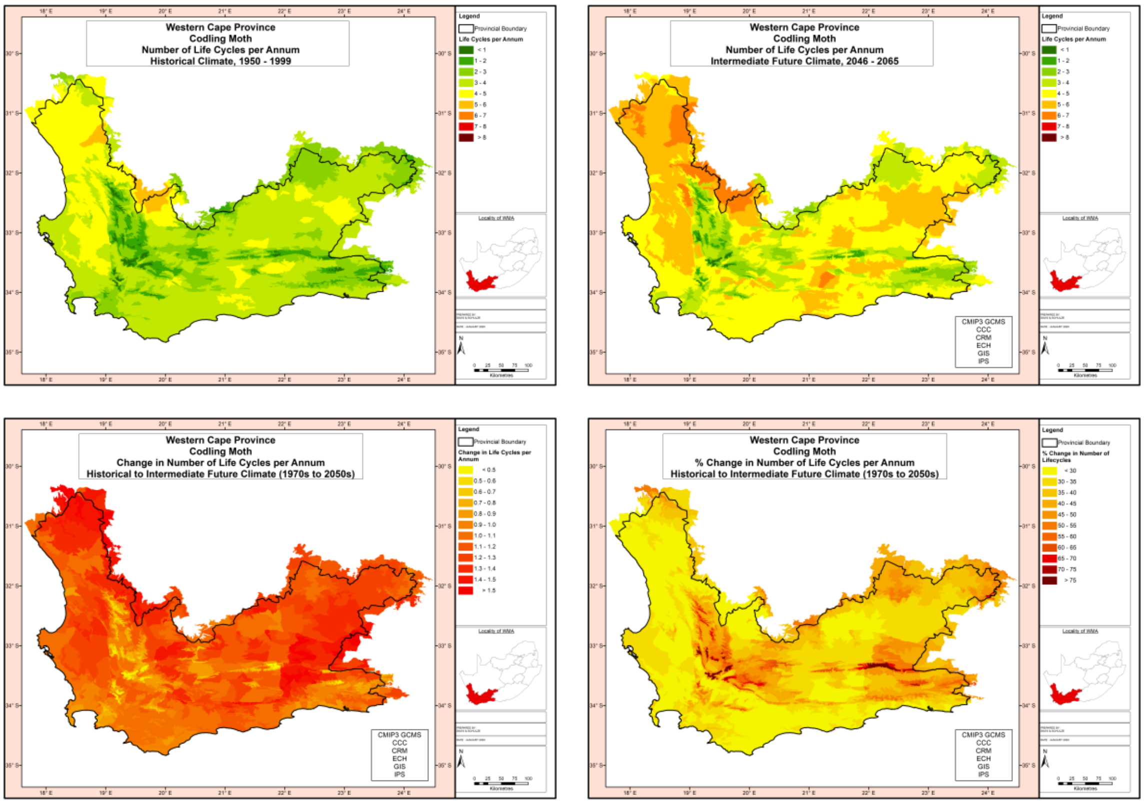


Figure 45. Number of life cycles of codling moth per annum under historical climatic conditions (top left), under intermediate future climatic conditions (top right), and projected changes in numbers of life cycles into the intermediate future (bottom left), also expressed (bottom right) as a percentage change.

5.6.3 Oriental Fruit Moth

5.6.3.1 Modelling life cycles of Oriental Fruit Moth

In the case of the oriental fruit moth, the lower and upper temperature (°C) thresholds and accumulated degree days for one life cycle of oriental fruit moths are given by Zalom et al. (1983) as 7.7°C, 32.2°C and 535°days.

Life cycles per annum of oriental fruit moths were thus determined by computing degree days using a base temperature of 7.7°C and an upper limit of 32.2°C. For historical climatic conditions, 50 years of daily values of maximum and minimum temperatures (1950-1999) were used at representative grid points for each of the Quinary catchments covering the region. To calculate the number of life cycles per annum of oriental fruit moths, the degree days accumulated over one year were divided by the degree days required for one life cycle to be completed by oriental fruit moths, i.e. by 535°days. For climate change assessments, the daily temperature values from the present (1971-1990) and intermediate future (2046-2065) climate projections of the multiple CMIP3 GCMs used in this analysis were interrogated in the same manner as for the historical climate.

5.6.3.2 Results

The modelling assumed that no factors other than 535 accumulated degree days affect the life cycle of an oriental fruit moth, and that, in theory, OFMs can be found throughout the region and in all seasons. Fig. 46 (top left) shows that under historical climatic conditions the number of life cycles per annum is generally up to 8 in the fruit production regions, with lower numbers in the mountain belts (up to 6) and higher numbers in the warmer stone fruit areas.

There is a distinct projected increase in the number of life cycles of OFM into the intermediate future of the 2050s (Fig. 46, top right), with some of the warmer stone fruit regions showing 9 or more life cycles per annum. When expressed as changes in the number of life cycles from the historical to the projected intermediate future climates, the bottom left map of Fig. 46 displays 1.5 to 2.5 more life cycles per annum in the fruit regions. This translates into an increase of up to 60% (Fig. 46, bottom right), with a lower percentage increase in the south-west (up to 40%) and higher increases in the mountain belts of the northern production regions as well as in the western Langkloof.

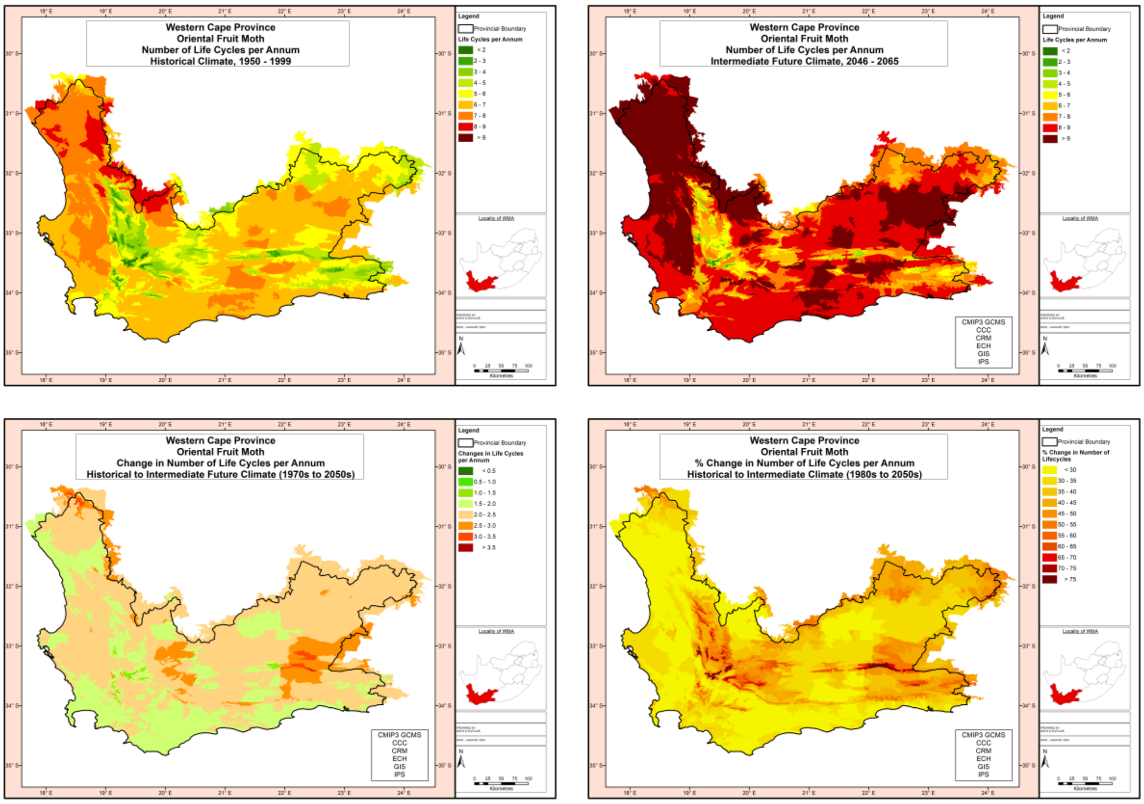


Figure 46. Number of life cycles of oriental fruit moths per annum under historical climatic conditions (top left), under intermediate future climatic conditions (top right) and projected changes in numbers of life cycles into the intermediate future (bottom left), also expressed (bottom right) as a percentage change.

5.6.4 Implications

This type of information is important for effective pest control under different climates at present and in the future. If the stages of pest life cycles can be predicted with some accuracy, conflict between cultural practices (such as the application of irrigation) and pest control (such as spraying) can be minimised.

CHAPTER 6

ADAPTATION IN THE POME/STONE FRUIT INDUSTRIES

6.1 Definitions and concepts around adaptation

Climate change adaptation is “The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.” (IPCC, 2014)

Furthermore, climate change scientists generally agree that *adaptive capacity* refers to “the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.” Adaptive capacity varies widely within and between sectors, geographically, and between social/ecological/economic systems. Adaptive capacity within an industry such as the fruit industry comprises the sum of all the capacities and efforts of every chain in the link, namely, growers, farm workers, input suppliers, packers, processors, marketers, insurers, financial institutions, industry bodies, government institutions (e.g. for water governance, disaster planning and response), and researchers.

It is important to be clear on what actors within this system need to be adapting *to*. For this reason, a grower or other actor must first identify the specific risks and impacts arising from the climate at a given location with a specific context, for the present climate and future time periods. A first step towards adaptation to future climate change is to reduce vulnerability and exposure to present climate variability and risk. This then leads to planning for the medium- to long-term future, considering changes in average climate (e.g. gradual warming), changes in variability from year to year, and changing risks of weather extremes. Poor planning, overemphasizing short-term outcomes, or failing to sufficiently anticipate unintended negative consequences can result in *maladaptation*. Some responses that may seem desirable in the short term can turn out to be maladaptive over longer time periods because they either increase vulnerability (e.g. building of structurally weak agricultural infrastructure in disaster-prone areas), or they become white elephants, also called ‘stranded assets’ (e.g. capital-intensive projects such as dams or cold storage facilities which become under-utilised as the climate shifts).

Another concept that must be considered is the *adaptation limit*, defined as “the point at which an actor’s objectives (or system needs) cannot be secured from intolerable risks through adaptive actions” (IPCC, 2014b). We can distinguish between a ‘hard adaptation limit’ (i.e. no adaptive actions are possible to avoid intolerable risks) and ‘soft adaptation limit’ (i.e. options are currently not available to avoid intolerable risks through adaptive action). The latter situation can be overcome through innovation and technology development, and transformations in farming practices.

The SmartAgri Plan[2] (Midgley et al., 2016b) states: “Responding to climate-related risks involves decision-making in a changing world, with continuing uncertainty about the severity and timing of climate change impacts and with limits to the effectiveness of adaptation. Iterative risk management with multiple feedbacks [see Fig. 47] is a useful approach for adaptation in agriculture. Assessment of the widest possible range of potential impacts, including low-probability outcomes with large consequences, is central to understanding the benefits and trade-offs of alternative risk management actions. The complexity of adaptation actions across scales and contexts means that monitoring and learning are important components of effective adaptation.”

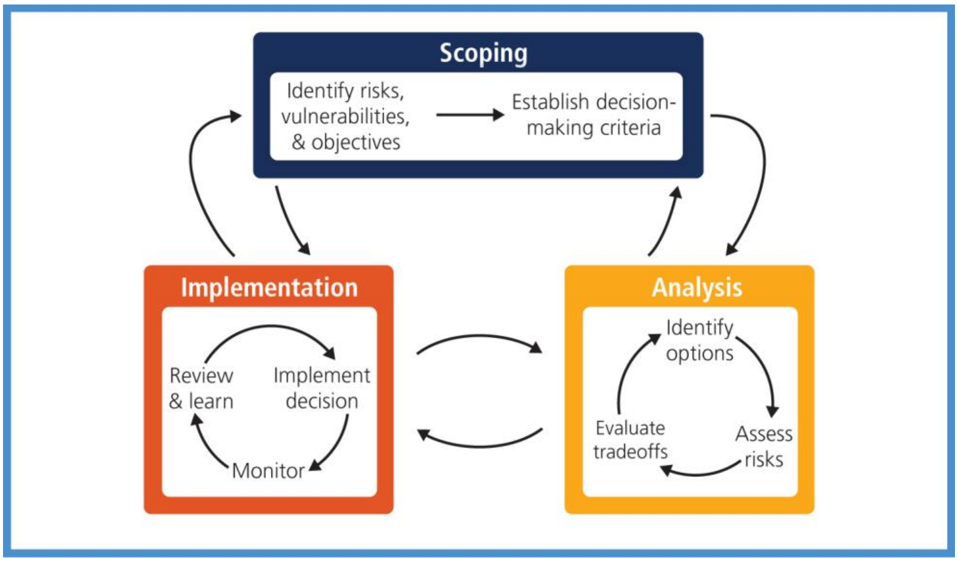


Figure 47 Climate-change adaptation as an iterative risk management process with multiple feedbacks. People and knowledge shape the process and its outcomes. Source: Jones et al. (2014).

Growers need a wide range of hard and soft technologies and approaches from which to make appropriate choices tailored to their own situation and needs. The inherent uncertainty in weather and climate projections means that sometimes very specific measures can be taken (e.g. flood defenses), whereas at other times so-called ‘no-regret’ measures, which are robust to a wide range of possibilities (e.g. good land management), are more appropriate. These prevent ‘lock-in’ and allow for flexibility in future choices.

In the agricultural sector, technology clearly plays a very important part in productive potential and adaptive capacity. Improvements of technologies support greater and more efficient production, lower costs, help farmers to reach new markets, and can also be employed to reduce risks. Technology includes physical infrastructure, machinery and equipment (e.g. irrigation systems), knowledge and skills (e.g. farmer training and awareness raising) and the capacity to organise and use all of these (e.g. water user associations); but also the biological technology (e.g. genetic choices) with which farmers produce. Biological technology complemented with advances in crop nutrition and crop protection, equipment and knowledge have been the primary drivers of increased productivity in agriculture. These should be

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[2] Western Cape Climate Change Response Framework and Implementation Plan for the Agricultural Sector (2016). Available at: https://www.greenagri.org.za/smartagri-2/smartagri-plan/

reevaluated and improved in the light of evolving situations and needs. Appropriate technologies are those which can be managed and maintained by farmers over the long term, and which integrate environmental, economic, and social sustainability principles.

In the past agricultural capital investments were planned for an economic lifetime of decades. However, the accelerating pace of changing consumer preferences and market price fluctuations has changed this situation significantly over the last 20 years or so. Perennial orchards are now replaced over shorter cycles as new cultivars become more popular, fetching a premium which justifies the investment. In this context, the notion that growers are always planning for the next 30-40 years has become outdated. However, built infrastructure, such as packhouses and cold storage facilities, has a long economic lifetime to achieve a return on investment.

Strategic choices can be made for the shorter term, e.g. planting lucrative present crops or cultivars even though risks of climate related crop losses are understood and factored into the farm's financial strategy. For less adapted crops and cultivars, climate ameliorating technologies such as shade netting can reduce the risks. At the same time, growers can begin to test the viability of more adapted crops or cultivars for the future and prepare for more transformational changes. Such a phased approach can be very effective by ensuring continued profitability while lessons are learned, and affordable and sustainable technologies developed and tested. Eventually, decisions must be made regarding the infrastructure that supports the whole value chain, such as placement of pack houses and processing facilities.

6.2 Growers' climate change adaptation decision making

It is insightful to see how fruit growers in other warm production regions view adaptation and what actions are being taken. A study in Australia (Santhanam-Martin and Stevens, 2017) found, amongst others, that (we quote):

- Climate change adaptation is already occurring as part of growers' routine management decision-making. Most growers do not separate climate adaptation decisions from other business management decisions aimed at meeting market demands and making profit.
- Most of the adaptation actions growers are currently undertaking are tactical decisions. They involve an adjustment to management practices to respond to changes in conditions that are being experienced now. This contrasts with strategic adaptation, which would see growers making decisions now to adapt their production systems to conditions they expect to experience in the future. This is to be expected since there is so much uncertainty about the timing and precise nature of future climate change.
- Installation of orchard netting is the most prominent current example of a strategic adaptation response. This is a major investment decision that many growers are making now, because they see it is a response to current conditions that they expect to become more pressing in the future. Adoption of more efficient irrigation methods (discussed below) is similar.
- In some locations, growers have already, or are considering, moving into different perennial fruit products that they think will be more suited to future climates. This allows

them to keep using skills and infrastructure that are suited broadly to growing tree crops, and is a helpful adaptation option.

- The security and availability of water resources is the main “game changer” in relation to climate change, and was identified as such by most participants in this research. Most growers have already made significant investments in technology and practices to improve irrigation efficiency. If in the future water supplies become unavailable, or unaffordable, then current products and production systems will not be able to continue.
- There is some tension between the highly market-responsive characteristic of orchard businesses and the need to build in climate change adaptation. This is seen most clearly in the case of variety selection. Growers perceive strong economic incentives to plant new varieties that promise higher margins, including proprietary (“club”) varieties, that may not be the most well adapted to current and future climate conditions. This tension is also evident in that some of the fruit characteristics that the market demands (e.g. uniform size, colouration and absence of blemishes) will become increasingly difficult and expensive to achieve as climate conditions become harsher. This raises the question as to whether there is a role of industry to educate or advocate to buyers and consumers on what varieties of fruit, and what characteristics of fruit, are going to be possible and profitable to produce under future climate conditions.
- Discussions of climate change adaptation in Australian agriculture have tended to focus on adaptation by growers. The findings of this study point to the need for adaptation along the value chain. Businesses supplying planting material should provide information about the susceptibility of new varieties to climate risks such as reduced winter chill and heat damage. Buyers and marketers should seek to shape market expectations towards varieties that are going to be possible and profitable to produce into the future.
- Growers are interested in having more, and more accurate, information products and decision support tools to assist them in making good tactical and strategic management decisions. However, much of this information, such as chill requirements and heat sensitivity of varieties and pest and disease physiological information to allow modelling of pest and disease processes is not available. This points to the need for ongoing scientific research to fill information gaps. Further discussion with growers is needed to prioritise information needs, and to understand the types of decision support tools they will find most useful.

All of these findings are also highly relevant to the South African farm context. However, there is also a growing need to move beyond the "low-hanging fruit" such as netting and water use efficiency, towards approaches that build long-term resilience such as soil health, i.e. "conservation agriculture" or "renewable agriculture" for tree fruit production systems. While this Guide focuses on climate change impacts and adaptation, farming practices that simultaneously increase carbon sequestration in the soil and contribute to the reduction in greenhouse gas emissions (e.g. greater fuel efficiency, switching to clean fuels, use of renewable energy for farm operations, etc.) must also be encouraged. This will ultimately make a contribution to reducing the rate of warming and associated climate risks.

6.3 Adaptation options for pome and stone fruit farms in South Africa

Pome and stone fruit growers will need to respond to the following categories of climate change and risk. More detailed information on adaptation can be found in the "Handbook for farmers, officials and others on adaptation to climate change in the agricultural sector of South Africa" (Schulze, 2017).

6.3.1 Adapting to higher winter temperatures and reduced chilling

In previous chapters we have highlighted the implications of climate change on three related parameters:

a. Reduction in days with a minimum temperature below 6°C, especially in mountainous and higher-lying interior regions (section 4.3.4). This has implications for the incidence and intensity of pests/diseases that are no longer kept in check by the low temperatures in the cold season. Adaptation options are discussed below in section 6.3.4. On the positive side, areas otherwise suited to deciduous fruit production but where the colder seasons are currently too cold (especially the transition period into spring), could come into production as the growing season is lengthened.
b. Reduction in frost days (section 5.1). This will also lengthen the growing season and allow some colder interior areas to become suited to fruit production. This must be carefully assessed since the risk of late frost may continue for some time into the future. It would be prudent to avoid lower chill, early flowering cultivars for orchard establishment and renewal in such areas.
c. Results presented in section 5.2 underscore the potentially severe implications of winter warming on chill accumulation and dormancy release in deciduous fruit species.

The following approaches to adaptation can be considered by growers:

- For current sensitive (high- to medium-chill) cultivars, seek new, cooler microsites on farms where PCU thresholds are still met i.e. establish such cultivars in cooler drainage lines, south-facing slopes, higher altitudes, and other terrain features that are cooler; this requires a very good understanding (preferably backed up by monitoring data) of the microclimate of the land in question;
- Optimise or introduce the application of chemical rest-breaking agents, including on fruit species that are not currently sprayed;
- Gradually adopt lower chill cultivars within each fruit type to replace the higher chill ones;
- Gradually plant or increase the plantings of lower chill fruit species;
- Identify sensitive cultivars and fruit types that must be gradually phased out on a specific farm as they become commercially unviable;
- Expand/diversify or move the enterprise to new cooler production regions.

6.3.2 Adapting to higher growing season temperatures

In this guide, the following parameters relate to the impacts of climate change on rising daytime temperatures in the growing season:

a. Increase in the monthly mean of daily maximum temperature in January (section 4.3.3)
b. Increase in days with a maximum temperature above 35°C (section 4.3.4)
c. Increase in evapotranspiration (section 4.4)
d. More rapid accumulation of heat units (section 5.3)
e. Increasing risk of conditions conducive to sunburn (section 5.4)
f. Reduction in days with conditions conducive to red colour development (section 5.5)
g. Increase in number of moth pest generations (section 5.6)

The following approaches to adaptation can be considered by growers:

- Gradually shift to cultivars that are specifically bred or tested for heat tolerance;
- Gradually shift to cultivars that are specifically bred or tested for sunburn resistance;
- Plant early ripening cultivars in sites with intense summers, and later ripening cultivars in sites with cooler summers;
- Plant other fruit types or annual crops that are less sensitive to heat stress and sunburn;
- Seek cooler microsites on farms where summer maximum temperatures are milder;
- Investigate the feasibility of establishing orchards on available land at higher altitude or other areas where heat units were historically too low for pome and stone fruit production;
- Ensure that irrigation practices are optimal and water stress is avoided;
- Use mulches and cover crops to reduce evaporative water losses, build carbon-rich soil organic matter, and improve the water-holding capacity of the soil;
- Install protective netting to reduce the heat load and sunburn risk;
- Evaporative cooling of the canopy during intense heat is effective in reducing the risk of heat stress and sunburn, but is only recommended on farms with excellent water supply, and taking care not to waste water and possibly cause tree damage from soils that are too wet;
- Apply effective approaches to tree training and canopy management to reduce the heat load on the fruit;
- Expose the fruit to additional light during the final two to three weeks before harvest (through pruning of leaves and non-fruiting shoots) to enhance red colour development, especially in later ripening cultivars where this period is already cooler and sunburn is no longer a high risk;
- Enhance red colour development by using reflective mulch under the trees;
- Do not overcrop the trees since high crop load can negatively affect red colour development and other fruit quality traits, and this can be exacerbated in areas prone to heat stress;
- Shift to night-time harvesting where feasible to avoid heat stress in pickers.

6.3.3 Adapting soil and water management practices

The relevant sections in this document relating to the impacts of climate change on soil water dynamics are:

a. Potential evapotranspiration (section 4.4);
b. Rainfall, dry spells, wet spells and long duration design rainfall (Appendix A);
c. Runoff (Appendix B.3);
d. Accumulated streamflow (Appendix B.4).

The following adaptations can be considered by growers: (for more information see Hortgro, 2018b)

- Use irrigation technologies and scheduling methods (including remote sensing tools) to maximise water productivity;
- Shift to fruit types with a greater physical and economic water productivity;
- Shift fruit cultivation to regions with greater rainfall in summer to reduce the irrigation water requirement;
- Diversify access to diverse sustainable water sources, e.g. utilisation of groundwater in areas where the resource supply is still well in excess of extraction rate and the water is of suitable quality;
- Maximise streamflows, base flows (especially during the dry season and during dry spells and droughts), groundwater recharge, and on-farm potential for water storage during the rainfall season by practicing clearing of invasive alien plants (with regular maintenance), protection / rehabilitation / restoration of wetlands, and using hydrologically appropriate drainage systems in planted areas;
- Use mulches and cover crops to reduce soil evaporative water losses, build carbon-rich soil organic matter, and improve the water-holding capacity of the soil;
- Help nature to provide water purification services and thus improve water quality by protecting (and not planting in) riparian buffer zones and wetland drainage areas;
- The installation of protective netting over orchards may provide some benefits in reducing water use without forfeiting production potential;
- Develop a River Maintenance Management Plan (MMP) in collaboration with LandCare to ensure long-term protection of the water resource and water-related infrastructure;
- Develop a Farm Drought Plan to guide management strategies and actions in times of dry spells and droughts;
- Ensure that drainage systems are properly designed and built to provide protection against wet spells, heavy rainfall and localised flooding.

6.3.4 Adapting to changing pest and disease pressures

The possible impacts of climate change on pests (specifically two moth species) are presented in section 5.6.

The following adaptations can be considered by growers:

- Monitoring-based control measures will remain the most important response to potentially increased risk under a future climate;
- In some areas and in some years, the deployment of traps may need to be adjusted;
- Moth control i.e. the optimal timing and frequency of insecticide applications, can be undertaken scientifically using degree-day models, using either a biofix point for °day accumulations starting at the first sustained adult catch with pheromone traps, or the more recently available no-biofix models. When based on measured temperatures on-farm or nearby, this will automatically adjust to a shifting climate over time.

6.3.5 Adopting agro-ecological / regenerative farming systems

While the science in support of agro-ecological, integrated or regenerative farming practices as climate change adaptation responses is still in the early stages, growers should engage with these approaches and assess what the benefits could be in their specific context. Scientifically sound on-farm research is needed in South African fruit orchards to establish effective and viable practical approaches, proven benefits (from both adaptation and mitigation perspectives) and possible negative effects.

6.3.6 Using weather and climate data smartly

Fruit growers in South Africa have been quick to adopt weather forecasting applications and use them to guide planning and day-to-day orchard management. In addition, growers should consider developing their own weather database, perhaps even installing cost-effective and properly maintained on-farm weather stations, to build a record of trends over time. Appropriate analyses of such databases can provide very useful information for planning purposes. Groups of growers could cooperate to build an area-wide long-term climate database, and make their data available to broader regional databases for sector-wide analysis.

New science-based decision tools (e.g. TerraClim[3]) are currently under development for use by the wine and fruit industries. TerraClim aims to provide a comprehensive climate and terrain database, using new technologies to spatialise climate and terrain. Integrated data resources are displayed through a user-friendly online spatial decision support system. At present, a TerraClim climate and terrain tool has been developed for the Elgin-Grabouw-Vyeboom-Villiersdorp production area, specific to pome fruit.

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[3] https://terraclim.co.za

APPENDIX A: Rainfall and rainfall variability

A.1 The importance of rainfall in agriculture

Among the various climatic variables that influence the growth characteristics of fruit crops, one of the most fundamentally important is rainfall and the availability of water. Water is essential for the maintenance of physiological and chemical processes within the cells and tissues, is necessary for growth, and is a carrier of nutrients and metabolites in solution. Limitations in water availability can be a restrictive factor in plant development, yield and fruit quality, as the recent severe drought in the region showed. Access to, and reliability of water supply is becoming increasingly problematic and could severely impact the sustainability of the industry. Almost all pome and stone fruit orchards in the region are irrigated using either stored water (from public and private dams), water from rivers, or groundwater. Since most rainfall occurs in winter and not during the fruit season (especially in the western parts of the region), the importance of rainfall is primarily related to hydrological systems and the knock-on effects on run-off (Appendix B.3) and accumulated streamflow (Appendix B.4).

A study of the patterns of rainfall in time and over an area must initially ask:

- how much it rains in the long term;
- where it rains (its spatial distribution);
- when it rains (its seasonal distribution);
- how frequently it rains; and
- the duration and intensity of rainfall events.

A grower also needs to consider:

- how variable the rainfall is from year-to-year, or for a given month, and
- how frequently droughts of a certain level of severity are likely to recur

The reservoir of water in the soil (not factoring in irrigation) is derived mainly from rainfall, with relatively minor contributions in the region from dew, fog and snow. Not all rainfall is, however, freely available to the crop through the soil, as some is intercepted by the plant before reaching the soil, a part enters streams as stormflow after rainfall events (without being utilised by plants), some percolates into the deeper soil layers beyond the root zones, and a portion is evaporated directly from the soil surface without being transpired through the plant.

A.2 Mean annual precipitation and projected changes

A.2.1 Background

The mean annual precipitation (*MAP*, in mm) characterises the long-term quantity of water available to a region for hydrological and agricultural purposes. Under non-irrigated conditions the *MAP* gives an upper limit to a region’s sustainable agricultural potential regarding biomass production if other factors (e.g. light, temperature, topography, soils) are not limiting.

Not only is MAP important as a general statistic in its own right, but it is probably also the one climatic variable best known to growers, and to which they relate many other things. Note that while simple to calculate and attractive to use, the concept of *MAP* nevertheless has its weaknesses, in that in the region (and elsewhere in South Africa) years with low rainfall are more numerous than the higher than average years. This is because *MAP*s are frequently inflated by a few very high annual totals from very wet years, especially in areas of low rainfall.

A.2.2 Results

MAP in the region is highly spatially variable (Fig. 48, top) with a range from < 150 mm to > 1 000 and even 2 000 mm. The lowest *MAP*s are in the arid north-west and central interior of the Karoo, while the highest *MAP*s are in the south-west mountain areas, the linear fold mountain belts and the south-east coastal area. Major variations in *MAP* frequently occur in locations within close proximity to one another.

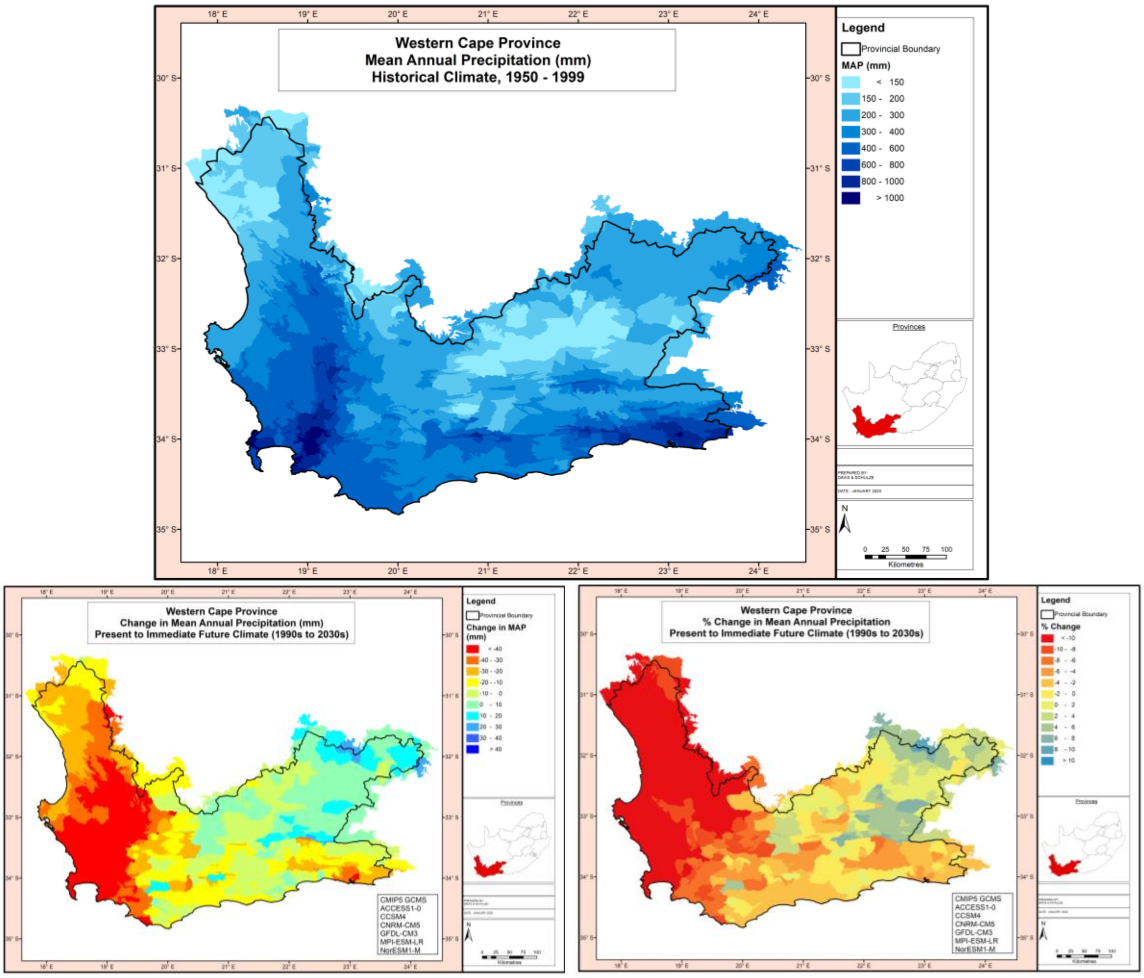

Figure 48. Mean annual precipitation (mm) under historical climatic conditions (top), and projected changes in mean annual precipitation in mm (bottom left) and as a percentage (bottom right) between present (1990s) and immediate future (2030s) climates. The latter two maps are derived from as yet unpublished outputs of multiple bias-corrected CMIP5 GCMs (CWWR, 2021; unpublished).

Projected changes in *MAP* in this region are subject to debate and are dependent on the set of GCMs used, the method of downscaling, and the future timeframe. In this analysis, when averaging outputs from six of the most recent as yet unpublished bias-corrected CMIP5 GCMs (Centre for Water Resources Research, UKZN, 2021; WRC Project 2833), *MAP* is projected to decrease markedly from the present of the mid-1990s into the immediate future of the 2030s, by > 40 mm per annum in large parts of the west, and by 10-20 mm in the south (Fig.

48, bottom left). In the north-east of the Province, *MAP* is projected to increase by 10-20 mm. In large parts of the central region, absolute changes (in mm) do not deviate much from zero (no change). When expressed as percentage changes (Fig. 48, bottom right), this translates into a > 10% decrease in the west, a 2-4% decrease over much of the south, and an increase of up to 8% in parts of the east.

The inter-annual variability of rainfall in the region is high at between 20% and 60%, with the highest variability in the more arid regions of the north-west and the Karoo (Fig. 49, left). Going into the immediate future (Fig. 49, right), the CV of annual rainfall increases slightly (by ~ 1-3%) in parts of the north-west and the north-east, with slight decreases (by ~ 1-3%) in the east. In the south-west the changes in the CV do not deviate much from zero.

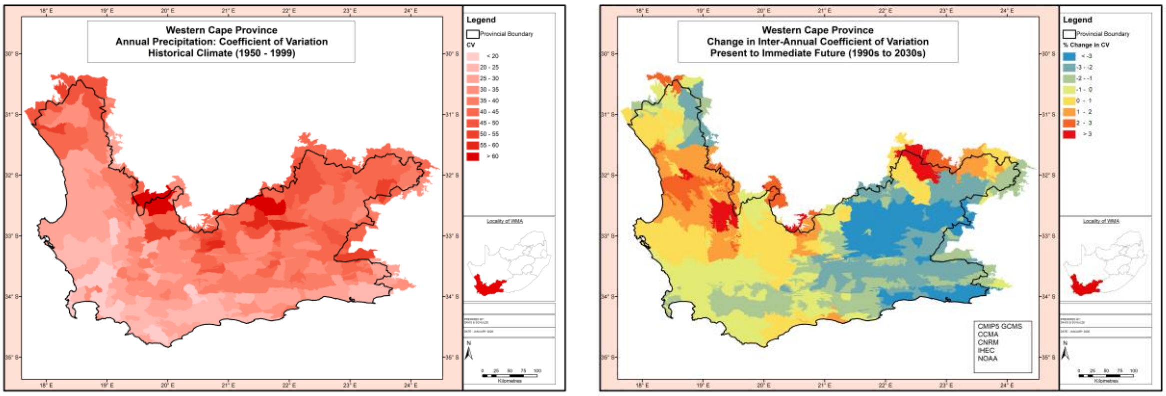

Figure 49. Inter-annual coefficient of variation of rainfall (CV%) under historical climatic conditions (left), and projected changes to the CV% from the present to the immediate future (right). The latter is derived from outputs of multiple CMIP5 GCMs.

A.2.3 Comparison of rainfall changes with other studies

The above modelling takes a specific approach that is focused on the immediate future (2030s), uses a specific set of GCMs, and uses a downscaling method that is one of several methods in use in South Africa. Downscaling approaches allow us to gain insights into local scale precipitation changes because of large-scale circulations changes captured by the GCMs. To guide the reader in interpreting the results, a selection of results from South Africa's Third National Communication under the UNFCCC (DEA, 2018) is included here.

Two downscaling approaches were used by the research groups involved in these studies: statistical downscaling as practised by climatologists at UCT, and dynamic downscaling as practised by climatologists at the CSIR. For the immediate (2016-2035) period, the downscaled models show mixed but relatively weak and not statistically significant messages of change in annual total rainfall across the country (Figs 50 and 52). Towards the intermediate period (2046-2065) many models show significant changes. However, the statistically downscaled projections show a much more even split between increasing and decreasing rainfall (Fig. 51) compared to the driving CMIP5 GCM projections. The latter (not shown here), and the dynamically downscaled projections of rainfall (Fig. 53) indicate reductions in winter rainfall over most of the region by mid-century. Statistically downscaled projections of rainfall show high uncertainty with growing evidence that increased orographic (mountain) rainfall in spring is a possibility (results not shown here). Given the current state of the science, both increased and decreased rainfall should be considered by decision-makers in the region. Therefore, two narratives have been developed for the Western Cape for the mid-century period (see section 4.1).

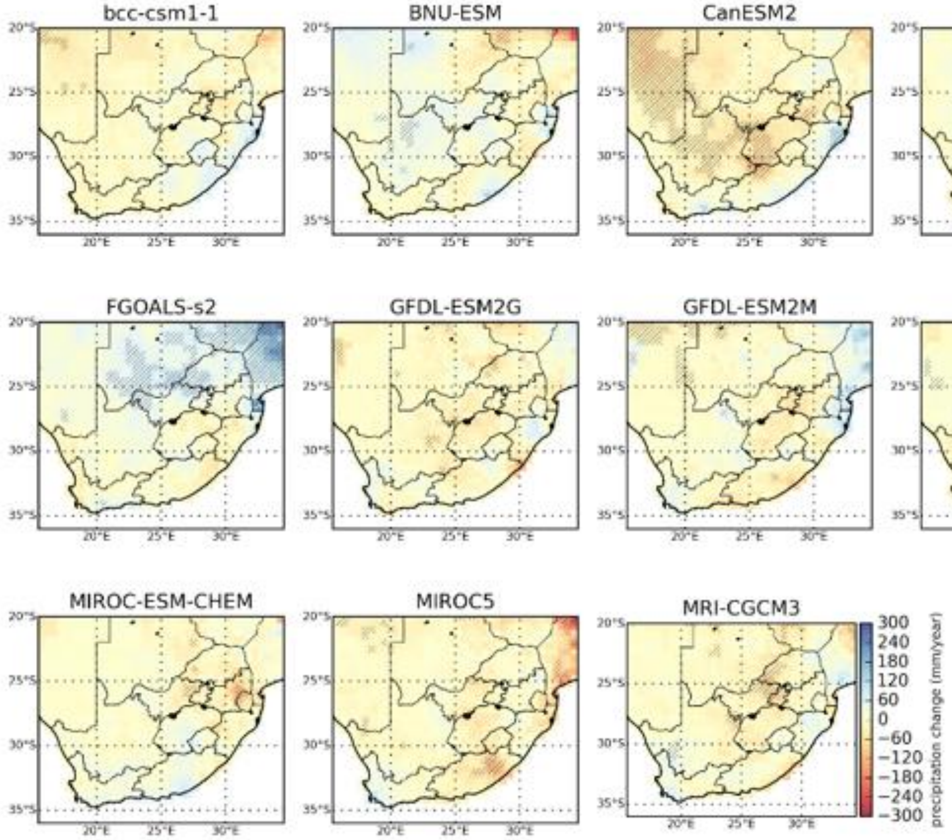

Figure 50. Statistically-downscaled projected changes in annual total rainfall under the RCP8.5 pathway for the 2016-2035 period. (Source: DEA, 2018)

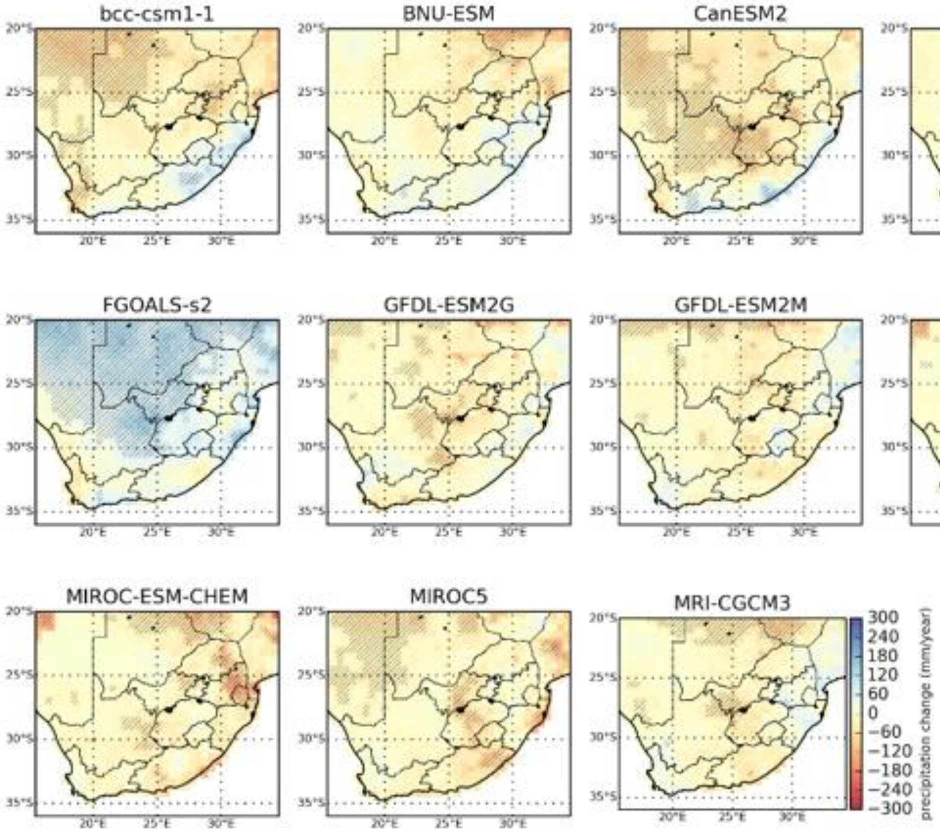

Figure 51. Statistically-downscaled projected changes in annual total rainfall under the RCP8.5 pathway for the 2046-2065 period. (Source: DEA, 2018)

A.2.4 Implications

The overall projected losses and in places slight gains in *MAP* and its CV could have major repercussions on year-on-year consistency of agricultural production. There will be impacts on the management of water resources for irrigation through operations of major reservoirs as well as smaller farm dams. As important as it may be to adapt to changes in annual rainfall and its variability, so much more critical it will be to take cognisance of projected changes in seasonal rainfall and its variability. This is especially important for the core winter rainfall period when dams are filled for the next growing season, and for the growing season when there are implications for irrigation needs. Importantly, the changes in variability of rainfall will not be consistent throughout the year.

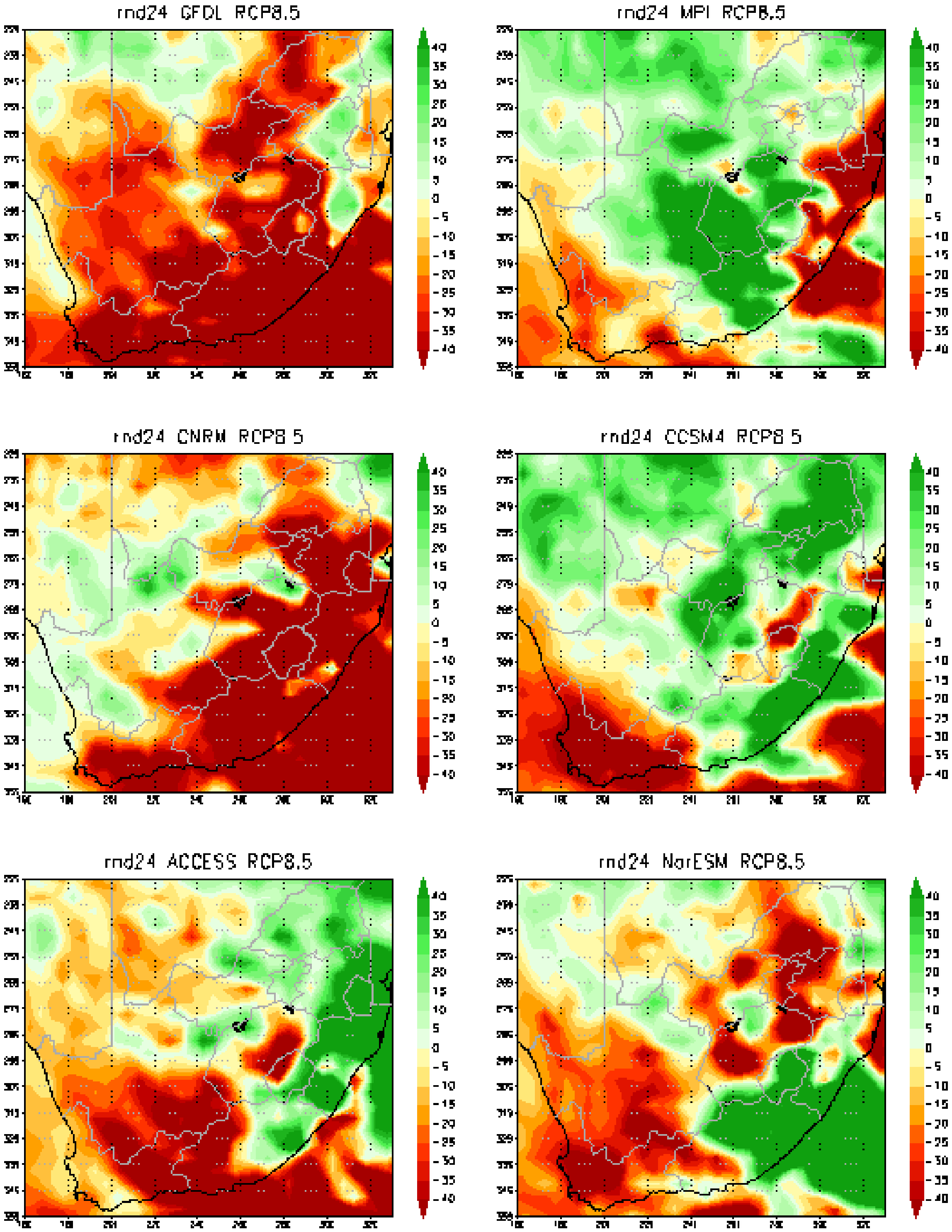

Figure 52. Dynamically-downscaled projected changes in annual total rainfall under the RCP8.5 pathway for the 2016-2035 period. (Source: DEA, 2018)

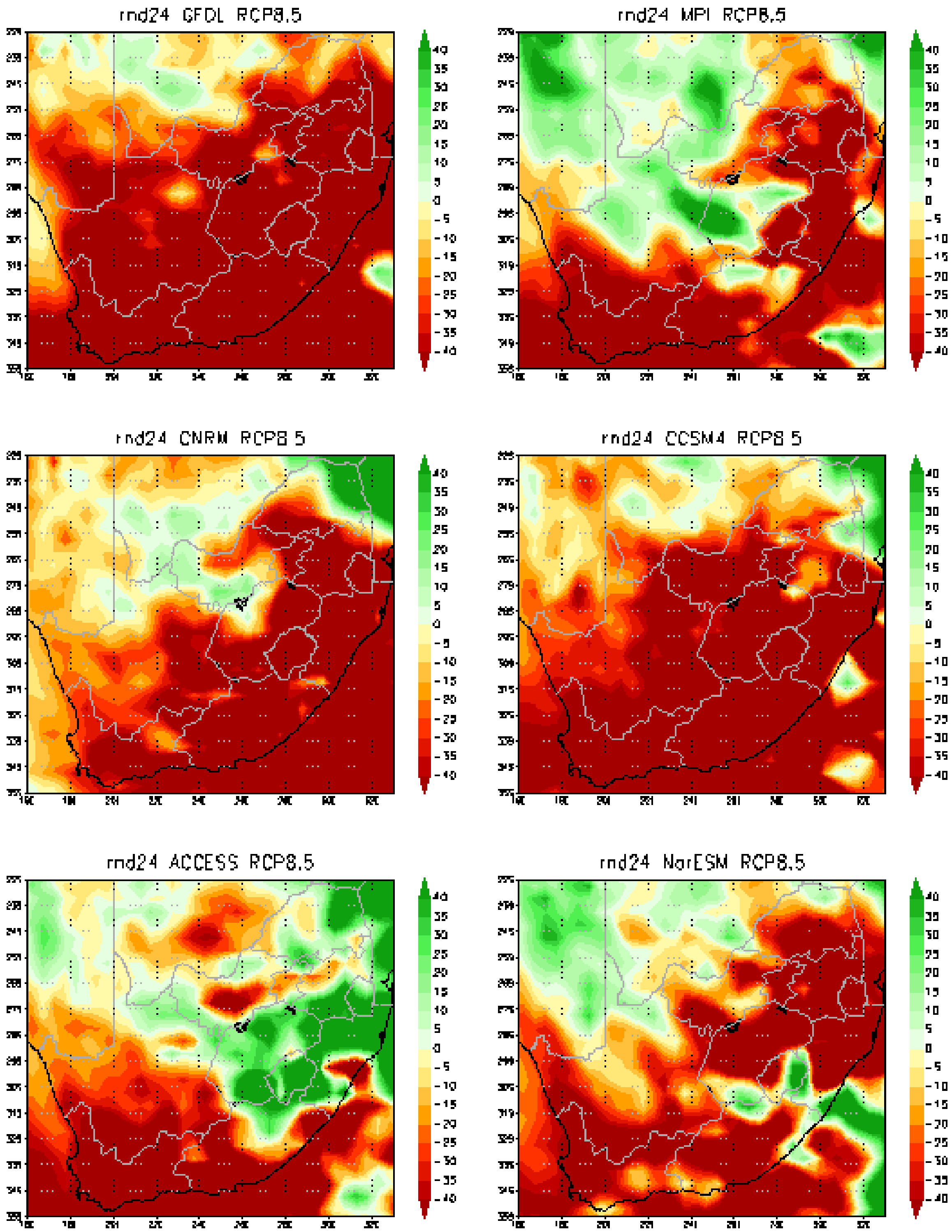

Figure 53. Dynamically-downscaled projected changes in annual total rainfall under the RCP8.5 pathway for the 2046-2065 period. (Source: DEA, 2018)

A.3 Dry spells and projected changes

A.3.1 Background

Dry spells are a creeping, slow onset natural hazard, which can manifest themselves through a lack of rainfall, a lack of available soil moisture for crops, a reduction of streamflows below a critical threshold, a reduction in the amount of water stored in reservoirs, or reduced levels of groundwater (Schulze, 2003; Schmidt-Thomé, 2006). However, unlike aridity, which is a permanent feature of the climate in low rainfall areas, dry spells are a temporary aberration that can occur in low as well as high rainfall areas.

Owing to the projected increases in temperature and changes in rainfall amounts and variability in future, it is anticipated that the frequency as well as the duration and magnitude of dry spells will change, either increasing or decreasing, with potentially significant economic, social and environmental implications.

A.3.2 What we understand by dry and wet spells

There are many definitions of dry and of wet spells within a context of agriculture and water resources. For this Guide, three durations of dry spells were considered for each Quinary catchment, *viz*. periods of either 2 consecutive months, or of 3 or 6 consecutive months of below normal rainfall. Normal rainfall for a 2-, or 3-, or 6-month period is defined as the sum of the median monthly rainfalls from a long rainfall record for the duration under consideration and for the Quinary being assessed. While not identical to, this approach of using medians of rainfall for consecutive months as the criterion is in line with approaches taken by others, e.g. UNDP (2004) or Lehner *et al*. (2006).

A.3.3 Determining and mapping dry spells

Since each Quinary has a unique median rainfall for each month of the year, the criteria for identifying a dry spell is unique to that Quinary. For a dry spell of a defined duration (i.e. 2 or 3 or 6 consecutive months) to be identified as ‘dry’ when analysing a monthly sequence of rainfalls over a 30- or 50-year period, its rainfall has to be 10% or more below the median. The number of dry spells of a defined duration (e.g. 3 consecutive months) in the years being assessed (e.g. a 30-year record from GCMs) are summed and then divided by the number of years in order to obtain an average of dry spells per year, which is then mapped. Note that in this evaluation neither the severity nor the seasonality of the dry spells was considered, only the frequency per annum. In this Guide, 2 consecutive months constitutes a mild dry spell, 3 consecutive months a moderate dry spell, and 6 consecutive below normal months a severe dry spell.

To assess the impact of projected climate change on dry spells, dry spell frequencies were first computed for a given duration using the 50-year historical record to obtain a ‘reference’, or baseline. Thereafter dry spell frequencies were computed from multiple CMIP5 GCMs for present climatic conditions (1976-2005) and then for the immediate future (2016-2045). Changes in the means of frequencies of dry spells, be they higher (implying more dry spells in future) or lower (signifying fewer dry spells in future), could then be computed on a Quinary basis, and mapped.

A.3.4. Results

To illustrate the approach used, Fig. 54 shows the distribution of average numbers of 2-month dry spells per annum under historical climatic conditions (Fig. 54, top left), as well as the averages under multiple GCM-derived present (Fig. 54, top right) and immediate future (Fig. 54, bottom) climates. In this case, a significant increase is evident in the average number of 2-month dry spells per annum from the present climate to that of the immediate future climate.

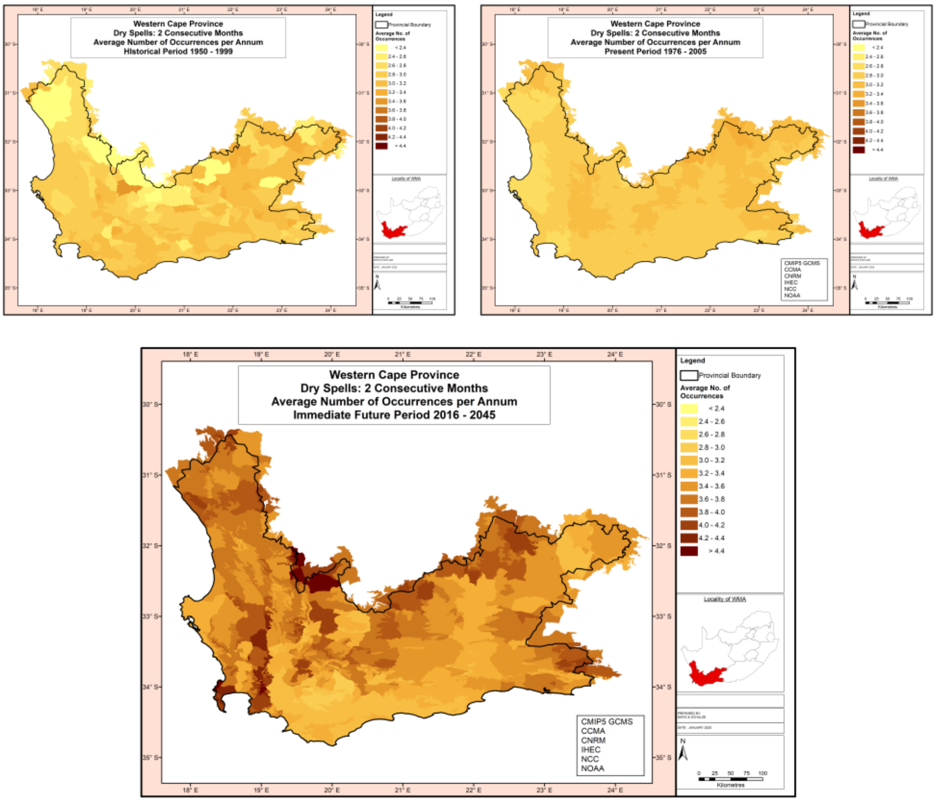

Figure 54. Two consecutive month dry spells under historical climatic conditions (top left), with 2-month dry spells under present (top right) and immediate future (bottom) climatic conditions. The latter two were derived from outputs of multiple CMIP5 GCMs.

Average numbers of 2, 3 and 6 consecutive month dry spells per annum shown in Fig. 55 for historical climatic conditions (left column of maps), along with changes in occurrences per annum of dry spells from the present into the intermediate future (right column). Overall, 2 and 3 consecutive month dry spells are projected to increase into the immediate future, especially in the west and along the northern border which show one or more additional occurrences per annum in some parts. For the 6 consecutive month dry spells the results are much more indeterminate.

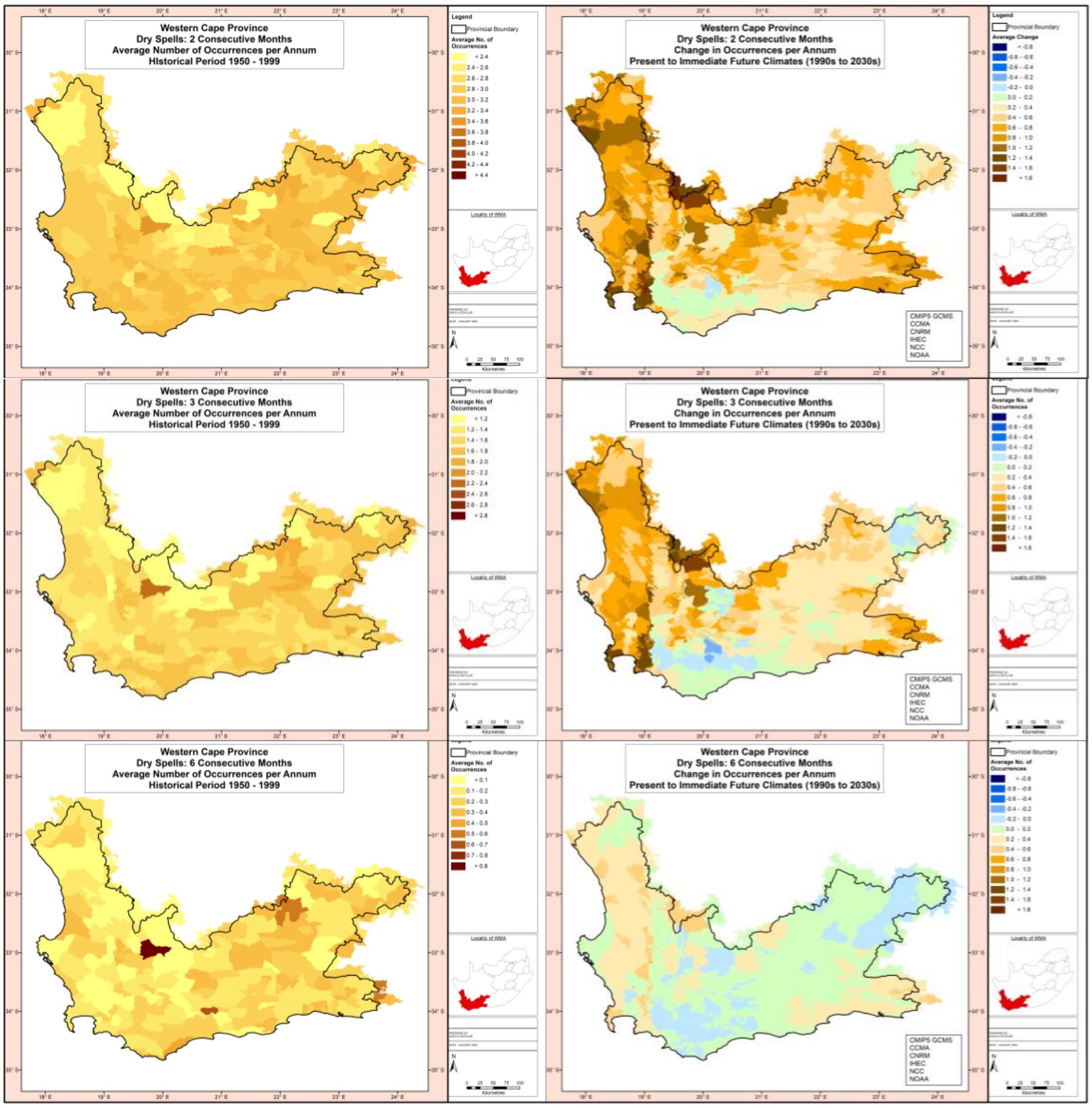

Figure 55. Two, three and six consecutive month dry spells under historical climatic conditions (left column, top to bottom), with corresponding projected changes (in number of occurrences per annum) from present to immediate future climatic conditions (right column, top to bottom). The latter maps were derived from outputs of multiple CMIP5 GCMs.

A.3.5 Implications

Dry spells of short and medium duration are a concern to water resource managers as they imply increases in irrigation water requirements and reductions in runoff. The projections of more dry spells per annum of 2 and 3 consecutive months' duration over the next 10-20 years would thus constitute a further concern to region's irrigators and water resource managers.

A.4 Wet spells and projected changes

A.4.1 Background

Wet spells in this analysis are the inverse of dry spells, with three durations considered for each Quinary Catchment covering the region: either 2, 3 or 6 consecutive months of above normal rainfall. Again, ‘normal’ rainfall for a 2- or 3- or 6-month period was defined as the sum of the median monthly rainfalls from a long rainfall record for the duration under consideration and for the Quinary being assessed. For a wet spell of a defined duration (i.e. 2 or 3 or 6 consecutive months) to be identified as ‘wet’ when analysing a monthly sequence of rainfalls over a 30- or 50-year period of time, its rainfall had to be 10% or more above the median. The number of wet spells of a defined duration (e.g. 3 consecutive months) in the years being assessed (e.g. a 30-year record) were summed and then divided by the number of years in order to obtain probabilities of wet spells per year, which were then mapped.

A.4.2 Results

Then number of wet spells of the three selected durations are shown for historical climatic conditions in the left column of Fig. 56. Of significance to the pome and stone fruit sectors are the projected changes into the immediate future (Fig. 56, right column). Projections point to generally fewer wet spells of 2- and 3-month duration, but the results for changes in 6-month wet spells are essentially inconclusive.

A.4.3 Implications

When considering both dry spells and wet spells, arguably the most significant finding is the ‘double whammy’ effect of simultaneous projections for increases in dry spells of 2 and 3 consecutive month durations and of decreases in wet spells of the same durations. This analysis clearly illustrates that one needs to go well beyond merely assessing impacts of climate change on an annual or even a seasonal basis. This “double whammy”, while not showing *when* the dry or wet spells occur over a year, could signify important impacts such as reduced irrigation water availability in dams.

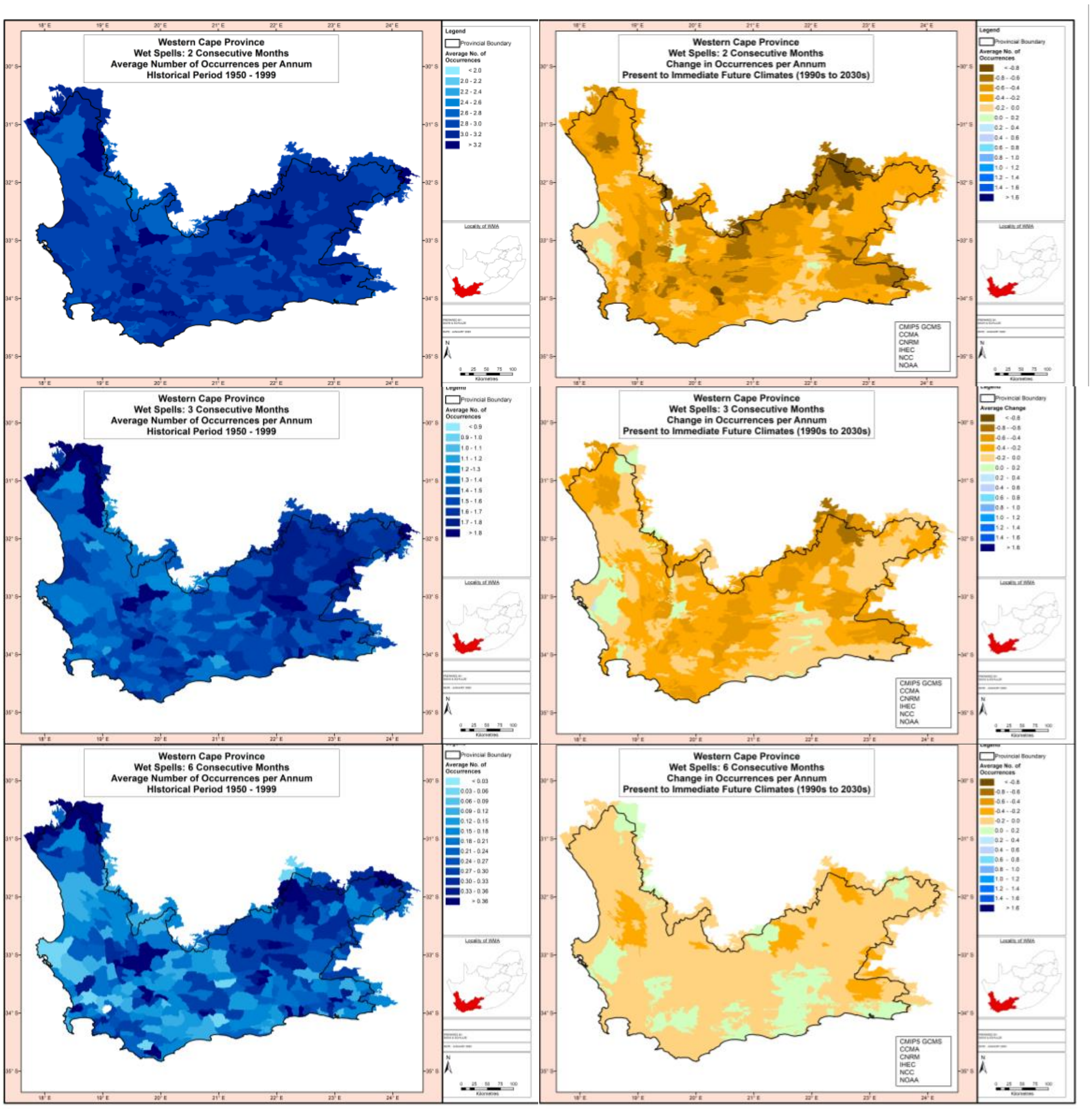

Figure 56. Two, three and six consecutive month wet spells under historical climatic conditions (left column, top to bottom), with corresponding projected changes (in number of occurrences per annum) from present to immediate future (1990s to 2030s) climatic conditions (right column, top to bottom). The latter maps were derived from outputs of multiple CMIP5 GCMs.

A.5 Long duration design ('extreme') rainfall

A.5.1 Background to design hydrological analysis

There are many types of agricultural conservation structures (e.g. contour banks) and hydraulic engineering structures (such as culverts, dam spillways or reticulation structures) which need to be designed to accommodate rainfall produced floods of a certain magnitude in order to function safely at a given level of risk. Should the structures fail, there are potential economic, environmental, and societal consequences. Hence, flood frequency analysis is of great importance. Models of flood attributes such as peak discharges and flood volumes, however, require inputs of so-called 'extreme' rainfall that may be expected to occur only very infrequently, e.g. with recurrence intervals of 2 or 10 or 50 or even 100 years, with recurrence intervals depending on the importance of the structure.

Climate change is expected to 'energize' the earth's atmosphere through increases in temperature and resultant perturbations to rainfall regimes, including changes to rainfall variability. This may lead to increases in the intensity and frequency of extreme rainfall events of both short durations of minutes to hours (not dealt with in this Guide) and longer durations of 1 day or 2 or 3 consecutive days. The latter is often associated with inundation, flooding and even breaching of structures. In the study region, especially in the winter and all year rainfall regions, it is the accumulated consecutive days of rain that tend to do most damage, especially in larger catchments and where slopes are flat. If an increase in such conditions is projected for the future, this might lead to inundation of orchards and have serious repercussions for the design of hydraulic structures which supply farms with supplementary water.

Because reliable estimates of flood magnitudes and frequencies based on long time series of good quality observed streamflow data are seldom available at a location of interest, rainfall-based methods of flood frequency estimations are usually resorted to. This requires a probabilistic approach to analysing rainfall or simulated streamflow for design purposes. The terms 'design rainfall' and 'design streamflow' are then used to describe the

- *depth* (i.e. magnitude, in mm or m^3) of rainfall or streamflow, for a critical
- *duration* (e.g. 1 day or 2 or more consecutive days), which depends on the size of the catchment, for a desired
- *frequency* of recurrence (e.g. statistically once in 2 or 10 or 20 or 50 or even once in 100 years, depending on the size and economic importance of the structure). This is commonly referred to as the 'return period'. A return period of, say, 10 years implies a statistical probability of recurrence once in 10 years or 10 times in 100 years, and not that it will recur regularly every 10 years. An estimate of design rainfall can then be used to generate design flood hydrographs when combined with catchment characteristics such as slope, size, land use and soils. This analysis is commonly termed a 'DDF' analysis.

A.5.2 Methodology for the computation of long duration design rainfall

For this Guide, historical estimates of design rainfalls of long duration were computed using the 50-year daily rainfall datasets (1950-1999) of each of the Western Cape's 1 401 Quinaries in the Quinary Catchments database (Schulze et al., 2010). For the climate change assessment, the daily rainfalls for the present (1976-2005) and the immediate future (2016-2045) scenarios from each of the CMIP5 GCMs were used, downscaled to Quinaries. The annual maximum series (AMS), i.e. the largest value of rainfall from each hydrological year (October – September) on 1, 2 and 3 consecutive days, was used for further statistical analysis. The General Extreme Value (GEV) distribution was applied to determine design rainfalls for selected durations and return periods. In this instance, this was done for the 1:10 and the 1:50 year recurrence intervals, representing (statistically) the rare once-in-a-decade and the exceptional once-in-half-a century rainfall.

A.5.3 Results

Historical 1 in 10 year and 1:50 year return period design rainfall maps for 1, 2 and 3 consecutive day durations are shown in Fig. 57. The first set of general observations is the progressive increase in design rainfall from one to two to three days' duration for a given return period, illustrated by the blue horizontal line for the 10 year return period maps (Fig. 57, top row) and the red horizontal line for the 50 year return period maps (Fig. 57, bottom row). The second general observation is the quite significant increase in design rainfalls from the 1:10 to the 1:50 year return period, shown for the different durations by the green vertical arrows.

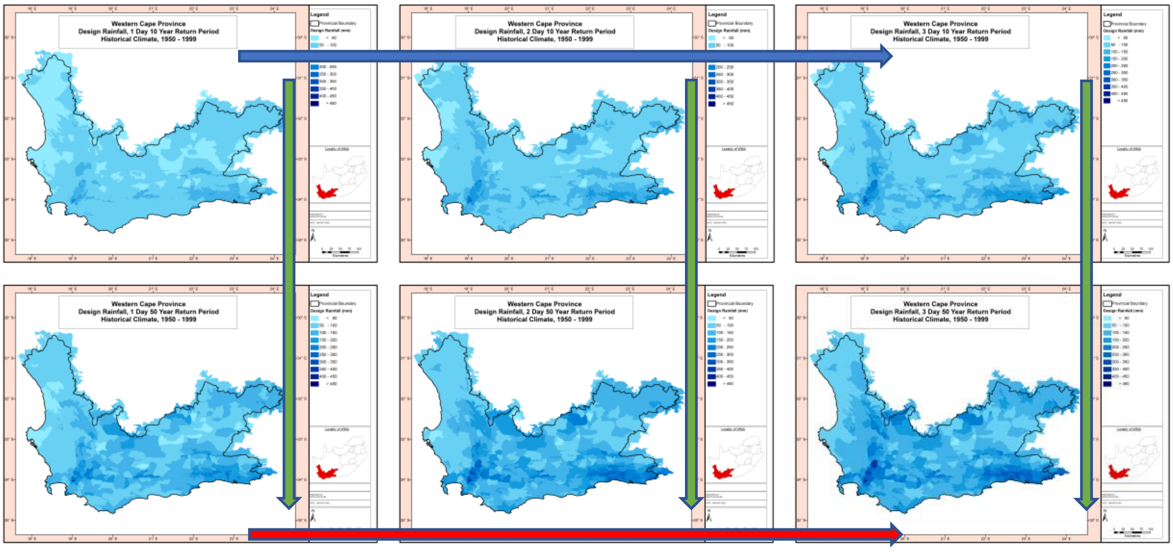

Figure 57. Historical 1 in 10 year return period design rainfall (mm) for a 1 day duration (top left), for 2 consecutive days (top middle) and for 3 consecutive days (top right), with 1:50 year design rainfalls for the same three durations in the bottom row.

For the historical period, the 1:10 year 1 day design rainfalls range from ~ 50-150 mm, with outliers around 200 mm (Fig. 57, top left). For both the 2 and 3 consecutive day 1:10 year rainfalls (Fig. 57, top middle and top right), the ranges remain similar, but progressively the areas covered by the higher 'extreme' events expand. For the 1:50 year extreme events (Fig. 57, bottom row) rainfall magnitudes are considerably higher – testimony to the long duration frontal rainfalls experienced over much of the region, and especially in the mountains, in the all year rainfall area in the south-east, and along the northern border, with multi-day extremes up to 400 and 450 mm.

A.5.4 Assessing the sensitivity of extreme rainfall events over a region

There are two approaches to assessing the sensitivity of extreme rainfall events over a region. The first identifies *where* an exceptionally rare event, in this case the 1:50 year event, is either not much larger in magnitude than a rare event, in this case the 1:10 year rainfall, or where it is much larger. The result has repercussions regarding safety of humans or protection of crops or of infrastructure. Fig. 58 shows that in the south-west of the region, essentially the winter rainfall region characterized by frontal rain, the 1:50 year event produces rainfall only 1.2-1.4 times that of the 1:10 year event, i.e. only 20-40% more. This is the case for both the 1-day event (Fig. 58, left) and for the 3 consecutive day event (Fig. 58, right). On the other hand, in the north-west and the central and eastern parts of the region the 1:50 year event can be up to twice the magnitude of the 1:10 year event.

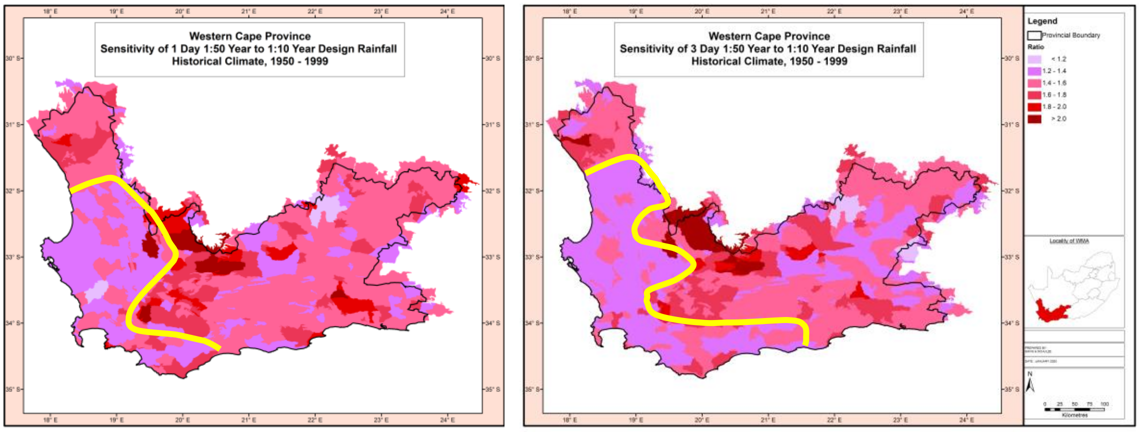

Figure 58. Sensitivity of historically (1950-1999) extremely rare (1:50 year) to rare rainfall events (1:10 year) of 1 days' duration (left) and 3 consecutive days' duration (right).

The second approach to sensitivity studies of extreme rainfall events is to assess by *how much larger* in magnitude (mm) a multi-day event is than a 1-day event. Fig. 59 shows that both 2-day events (top maps) and especially 3-day events (bottom maps) are very much larger than a 1-day event in the west, where multi-day frontal rains dominate in the winter, and in the south, an all year rainfall region. In the case of 3-day events these are up to 1.8 times, i.e. up to 80%, larger in the south and west. Noticeable is, furthermore, that for the 1:10 year extremes (Fig. 59, left top and bottom), the multi-day to 1-day magnitudes are spatially much more homogeneous than the 1:50 year events (Fig. 59, right top and bottom), which are spatially patchier. This is because in the 50-year record of analysis, a specific area may, or may not, have experienced one relatively localised outlier event.

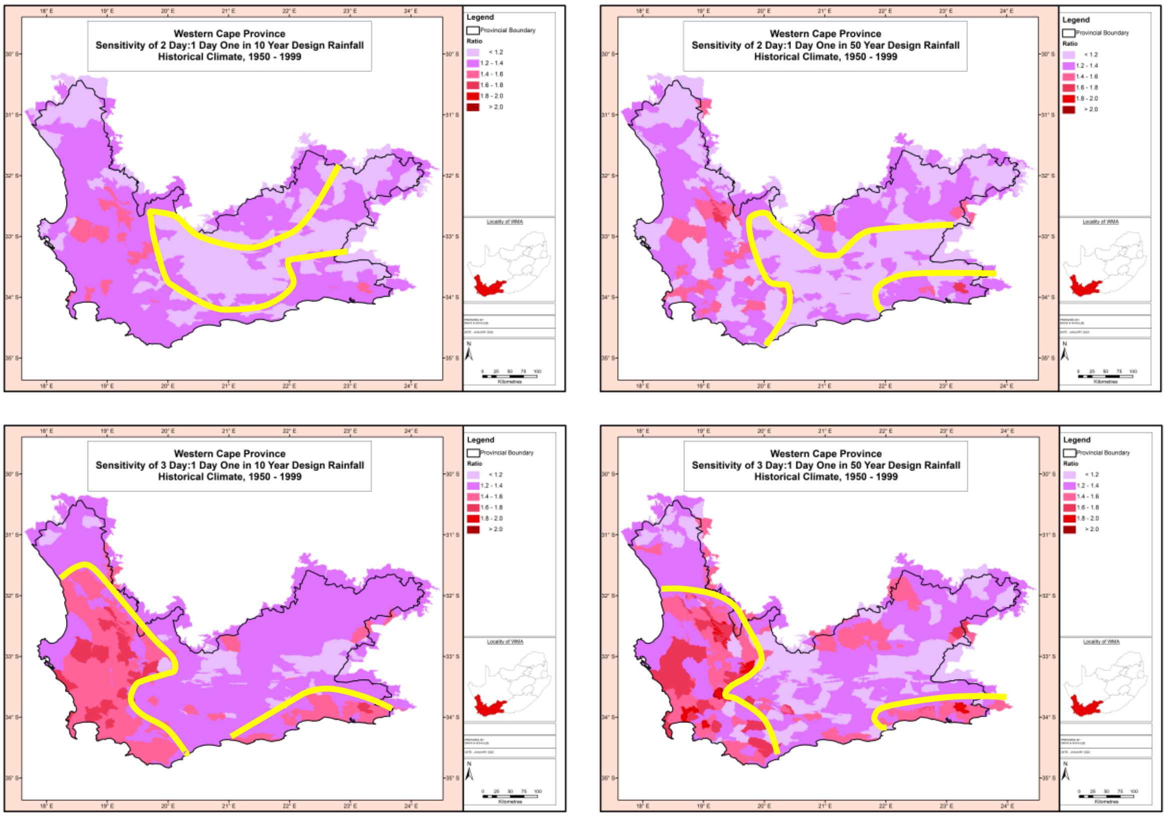

Figure 59. Sensitivity of 2-day to 1-day design rainfalls (top maps) and of 3-day to 1-day design rainfalls (bottom maps) for rare events (1:10 year; left column) and extremely rare events (1:50 year; right column).

A.5.5 Implications

The following are important to bear in mind when interpreting results from design rainfall in agricultural planning:

- Spatially within the region, some areas have considerably higher magnitudes of 'extreme' rainfall events of a given return period than others.
- Given different rainfall producing mechanisms within the region, some areas have considerably higher multi-day than one-day extreme rainfalls than others.
- Some areas are more sensitive than others in that an exceptionally rare 1:50 year rainfall event for a given duration is much higher than a rare 1:10 year rainfall event.
- Some areas are more sensitive than others in that, for a given return period rainfall, a multi-day design rainfall is much larger than a single day event.
- Note again that the magnitude of rainfall for a specific return period (e.g. 1 in 10 years) is a calculated statistic that does NOT recur regularly at that specified recurrence interval (e.g. every 10 years), but may occur more frequently in nature (say, in successive years or even twice in a single year), but then not again for many decades.

APPENDIX B: SOIL AND WATER BUDGETS AND IMPACTS OF CLIMATE CHANGE ON RUNOFF AND STREAMFLOW

Before a soil water budget and hydrological water budget can be presented for the region, spatial characteristics of soils need to be assessed.

B.1 Soils

B.1.1 Soil attributes of importance

Marked spatial differences in agricultural productivity occur within a region because of different soil properties. The vertical sequence of soil properties regulates water entry into, storage and retention in, and redistribution within and out of the soil profile.

The following considerations are important in the context of this Guide:

- Respective thicknesses of various soil horizons.
- Surface properties (e.g. crusting, sealing, cracking, tillage) which affect its infiltrability.
- The sequence of soil horizons in regard, for example, to the distributions of clay, sand and silt percentages within the soil profile. These to drainage characteristics of the soil, or impeding layers within the soil profile, either natural or man-made, which may cause drainage/waterlogging problems.
- The water holding capability of the soil, which finds expression, *inter alia,* through the
    - soil profile’s depth, its
    - texture (sand, silt, clay make-up) and its
    - soil water content at specified/critical soil water conditions, *viz*. at its
    - permanent wilting point, i.e. the soil water content constituting the lower limit of soil water available to the plant, at its
    - drained upper limit, previously termed ‘field capacity’, being the soil water content held by capillary forces that are great enough to resist gravity after natural percolation from the soil has ceased, and when the soil water content is at
    - total porosity, i.e. at saturation when all pore spaces are filled with water
- The plant available water of the soil, as an integrator of many of the above attributes.
- Overall runoff potential of the soil.

B.1.2 Maps of relevant soil attributes

A selection of these agro-hydrologically important soils attributes was mapped for the region in Fig. 60 and Fig. 61 at a spatial resolution of terrain units which are made up of crests, scarps, mid-slopes, foot-slopes and valley bottoms.

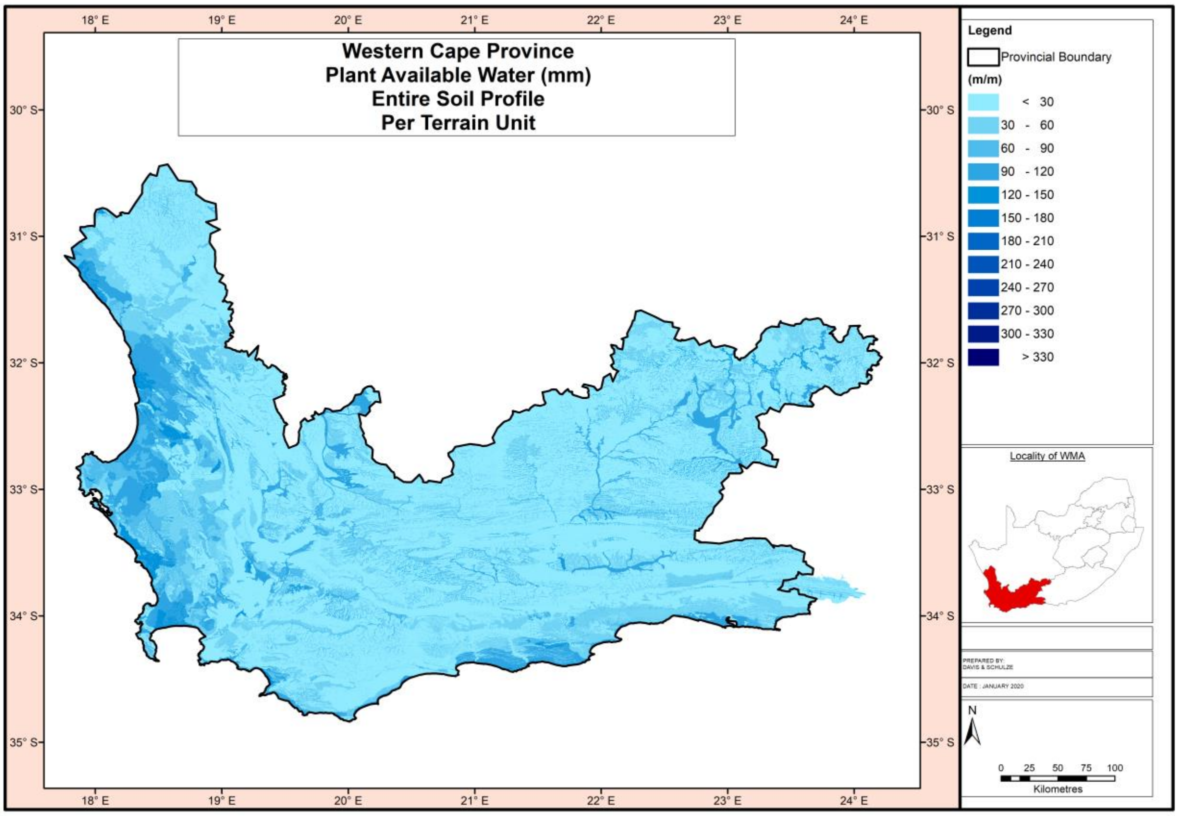

Figure 60. Plant available water (mm) across the region as an integrator of soil properties (from Schulze and Schütte, 2018).

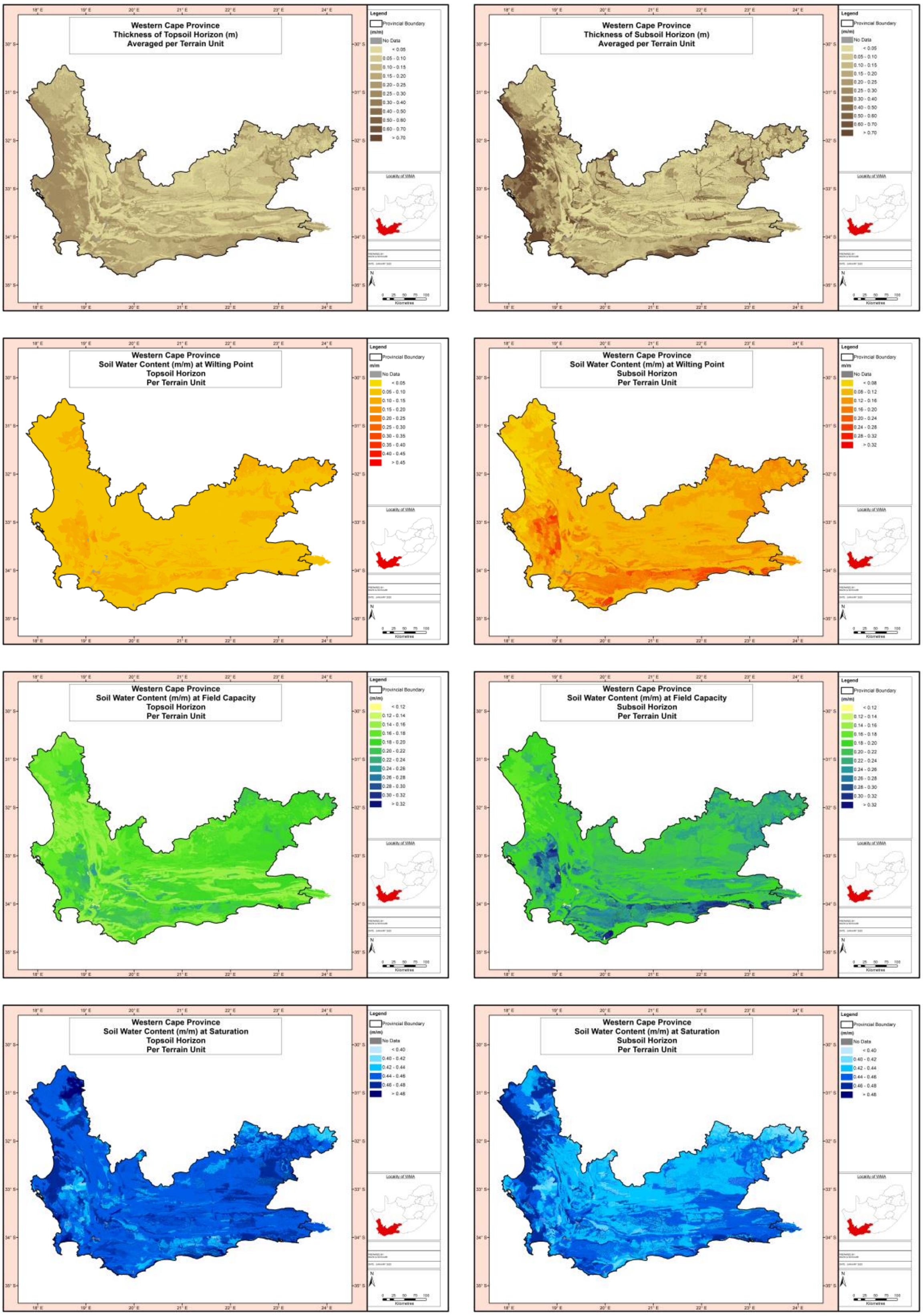

Figure 61. Key agricultural soil characteristics, from top to bottom: thickness (m), soil water content (m/m) at the permanent wilting point, soil water content at field capacities (i.e. drained upper limits), and soil water content at saturation. The left column shows results for the topsoil horizon, whereas the right column shows results for the subsoil horizon (from Schulze and Schütte, 2018).

B.2 The water budget under natural conditions and its components

In its simplest form the water budget at a given location or catchment area, under natural conditions, may be expressed in terms of the disposition of precipitation as

$P_r = [Q + E + \Delta S] + Q_u$

where, on any given day

P_r = precipitation (mm)

Q = runoff (mm) from that specific catchment area, the generation of which depends largely on the magnitude of the rainfall; and with Q made up of

Q_s = stormflow, generated on or near the surface, and dependent on the magnitude of the rainfall, the initial abstractions which depend on the rainfall intensity and on soil properties such as texture, and the soil's wetness just prior to the rainfall which is producing the stormflow, and

Q_b = baseflow, which is generated from a groundwater store that is fed by deep percolation when the subsoil's soil water content is above the soil's saturation level and this excess water percolates into the groundwater store from where it is then released slowly back into the stream depending, *inter alia*, on the magnitude of the groundwater store

Q_u = runoff from catchments upstream of the catchment in question, with the sum of Q and Q_u being termed accumulated streamflow

E = actual evaporation, driven by

E_r = the atmospheric demand, or reference potential evaporation, on a given day (often expressed by an A-pan equivalent evaporation as a function of the day's solar radiation and temperature, enhanced by wind and moderated by the humidity of the overlying atmosphere), and made up of

E_t = plant transpiration, with transpired water drawn from both the topsoil and the subsoil horizon, and

E_s = soil water evaporation, a loss from the topsoil only, and dependent on the wetness of the topsoil and the degree of protection from evaporation afforded by surface cover

With E_t modulated by

K_c = a water use coefficient representing the fraction of the reference potential evaporation that is transpired by the plant when not under soil water stress, with

E_t modulated further by soil water content, the levels of which determine transpiration losses by the soil's being either too wet, at an optimum wetness or too dry

ΔS = the change in soil water status at the end of a day, dependent on the soil's texture, its thickness and horizon attributes as well as on the balance of previous gains through rainfall infiltration and losses by evaporative processes.

The precipitation (Appendix A.2) and reference potential evaporation (section 4.4) components of the water budget have already been discussed. What follow are sections on runoff and accumulated streamflows under natural conditions for the region.

B.3 Runoff and projected changes

B.3.1 Background

Runoff in the context of this document consists of stormflow plus baseflow from a specific catchment, where stormflow is generated from rain falling on the soil/vegetation surface with the stormflow magnitude (amount) depending on the amount of rain on a given day, how much is intercepted by the vegetation cover and how moist the topsoil is from previous rainfalls, while the baseflow depends on soil drainage characteristics into the groundwater zone and the groundwater store of baseflow, with water from this store released slowly into the stream, maximally at 0.009 of the store.

B.3.2 Modelling runoff

Daily runoff was simulated with the *ACRU* model under historical climatic conditions (1950-1999) as well as assuming present (mid-1990s) and projected immediate future (mid-2030s) climatic conditions. The latter two climate scenarios were derived from daily climate inputs into the *ACRU* model from 6 bias-corrected CMIP5 GCMs used in a current (as yet unpublished) WRC Project at the Centre for Water Resources Research at the University of KwaZulu-Natal.

B.3.3 Results

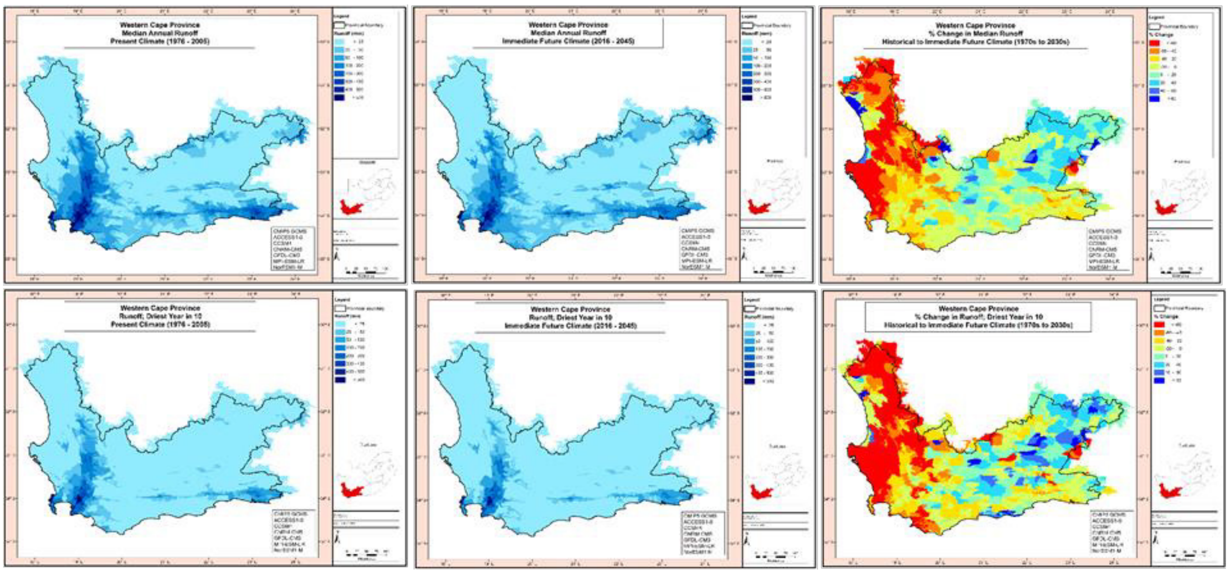

Figure 62. ACRU model derived median annual runoff (mm) under present climatic conditions (top left) and projected climates from 6 bias corrected CMIP5 GCMs of the immediate future (top middle), expressed as mm, and as percentage changes from the historical to the immediate future climates (top right), with the same sequence of maps but for the lowest flows in 10 years in the bottom row.

The median annual and 1:10 low flow year runoff maps (Fig. 62, top and bottom left) reflect the high runoffs in the fold mountain areas of the south-west and south and the marked decrease in runoff in dry years. At the scale of these maps there is little difference in runoff to the naked eye into the immediate future (Fig. 62, middle maps), but there are significant decreases in runoff of over 40% in the west when changes into the future are expressed as percentages, and corresponding increases of up to 30% in parts of the east (Fig. 62, top and bottom right).

B.3.4 Implications

Runoff, as simulated here, is a local phenomenon in that it considers only the responses at individual Quinary catchments level, with no contributions from upstream Quinaries. It is, therefore, the local water available for irrigation of orchards. In that regard it is especially the decreases in available irrigation water in the west that will be a concern to irrigators there, implying on the one hand the necessity for more efficient irrigation application techniques to be used, and on the other the likely necessity for farm dams to require larger (and more expensive) water storage facilities.

B.4 Accumulated streamflows and projected changes

B.4.1 Background

In Appendix B.2 the term ‘accumulated streamflow’ was defined as the runoff (i.e. stormflow plus baseflow) from a specific catchment *plus* the runoff from all catchment areas upstream of the specific catchment in question. The ‘specific catchments’ refer to the Quinaries described in section 3.2.2. From these, the accumulated streamflows were derived and are mapped.

B.4.2 Assumptions made for modelling of streamflows

Daily values of local runoff and hence accumulated streamflows, were computed for all 1 401 Quinary catchments within the Western Cape with the daily time-step and process-based *ACRU* simulation model (Schulze, 1995; 2004 and updates). All computations utilised the 50 years of daily climate plus soils and land cover inputs from the Quinary Catchment Database (Schulze *et al*., 2010). A baseline land cover of natural vegetation was used, represented by Acocks’ (1988) Veld Types, the hydrological attributes of which are described by Schulze (2004), and using soils attributes from Schulze and Horan (2010).

Similarly, for GCM based climate scenarios, streamflows were simulated with the *ACRU* model using daily climate inputs from present (mid-1990s) and projected immediate future (mid-2030s) climatic conditions derived from 6 bias-corrected CMIP5 GCMs used in a current (as yet unpublished) WRC Project at the Centre for Water Resources Research at the University of KwaZulu-Natal.

B.4.3 Results

Shown clearly in Fig. 63 (left), with its non-linear legend, is the very wide range of mean annual streamflows in the region. These range from < 10 mm equivalent to ~ 400 mm under historical climatic conditions, with highest streamflows in the high-altitude mountains (yellow ring) and in the major river systems such as the Olifants in the north-west and the Breede in the south (red rings).

Equally striking is the wide range in the inter-annual variability of streamflows shown as the CV (%) of accumulated annual streamflows in Fig. 63 (right), ranging from < 40% to > 200%. In general, an inverse relationship exists between the magnitude of streamflows and the magnitude of CVs, with low CVs in the high streamflow mountains (yellow ring) and the major river systems (blue rings) and highest variability of flows in the north-west and in the Karoo, where annual streamflows are low. An interesting exception is the southern Cape, where annual streamflows are relatively high but a higher CV is experienced compared to the river systems in the west.

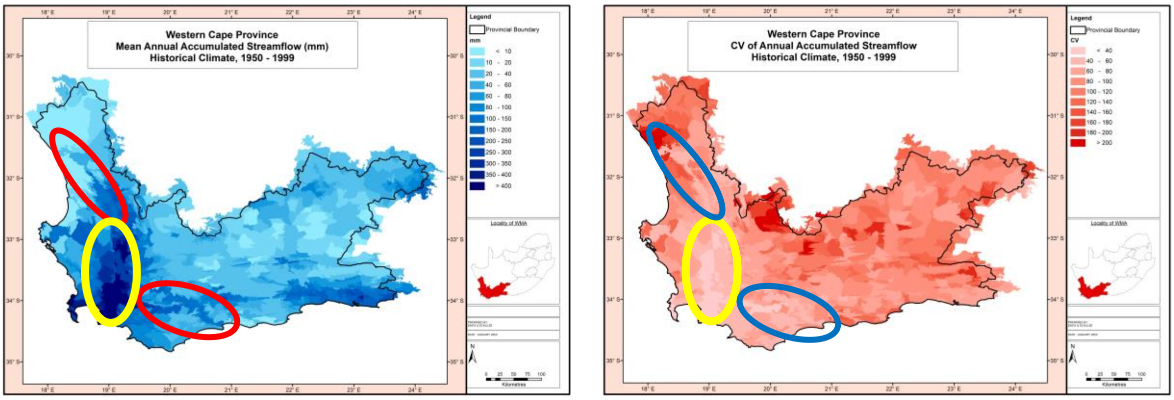

Figure 63. Mean annual accumulated streamflows under historical climatic conditions (left) and the historical inter-annual coefficient of variation (CV) of streamflows (right).

In Fig. 64, *ACRU* model-derived median annual streamflows are shown in mm equivalents under present (1990s) climatic conditions (top left), with projected changes into the immediate future (2030s) of median annual streamflows, expressed volumetrically as mm (Fig. 64, top middle), and then (Fig. 64, top right) as percentage changes. The same sequence of maps, but for the lowest flows in 10 years, are shown in the bottom row of Fig. 64.

Clearly evident under present climatic conditions is that the accumulated flows of the larger river systems such as the Berg and Breede, and to a lesser extent the Olifants exhibit higher absolute (mm equivalent) flows than the adjacent Quinary catchments feeding them.

Largest absolute (mm equivalent) reductions are projected in the western mountain ranges – the "water tower" of the Western Cape (Fig. 64, middle column), with the western two-thirds of the Western Cape displaying slight absolute reductions in streamflows while the east shows slight increases.

In relative (percentage) terms the west is projected to experience streamflow reductions of 50% and more in places, but with the north-east's streamflows projected to increase by up to 30% (Fig. 64, right column). What is clearly evident is that the major river systems of the Western Cape such as the Olifants, Berg and Breede can expect lower percentage changes than the smaller rivers.

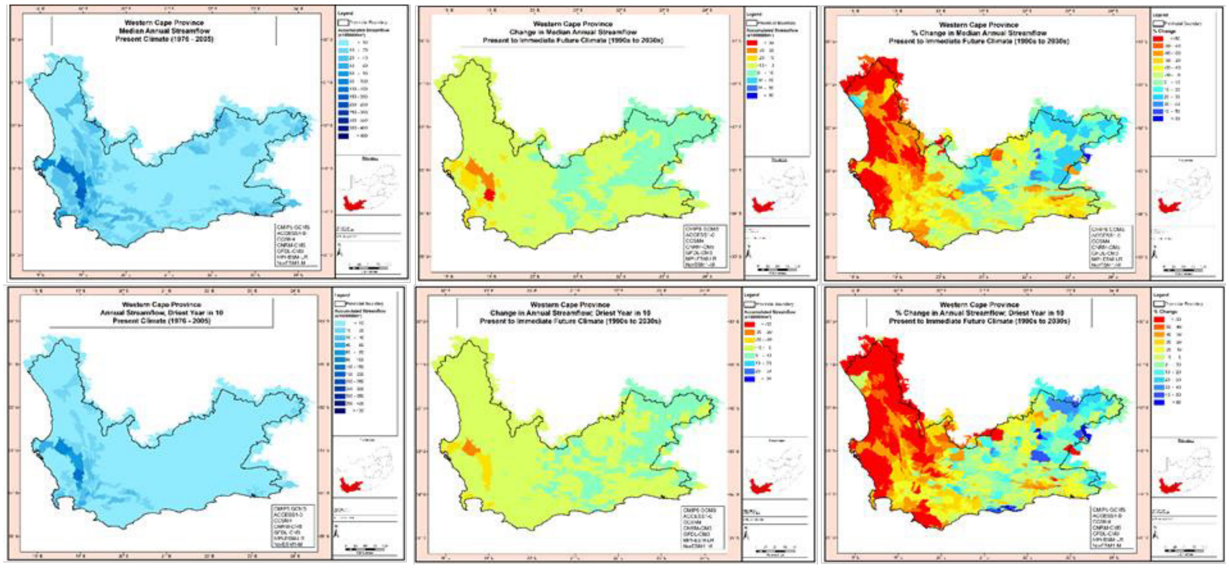

Figure 64. ACRU *model derived median annual streamflows (mm equivalents) under present climatic conditions (top left), with projected changes into the immediate future, based on climates from 6 bias corrected CMIP5 GCMs, of median annual streamflows, expressed as mm (top middle) and as percentage changes (top right), with the same sequence of maps but for the lowest flows in 10 years in the bottom row.*

B.4.4 Implications

In an already water stressed region, any projected reductions in streamflows do not auger well for the pome and stone fruit sectors which are heavily irrigation dependent. In addition to these regions potentially experiencing lower streamflows in future, the higher temperatures and enhanced evaporation rates will imply higher irrigation demands. However, in some catchments, projected increases in streamflows could alleviate future conditions to some extent. Given the relatively small volumetric changes one should, however, be cautious in over-interpreting the significance and impact on agriculture.

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