ANTARCTIC CLIMATE & ECOSYSTEMS CRC

climate futures for tasmania

TECHNICAL REPORT

Impacts on Agriculture

Holz GK, Grose MR, Bennett JC, Corney SP, White CJ, Phelan D, Potter K, Kriticos D, Rawnsley R, Parsons D, Lisson S, Gaynor SM and Bindoff NL

December 2010

Climate Futures for Tasmania
Impacts on Agriculture Technical Report

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Climate Futures for Tasmania: impacts on agriculture

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Foreword

The Climate Futures for Tasmania research project is Tasmania's most important source of climate change data at a local scale. In a first for Australia, and possibly the Southern Hemisphere, Climate Futures for Tasmania has generated local climate information at a scale and level of detail not previously available. It is an essential part of the Tasmanian Government's Framework for Action on Climate Change. Climate Futures for Tasmania is invaluable to informing evidence-based decision making in all sectors of government, industry, business and communities in Tasmania.

This collaborative research project, led by Professor Nathan Bindoff, has demonstrated innovative leadership by involving and engaging external stakeholders on all levels. It is unique in the research environment in that the researchers have invited input and direction from funders and interested end-users from the beginning of the project. The opportunity for the Department of Primary Industries, Parks, Water and Environment (DPIPWE) to be involved from the start has meant that the results and outputs from the science are relevant to the Department and the agricultural community.

The project results and conclusions contained in this technical report will inform our business decisions. We have worked closely with lead author Dr Greg Holz and his colleagues, and are confident of the quality of the new climate change data and research conclusions presented.

The report has passed the rigours of an external scientific review process and I appreciate the efforts of the respected scientists who gave their time and expertise to confirm the research outcomes. Thanks to Professor Holger Meinke, previously of Wageningen UR (University and Research Centre), The Netherlands, and now Director of the Tasmanian Institute of Agricultural Research (TIAR); Dr Peter Hayman (South Australian Research and Development Institute [SARDI] Climate Applications Unit); and Dr Barry White (Brisbane based consultant).

In acknowledging the research contributors, it is also important to highlight the valuable input of the department's research, development and extension provider, the Tasmanian Institute of Agriculture Research. TIAR has guided the scientific research and allowed the project to access existing networks, which was central to the success of the collaborative nature of the research.

The project has become one of the high profile climate change projects under the auspices of the Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC). Thanks to Dr Tony Press and his staff for hosting and driving the project management activities to deliver on time and budget.

Kim Evans, Secretary

DPIPWE

Executive Summary

Climate Futures for Tasmania has produced some of the most advanced fine-scaled climate projections available for the agricultural regions of Tasmania.

We have used the Conformal Cubic Atmospheric Model (CCAM) to dynamically downscale six global climate models - five of the 23 global climate models (GCM) used in the IPCC fourth assessment report plus the CSIRO-Mk3.5 global climate model. The downscaling increased the spatial resolution from 2-degree to 3-degree grids in the GCMs to a 0.1-degree grid (approximately 10 km) for Tasmania. Two emissions scenarios - A2, a high-greenhouse gas emissions scenario, and B1, a lower greenhouse emissions scenario - were used in the projections. Each simulation of the future climate includes key agricultural climate variables at daily time intervals for the period 1961 to 2100.

Climate Futures for Tasmania has used a bias-adjustment technique to allow fine-scaled climate projections to be used directly in biophysical models and to calculate agricultural climate indices.

A feature of this project is the use of quantile-quantile bias-adjusted modelling outputs. The bias-adjustment process in this project allows the climate variables from the models to be used directly to calculate agricultural indices and in biophysical models. The process preserves changes in the frequency distributions of climate events that have resulted from changes in the synoptic drivers of the Tasmanian weather. The method captures the benefits of dynamical downscaling and these climate datasets are a useful legacy of the project.

Temperatures across Tasmania are projected to increase by around 2.9 °C by the end of the century under the high emissions scenario and 1.6 °C under the low emissions scenario.

Due to a combination of the latitude and rainfall patterns in Tasmania, temperature has historically been a major driver for the choice and management of crops. Small changes in average temperature can have large impacts on agricultural production.

Frost incidence is projected to reduce by around half by the end of century under the A2 emissions scenario.

The incidence of frost is projected to substantially reduce by the end of the century with many sites likely to experience less than half the current number of frosts. The period of frost risk is projected to shorten from March-December to May-October for many areas in Tasmania but there may still be damaging late winter and spring frosts, especially since bud burst is likely to occur earlier.

The incidence of drought is projected to be similar to historical experience in most of the agricultural regions except for a slight increase in the north-west and a slight decrease in the east and south-east.

Rainfall projections for the agricultural regions indicate little change in mean annual rainfall but with some changes in seasonality - in particular, reductions in summer rainfall in the far north-west and increases in autumn and summer rainfall in the east of Tasmania. Indices of meteorological and agricultural drought indicate the episodic and regional nature of drought events will continue. There is considerable inter-model variability indicating uncertainty, but general trends suggest a reduction in the proportion of time subject to meteorological drought in the south-east, north-east and south-west of Tasmania and an increase in the central to north-west regions.

Chill hours are projected to decrease at sites below 400 m to 500 m and increase at higher elevation sites.

Chill hours are projected to decrease in the lower-elevation warmer regions and increase at higher elevations. There is likely to be limited impact on the majority of crops that require vernalisation, though current varieties of blackcurrants may be forced to higher-elevation sites or sites with colder mesoclimates later this century. Yields and quality of high-chill fruit varieties, such as for some cherries, may be adversely affected in lower-elevation, warmer coastal areas.

Increases in heat available to grow crops will have profound effects, including changes in crop types, reduced crop duration (that is, time to flowering and to reach maturity), changes to crop yields and crop quality and changes to pest incidence and severity.

Projected increases in Growing Degree Days (GDD) are likely to lead to changes in crop types and varieties. A crop requiring 1000 (10 °C base) GDD will by 2030 mature approximately one month earlier than the baseline period of 1961-1990 and two months earlier by the end of the century. Wine varieties such as cabernet sauvignon will ripen reliably by the middle of the century in current grape-growing regions. By 2085, varieties such as pinot noir will be harvested around mid-February, more than two months earlier than the baseline period of 1961-1990. These changes are likely to have significant implications for wine quality and suitable vineyard locations.

Yields of dryland temperate pastures are projected to increase throughout the century, especially at those sites currently most temperature-limited.

Dryland pasture production from ryegrass and other C3 species is projected to increase by 10% to 100% (depending on region) by 2085. Those areas of Tasmania that are currently temperature-limited will have the greatest increases, mainly through an earlier start to spring and higher growth during spring and early summer. Substantial increases in annual yield of phalaris-subclover pastures are projected for the Midlands to the middle of the century but thereafter to decline in response to hot summer days. The contribution from subclover is projected to increase by about 50% throughout the century as this winter-growing species benefits from increased winter temperatures.

Yields of irrigated pasture are projected to increase until around 2040 and thereafter decrease due to high temperatures during the summer months.

Irrigated ryegrass yields are projected to increase by around 20-30% by 2040 but thereafter to decline to current levels due to increases in the number of hot days during summer months. Farmers may have to consider alternatives to meet summer feed demands as increasingly higher temperatures reduce ryegrass (and other C3 species) yields.

Pasture simulations indicate that the demand for irrigation water from pastures (and most probably other crops) is likely to remain unchanged throughout the century, despite substantial increases in yields.

Simulations of irrigated C4 pastures (that will not be growth-limited by the projected high temperatures) suggest that increased water use efficiency resulting from elevated CO_2 will offset increased water demand due to higher yields.

Simulations of wheat cropping suggest there is potential for 10%-15% increases in yields given adequate levels of inputs such as fertiliser and irrigation.

Wheat yields from crops simulated with irrigation and adequate nutrients are projected to increase near Bothwell and Tunbridge. Wheat yields from dryland wheat crops simulated with a fertiliser regime comparable to that currently practised by farmers are projected to decrease, mainly due to nitrogen stress.

Increased temperature is likely to lead to new agricultural opportunities, particularly in regions currently primarily temperature-limited.

Land use is likely to change in response to a changing climate. Increasing temperatures on currently temperature-limited land (in particular, high-elevation areas) will allow for more choices that are likely to lead to changes to land uses.

Substantial changes can be expected to the survival, behaviour and interactions among pests in Tasmania, with increased threats to biosecurity.

The spectrum of significant vertebrate and invertebrate pests, weeds and pathogens is likely to change. For example, the Tasmanian climate is currently unsuitable for Queensland fruit fly. However, if introduced, future populations could potentially establish on the Bass Strait islands and in the north and north-east of Tasmania by the end of the century.

FREQUENTLY USED ABBREVIATIONS

Agricultural Production Systems Simulator	APSIM
Average Recurrence Interval	ARI
Australian Water Availability Project	AWAP
Biologically Equivalent Growing Degree Days	BEGDD
Climate and Species Distribution Model	CLIMEX
Conformal Cubic Atmospheric Model	CCAM
Pasture Growth Simulation Model	DairyMod
Dry Matter	DM
Ecoclimatic Index	EI
Global Climate Model	GCM
Growing Degree Days	GDD
Growth Limiting Factor	GLF
Growth Limiting Factor – Temperature	GLFtemperature
Growth Limiting Factor – Water	GLFwater
Intergovernmental Panel on Climate Change	IPCC
Population Degree Days	PDD
Queensland Fruit Fly	QFly
Soil Moisture Deciles-based Drought Index	SMDDI
Soil Water Deficit	SWD
Special Report on Emissions Scenarios	SRES
Standardised Precipitation Index	SPI

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1 Introduction

A changing climate will have a profound impact on current systems of agricultural production at global and regional scales (IPCC 2007; Parry et al 2007). Agricultural production is a function of the interaction of a genome (crop, livestock) with land resources (landscape, soils), climate and management. Agriculturalists can make choices about land resources (location), about the genome selected for production (crop type, cultivar) and about management (timing, inputs) but weather (climate) is an independent input to agricultural production. Managers cannot control rainfall, heat waves or high winds but use infrastructure and management to moderate the impact of weather as it affects their enterprises on daily, seasonal, annual and decadal timeframes. Thus, agricultural production is particularly sensitive to climate variability and to changes in the baseline climate.

Agriculture is an important component of Tasmania's economy, with the gross value of agricultural production at the farm gate (crops and livestock) contributing $984 million in 2006-2007 (ABS 2010a) and that equals 5% of gross state product, the largest proportion of gross state production of any Australian state (ABS 2010b). The total food revenue to Tasmania (including seafood) at that time was $3,109 million (DPIPWE 2010a), which is 3.2 times the farm-gate value. The total contribution of agriculture to the Tasmanian economy is estimated to be around 16% of the gross state product (TFGA 2010). Dairy is the largest agricultural contributor, accounting for 29% of the gross value of production in 2007-2008 (Figure 1.1), followed by livestock (27%) and vegetables (21%). Changes to agricultural production are therefore significant to the Tasmanian economy.

Understanding the negative and positive impacts of a changing climate on agriculture and the merits and costs of adaptation strategies will enable policy makers to take advantage of opportunities, and to plan for and offset transformations to existing industries and farming systems.

Many generations of farmers have dealt with climate variability and as a result, a culture of resilience and adaptation has developed providing farmers with the tools they can use to accommodate climate change. A basic assumption in dealing with climate variability has been that the weather will fluctuate around a baseline or long-term average over short to medium time frames. Managing and adapting to climate change differs from managing climate variability due to uncertainty about changes in the baseline, changes that may be difficult to differentiate from background variability.

Many aspects of agricultural management are based on long-term history of climate and an understanding of the interaction of the farming system with climate in each region and on each farm. Experience over many years has taught farmers the best time to plant to avoid frost and the best time to calve or shear their sheep. These rules that reflect deeply held understandings, passed down through generations, are likely to be less effective with climate change. Much hard-fought-for knowledge will need to be re-evaluated and new decision-making tools incorporated into farm management. Natural resource management, an integral component of agricultural production, will face similar issues as understanding of the functions and processes of natural ecosystems can potentially be compromised by a changing climate.

Unless early and proactive adaptation measures are taken, the projected changes to Australia's climate are expected to reduce the quantity and quality of agricultural produce and the reliability of supply and detrimentally impact the natural resource base on which agriculture depends (Hennessy et al 2007). However, there are scale-related uncertainties where general or average changes projected for the globe, for a continent or for a latitude, do not necessarily reflect changes to a region, community or farm.

We have used the Conformal Cubic Atmospheric Model (CCAM) to dynamically downscale five of the 23 global climate models (GCMs) reported in the IPCC fourth assessment report and a sixth GCM, CSIRO-Mk3.5. The downscaling increased the spatial resolution from 2-degree to 3-degree grid cells in the GCMs to a 0.5-degree grid for Australia and to an 8 km to 14 km conformal cubic grid for the Tasmanian region. This model grid was then interpolated onto a 0.1 degree (approximately 10 km) latitude/longitude grid. Two SRES emissions scenarios - A2, a high-greenhouse gas emissions scenario, and B1, a lower emissions scenario (Nakicenovic & Swart 2000) - were used in the projections. The models used were CSIRO-Mk3.5, UKMO-HadCM3, ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1 and MIROC3.2(medres). These GCMs were chosen mainly on objective metrics of their skill in simulating the climate over south-east Australia (Corney et al 2010). Each model's outputs include approximately 140 climate variables at six-hourly and daily time steps for the period 1961 to 2100. More details of the modelling methods are described in Corney et al (2010).

About the project

Climate Futures for Tasmania is the Tasmanian Government's most important source of climate change data at a local scale. It is a key part of Tasmania's climate change strategy as stated in the Tasmanian Framework for Action on Climate Change and is supported by the Commonwealth Environment Research Facilities as a significant project.

The project used a group of global climate models to simulate the Tasmanian climate. The project is unique in Australia: it was designed from conception to understand and integrate the impacts of climate change on Tasmania's weather, water catchments, agriculture and climate extremes, including aspects of sea level, floods and wind damage. In addition, through complementary research projects supported by the project, new assessments were made of the impacts of climate change on coastal erosion, biosecurity and energy production, and the development of tools to deliver climate change information to infrastructure asset managers and local government.

As a consequence of this wide scope, Climate Futures for Tasmania is an interdisciplinary and multi-institutional collaboration of twelve core participating partners (both state and national organisations). The project was driven by the information requirements of end users and local communities.

The Climate Futures for Tasmania project complements climate analysis and projections done at the continental scale for the *Fourth Assessment Report* from the *Intergovernmental Panel on Climate Change*, at the national scale in the *Climate Change in Australia Report* and data tool, as well as work done in the south-east Australia region in the *South Eastern Australia Climate Initiative*. The work also complements projections done specifically on water availability and irrigation in Tasmania by the *Tasmania Sustainable Yields Project*.

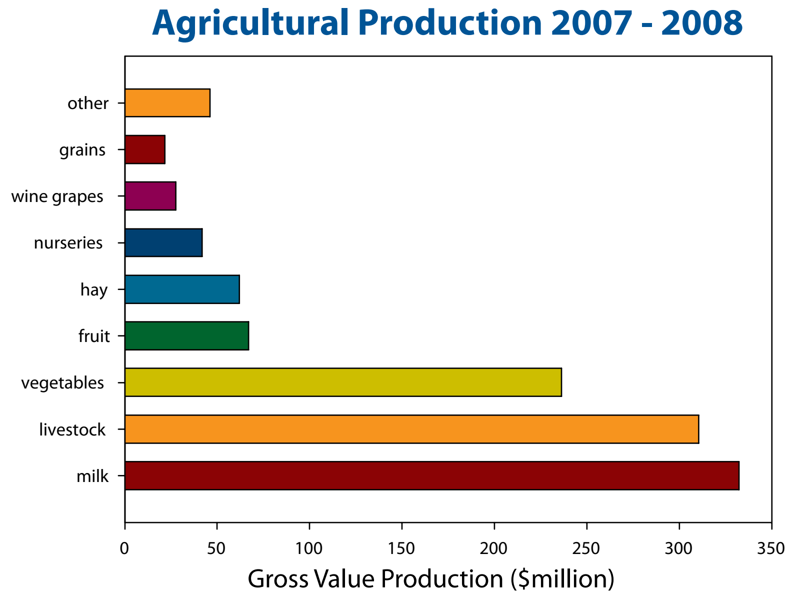


Figure 1.1 Gross value of agricultural production in Tasmania 2007-2008. Source: Australian Bureau Statistics 2010a

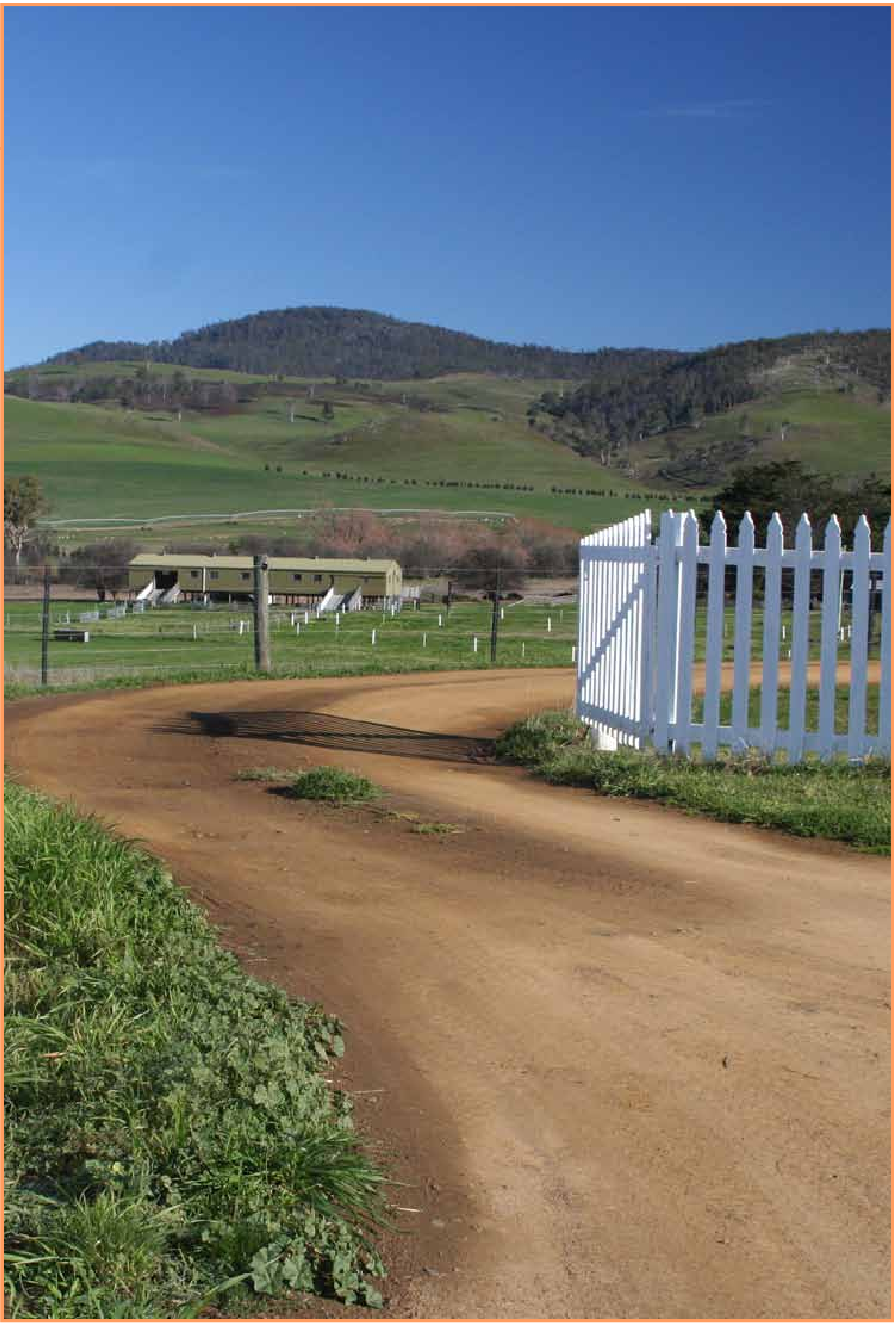
Most of the impacts on agriculture in this report were based on projections from the A2 emissions scenario, presented as trends from the 1961-1990 baseline to 2071-2100. Agriculture indices and biophysical model outputs were not calculated for B1 projections. However, the trends and regional patterns of change for the B1 emissions scenario were very similar to those of the A2 scenario for all variables but with a lesser amount of change (see Grose et al 2010)

Dynamical downscaling allows synoptic weather systems to be expressed at finer scales than those in GCMs. Changes in those synoptic systems interact with the Tasmanian topography and this process provides for more geographically precise projections than those from GCMs. Dynamical downscaling creates the information to explore regional and sub-regional differences. It is in this context that this project has investigated climate change and its impact on agriculture in Tasmania.

Agriculture is extremely diverse and includes extensive and intensive animal production, dryland and irrigated broadacre and row cropping, and horticultural crops. Sustainable agriculture includes management of natural resources, vertebrate and invertebrate pests, pathogens and weeds. All of these components will be affected by changes in climate and it is clearly beyond the resources available for this report to comprehensively address all of the issues. Topics discussed in this report are only some of those relevant to Tasmania but they provide insights into the potential impact of climate change.

Carbon dioxide fertilisation is not specifically addressed but the impact of elevated concentrations of carbon dioxide have been incorporated in the crop and pasture model projections. The impact of high carbon dioxide concentrations may be variable and species-specific (Williams et al 2007). In general, they are expected to result in increases in the efficiency of use of solar radiation and water and thereby increase plant growth rates, benefit C3 plants more than C4 plants, favour legumes over grasses, increase the carbon to nitrogen ratio (C:N ratio), and reduce protein content and feed quality (Stokes & Howden 2010).

This report begins with a brief summary of the projections of future climate, climate extremes and hydrology from the dynamically downscaled GCMs described comprehensively by Corney et al (2010), Grose et al (2010), White et al (2010) and Bennett et al (2010). This is followed by a discussion about some agriculturally significant climate indices such as growing degree days, chill hours, drought and frost incidence. Biophysical models such as DairyMod (Johnson et al 2008) and APSIM (Keating et al 2003) were used to evaluate the impact of a changing climate on pastures and crops. The impacts on land use and land use change are addressed by evaluating potential responses to climate change along altitudinal gradients such as on the north-west coast of Tasmania. Finally, the potential for Queensland fruit fly infestations using the CLIMEX model has been used as an example of an impact on biosecurity. Issues not addressed in this report include the impact on agriculture from changes in climate extremes and changes in runoff and river flows, the direct impact of extremes on livestock and impacts on forestry.



2 Projections from downscaled climate models

2.1 Bias-adjustment and features of climate model variables

Climate indices and biophysical and hydrological models are essential tools needed to quantify the impacts of a changing climate on agriculture and to evaluate adaptation strategies. Climate indices include simple thresholds of crop requirements, such as ranges of mean annual temperature or rainfall, and more complex calculations, such as growing degree days and chill hours. Biophysical models include those that simulate crop or pasture growth, or the distribution and dynamics of pests. Hydrological models are used to estimate water yields from catchments. Long-term meteorological records are generally only available for a few variables. Biophysical models are therefore usually developed to use data that is commonly available. Many require only daily minimum and maximum temperature and rainfall, while others can utilise potential evapotranspiration, solar radiation and relative humidity. Most models require daily data and some, monthly averages. An exception is the index for chill hours that requires hourly temperatures.

Climate indices and biophysical models are calibrated and parameterised using climate observations and are often sensitive to relatively small changes in the scale of these variables. For example, temperature response curves (eg, for a crop species) that describe the relationship between temperature and growth rate are typically strongly non-linear and have steep slopes in sections of the response curve (small changes in temperature may have substantial effects on growth). There are often critical thresholds above or below which growth is dramatically reduced or increased (Figure 2.1).

Climate models, the tools used for projecting future changes in climate, have variable skill and inherent biases (Corney et al 2010). The result of these biases is that climate modelling outputs should not be used directly as inputs to a biophysical model to assess the growth potential of a crop at a certain location. To overcome these biases this study has used a process of bias-adjustment to scale the climate modelling outputs to the same scale as observations (over the period for which there are observations) and this adjustment process enables climate modelling projections to be used directly in biophysical (and hydrological) models. The bias-adjustment process assumes that the biases in the climate models during the training period (1961-2007) are constant throughout the length of the model run (1961-2100).

The raw climate modelling outputs were bias-adjusted using a quantile-quantile method (Bennett et al 2010; Boe et al 2007; Corney et al 2010; Deque 2007; Wood et al 2004). The bias-adjusted projections of daily minimum and maximum temperature, rainfall, solar radiation and potential evaporation are available for each model and each emissions scenario (A2 and B1) for the period 1961-2100. They provide a valuable resource for any climate change research in Tasmania using biophysical models and requiring climate projections. These projections are available at www.tpac.org.au.

Optimal use of these projections requires some understanding of the features of the climate model output and of observed data. Firstly, some comments about observed data. There are three commonly used sources of historical, continuous, daily climate data:

1. SILO Patched Point Data - observations at climate stations with missing observations interpolated (Jeffrey et al 2001)
2. SILO DataDrill - 0.05-degree gridded dataset with all values interpolated (Jeffrey et al 2001)
3. Australian Water Availability Project (AWAP) - 0.05-degree gridded dataset of interpolated values (Jones et al 2009)

The SILO products (www.longpaddock.qld.gov.au/silo/) are currently the most easily accessible and commonly used in agricultural models, with the more recent Bureau of Meteorology and CSIRO-developed AWAP data becoming more widely known. The three observational daily datasets are not fully consistent with one another because of scale (point scale and grids) and interpolation methods. Therefore, there may be differences in outputs from a biophysical model depending on which of these three observed climate data were used.

Climate datasets used to evaluate the impact of climate change scenarios are most commonly generated by perturbing historical data with anomalies calculated from global climate models (GCMs), such as in the OZClim database www.csiro.au/ozclim. This anomaly (perturbation or delta) method (Boe et al 2007) guarantees the baseline is the same scale as observations. However, the frequency distribution of the projected period is the same as the baseline period and does not take into account changes, for example, to the number of rain days. Climate projections are generated by adjusting the baseline observations by the anomaly

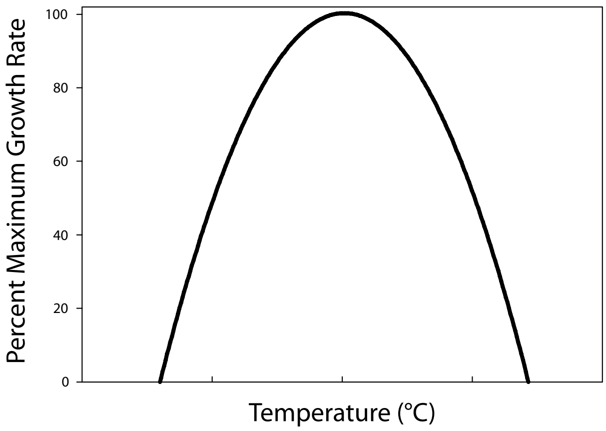


Figure 2.1 Typical shape of a temperature response curve used in biophysical models for plants.

(projection = baseline + anomaly). Variables such as temperature are adjusted additively and rainfall is adjusted proportionately. The anomaly may be calculated monthly, seasonally or annually, for each cell or for the state as a whole.

Changes in climate at any particular location will be due to changes in synoptic meteorology and local climate processes. Changes in the seasonality, frequency and intensity of synoptic patterns such as high and low pressure systems and frontal systems will change the frequency distributions of climate variables such as rainfall, temperature, evaporation, wind and solar radiation in annual, seasonal and daily time frames. In this project, analysis of large-scale climate drivers from the downscaled-GCM modelling outputs found substantial changes for Tasmania, changes that were consistent and plausible within each model (Grose et al 2010). An objective of the research was to maintain the frequency distributions present in the climate models and adjust the scale of each variable to the same absolute scale it has in observations in the training period. Therefore, the outputs from the biophysical models and indices include the impacts of the changes in the projected frequency distributions.

The quantile-quantile bias adjustment of the climate modelling outputs was made with AWAP 0.05-degree daily data (Jones et al 2009; Raupach et al 2008) interpolated to a 0.1-degree grid covering Tasmania. Only variables in the AWAP data could be used to bias-adjust the downscaled-GCM modelling outputs. These variables included daily rainfall, minimum and maximum temperature, potential evaporation and solar radiation. A climate described with these five bias-adjusted variables satisfies the requirements of nearly all biophysical models commonly used in agriculture.

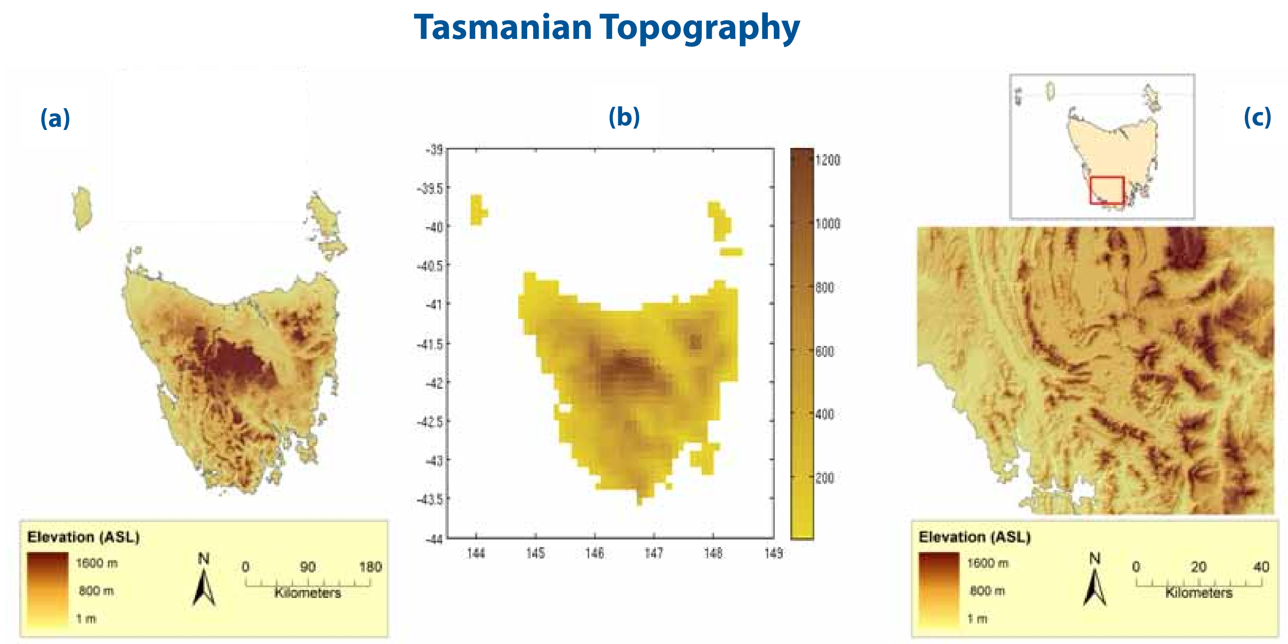


Figure 2.2 Topography of Tasmania used in the dynamical downscaling. Middle panel (b) is the elevation (m) from the downscaled simulations on 0.1-degree grid. Left panel (a) is the elevation from the 250 m digital elevation map and the right panel (c) shows detail of the elevation in the southwest of Tasmania from the 250 m digital elevation map.

The process of downscaling using the Conformal Cubic Atmospheric Model (CCAM) allows for dynamic interaction of synoptic weather patterns with the topography of Tasmania. However, due to the resolution of the climate model, the topography is necessarily coarse when compared to the often jagged topography of Tasmania (Figure 2.2a). The topography in the model (for example, the elevation of each grid cell, Figure 2.2b) is calculated from the mean elevation and standard deviation of the elevation of the area within each cell. A 250 m digital elevation model (DEM) is used in order to better represent the topographical roughness and the way weather systems deliver rainfall across the state. In Tasmania, there are often sharp altitudinal gradients within each of the 0.1-degree (approximately 10 km by 10 km) grid cells (Figure 2.2c). Therefore, there may be substantial altitudinal ranges within each grid cell that are only partially represented in the climate model. This issue of model resolution also means that, for example, the grid cells with the highest elevation are around the central plateau where the land is uniformly high, rather than in the west or southwest. Each grid cell represents the mean climate over the cell. Thus, when a grid cell covers an area containing a strong altitudinal gradient, a specific point of interest (for example, a weather station, farm or experiment) within that cell may not necessarily be well represented by the value of that cell. This averaging within each cell must be taken into account when interpreting climate modelling outputs to represent scales finer than 0.1-degree.

For example, temperatures are strongly related to elevation. Lapse rates for all six downscaled-GCMs (Figure 2.3) were approximately 5.8 °C to 5.9 °C 1000·m^{-1} for daily maximum temperature (Tmax) in the 1961-1990 period and 5.2 °C to 5.8 °C 1000·m^{-1} in 2071-2100. Lapse rates were 6.8 °C to 7.0 °C 1000·m^{-1} for daily minimum temperature (Tmin) in both periods. Thus, spatial patterns of, for example, species distributions based on critical temperature thresholds, should be interpreted carefully since the model's variables will reflect the model elevation of each grid cell.

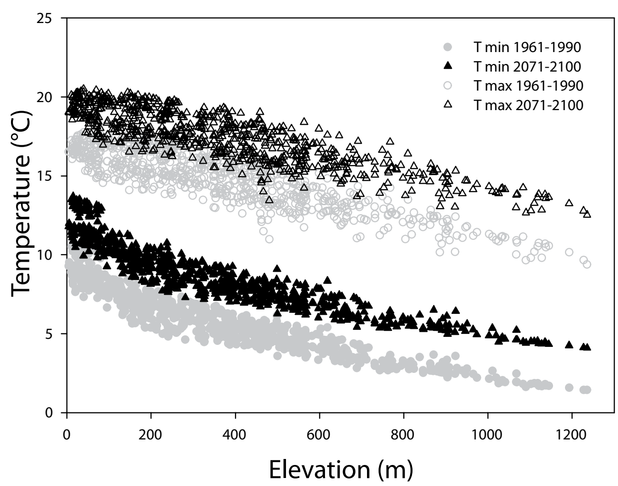


Figure 2.3 Relationship between elevation (of each grid cell) and mean daily maximum and minimum temperatures (Tmax and Tmin) averaged over the six downscaled-GCMs for the periods 1961-1990 and 2071-2100 for the A2 emissions scenario.

Locations

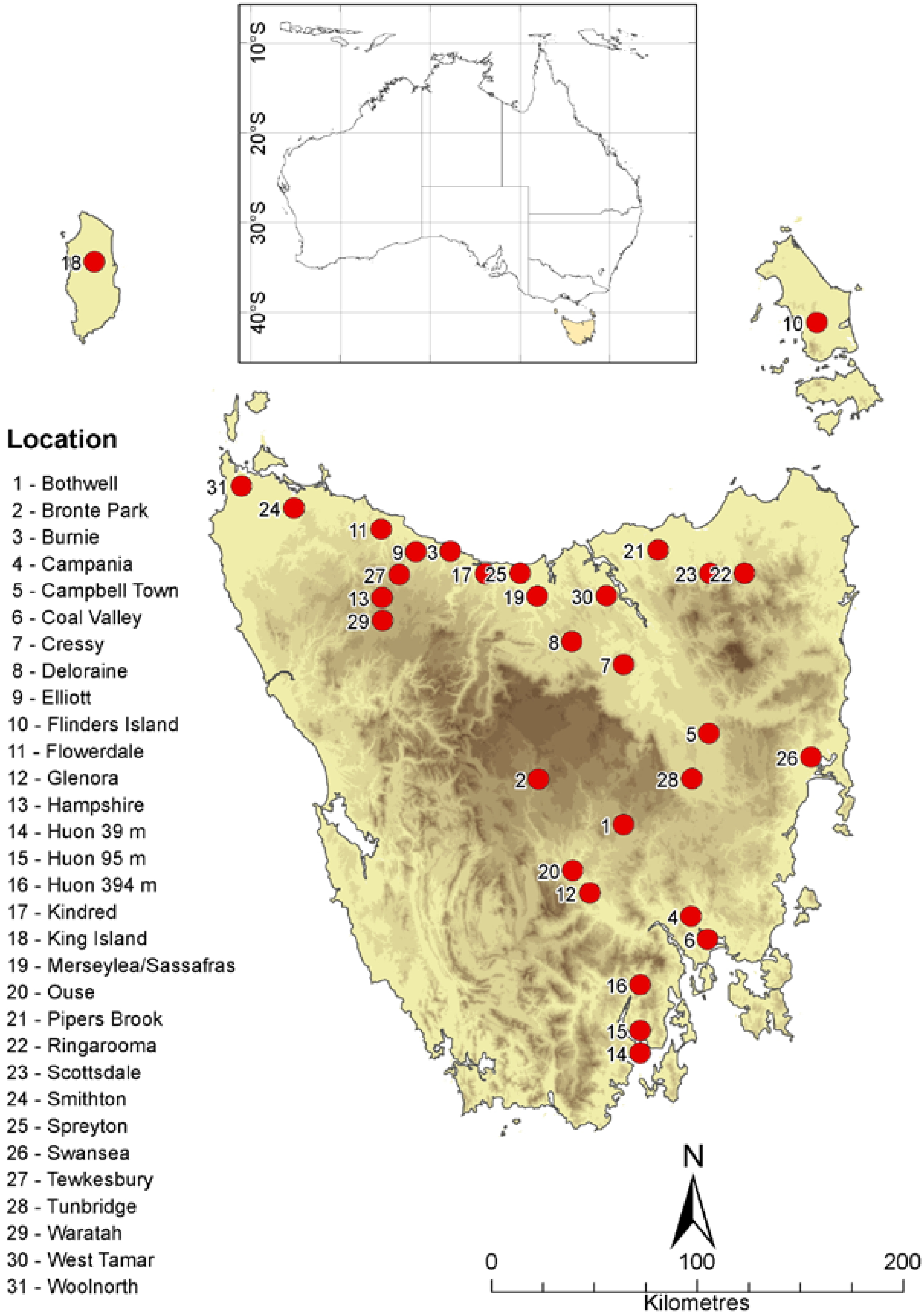


Figure 2.4 Locations referred to in the report.

The downscaled climate modelling produced daily climate variables from 1961 to 2100. Consistent with the IPCC (IPCC 2007) and many previous studies, changes in climate have been reported on in periods of 30 years. Thus the climate of 2030 is described by a variety of statistics calculated from the years 2016-2045 and the 2085 climate from 2071-2100. The 30-year period 1961-1990 used to define the baseline period in many cases is consistent with the baseline period used in the IPCC assessment reports.

In this report, climate data are presented for centres such as Burnie and Campbell Town. These centre names have been used for the convenience of the reader and should be interpreted as the 0.1-degree grid cell that overlies that centre, rather than explicitly describing the climate at that location. The location of each centre is shown in Figure 2.4 and grid cell coordinates and elevation for each of the place names used in the report are given in Appendix 1.

The climate variables that come from each of the downscaled-GCMs form independent realisations of current and future climates. That is, although the bias-adjusted simulations have a similar climate to observations (for example, mean annual rainfall and mean annual temperature) (Corney et al 2010), the timing and magnitude of weather events in each simulation are independent of each other and independent of observations.

In order to use the bias-adjusted simulations in biophysical models, the similarity between the frequency and magnitude of weather events in the models and in an observed dataset was evaluated. These similarities included the relativities between different climate variables within each model. For example, a rainy day would likely have a lower temperature, higher relative humidity, lower potential evaporation and lower solar radiation than a sunny day. The suitability of the bias-adjusted data for use

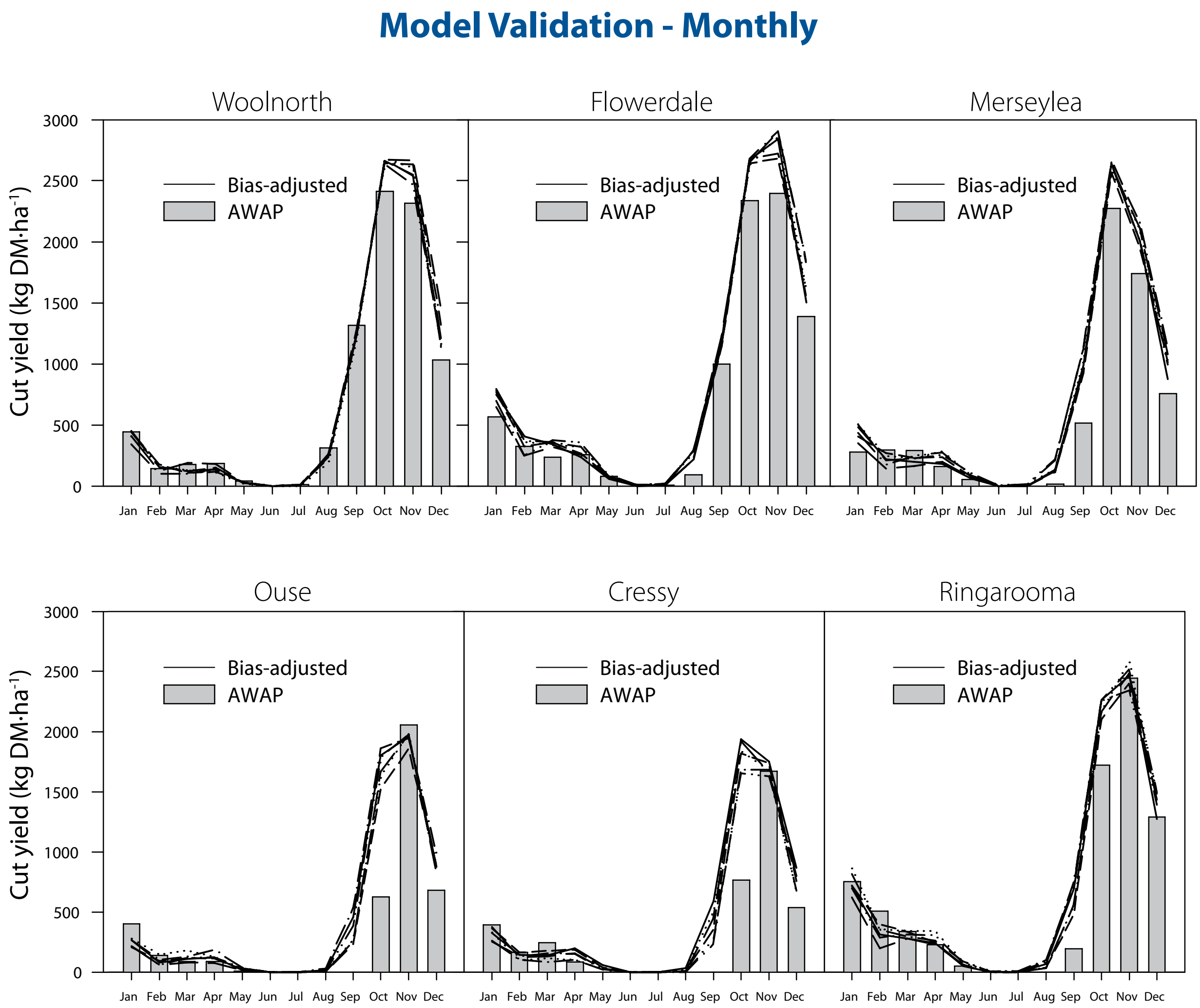


Figure 2.5 Average cut yield (kg DM·ha^{-1}·month^{-1}) of ryegrass at Woolnorth, Flowerdale, Merseylea, Cressy, Ringarooma and Ouse using climate data from AWAP and bias-adjusted model outputs from CSIRO-Mk3.5, GFDL-CM2.0 and GFDL-CM2.1, ECHAM5/MPI-OM, MIROC3.2(medres) and UKMO-HadCM3 for each month, 1991-2007, using the biophysical model DairyMod, A2 emissions scenario. The six downscaled simulations overlay each other and cannot be easily distinguished.

Model Validation - Annual

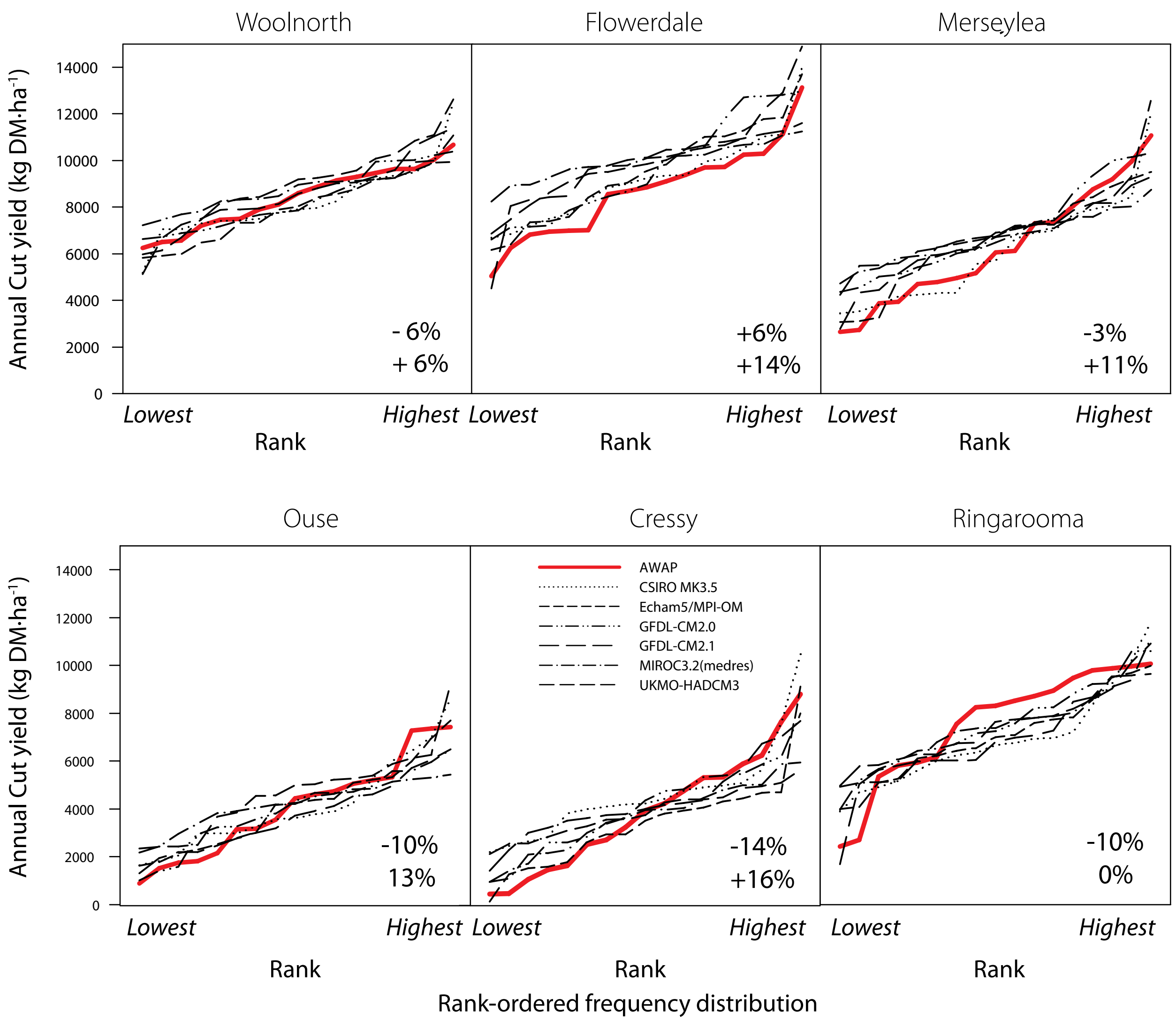


Figure 2.6 Comparison of ranks of cut yield (kg DM·ha^{-1}·year^{-1}) between AWAP data and each of the six bias-adjusted downscaled-GCMs over the period 1991-2007.

in biophysical models (that is, its 'biologicalness'), was tested by comparing simulated pasture yield (as outputs from the biophysical model DairyMod) from downscaled bias-adjusted climate data with that from the 0.1-degree AWAP data. The DairyMod outputs were averaged over the period 1990-2007, the period in the AWAP data with unique daily observations of solar radiation.Simulations of pasture yield using AWAP data and bias-adjusted data from the downscaled GCMs are not directly comparable in time because the GCMs produce weather events that are independent of the observations. It is the climate statistics and outputs from biophysical models that can be expected to be similar, though not identical, over periods of around 20 years. Mean annual pasture yields simulated from the bias-adjusted downscaled-GCMs (Figures 2.5 and 2.6) were a maximum of -14% to +16% of those from the AWAP data. There were some differences in mean monthly values of simulated pasture yields, probably due to the low rainfall experienced in Tasmania over the past 10-15 years reflected in the AWAP data. However, in general, monthly and annual yields (Figure 2.6) were directly comparable between the simulated DairyMod pasture yields using AWAP and the downscaled GCMs. That is, the seasons, frequency, magnitude and relative sizes between the modelled climate variables were interpreted by the biophysical model (DairyMod) in a very similar way to observed climate data, giving confidence that bias-adjusted climate simulations are suitable for projections of agriculture production.

2.2 Climate projections for Tasmania

Comprehensive accounts of the impact of climate change in Tasmania are presented in accompanying reports of this project, including modelling (Corney et al 2010), general climate (Grose et al 2010), extreme events (White et al 2010) and, water and catchments (Bennett et al 2010). Some of the results from those reports that are of particular relevance to agriculture are included here to provide the reader with the contextual framework for climate change impacts on agriculture.

The dynamical downscaling was undertaken for both the A2 and B1 emissions scenarios. Results for the A2 emissions scenario have mostly been used to evaluate the impact of climate change on agriculture in this report because emissions are currently tracking above the A2 emissions scenario and because the B1 projections exhibit the same trend as the A2 projections. Projections for the B1 emissions scenario have been described in Grose et al (2010) and in general exhibit the same trends and spatial patterns as for the A2 emissions scenario but to a lesser magnitude. For example, spatial patterns of projected changes in annual rainfall are similar between the A2 and B1 emissions scenarios (Figure 2.8). Therefore, end-of-century climate variables (and therefore impacts) from the B1 emissions scenario can be interpreted as occurring between those in the baseline period and those from the A2 emissions scenario.

The mean of daily maximum and daily minimum temperatures across Tasmania are projected to rise by 2.9 °C under the A2 emissions scenario and 1.6 °C for the B1 emissions scenario (Figure 2.7). Mean annual temperature projections for selected sites representing some agricultural regions of the state (Table 2.1) indicate changes in these areas of around 2.8 °C, with ranges in mean annual temperature across the downscaled-GCMs of about 0.1 °C for the baseline period, 0.4 °C for 2016-2030 and 0.7 °C to 0.8 °C for 2071-2100.

2.2.1 Rainfall

Rainfall is arguably the most important climate variable for agriculture and is also one of the most difficult variables for climate models to simulate. In brief, mean annual state-wide rainfall is projected to remain constant within decadal variability by 2100. However, there are temporal (seasonal) and regional changes projected to occur progressively over the century. The mean of the projected changes among the six GCMs suggests increases of 20% to 30% in summer and autumn rainfall along the east coast, on the west coast 15% increases in winter and 18% decreases in summer rainfall, and reductions in rainfall on the central plateau in all seasons (Figure 2.8).

There are variable trends among the models. Projections from CSIRO-Mk3.5 exhibit a drying trend over much of Tasmania while in contrast projections from UKMO-HadCM3 exhibit a wetting trend for most areas. These trends tend to be small relative to the mean annual rainfall (Grose et al 2010).

Changes in annual rainfall for many of the major agricultural regions are projected to be relatively modest to the end of the century, with little change or slight increases. Ten-year running means of annual rainfall for selected sites representing agricultural regions of Tasmania (Figure 2.9) demonstrate rainfall trends, decadal and intermodel variability. Annual and seasonal rainfall trends and GCM model ranges are quantified in Table 2.2.

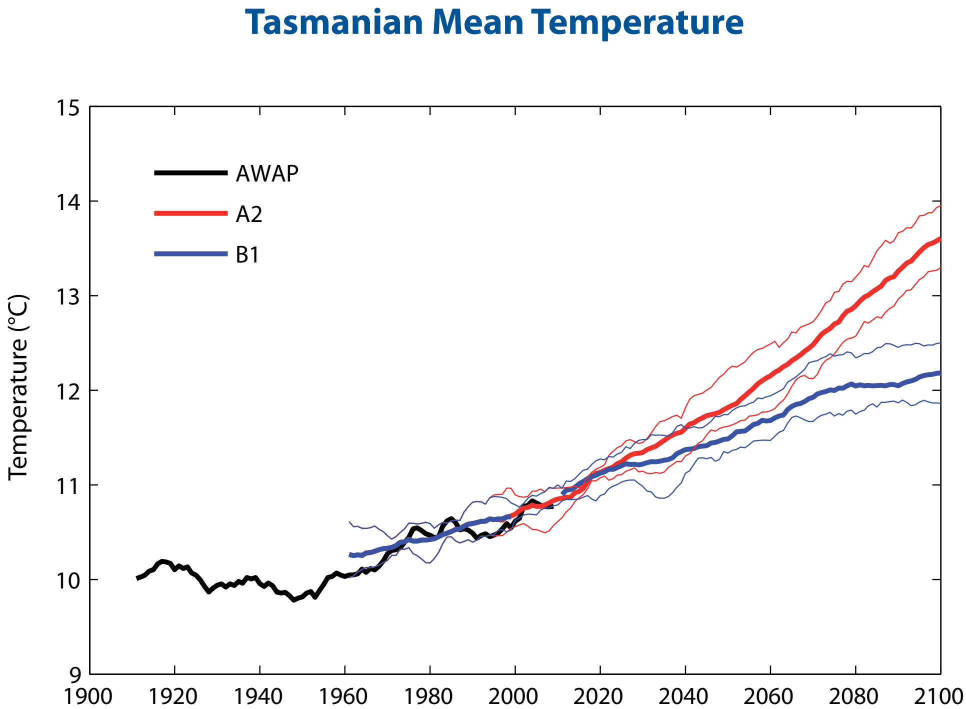


Figure 2.7 Daily mean screen temperature for all grid cells across Tasmania. The time series plots show an 11-year moving average for observations (AWAP) over the period 1910 to 2009 (bold black line) and the mean of six downscaled-GCMs for B1 (bold blue line) and A2 (bold red line) emissions scenarios over the period 1961-2100. The range of the six models shown as respective faint lines, adapted from Grose et al (2010).

Table 2.1 Mean annual temperature of AWAP (1961-1990) and mean annual temperature and range of the six downscaled-GCMs for the periods 1961-1990, 2016-2045 and 2071-2100 for selected sites, A2 emissions scenario.

	AWAP	**Downscaled-GCMs**		
	1961-1990 (°C)	**1961-1990** (°C)	**2016-2045** (°C)	**2071-2100** (°C)
Flowerdale	12.2	12 (11.9 – 12.1)	13 (12.7 – 13.1)	14.7 (14.3 – 15.1)
Deloraine	10.9	10.7 (10.6 – 10.7)	11.7 (11.5 – 11.9)	13.5 (13.2 – 13.9)
Scottsdale	12.2	12 (11.9 – 12.0)	13.0 (12.7 – 13.1)	14.8 (14.5 – 15.2)
Tunbridge	11.3	11.1 (11.0 – 11.1)	12.1 (11.9 – 12.3)	13.9 (13.5 – 14.3)
Bothwell	9.4	9.2 (9.1 – 9.3)	10.2 (10.0 – 10.4)	12.0 (11.7 – 12.4)
Swansea	12.6	12.5 (12.4 – 12.5)	13.4 (13.2 – 13.6)	15.1 (14.8 – 15.6)

Changes to Rainfall

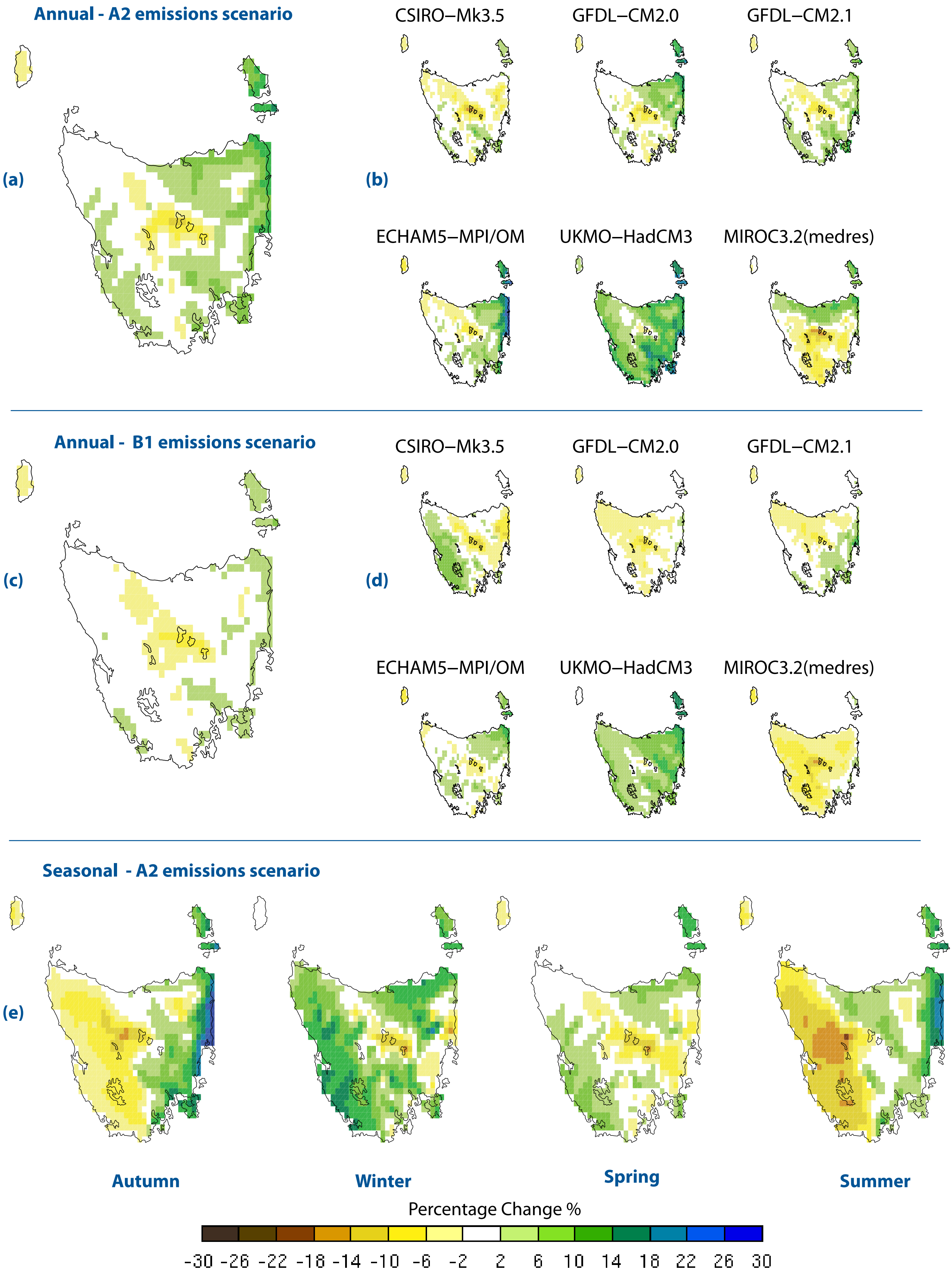


Figure 2.8 Percentage change (%) in annual rainfall 1961-1990 to 2071-2100 mean of six downscaled-GCMs (a) and (c), and each downscaled-GCM (b) and (d), A2 and B1 emissions scenarios respectively. Change in seasonal rainfall 1961-1990 to 2071-2100 (e), mean of six downscaled-GCMs, A2 emissions scenario (adapted from Grose et al 2010).

Changes to Rainfall

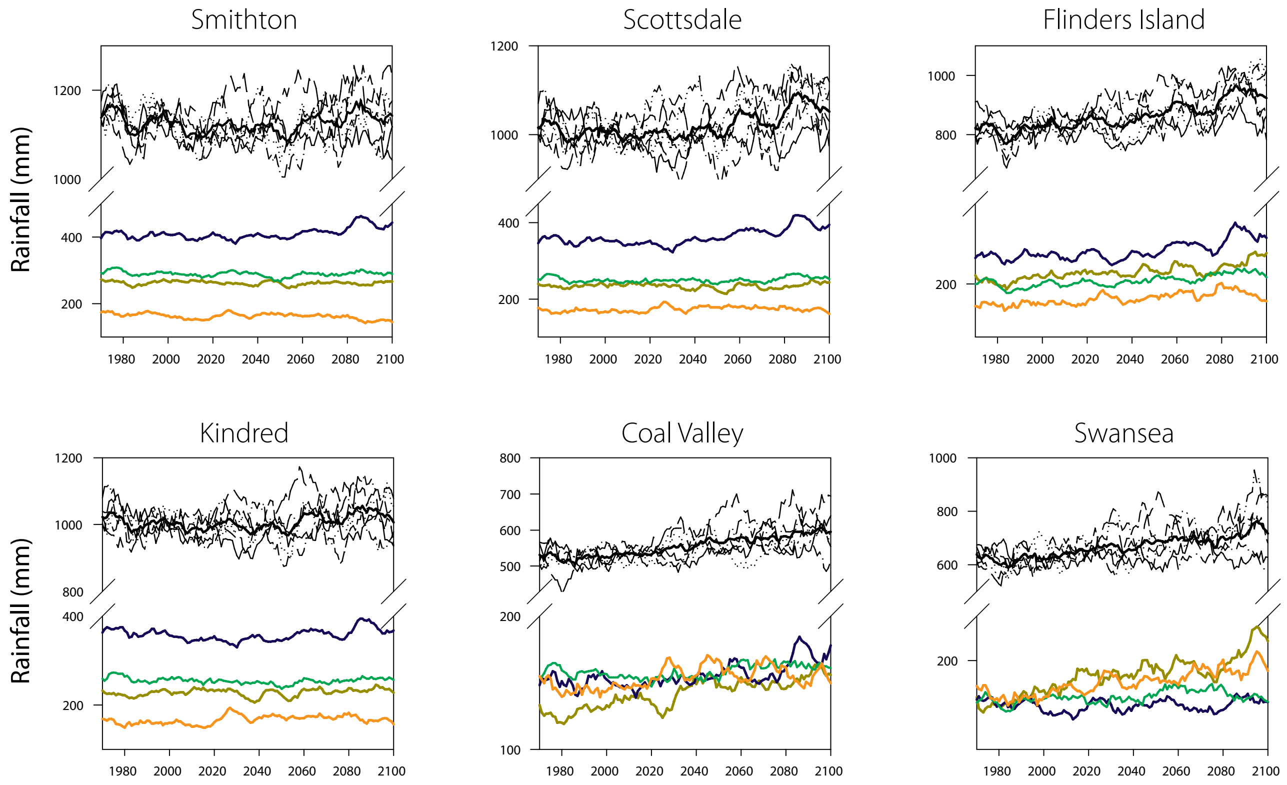


Figure 2.9 Ten-year running mean of annual rainfall for six downscaled-GCMs (bold lines) and each downscaled GCM (thin black lines), and six-model mean of seasonal rainfall (coloured bold lines) for selected agricultural areas in Tasmania 1970-2100, A2 emissions scenario. Rainfall scales are site-dependent.

Table 2.2 Mean, minimum and maximum percentage change (%) in annual and seasonal rainfall 1961-1990 to 2071-2100 at six locations, for six downscaled-GCMs, A2 emissions scenario.

	Annual (%)	Summer (%)	Autumn (%)	Winter (%)	Spring (%)
Flowerdale	1.2 (-4.5 – 9.2)	-10.9 (-16.6 - 0.1)	-1.0 (-5.2 11.4)	8.8 (5.4 - 16.8)	-0.3 (-6.3 - 3.9)
Deloraine	5.4 (-3.7 - 13.4)	0.4 (-7.8 - 18.5)	1.6 (-20.2 -17.7)	12.3 (-5.8 - 21.4)	3.1 (-7.4 – 13.1)
Scottsdale	14.7 (3.4 – 24.5)	16.3 (-7.0 - 29.5)	16.5 (-9.6 – 41)	14.5 (7.4 – 24.9)	12.0 (3.4 – 26.4)
Tunbridge	2.1 (-4.1 – 10.4)	4.7 (-3.1 – 15.4)	3.2 (-17.1 - 15.7)	2.0 (-5.4 – 9.6)	-0.2 (-5.7 – 7.1)
Bothwell	12.8 (2.5 - 29.4)	9.2 (-16.6 – 24.9)	25.4 (7.9 – 42.1)	14.1 (3.1 – 33.6)	5.4 (-5.6 – 18.8)
Swansea	14.0 (-1.2 – 27.4)	18.8 (-13.1 – 41.4)	33.2 (-8.0 – 81)	-0.4 (-7.9 – 12)	5.0 (-8.6 – 21.1)

2.2.2 Solar radiation

Solar radiation is used in biophysical models such as DairyMod and is an important variable for future and current agricultural simulations. Solar radiation is projected to change by less than 5% with a decrease on the east-coast and an increase on the west coast, mostly due to changes in cloud cover during the summer months (Figure 2.10). Climate model projections of interannual variability in solar radiation for a number of sites in agricultural regions was ±4-7%, both for the baseline period and for the period 2071-2100.

2.2.3 Evapotranspiration

Evapotranspiration is an important climate variable used in conjunction with other variables such as rainfall and soil water-holding capacity to assess crop water relations. There are a number of methods used to estimate potential evapotranspiration, a complex phenomenon driven by solar radiation, wind, vapour pressure and temperature. This complexity is reflected in recent pan evaporation observations and attribution studies in Australia and elsewhere that found decreased trends in evaporation were due to decreased wind and increased cloud cover despite increases in temperature (Donohue et al 2010; Roderick et al 2007). The projections of pan evaporation from the downscaled-GCMs suggest increases of around 19% by the end of the century (Grose et al 2010). Areal potential evapotranspiration was calculated for the hydrological modelling using Morton's wet method (Morton 1983) from daily temperature, vapour pressure and solar radiation (Bennett et al 2010). The projections using this method suggest increases of the order of 3% to 5% across all regions of Tasmania but proportionately less in the east and more in the west (Figure 2.11). These regional differences are driven largely by changes to summer relative humidity and solar radiation (cloud cover), summer being the season when most of the annual evapotranspiration occurs.

2.2.3 Extreme events

Agriculture is susceptible to extreme climate events such as hot days, high-intensity rainfall or extreme wind gusts. Changes to the frequency and character of these events are more fully described in White et al (2010) and Cechet et al (2010).

An increase in rainfall intensity is projected across the state. The intensity of the 100 year and 200 year daily average recurrence interval events are projected to increase at all locations over Tasmania

Solar Radiation

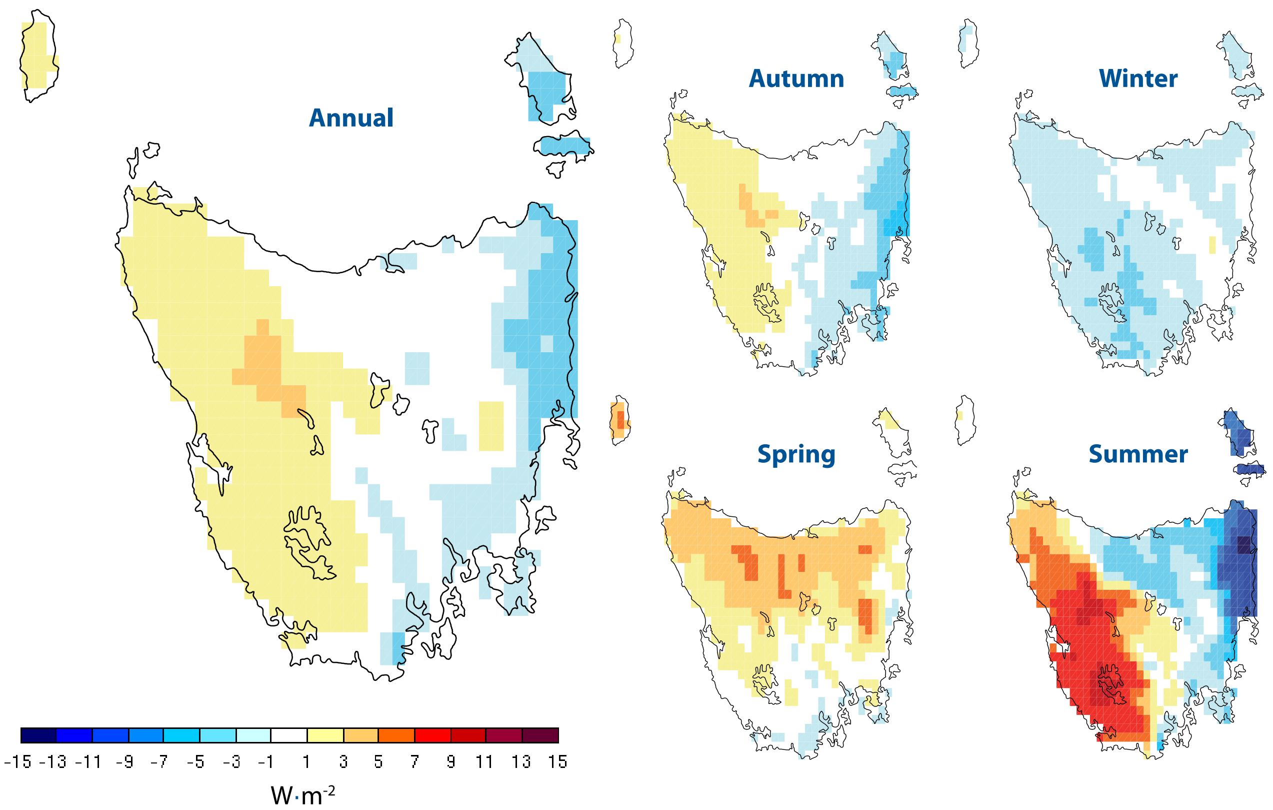


Figure 2.10 Change in annual and seasonal solar radiation (W·m^{-2}) 1961-1990 to 2071-2100, A2 emissions scenario, mean of six downscaled-GCMs, adapted from Grose et al (2010).

Evapotranspiration

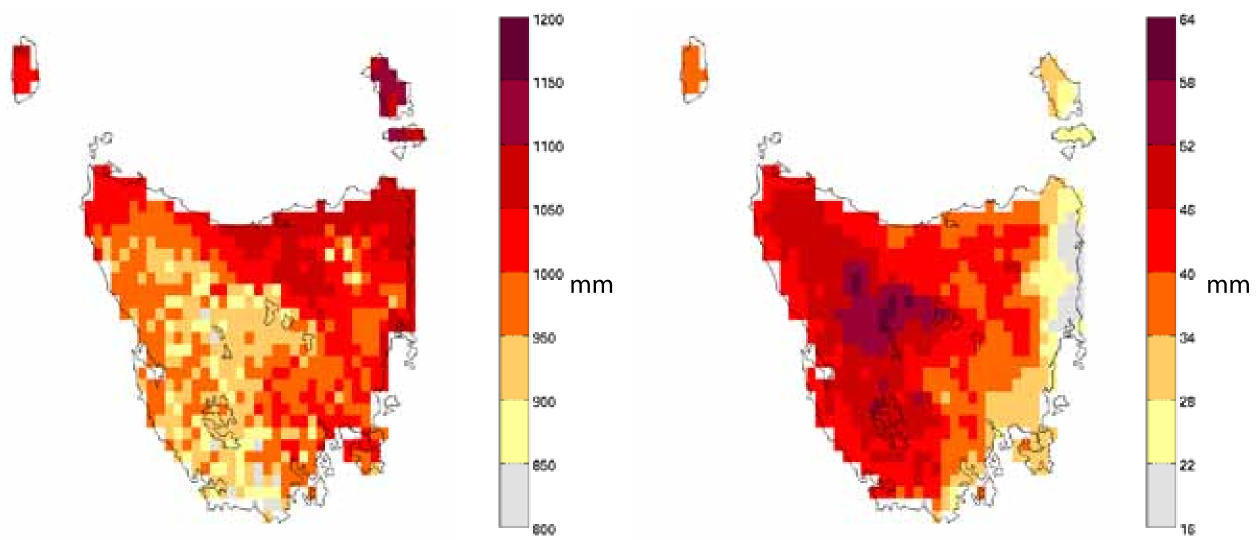


Figure 2.11 Annual areal potential evapotranspiration (mm) 1961-1990 (left) and change (mm) between 1961-1990 and 2071-2100 (right), using Morton's wet method, mean of six downscaled-GCMs, A2 emissions scenario, adapted from Bennett et al (2010).

(White et al 2010). Analysis of the 200-year average recurrence interval event for St Helens (Figure 2.12) shows that a 1:200 year event is likely to occur at an increased frequency of around 1:20 years by the end of the century. Increased rainfall intensity is amplified through increases in runoff (Bennett et al 2010), potentially increasing the risk of flooding and in cropping areas, increasing the potential for soil erosion.

The number of warm spells experienced in Tasmania is projected to progressively increase (Figure 2.13). Warm spells, defined as three consecutive days exceeding 28 °C, increase by the end of the century in the midlands, Derwent Valley and the south-west - areas that are affected by the Foehn effect. The Foehn effect is a meteorological phenomenon that results in warm air flowing down the leeward side of a mountain range (for example, from the north-westerly winds over the central highlands leading to the high temperatures often felt in the Derwent Valley). However, although these temperature increases are likely to have some effect on agriculture (for example, C3 plants), extreme temperature events in Tasmania will remain relatively mild when compared to those experienced on the mainland.

2.2.5 Runoff

Runoff and flows into farm dams and rivers facilitates stock watering and irrigation, and thus is an important aspect of agricultural production. Bennett et al (2010) projected runoff and river flows to 2100 using five hydrological models and the six downscaled-GCMs. These runoff projections show annual runoff (millimetres) modelled during the baseline period and projected changes to the end of the century using one of the hydrological models, Simhyd. Runoff of 100 mm·ha^{-1} is equivalent to 1 ML·ha^{-1} (Figure 2.14).

The overall implications for agricultural production from the projected changes in runoff require a more detailed and comprehensive analysis than can be accomplished in this report. However, marked seasonal changes to runoff are likely to occur in some regions over the coming century (Figure 2.14). These patterns of change are more important than the relatively small statewide changes. Annual runoff on the west coast is not projected to change greatly by 2100, however west coast runoff is likely to increase in winter and decrease strongly in summer and autumn. Increases in runoff in the lower South Esk River and the lower Macquarie River are projected to be greatest in winter (Bennett et al 2010).

Annual runoff is likely to decrease significantly in Tasmania's central highlands, with 30% less runoff in some areas. This will decrease inflows to irrigation storages dependent on inflows from the central highlands, including Lake Crescent/Sorell as Meander Dam as well as those Hydropower storages that supply water for irrigation (e.g. Great Lake and Arthurs Lake). On average, annual runoff in eastern areas of Tasmania is generally projected to increase (Figure 2.14). In the lower Derwent Valley, annual runoff is likely to increase, likewise in the lower south Esk River and lower Macquarie River catchments. These increases may be more than 50% in some areas of the Derwent Valley and more than 15% in the lower South Esk River and lower Macquarie River catchments.

Of the 78 rivers modelled, on average 32 are projected to have changes to mean annual flows of more than ±10% by 2100 (Bennett et al 2010). Changes of this size can have implications for water management and infrastructure development. On average, 28 of the 78 rivers modelled are projected to have decreased flows by 2100, while 50 rivers are projected to have increased flows. However, for one climate projection from one GCM, as many as 55 of 78 rivers have decreased flows, while for another GCM climate projection 77 of 78 rivers have increased flows.

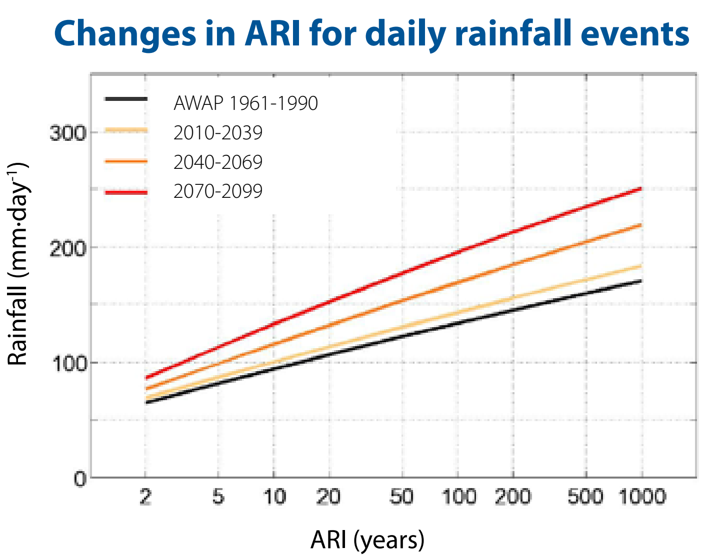


Figure 2.12 Average recurrence interval (ARI) of daily rainfall at St Helens for AWAP (1961-1990) and mean of six downscaled-GCMs for 2010-2039, 2040-2069 and 2070-2099, A2 emissions scenario, from White et al (2010).

Warm Days

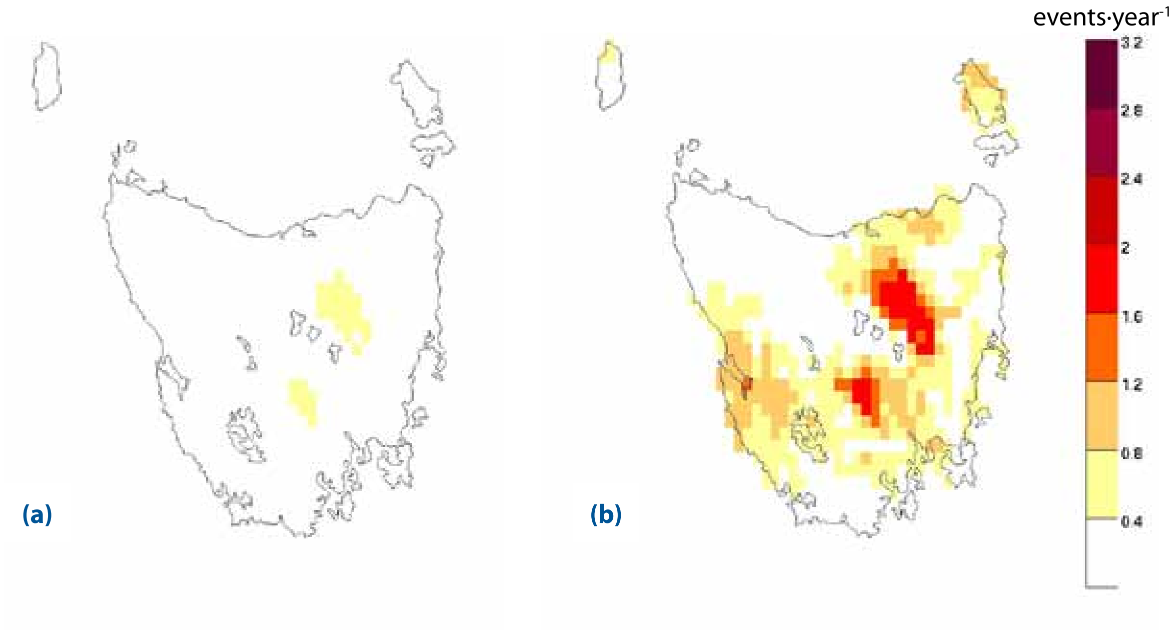


Figure 2.13 Events per year when three consecutive days exceed 28 °C (a) 1961-1990, (b) 2070-2099. Mean of six downscaled-GCMs, A2 emissions scenario, from White et al (2010).

Changes to Runoff

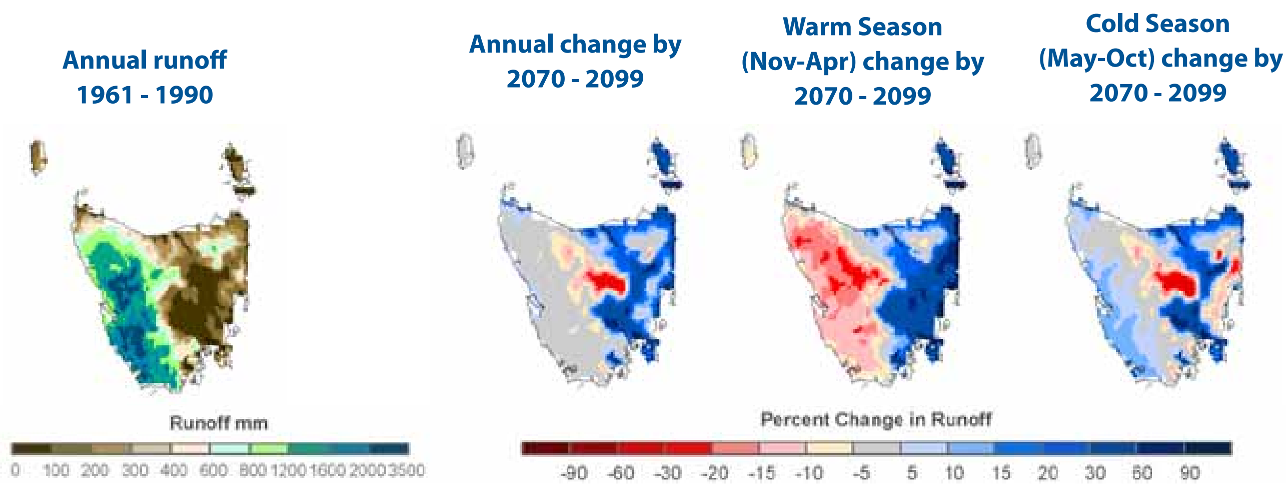


Figure 2.14 Annual runoff 1961-90 and percent change to 2070-2099 using the hydrological model Simhyd, mean of six downscaled-GCMs, A2 emissions scenario, adapted from Bennett et al (2010).

3 Agriculture climate indicies

3.1 Frost

Frost is an important feature of agriculture and horticulture in Tasmania. In the past, frosts have caused significant damage to broadacre and horticultural crops. Many crop and pasture species grown during the frost-prevalent periods are relatively tolerant of low temperatures but there are times during a crop's development when it is particularly sensitive - that is, a crop may be sensitive not so much to the number of frosts but to their timing and severity. Just one frost at a critical time of crop development, such as fruit tree flowering and early fruit development from October to November, may be very significant to an industry, even if it occurs only once every 5-10 years. For example, frosts of around minus 2 °C were reported in vineyards across Tasmania on 16 and 21 October 2006 (following bud burst) that resulted in widespread tip burn, loss of primary and secondary buds, and substantial reductions in grape yield and quality in that season (Jones et al 2010).

Despite the widely-reported negative impact of frost, cold events and frost also play a positive role in agricultural and natural systems by providing breaks in life-cycle development of pests. Changes to the incidence and severity of frosts are therefore of particular interest to the rural community.

Frost and frost damage are complex phenomena. Frosts occur when the earth surface temperature falls to 0 °C and ice crystals form (Rosenberg et al 1983). In general, frosts are classified as advection (synoptic scale incursion of a cold air mass) or as radiation (heat loss during cold clear nights, leading to the formation of loosely deposited white ice crystals). In Tasmania, most frosts are radiation frosts, but are often accompanied by significant local advection, with complex topography leading to well-known katabatic flows (Wilson 2009). There are many factors that result in frost formation, including the preceding and current synoptic patterns, vegetation (crop) structure and characteristics (height, leaf area), soil conditions (colour, moisture levels) and very significantly, local topography. Frost incidence and severity may be very different over relatively short distances depending on slope characteristics (convex or concave), aspect, cold air drainage and local obstructions such as tree lines. The scale of the climate modelling (0.1-degree grids) means that local topographic effects cannot be taken into account in this analysis but the trends should be applicable at a local scale.

Plant damage from low temperatures may be due to cell necrosis resulting in dehydration during a freezing event or due to cold-induced photoinhibition (Close et al 2000). Crop sensitivities to cold temperatures change over time as crops harden and become tolerant of cold temperatures through the autumn, or avoid cold temperatures during dormancy through the winter.

Frost incidence - that is, ice formation - has mostly only been recorded manually, and for those records for which there are no manual observations, the occurrence of a frost has been implied from Stevenson Screen temperatures or in some instances, from grass temperatures. The difference in temperature between that in a screen at around 1.2 m to 1.3 m and ground level varies but is around 1.8 °C to 2.2 °C. Therefore, a Stevenson Screen temperature of 2 °C can be used to indicate the potential for frost, though not all 2 °C events will be frosts (Kalma et al 1983; Marcellos & Single 1975). A Stevenson Screen temperature of 0 °C or minus 2 °C is more appropriate for tree crops and vines, as the susceptible parts of the crop (leaves, flowers) are above ground level or above the level of the Stevenson Screen. In this report, the incidence of potential frosts is presented as days when the minimum screen temperature is less than 2 °C and less than 0 °C - that is, approximately 0 °C and minus 2 °C at ground level.

Minimum and maximum temperatures in Tasmania have been increasing over the past 50 years (Grose et al 2010). However, declining trends in the number of frost days have not been clearly evident at all sites, in part because of the complexity of factors leading to frost events such as rainfall and cloud cover. The number of days less than 2 °C·year^{-1} for four sites across Tasmania (Figure 3.1) shows that over the period 1961-2007 the only significant declining trend in frost days was at the Huon 95m site. There were significant trends from each of the downscaled-GCMs over the same period that represent the frequency of frost events reducing by around 0.2-0.4 frosts·year^{-1}.

Changes to Frost

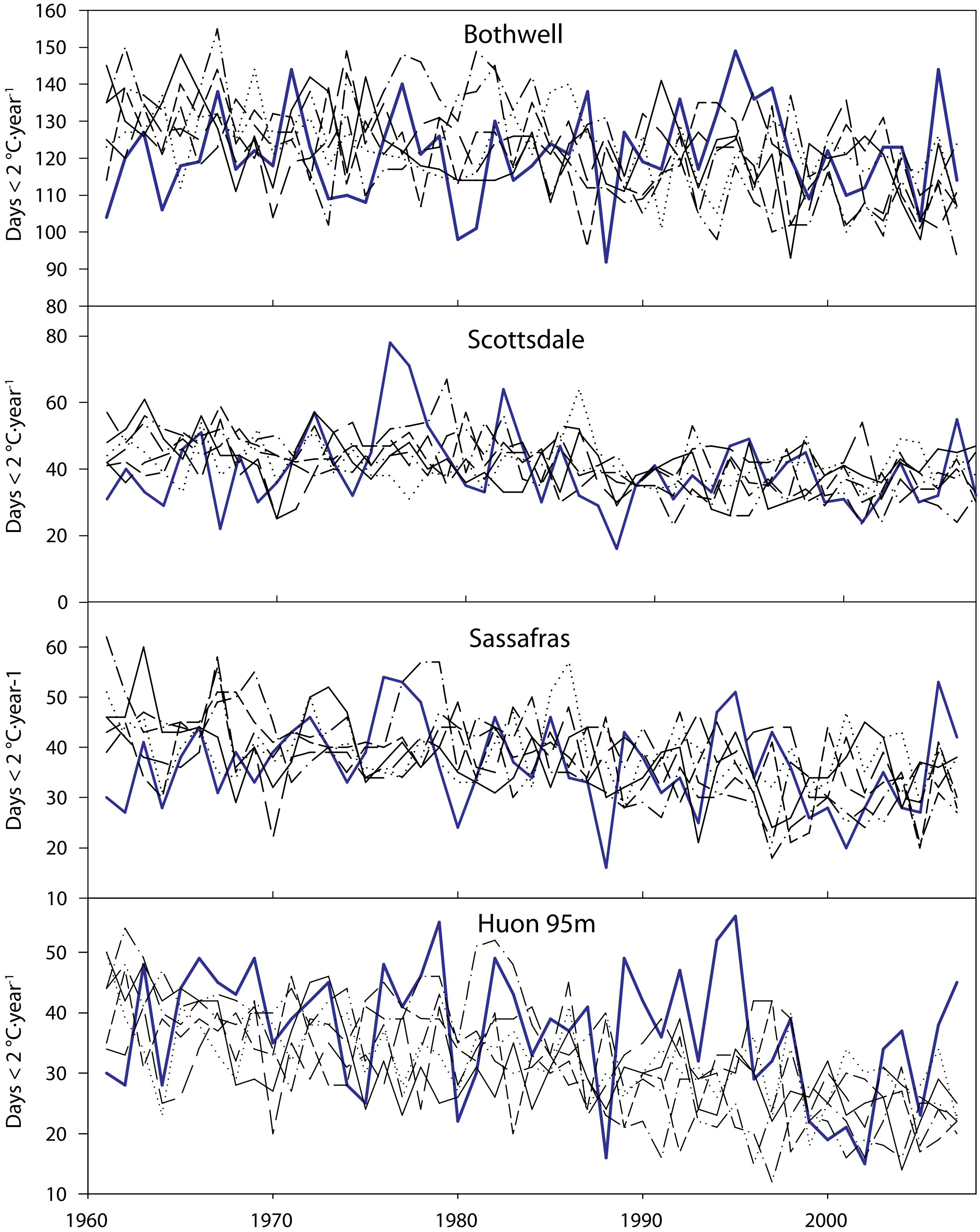


Figure 3.1 Number of days less than 2 °C.year^{-1} for Bothwell, Scottsdale, Sassafras and Huon 95m over the period 1961-2007 using AWAP (blue solid line) and each downscaled-GCM (black lines). The vertical axes have different scales for each site.

Changes to Frost

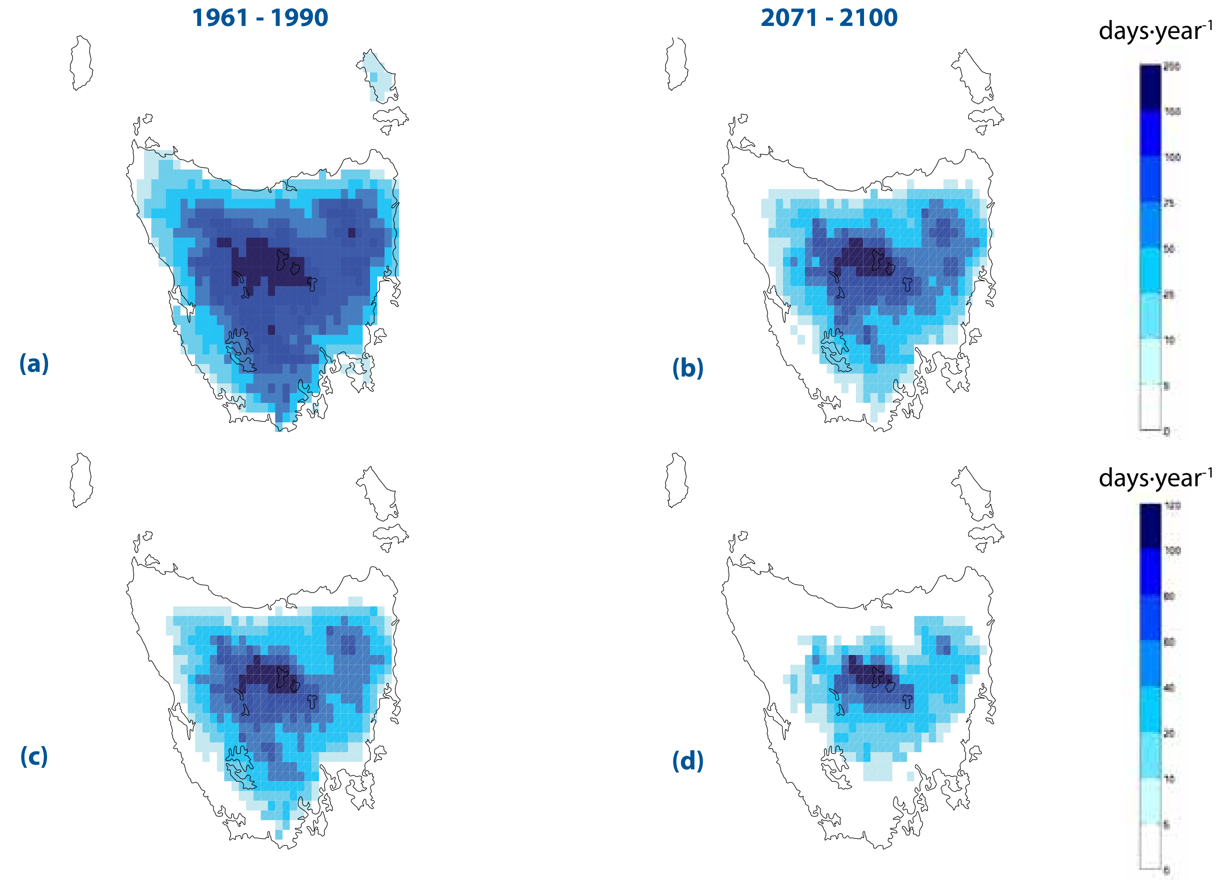


Figure 3.2 Days less than 2 °C·year^{-1} (a and b) and days less than 0 °C·year^{-1} (c and d) 1961-1990 (left) and 2071-2100 (right), mean of six downscaled-GCMs, A2 emissions scenario (see also White et al 2010).

By 2085, the climate modelling projections suggest there will be substantial reductions in the number of days less than 2 °C and less than 0 °C across Tasmania (Figure 3.2). The mean number of days less than 2 °C·year^{-1} (with the model range in brackets) from the downscaled-GCMs for Campbell Town 1961-1990 is 95 (93-98) and this reduces to 38 (31-43) days by 2071-2100. Comparable reductions for Scottsdale are 43 (42-45) days to 8 (4-12) days and for Bothwell 126 (124-129) days to 49 (38-58) days.

The projections suggest there will be a shorter period each year when overnight minimums will fall below 2 °C, defined as a 'cold day'. The monthly frequency of cold days (Figure 3.3) indicates the period with more than four cold days per month will decrease from March-December 1961-1990 to around May-October by 2071-2100 for many centres.

In order to assess future risks of frost events during the critical October to November period, the frequency of frost for each day (September 1 to November 30) was calculated by accumulating the six models' estimates of each day for two 30-year periods, 1961-1990 and 2071-2100. This gave 180 estimates per calendar day for each period. Figure 3.4 shows the frequency of days less than 2 °C from AWAP data (that is, gridded data interpolated from observations 1961-2007) and from the mean of the six models 1961-1990 and 2071-2100, for six sites. The higher variability of daily estimates for the AWAP data reflects the smaller population of only 47 measures per calendar day. However, the trends among the sites are clear, with a substantial reduction in the frequency of days less than 2 °C and a shortening of the susceptible period. However, despite these general trends, frost events still occur in November at Scottsdale and Campbell Town, albeit at very low frequencies. This indicates there will still be some potential for damaging late spring frosts in these areas.

While these projections suggest a reduction in frost-related crop losses, the complexity of frosts and frost damage demands a cautious interpretation. Warmer winter and early spring conditions are expected to lead to earlier budburst and plant growth in some crops (see Section 3.4), exposing frost-sensitive plant tissue to spring frosts. Interpretations of projected frost impact are further complicated by reports that higher atmospheric carbon dioxide concentrations lead to increased frost sensitivity in some crops (Barker et al 2005; Gu et al 2008).

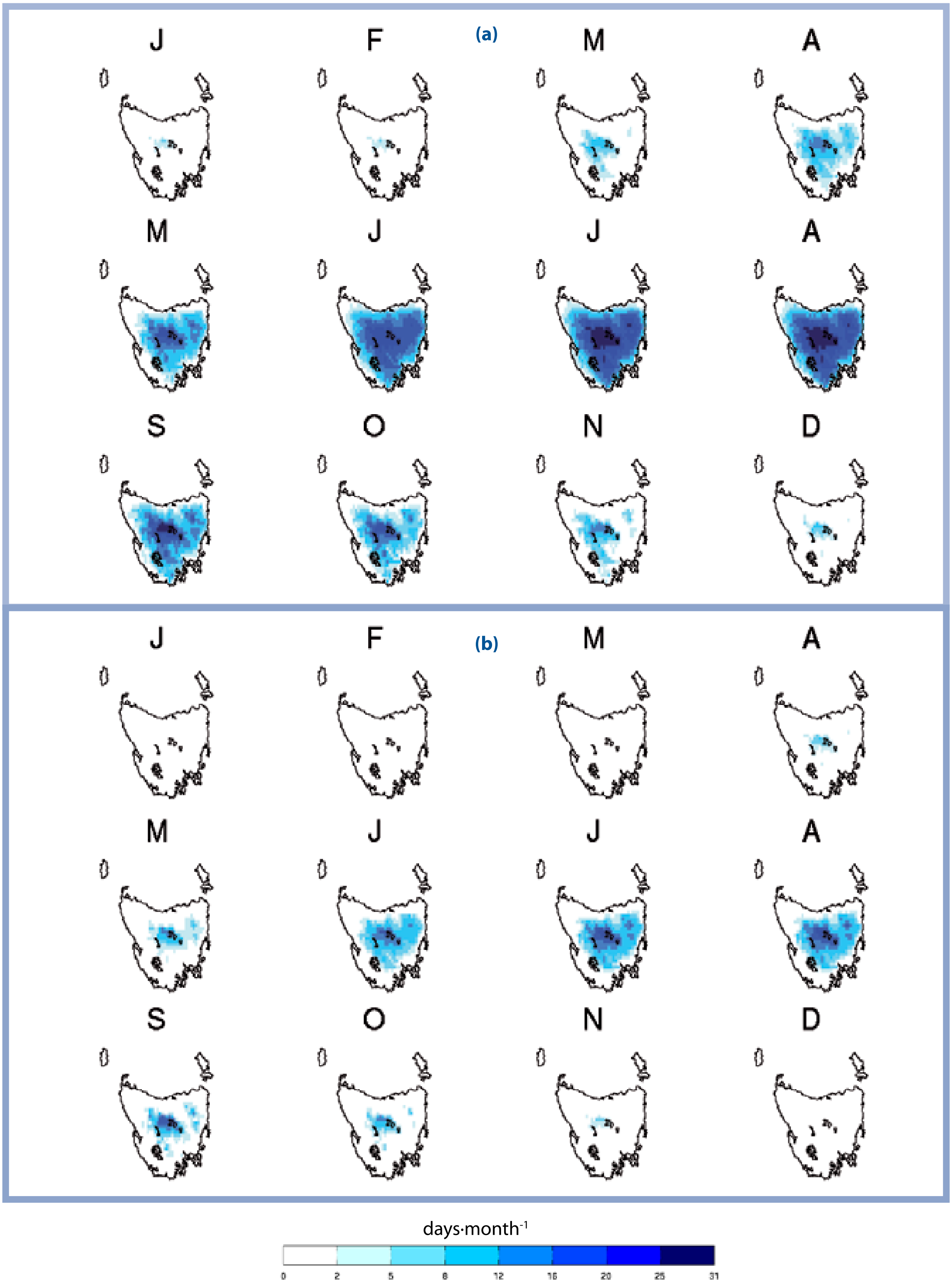


Figure 3.3 Number of days less than 2 °C·month^{-1} 1961-1990 (a) and 2071-2100 (b), mean of six downscaled-GCMs, A2 missions scenario.

Changes to Frost Incidence

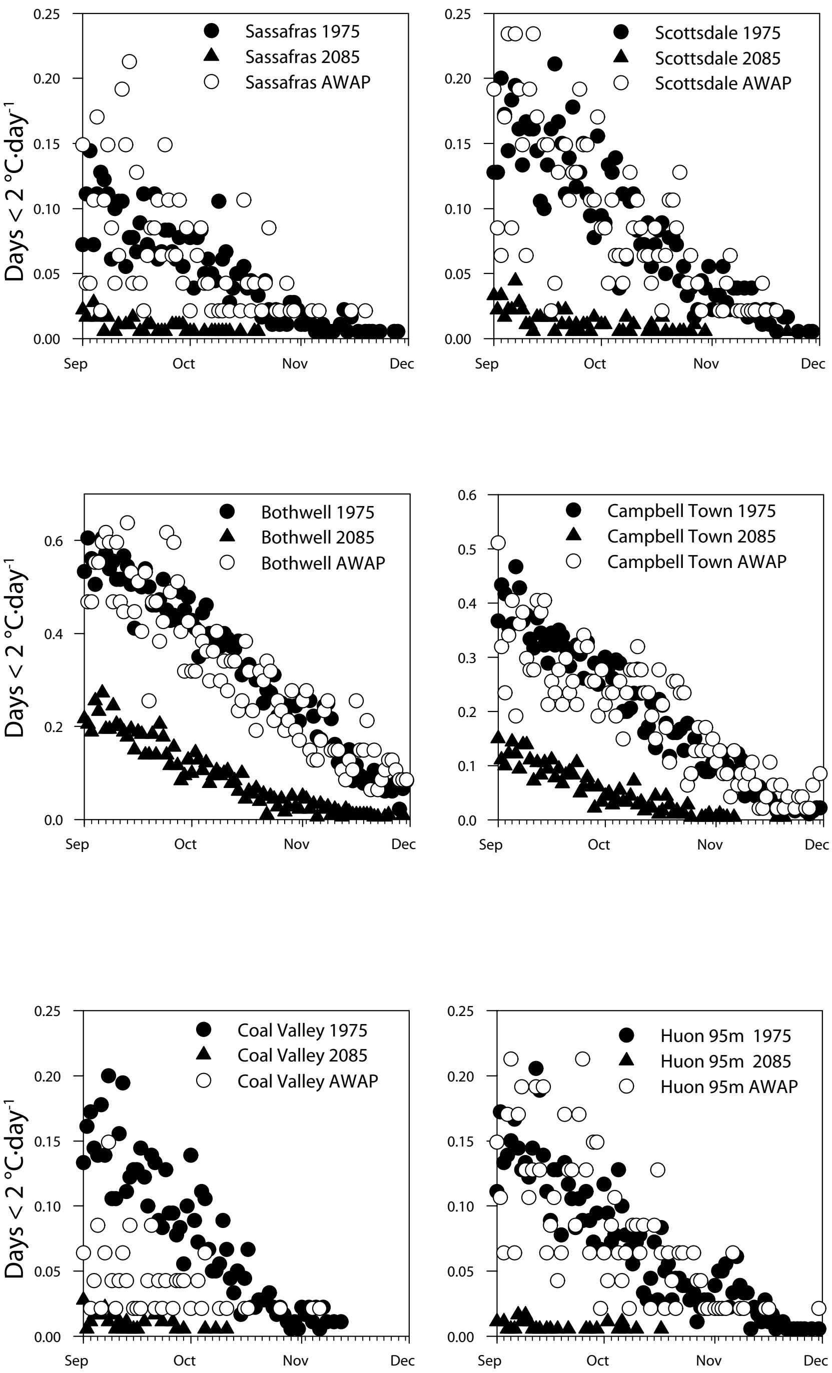


Figure 3.4 Frequency of days less than 2 °C for each calendar day from September 1 to November 31 for six sites across Tasmania, mean of six downscaled-GCMs, A2 missions scenario.

3.2 Drought

Drought is a recurrent feature of agricultural production in Tasmania. Fundamentally, drought is due to a lack of rain and is "*a period of abnormally dry weather sufficiently prolonged … that causes a serious hydrological imbalance*" (Mpelasoka et al 2008). The consequences of drought involve a number of components that have an impact on the environment, agriculture and society in different ways. Several authors, including Hennessy et al (2008) and White and Walcott (2009), have recently defined different forms of drought as:

- Meteorological drought (low rainfall).
- Agricultural drought (low soil moisture at a critical time in the growing season of a crop or pasture that precludes or reduces production).
- Hydrological drought (reduced surface and subsurface water supply, low lake and dam levels).
- Socio-economic drought (low economic returns and an impact on human well-being as a result of low production).

Consequently, as there is no universal definition of drought, indices ranging from rainfall deciles to agricultural model metrics have been developed to service the various stakeholders, each of whom have different interests and requirements (Lodge & Johnson 2008; White & Walcott 2009). An index becoming more commonly used to monitor and characterise meteorological drought is the Standardised Precipitation Index (SPI) (Lloyd-Hughes & Saunders 2002; McKee et al 1993, 1995). The SPI has been used extensively around the globe (Cancelliere et al 2007; Lana et al 2001; Sönmez et al 2005; Wu et al 2007; Zhang et al 2009).

> *"Experts participating in the Inter-Regional Workshop on Indices and Early Warning Systems for Drought, held at the University of Nebraska-Lincoln, USA, from 8 to 11 December 2009 made a significant step through a consensus agreement that the Standardized Precipitation Index (SPI) should be used to characterize meteorological droughts by all National Meteorological and Hydrological Services around the world."*

Source: www.wmo.int/pages/mediacentre/press_releases/pr_872_en.html

The SPI (or Z value) is essentially the number of standard deviations from the mean of a normalised cumulative rainfall distribution.

Previous studies have estimated changes in drought frequency over Tasmania. Mpelasoka et al (2008) compared changes in a Soil Moisture Deciles-based Drought Index (SMDDI) and a Meteorological Drought Index from a baseline of 1975-2004 calculated from two climate models on a 0.25-degree grid (Canadian Climate Center and CSIRO-Mk2) and two emissions scenarios (SRES B1 and A1FI) for 2030 and 2070. They concluded the SMDDI was more relevant to resource management than the Meteorological Drought Index and that, for the high emissions scenario, there would be an increase in drought frequency of up to 20% in Tasmania by 2070. For the low emissions scenario by 2070, there was a decrease of up to 20% in projected drought frequency.

Hennessy et al (2008) estimated changes to temperature, rainfall and soil moisture 1900-2007 and between 2010-2040 using a deciles-based approach for 13 climate models for the A1B emissions scenario downscaled to a 25 km grid. They suggest a 3.0% to 13.9% increase (low and high models) to the area of Tasmania and Victoria having exceptionally low (5th percentile) annual rainfall. They also suggest the return period for exceptionally low rainfall years will change from 18.3 years for 1900-2007 to a range of 6.9 to 20.4 years by 2010-2040 - that is, the frequency of low rainfall years could increase or decrease but will more likely increase. Finally, they project an increase in the area experiencing exceptionally low annual-average soil moisture from a historical 6.6% to between 7.0% and 15.2% by 2010-2040.

Changes in the frequency and characteristics of cumulative rainfall and consecutive dry and wet days have been quantified in White et al (2010).

This report addresses the issue of projected changes to drought across Tasmania using meteorological and agricultural indices of drought. The SPI has been used as an index of meteorological drought and calculated (using code from Taesam Lee, Matlab Central, 2009) for AWAP data from 1900-2009 and for each of the downscaled GCMs from 1961-2100. SPIs are presented spatially and as time series for grid cells representative of some agricultural areas across the state. Terms used to describe the severity of a drought based on the SPI value (McKee et al 1993) are: SPI of minus 1 to minus 1.49, *moderately dry*; SPI of minus 1.5 to minus 1.99, *severely dry*; SPI less than minus 2, *extremely dry*. Two standard deviations (SPIs) include 95% of the area under a normal distribution. The extreme dry end of the distribution (SPI less than minus 2) includes about 2.5% of that area, equivalent to a 1:40 year event. A SPI of less than minus 1.65 is equivalent to a 1:20 year event.

Changes in the incidence of agricultural drought were addressed by using soil moisture deficits (Lodge & Johnson 2008) from the pasture growth model DairyMod. Cressy and Ouse were chosen because they are in relatively low rainfall areas and pasture modelling outputs were available. Daily soil water content (mm) in 0 cm to 80 cm of soil (Garwood &

Sinclair 1979) was derived from modelling nitrogen non-limited pasture growth. A drought event is defined as when the soil water deficit falls below the critical soil moisture content. The frequency and duration for these events were calculated for three time periods of 90 days, 180 days and 220 days. Three downscaled models were chosen (CSIRO-Mk3.5, GFDL-CM2.1 and UKMO-HadCM3), representing dry, middle and wet ranges of the modelling projections. The critical soil moisture content was calculated for each site by firstly removing the effect of low pasture growth due to temperature and then averaging soil moisture content for days when the Net Positive Growth Rate was 0-5 $kg{\cdot}ha^{-1}{\cdot}day^{-1}$. This corresponds to a low growth rate that is not temperature-limited but soil moisture-limited. The critical soil water content was 265 mm at Cressy and 292 mm at Ouse.

Historical patterns of drought as measured using the SPI (Figure 3.5) show substantial spatial and temporal heterogeneity where different regions of the state have been subject to low rainfall events at different periods of time during the last century. For example, the west coast was the most affected in the state by low rainfall 1950-1979 but was least affected during 1980-2009.

The regionality of drought is also reflected in the SPI less than minus 2 events (Figure 3.6), where different sites experienced drought events at different times. Note the declining trend in the SPI from the mid-70s, particularly for Flowerdale and Scottsdale, and the absence of high rainfall (SPI greater than 2) events during this period, a feature of the rainfall decline in recent times (I Barnes-Keoghan, 23 September 2010).

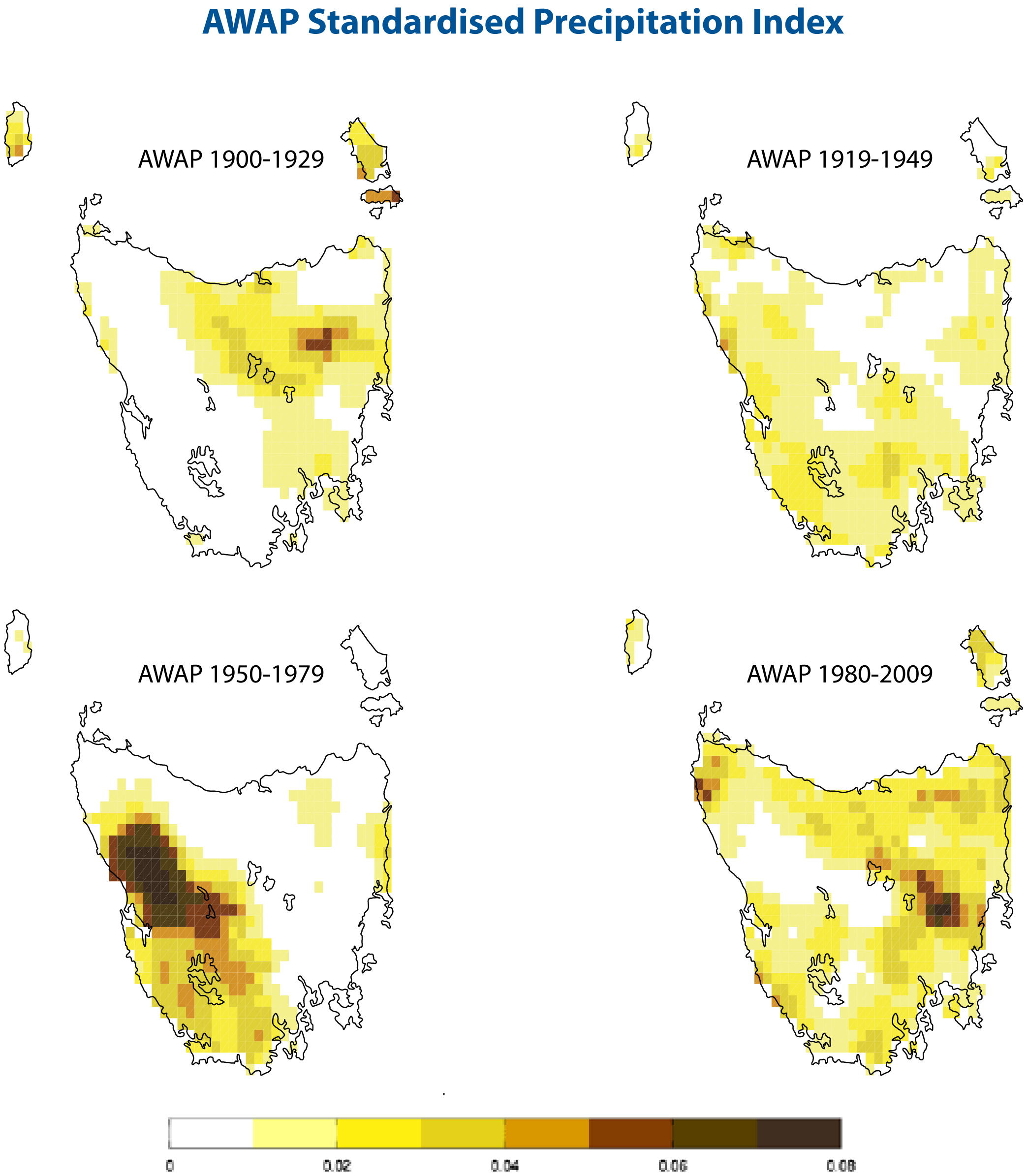


Figure 3.5 The proportion of time the Standardised Precipitation Index (cumulative 12 monthly precipitation) was less than minus 2 during 30-year periods from 1900-2009 using AWAP.

AWAP Standardised Precipitation Index

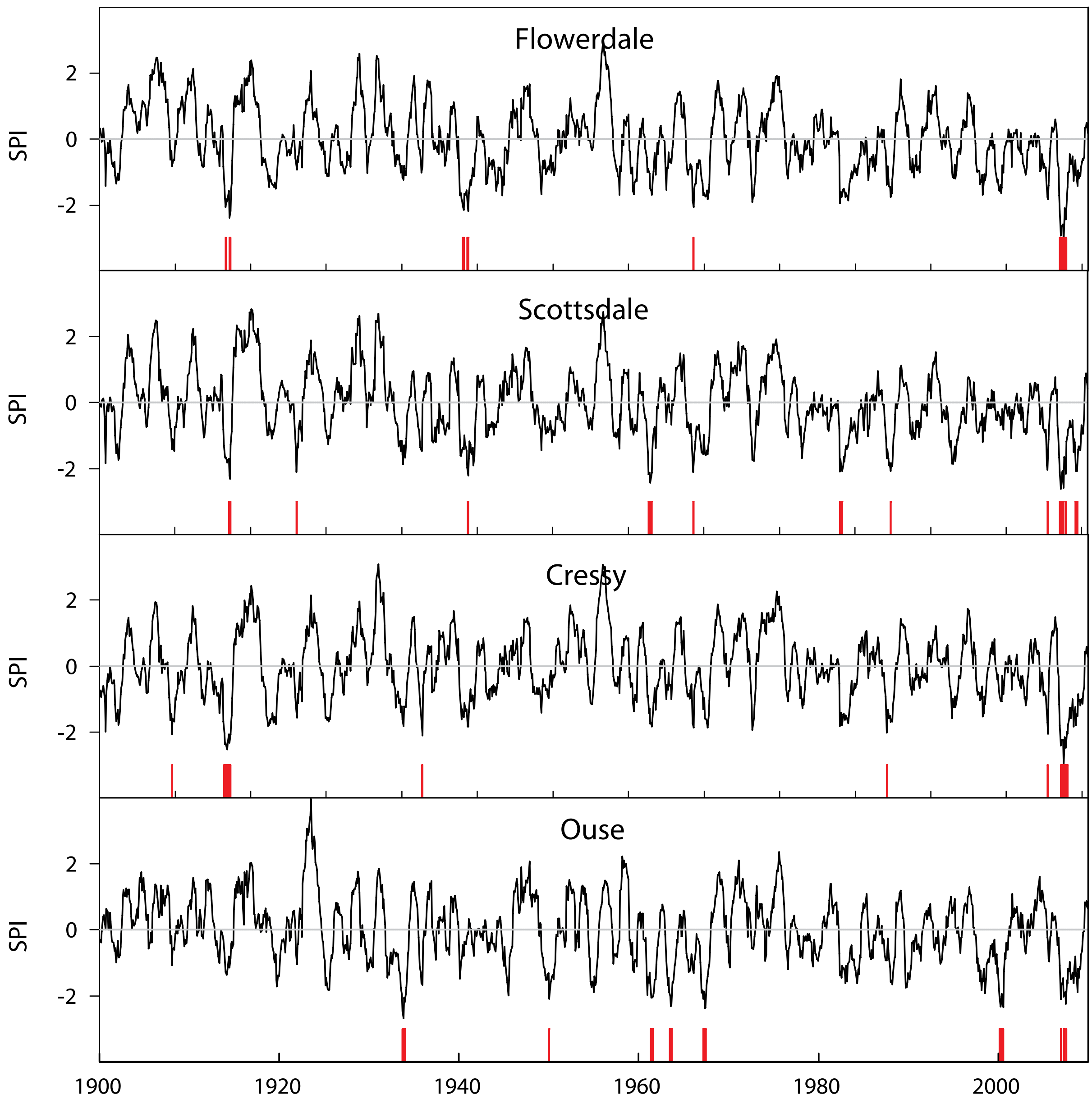


Figure 3.6 Standardised Precipitation Index (SPI) for cumulative 12-month precipitation 1900-2009 using AWAP for Flowerdale, Scottsdale, Cressy and Ouse. Events with SPI less than minus 2 shown by vertical red bars.

The episodic temporal and spatial patterns evident in the SPI reflect regionally coherent rainfall. Similar patterns are also a feature in the downscaled-GCM projections (Figure 3.7).

Despite temporal and spatial complexities of the SPI in the 140 years of projections, there appears to be a general trend among the models for increasing droughts in the central west and north-west of Tasmania and for decreasing droughts in the far south-west, south-east and north-east.

Site-specific trends have been quantified for sites representing agricultural regions. Projections of SPI and SPI less than minus 2 drought events for each of the downscaled-GCMs at Cressy (Figure 3.8) demonstrate the stochastic nature of these kinds of events and inter-model variability. Some of the models indicate an increase in drought events (GFDL-CM2.1), while others a decrease (UKMO-HadCM3). The mean of all models for Cressy projects a reduction in the proportion of time when the SPI was less than minus 2, from 2.2% (1.0%-3.3%) in 1961-2010 to 1.6% (0.3%-3.7%) in 2051-2100.

Projections for other sites representing agricultural areas (Table 3.1) quantify the general trends. For example, from 1961-2010 to 2051-2100 the period of time when the SPI is less than minus 2 changes from 1.9% (0.8%-2.8%) to 2.9% (0.5%-5.0%) at Woolnorth in

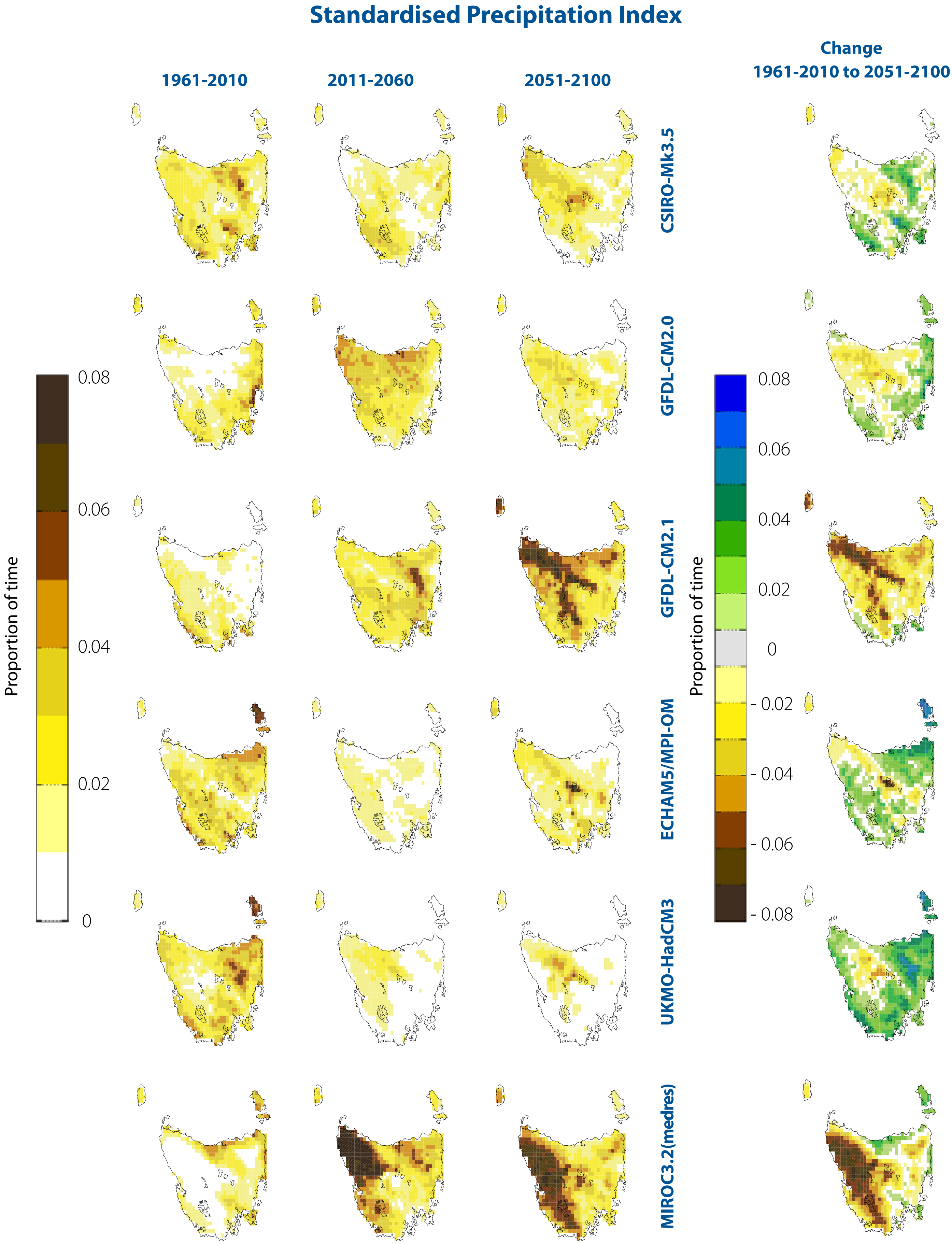


Figure 3.7 The proportion and change in proportion of time the Standardised Precipitation Index (cumulative 12-month precipitation) was less than minus 2 during three 50-year periods, 1961-2010, 2011-2060 and 2051-2100, for each downscaled-GCM, A2 emissions scenario.

Model Range of Standardised Precipitation Index

Cressy

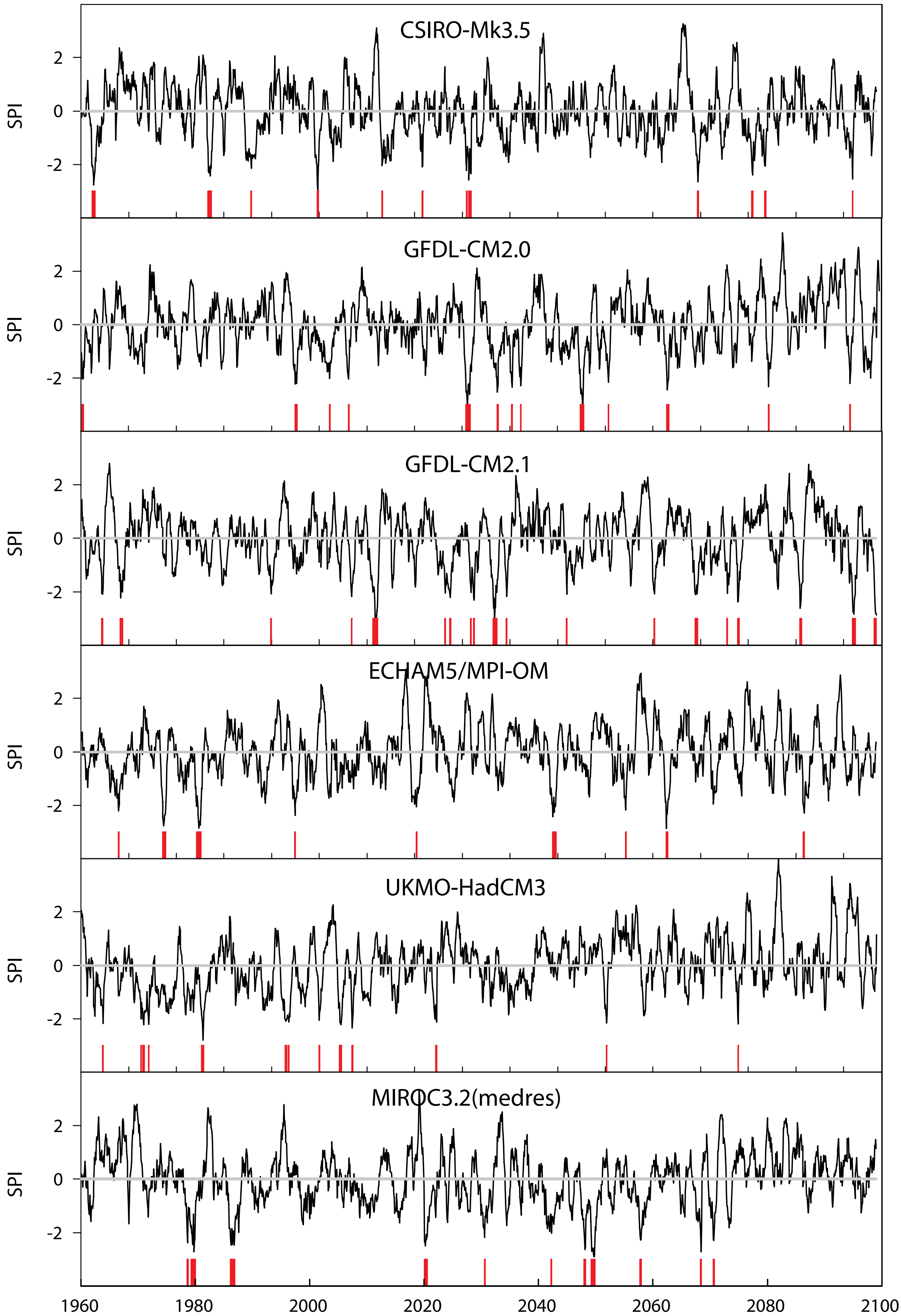


Figure 3.8 Standardised Precipitation Index (SPI) for cumulative 12-month precipitation at Cressy 1961-2100 for each of the six downscaled-GCMs, A2 emissions scenario. Events with SPI less than minus 2 shown by vertical red bars.

Table 3.1 Percentage of time (mean of six downscaled-GCMs and range) when SPI is less than minus 2 for cumulative 12-month rainfall at a number of sites across Tasmania for 50-year periods 1961-2010, 2011-2060 and 2051-2100, A2 emissions scenario.

	1961-2010 %	2011-2060 %	2051-2100 %
King Island	1.8 (1.2-2.8)	2.1 (1.2-3)	3.3 (1.5-5.8)
Woolnorth	1.9 (0.8-2.8)	2.9 (0.6-7.2)	2.9 (0.5-5.0)
Flowerdale	1.6 (0.5-2.3)	2.6 (0.7-4.9)	2.9 (1.7-5.7)
Merseylea	2.3 (0.5-4.5)	2.1 (0.7-4.2)	1.8 (0.7-4.5)
Cressy	2.2 (1.0-3.3)	2.3 (0.5-3.8)	1.6 (0.3-3.7)
Ringarooma	2.3 (0.2-4.7)	2.3 (0.7-3.8)	1.8 (0.2-4.3)
Flinders Island	3.3 (0.7-5.5)	1.2 (0 -2.0)	0.9 (0-1.5)
Tunbridge	2.1 (0.7-3.8)	1.8 (1.6-3.3)	1.6 (0.3-3.3)
Swansea	2.5 (0.8-5.5)	1.4 (0-3.3)	0.5 (0-1.3)
Bothwell	1.7 (1.3-2.3)	1.5 (0-3.2)	1.6 (0-3.7)
Coal Valley	2.7 (1.3-3.7)	1.4 (0-3-4)	1.1 (0-2.2)
Ouse	2.2 (1.3-3.2)	1.4 (0.3-3.5)	1.9 (0.3-3.8)
Huon	2.6 (1.5-4.2)	1.3 (0.2-3.2)	1.4 (0-2.5)

Standardised Precipitation Index for Different Time Periods

Ouse

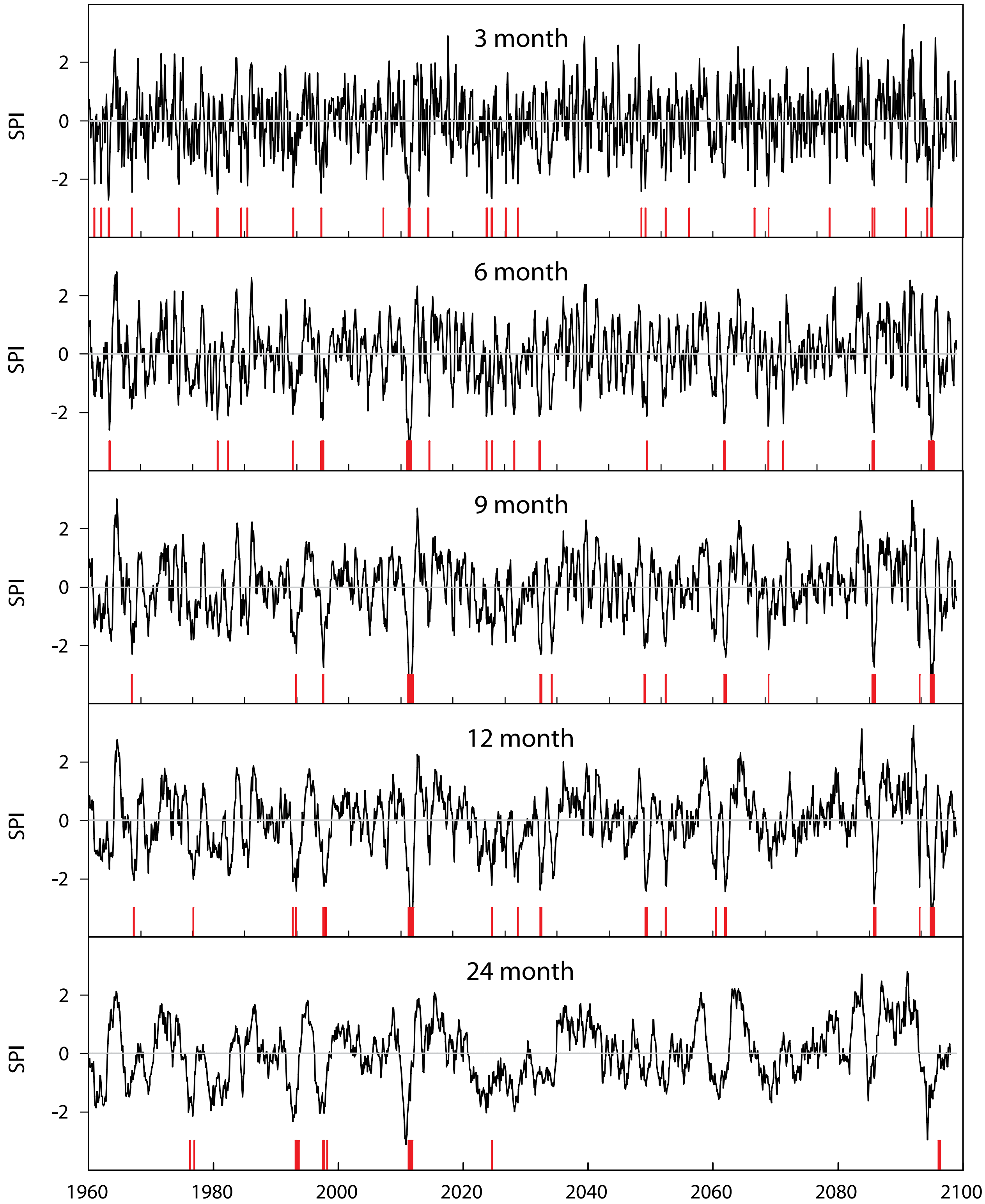


Figure 3.9 Standardised Precipitation Index (SPI) for cumulative rainfall over 3-month, 6-month, 9-month, 12-month and 24-month periods from 1961-2100 at Ouse, downscaled-GCM GFDL-CM2.1, A2 emissions scenario. Events with SPI less than minus 2 shown as vertical red bars.

the north-west of Tasmania, an area projected to have more drought, but changes from 3.3% (0.7%-5.5%) to 0.9% (0% -1.5%) on Flinders Island in the north-east, a region projected to have less drought.

Droughts occur over different durations and the impact of the projections on cumulative rainfall over 3 months, 6 months, 9 months, 12 months and 24 months was investigated for Ouse (Figure 3.9 and Table 3.2). For Ouse, the downscaled-GCM GFDL-CM2.1 suggests there is likely to be little change in the frequency of droughts of 3 months to 9 months in duration throughout the century but there is a likely reduction in 12-month and 24-month duration events by 2051-2100.

Projections of the incidence of agricultural drought at Ouse and Cressy (Table 3.3) indicate there will be little change in the frequency of periods of soil water deficit in the future. For example at Ouse, periods of 180 consecutive days of soil water deficit occur once every 1.2 years in 1971-2000 but are projected to occur once every 1.4 years by 2071-2100.

The total amount of time when the soils are in moisture deficit is projected to slightly decrease at both sites (Table 3.3). This is consistent with projections of change in annual rainfall for Ouse, with a mean increase of 5.5% (-3.9%-20.4%), and Cressy, 5.0% (2.6%-15.8%).

Table 3.2 Proportion of time (%), mean of six downscaled-GCMs and range across GCMs, when SPI is less than minus 2 for cumulative rainfall over three, six, nine, 12 and 24-month periods for 1961-2010, 2011-2060 and 2051-2100 at Ouse, A2 emissions scenario.

Cumulative rainfall	1961-2010 %	2011-2060 %	2051-2100 %
3 month	2 (1.7-2.3)	1.7 (0.8-2.5)	2.0 (1.0-3.2)
6 month	2.3 (1.3-3.5)	1.5 (0.5-2.8)	2.0 (0.5-3.5)
9 month	1.9 (0.7-2.7)	1.3 (0.2-2.8)	2.1 (0-3.3)
12 month	2.2 (1.3-3.2)	1.4 (0.3-3.5)	1.9 (0.3-3.8)
24 month	2.4 (0.8-4.8)	0.9 (0.5-1.5)	0.7 (0-1.5)

Table 3.3 Return interval (years) of 90-day, 180-day and 220-day periods of soil water deficit (SWD) and percent total time in SWD for Ouse and Cressy, 1971-2000 and 2071-2100, mean of three downscaled-GCMs, A2 emissions scenario.

	Return Interval (years)			
	Ouse		Cressy	
	1971-2000	2071-2100	1971-2000	2071-2100
Year·90 day^{-1} SWD	1	1	1	1
Year·180 day^{-1} SWD	1.2	1.4	1.7	2.4
Year·220 day^{-1} SWD	1.8	2.3	5	5.7
% total time in SWD	67%	62%	55%	52%

3.3 Chilling

Temperate, deciduous fruit trees (apples, pears, cherries and apricots), berry crops (strawberries, raspberries, blackcurrants) and nuts (hazelnuts and walnuts) undergo a period of dormancy each winter after leaf fall in the autumn. During this time, there is no apparent growth, with leaves and other sensitive tissue hidden in structures that protect from potentially damaging cold temperatures and frosts. The physiological mechanisms that control entry into and exit from dormancy are not fully understood but empirical evidence clearly shows that a minimum cumulative exposure to cold temperatures (chilling or vernalisation) is required to break the dormancy and lead to uniform spring budburst, flowering and fruit set. Insufficient chilling may lead to fewer buds, delayed and uneven budburst, sporadic flowering and fruit set, irregular fruit size, and reduced fruit yields and quality (Lorimer 2006; Saure 1985). Different species and different cultivars within species require different amounts of chilling. Detailed and explicit knowledge about the requirements of each species is required to maximise production and profitability. The chilling requirements of most crops can be manipulated by using chemical sprays but this is difficult to manage and adds significantly to cost and to the overall chemical load in an intensive production system.

There are a number of winter chill models used to calculate the effective cumulative exposure to cold temperatures. These models calculate the sum of effective chill hours through the winter months and recognise that there are optimum temperatures for accumulating chill. There are uncertainties about the optimum temperatures for different species. For example, Westmore (2004) suggested that 2 °C may be better correlated with blackcurrant response than the traditional 7.2 °C. Thompson et al (1975) suggested 2 °C is optimum for Jonathon apples while Jacobs et al (2002) found that time of exposure was more important than a specific temperature. It would seem probable that different optimum temperatures would apply to different species in different regions (Luedeling et al 2009a; Luedeling et al 2009b). Consequently, without specific relationships between the chill model and crop performance, measures of chill are better regarded as indicative and most useful in comparing sites and cultivars, rather than as an absolute accumulation for a site or a specific requirement for a cultivar.

Common chill accumulation models include the below 7.2 °C critical threshold model, the Utah model (Richardson et al 1974), the modified Utah model (Linvill 1990) and the Dynamic model (Erez et al 1990). Each of these provides different estimates of the cumulative winter chill and interpretation of the absolute scale depends on empirically established relationships between the index and crop or cultivar performance. These relationships are usually established by artificially manipulating temperatures in refrigerators.

Evaluating the impacts of climate change on chill involves two quite separate considerations. First, projected changes in temperature relative to the critical threshold of some species ultimately have an impact on the suitability of specific locations. Second, relative changes into the future that are quantified by increased or decreased chill, compared with the current accumulation, allow for an objective comparison without concerns about threshold temperatures for specific crops. Accurately assessing the first consideration is difficult given the need for specific relationships between the index and species or cultivar and the importance of local site conditions that will not be simulated by the scale of the downscaled models. However, relative changes allow for a more flexible interpretation of changes based on local knowledge and experience.

In this project, the modified Utah chill model (Linvill 1990) was chosen. It was used in a recent Australian study on chilling and climate change by Hennessy and Clayton-Greene (1995). Results will provide a basis for comparison with this earlier study though there are some differences in the methods. Estimates of the proportionate change in chill hours will depend on which model is used (Luedeling et al 2009b).

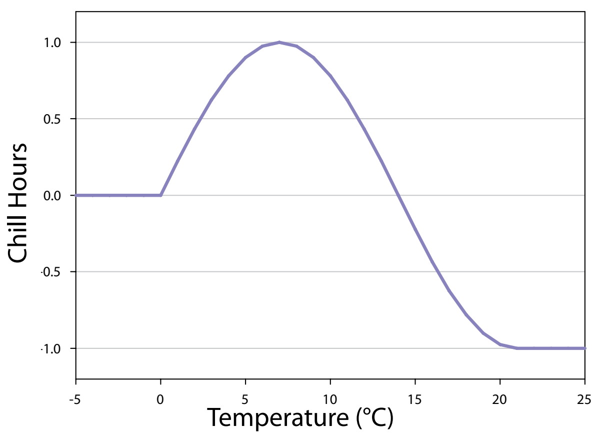


Figure 3.10 Chill units allocated for hourly temperatures using the modified Utah model.

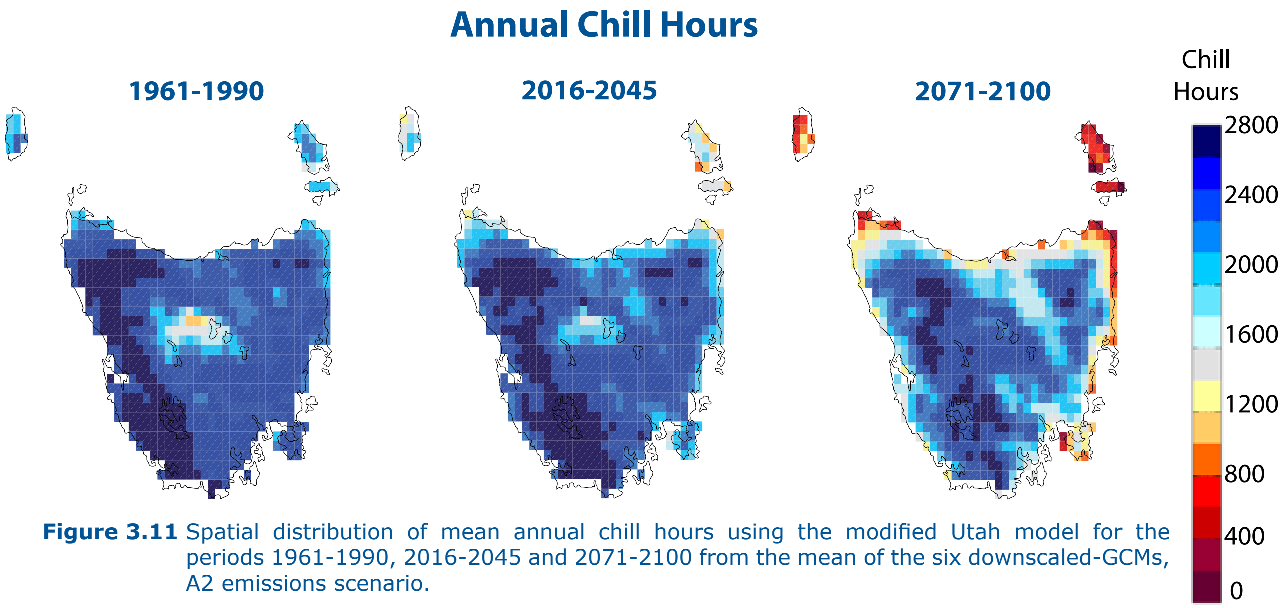


Figure 3.11 Spatial distribution of mean annual chill hours using the modified Utah model for the periods 1961-1990, 2016-2045 and 2071-2100 from the mean of the six downscaled-GCMs, A2 emissions scenario.

Chill hours were calculated using the function:

Equation 1

chill unit at (t) = 0 when $T(t) \leq 0$ °C

Equation 2

chill unit at (t) = $\sin(2\pi T(t)/28)$ when $0 < T(t) \leq 21$ °C

Equation 3

chill unit at (t) = -1 when $T(t) > 21$ °C

where T is temperature (°C) at hourly time (t).

As will be demonstrated, understanding the form of the sine function (Figure 3.10) is important to interpreting the spatial changes in accumulated chill.

Calculating chill hours depends on access to a dataset of hourly data. These hourly data are often interpolated from observed daily maximum and minimum temperatures using curves based on season and latitude (Baldocchi & Wong 2008; Hennessy & Clayton-Greene 1995; Luedeling et al 2009a). Our climate simulations contain screen temperatures. Hourly temperatures were linearly interpolated from three-hourly values to allow the calculation of chill hours from the simulations. Bias-adjusted simulations were not used because there are no three-hourly observational datasets to bias-adjust against, and comparisons between daily unadjusted minimum and maximum temperatures, and observed temperatures indicated that the models were sufficiently skilful to justify using the raw modelling outputs (Corney et al 2010). Chill units were accumulated from May to September inclusive. These months reflect the period between leaf fall and budburst in the baseline climate. However, increasing temperatures in future climates, particularly those in the period 2071-2100, may lead to negative accumulated chill in May and September in the low-elevation warmer sites and thereby underestimate the effective cumulative winter chill in warmer sites.

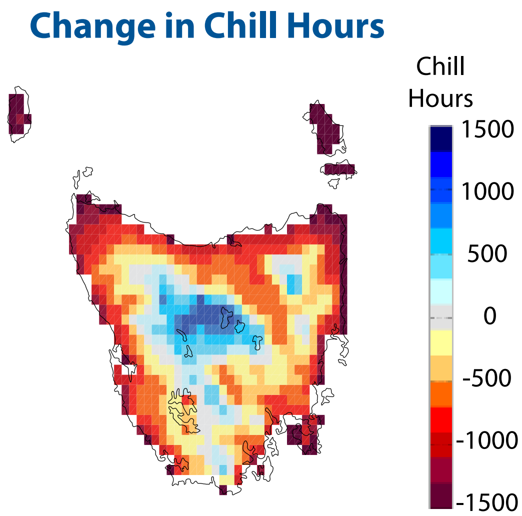


Figure 3.12 Change in annual accumulated chill hours using the modified Utah model for the periods 1961-1990 to 2071-2100, mean of six downscaled-GCMs, A2 emissions scenario.

Chill units for the baseline period were averaged over 30 years from 1961-1990. For the near future (2030), modelling outputs were averaged over the period 2016-2045, and for the end of the century (2085), modelling outputs from 2071-2100 were used.

Chill hours are strongly related to elevation lapse rate. Temperatures in each grid cell in the simulations depend on the mean elevation of all the points in that cell (based on 250 m Digital Elevation Model). Temperature outputs and accumulated chill from the modelling outputs should be interpreted in the context of the model elevation (Figure 2.2).

The change in the spatial pattern between the baseline and future periods (Figure 3.11 and Figure 3.12) is counterintuitive, as there are fewer chill hours at high elevation than at lower elevations. This difference is due to the high number of hours below zero at high elevation during the winter months that (according to the chill model used) do not contribute to cumulative chill. As the climate warms towards 2100, the frequency distributions of temperature move to the right through the temperature range that accumulates chill hours (Figure 3.10). At low-elevation sites, the frequency distribution moves out of the chill accumulation range and chill hours decrease. This phenomenon is demonstrated at Swansea and Spreyton where chill hours decrease by around 40% from 1975 to 2085 (Table 3.4). At high-elevation sites, temperatures move into the range of effective chill, thus chill hours increase, as demonstrated at Bronte Park (Figure 3.13), where chill hours increase by 24% from 1975 to 2085. Mid-elevation sites (Bothwell and Huon 394 m) are characterised by a transition through the range of effective chill and show a slight increase in chill for a period to around 2035, followed by a slight decline to 2100 as temperatures continue to increase.

Year-to-year variation in chill hours is projected to change. Low-elevation sites are likely to experience greater variation, high-elevation sites less. At the Huon 95 m site the standard deviation using all downscaled-GCMs increases from 83.2 chill hours for the period 1961-1990 to 245.5 chill hours for 2071-2100. In contrast, at Bronte Park, the standard deviation decreases from 120.7 chill hours to 91.6 chill hours over corresponding periods.

The reduction in chill hours at low-elevation sites may mean that some crops will accumulate insufficient chill hours to remain viable without some management or variety changes. This result is of particular relevance to blackcurrants that have a high chill requirement relative to other deciduous crops. Westmore (2004) found that some of the current blackcurrant production regions of Tasmania were becoming marginal and identified one of those areas as Glen Huon. Mean chill hours 1961-1990 calculated for an elevation comparable with Glen Huon was 2500 chill hours and this was used as the critical

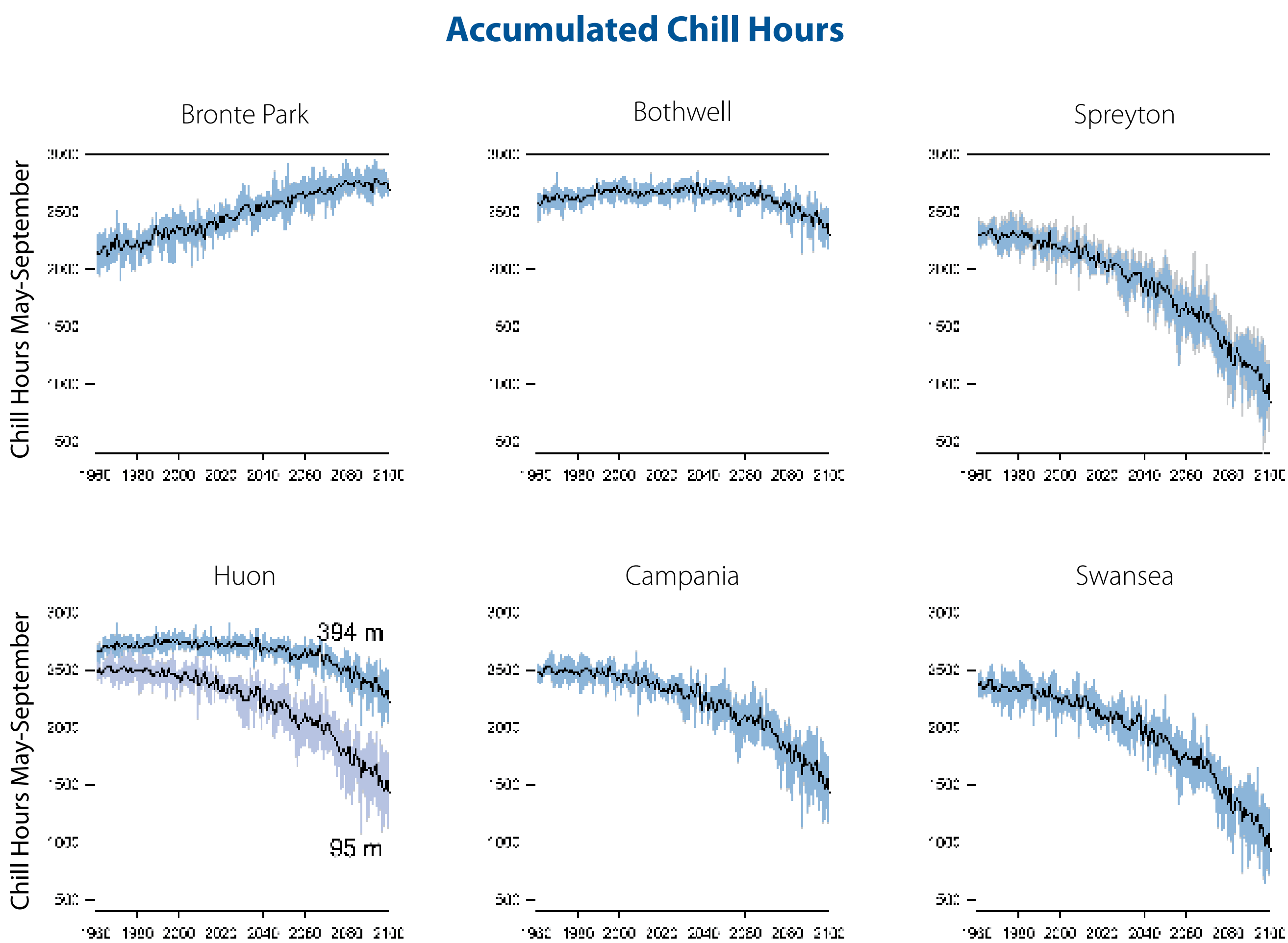


Figure 3.13 Accumulated chill hours May to September using the modified Utah model 1961-2100 for seven locations around Tasmania, mean (black line), minimum and maximum (shaded) of six downscaled-GCMs, A2 emissions scenario. Huon plot shows sites at two elevations (95 m and 394 m above sea level).

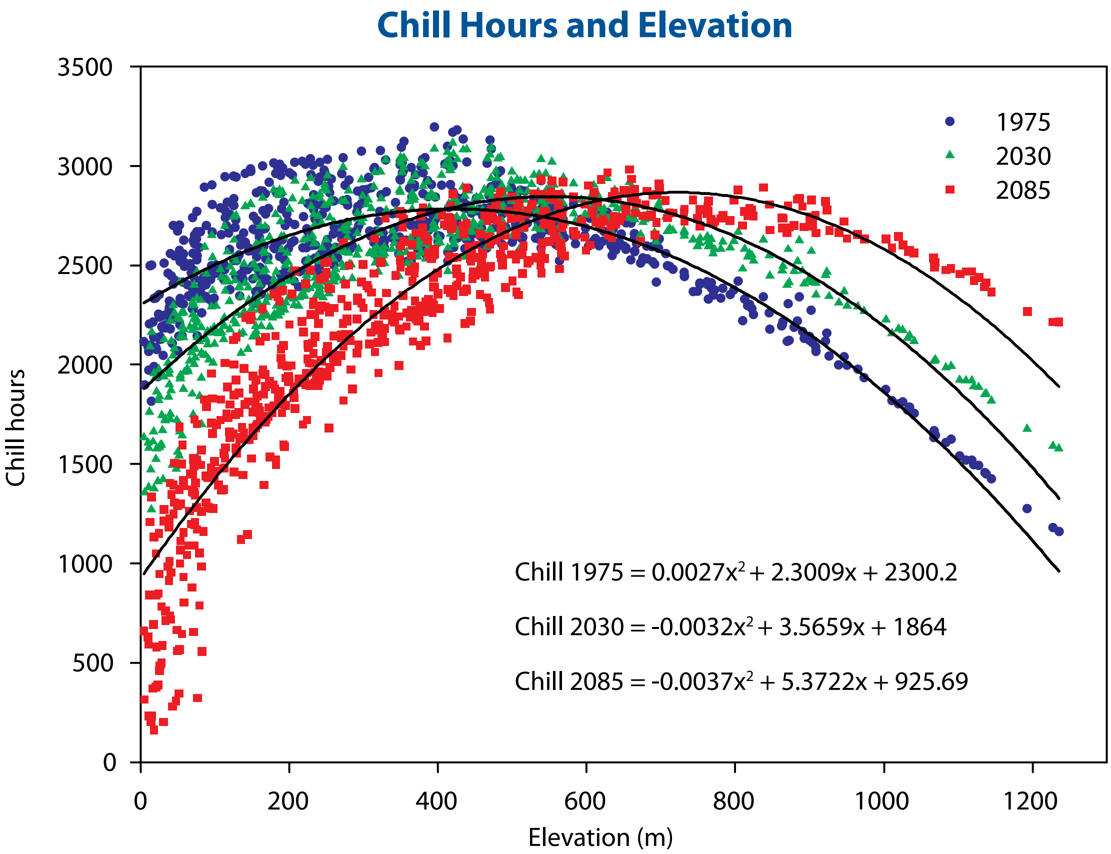


Figure 3.14 Relationship between accumulated chill hours (modified Utah model) and elevation for the periods 1961-1990 (1975), 2016-2045 (2030) and 2071-2100 (2085), downscaled-GCM GFDL-CM2.1, A2 emissions scenario.

Table 3.4 Accumulated chill hours (May-September) for seven sites around Tasmania, mean, minimum and maximum of six downscaled-GCMs for 30-year periods, A2 emissions scenario.

	Elevation (CCAM)	**1961-1990** Chill hours	**2016-2045** Chill hours	**2071-2100** Chill hours
Bronte Park	864 m	2215 (2182 – 2248)	2495 (2432 – 2564)	2736 (2671 – 2843)
Campania	160 m	2488 (2460 – 2505)	2298 (2259 – 2331)	1738 (1525 – 1854)
Bothwell	520 m	2624 (2602 – 2654)	2684 (2661 – 2726)	2498 (2385 – 2579)
Spreyton	38 m	2288 (2254 – 2321)	1971 (1887 – 2038)	1222 (998 – 1349)
Huon (95 m)	95 m	2497 (2474 – 2511)	2292 (2235 – 2334)	1705 (1476 – 1848)
Huon (394 m)	394 m	2710 (2692 – 2737)	2711 (2694 – 2747)	2437 (2294 – 2518)
Swansea	87 m	2342 (2319 -2358)	2046 (2003 – 2097)	1305 (1091 – 1441)

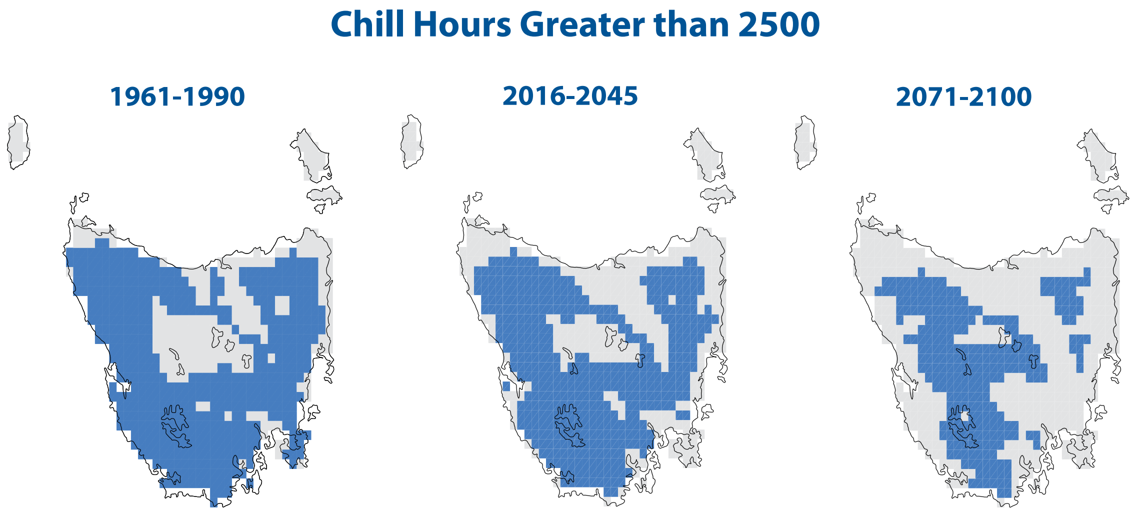


Figure 3.15 Grid cells with greater than 2500 accumulated chill hours (in blue) for the periods 1961-1990, 2016-2045 and 2071-2100, mean of six downscaled-GCMs, A2 emissions scenario.

threshold for blackcurrant production in Tasmania. Grid cells in which chill hours exceeded 2500 (shaded in Figure 3.15) for the periods 1975-1990, 2016-2045 and 2071-2100 indicate a contraction in the areas climatically suitable for blackcurrants. Fitting quadratic equations for the lines of best fit from Figure 3.14 for a minimum winter chill of 2500 chill units suggests that the suitable areas for blackcurrants currently lie between 98 m and 753 m above sea level. By 2030, the suitable elevations will be 223 m to 892 m and by 2085, 408 m to 1043 m. These elevation ranges are indicative only as mesoclimate significantly effects temperature profiles and accumulated chill. Nevertheless, the underlying principle is that given current genotypes, low-elevation sites are likely to have insufficient chill into the future for blackcurrant production. There is however, an opportunity for production to move to higher elevations, provided of course that sites with an acceptable incidence of spring frost and suitable topography for this mechanically harvested crop are available.

If the line of best fit from Figure 3.14 is solved for 1300 chill hours, an indicative value can be calculated for apple and pear varieties with relatively high chill requirements (Ghariani & Stebbins 1994; Thompson et al 1975) and for the leading sweet cherry varieties (Mahmood et al 2000). In general, varieties with requirements of less than 1300 chill hours should not be affected in Tasmania during the coming century. The results suggest that there will be adequate chilling at low elevations to 2030 but that by 2085, areas below 60 m above sea level may require attention to cultivars or other management inputs to deal with insufficient or marginal chill hours. Figure 3.16 shows locations in Tasmania with the percentage years in the 30-year period 2071-2100 for which accumulated chill hours are less than 1300. This suggests that there may be some low-elevation sites adjacent to the coast and on the Bass Strait islands that will have insufficient chill for some varieties of apples, pears and cherries.

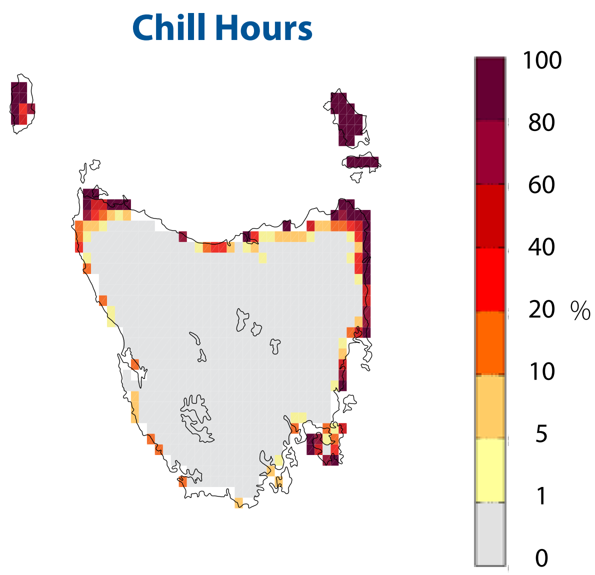


Figure 3.16 Percentage of years with less than 1300 chill hours 2071-2100, mean of six downscaled-GCMs, A2 emissions scenario.

3.4 Growing Degree Days

All of the downscaled simulations are consistent in predicting increases in both minimum and maximum temperature to 2100. These temperature trends are likely to have significant impacts on all levels of biota through increases in rates of metabolic processes and therefore, on rates of development. An increase in the rate of development leads to reduced times to crop maturity, changes to the most suitable crops or crop varieties and changes in yield and quality. In the absence of a specific growth model for the organism or crop of interest, a useful index to relate temperature and biological response is a cumulative thermal unit, such as growing degree days (McMaster & Wilhelm 1997). Growing degree days (GDD) have been used since 1735 (Mix et al 2010) and are calculated from daily (or monthly) minimum and maximum air (screen) temperature

Equation 4

$$GDD = \sum_{1}^{365}\left[\left(\frac{T\min + T\max}{2}\right) - \text{Threshold}\right]$$

where Tmin and Tmax are daily minimum and maximum temperature and the threshold or base temperature is chosen to represent a temperature above which the organism or crop begins to develop and grow. The most commonly used threshold temperature is 10 °C and GDD are generally accumulated from the time of planting, or in the case of deciduous crops, budburst. For the latter, GDD accumulation between the completion of winter dormancy and budburst may also determine time of budburst. This has important ramifications for exposure of newly opened buds to damaging frosts (see earlier discussion of frost).

Growing degree days have been used for many different applications. Cho and Son (2007) used GDD with a baseline temperature of 13.5 °C to quantify leaf development of pak-choi. Olivier and Annandale (1998) used GDD to quantify time to germination, emergence and harvest of peas. Mix et al (2010) demonstrated significant reductions in growing season length in Colorado using threshold temperatures of 10 °C (cereals), 5.5 °C (alfalfa) and 4.4 °C (potato). Jovanovic et al (1999) calculated the GDD required to harvest time in vegetables ranged from 656 GDD to 1234 GDD for lettuce and cabbage respectively, using threshold temperatures of 7.2 °C and 4.4 °C. Ojeda-Bustamante et al (2004) used GDD to schedule irrigation in potatoes and Villordon et al (2009) used a threshold of 15 °C to predict harvest date in sweet potatoes. Patterns in pasture growth on the South Island of New Zealand are strongly correlated with GDD (Hutchinson et al 2000) and a high-density network of climate stations was established to measure GDD and better manage pasture growth based on a threshold of 4 °C (though 5 °C is commonly used for temperate pastures). In Tasmania, GDD have also been used to quantify and predict the dynamics of a forest pest (*Paropsisterna agricola*) (Nahrung & Allen 2004; Nahrung et al 2004) and multi-trophic interactions (Rice & Allen 2009). Kim et al (2000) forecast the emergence of peach fruit moth (*Carposina sasakii*) in apple orchards in Korea using GDD.

As can be seen from the preceding examples, GDD can be used for many different and specific applications in Tasmania. In this report, two potential applications will demonstrate the trends and nature of the impact from the projected changes in GDD. It should be noted that GDD represent only the impact of temperature. Changes in other climate variables such as rainfall and carbon dioxide concentrations need more comprehensive models to fully evaluate the impact of climate change on a crop or pest species. For example, crop and pasture growth will be addressed in section 4 of the report using growth models that incorporate more biological and climate processes.

Growing degree days were calculated using bias-adjusted simulations from each of the six GCM modelling outputs for the A2 emissions scenario and compared to GDDs calculated from the AWAP data for the period 1961-2007 for all grid cells across Tasmania. The GDD indices calculated from the bias-adjusted data were strongly correlated with those calculated from the AWAP data (Figure 3.17).

The GDD were calculated using a 10 °C threshold. Using this general threshold, six sites were selected to represent agricultural regions, including King Island, the north-west coast from Burnie, Kindred to Deloraine, Scottsdale in the north-east and the Coal Valley in the south. GDD were calculated

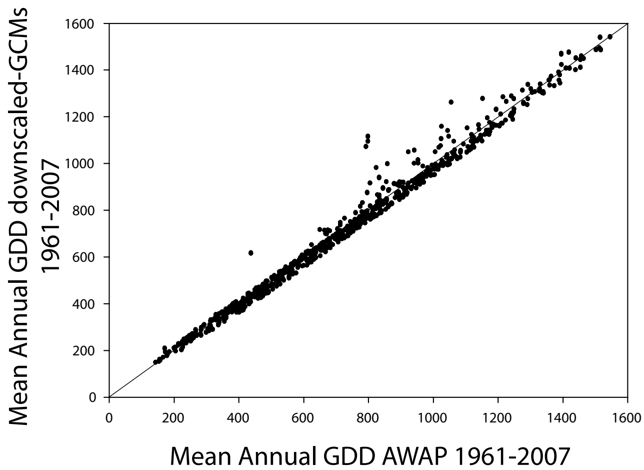


Figure 3.17 Correlation between mean annual GDD calculated from AWAP and the mean of six downscaled-GCMs, 1961-2007, for all grid cells across Tasmania.

as accumulating from July 1. An arbitrary target threshold of 1000 GDD was used to demonstrate changes to time to harvest, though the target value depends on the particular crop of interest.

The projections suggest that there will be a gradual increase in annual GDD for each grid cell across the state from 1961 to 2100 (Figure 3.18 and Figure 3.19). Agricultural regions can expect increases of 600 to 800 GDD (Figure 3.19 a) or increases of 60% to 90% on 1975 levels (Figure 3.19 b). These changes are likely to have a significant impact on the choice of crops, length of growing season, and on yield and quality. Some aspects of these changes are presented below.

The increases in GDD are also likely to have significant implications for native vegetation due to changes in, for example, growth rates of vegetation. They are likely to change the competitive advantage of different plant species. This change in competitive advantage is likely to lead to changes in the distributions of species and of communities. The projections suggest that the higher elevation sites will experience the greatest relative increases in GDD. This is particularly likely to have an impact on those species that exist within narrow elevation intervals. There are also likely to be other indirect impacts on native plant communities through changes to the population dynamics of herbivores, particularly insects, and on the parasites that feed on those herbivores. These are complex changes that are difficult, if not impossible, to predict with any certainty, and need to be evaluated case by case.

Annual GDD and the number of days to reach a target of 1000 GDD for the (30-year) climates representing 1975, 2030 and 2085 for some agricultural areas are given in Table 3.5. The sites demonstrate a range of different thermal characteristics of regions in Tasmania. Some sites on average do not achieve 1000 GDD under the baseline climate (for example, Deloraine). However, the general trend is clear: the projections suggest that there will be substantial increases in GDD and reductions in the length of time to crop maturity (more than 20%) during the 21st century. The steeper curve around harvest in 2085 suggests narrower harvesting windows for vegetable crops (Figure 3.20 and A Gracie pers comm 18 October 2010).

For the reference period (1961-1990), there are few GDD accumulated prior to October (Figure 3.20). Projections indicate the start of the growing season will begin earlier at all sites. For example, in the Coal Valley under the baseline climate, approximately 50 GDD will accumulate by October 1. The projections suggest 50 GDD will accumulate by 9 September in 2030 and by 13 August in 2085.

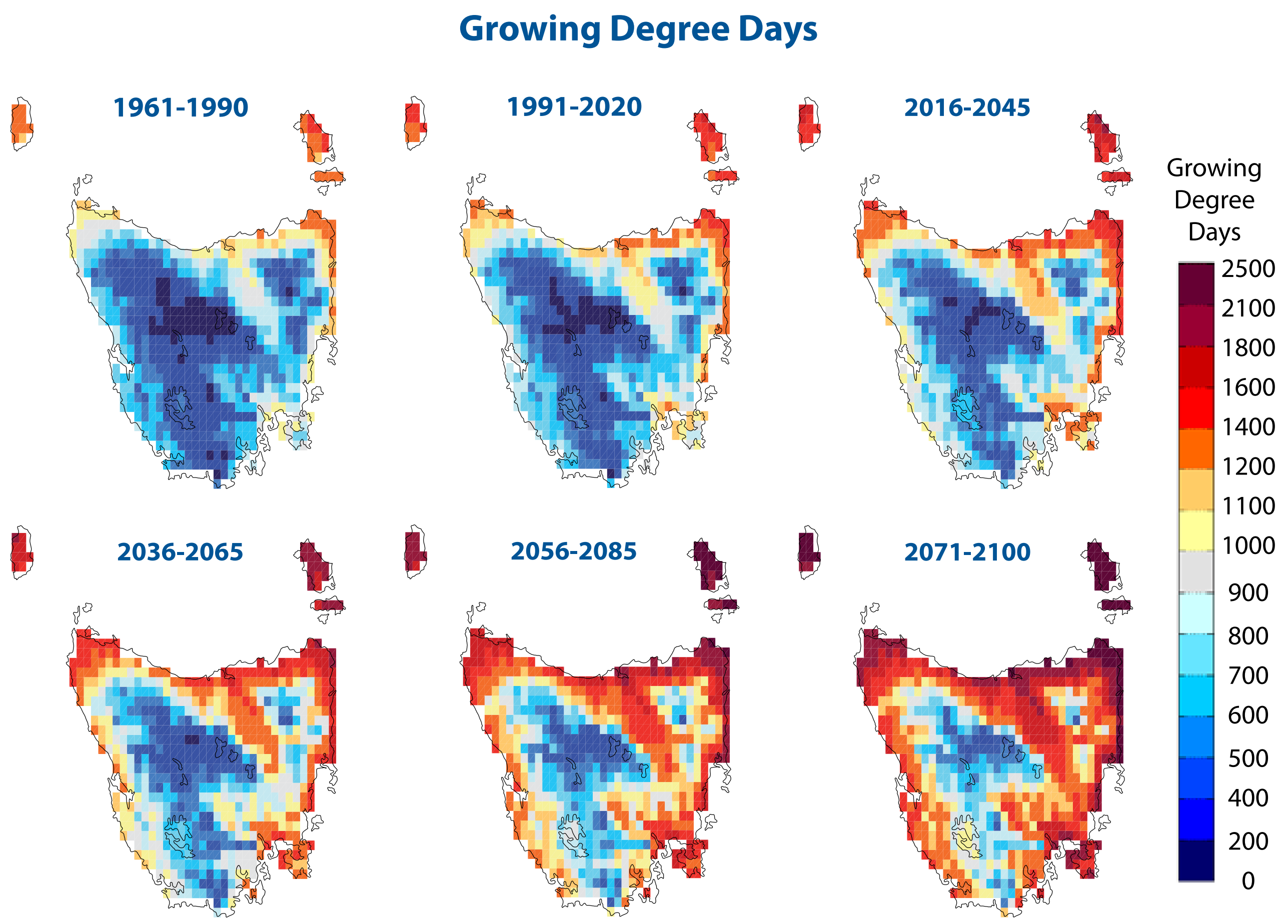


Figure 3.18 Annual growing degree days (GDD, 10 °C) for six periods. Mean GDD from six downscaled-GCMs, A2 emissions scenario.

Change in Growing Degree Days

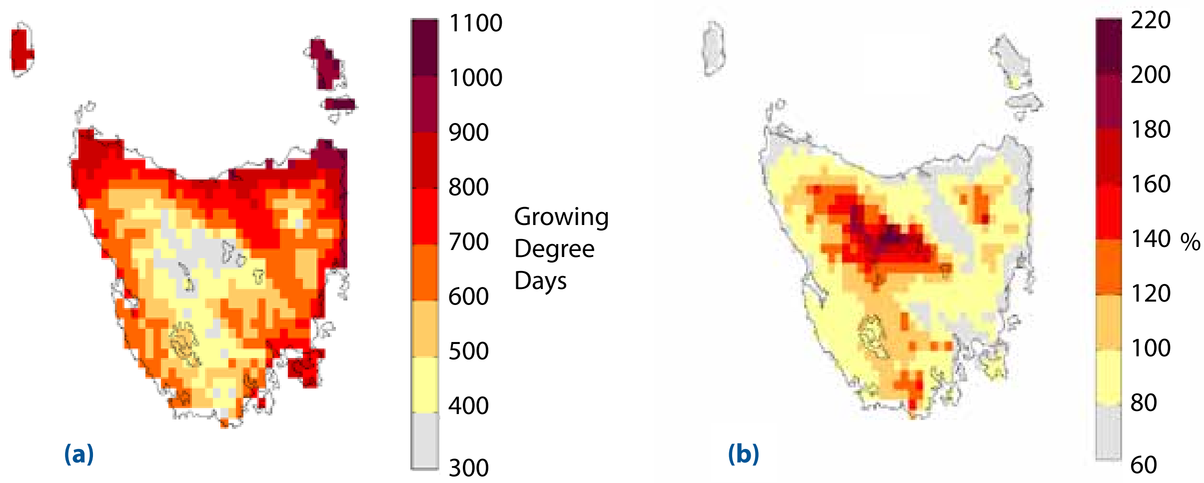


Figure 3.19 Change in mean annual GDD (10 °C) from 1961-1990 to 2071-2100 (a) and (b) percent change, mean of six downscaled-GCMs, A2 emissions scenario.

Table 3.5 Annual GDD (10 °C) and days to target of 1000 GDD (10 °C) from July 1 for three periods, mean of six downscaled-GCMs, A2 emissions scenario.

	1961-1990		2016-2045		2071-2100	
	Annual GDD	Days to target	Annual GDD	Days to target	Annual GDD	Days to target
King Island	1328	262	1628	235	2174	200
Smithton	1036	324	1314	259	1840	217
Kindred	964	349	1232	269	1755	223
Deloraine	760	365	988	333	1447	238
Scottsdale	1009	329	1274	259	1803	219
Coal Valley	1154	277	1410	243	1905	207

Growing Degree Days

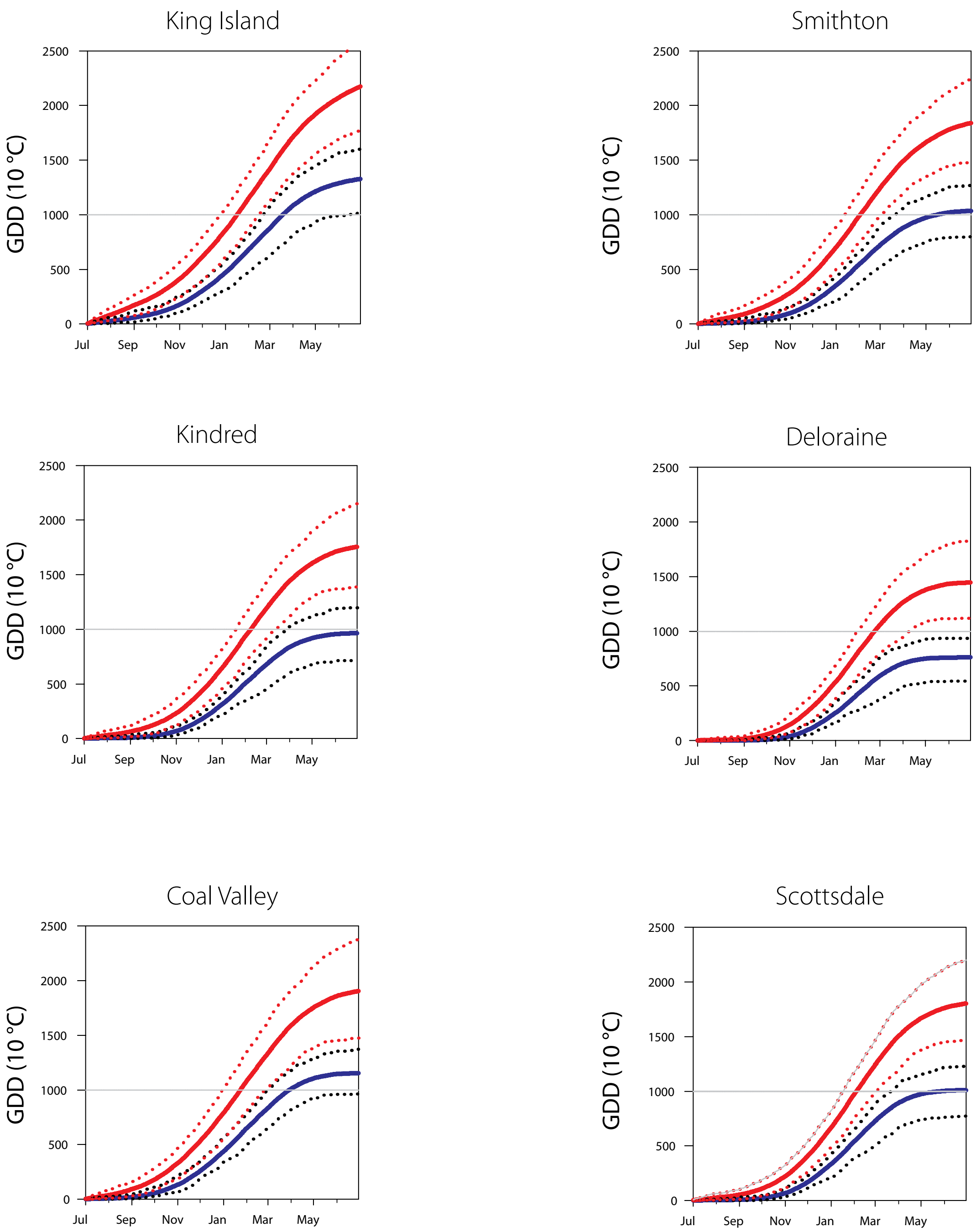


Figure 3.20 GDD (10 °C) accumulated from July 1 for six sites representing agricultural areas in Tasmania (see Figure 2.4), mean of six downscaled-GCMs, A2 emissions scenario, (▬) 1961-1990, (▬) 2071-2100, (▪▪▪ and ▪▪▪) indicate daily range across GCMs and (▬) 1000 GDD.

4 Impact on crops, pastures and land use

4.1 Pasture Production

Profitability of Tasmanian dairy farms is in part dependent on reliable and high-quality pasture that provides the base of the feed supply (Chapman et al 2008). Dairy pastures are based predominantly on perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). These pastures are intensively managed with high fertiliser inputs and with large areas of irrigation. Grazing of sheep and beef cattle is generally undertaken with less fertiliser and irrigation than dairying. Extensive grazing farming systems also rely on ryegrass and white clover in high-rainfall areas but in low-rainfall areas such as the midlands pasture species include phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*) and subclover (*Trifolium subterraneum*). These species yield more reliably than ryegrass under low rainfall and are generally managed with fewer inputs, mainly phosphorus fertiliser, with little or no nitrogen applied.

The impact on dairy pastures of the projected changes in climate in Tasmania have been addressed in this report by using the pasture growth model DairyMod 4.7.5 (Johnson et al 2008). DairyMod has been shown to be an accurate biophysical model for estimating pasture growth for Australian pastoral regions (Cullen et al 2008) and Tasmanian conditions (Rawnsley et al 2009). Growth response to elevated CO_2 and the explanation for dealing with elevated CO_2 in the model are given in Cullen et al(2009). The model was parameterised to simulate a perennial ryegrass pasture. The model was run as nutrient non-limited. Dairy farmers attempt to maintain pasture soil fertility at optimum levels. This maximises the production of grass, which is the cheapest component of the feedbase.

Carbon dioxide concentrations were increased annually from 1961 to 2100 consistent with the A2 emissions scenario - that is, from around 320 ppm CO_2 in 1961 to 820 ppm CO_2 in 2100. Climate datasets used in the pasture modelling came from downscaled modelling outputs from each of the six downscaled-GCMs (CSIRO-Mk3.5, GFDL-CM2.0, GFDL-CM2.1, ECHAM5/MPI-OM, MIROC3.2(medres) and UKMO-HadCM3). Each climate dataset was run independently. The same soil physical and chemical parameters (deep clay loam) were used across all sites as the primary aim was to evaluate climate differences and trends. Both dryland and fully irrigated options were simulated at each site.

DairyMod was run from 1961-2100 in daily time steps with the first 10 years of results discarded to allow the model to equilibrate. The metrics used to measure and explain changes in productivity were annual and monthly cut yield (kg dry matter (DM)·ha^{-1}) where the pasture was harvested to a residual of 1400 kg DM·ha^{-1}. Threshold temperatures for pasture growth stress were 28 °C (Mitchell 1956; Waller & Sale 2001) and 2 °C (model defaults) above and below which a recovery period for the pasture was required. Growth limiting factors (on a scale of 0 to 1) were recorded for temperature and water. Growth was non-limited when the Growth Limiting Factor (GLF) was one and becomes increasingly more limited as the GLF decreases towards zero. The simulations of irrigated pasture production were the same as for dryland but with an irrigation scheduled when the GLFwater fell below 0.9. This ensured water was essentially non-limiting for pasture growth.

Yields simulated by DairyMod do not take account of changes to sward density or botanical composition that result from elevated CO_2 or from preceding adverse conditions such as severe cold or dry. Therefore, yields may be overestimated in locations subjected to extreme conditions.

Climate projections for six sites were chosen to represent the dairying areas of the north-west and King Island (Woolnorth), central-north (Flowerdale and Merseylea), the northern midlands (Cressy), the north-east (Ringarooma) and the south (Ouse).

At Tunbridge and Bothwell, extensive grazing systems were simulated using the Sustainable Grazing Systems (SGS) Pasture Model (Johnson et al 2003), which is essentially the same as DairyMod. These sites represent lower rainfall and lower potential pasture growth areas. The sites were parameterised with duplex soil profiles, with a phalaris and subclover pasture that was cut to a residual of 750 kg DM·ha^{-1}. Nutrients from cut pasture were returned to the soil as dung and urine and are therefore mostly non-limiting under this regime. Only GFDL-CM2.1 climate projections were used with the A2 emissions scenario.

4.1.1 Intensive dryland pasture production

Annual cut yield of ryegrass under dryland conditions is projected to increase significantly over the course of this century at all simulated sites (Figure 4.1). Yield increases are largest at the sites with the lowest potential baseline yield (for example, Ouse +85% and Cressy +103%). These increases are approximately linear throughout the modelling period (Table 4.1). These sites (as are many in Tasmania) are primarily temperature-limited under current climate conditions (Figure 4.2) and it is the temperature growth limiting factor (GLFtemperature) that the pasture modelling indicates will decrease most into the future (Figures 4.2 and 4.3). There are, however, small projected increases in mean annual rainfall at some sites that may also contribute to the increase in yields.

Yield increases at those sites with currently high potential yields are projected to increase less than the current lower yielding sites and also to reach a threshold throughout the course of this century. The explanation is likely to be due at least in part to high temperatures that will be discussed in the following section on irrigated pastures.

The increase in pasture yields by 2071-2100 comes mostly from an earlier start to and higher production during spring (Figure 4.4). At those sites that are primarily temperature-limited, the winter-spring break is projected to be a month or two earlier than the current climate. Sites that currently have relatively mild spring temperatures, such as Woolnorth, are not projected to substantially change the timing of pasture production but there should be more feed available in spring and early summer. These changes are likely to affect fodder conservation and fertiliser strategies on farms. It is likely then there will be increased emphasis on hay and silage production and a greater demand for nitrogen fertiliser (and other nutrients) if these potential increases in growth are to be captured.

Simulated Dryland Ryegrass Yields

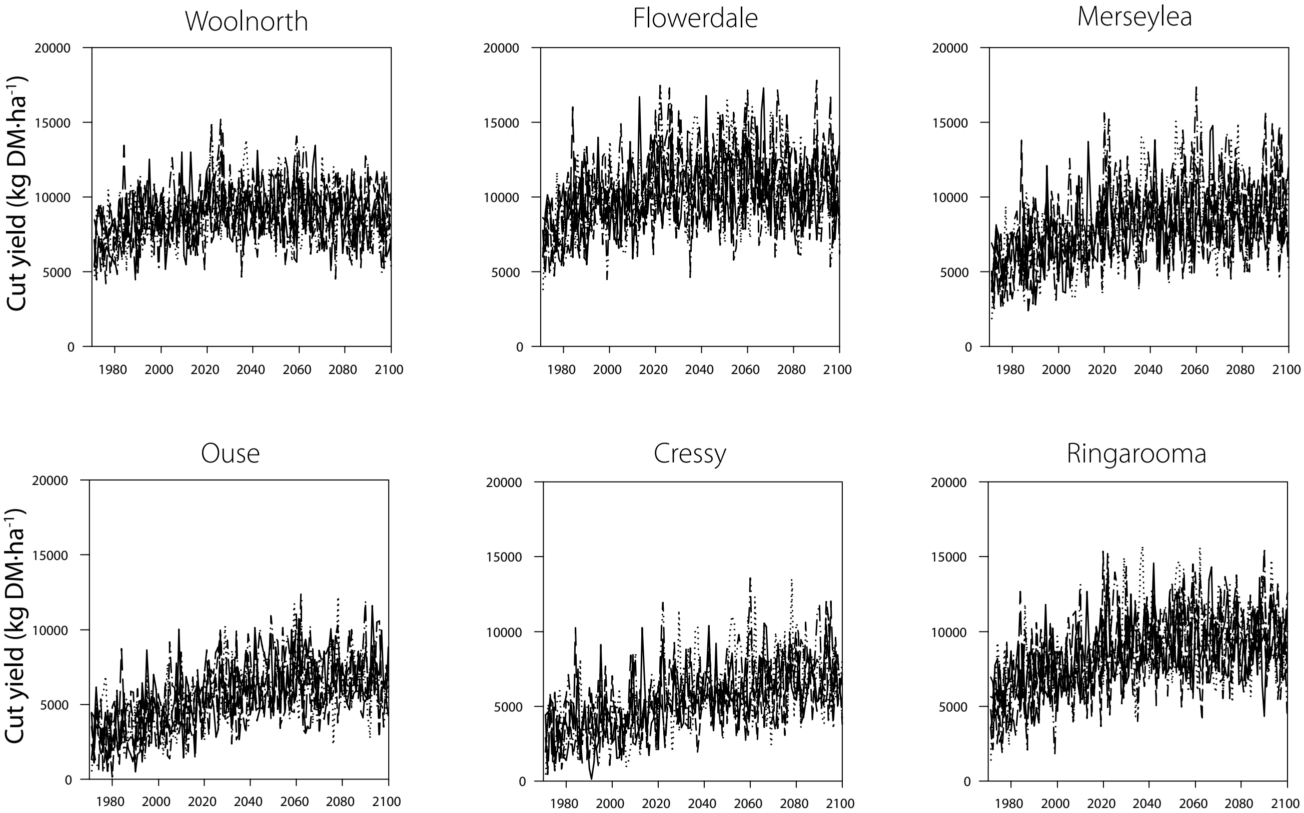


Figure 4.1 Annual cut yield (kg DM·ha^{-1}) of dryland perennial ryegrass for pasture simulations using six downscaled-GCMs, A2 emissions scenario over the period 1971 to 2100.

Growth Limiting Factors

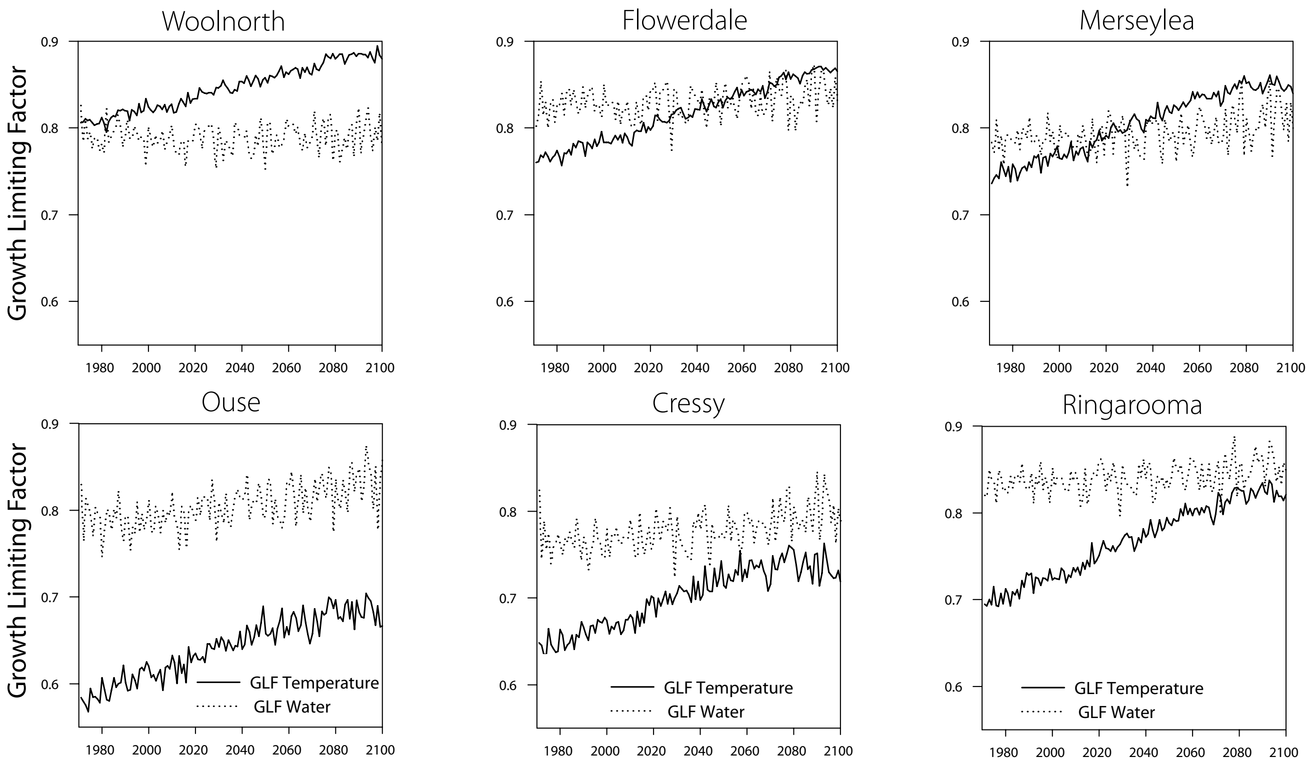


Figure 4.2 Annual mean of Growth Limiting Factors (DairyMod) for temperature and water for dryland ryegrass at six sites over the period 1971-2100, mean of pasture simulations using six downscaled-GCMs, A2 emissions scenario.

Table 4.1 Annual cut yield (kg DM·ha^{-1}) of dryland ryegrass and projected change in mean annual rainfall, A2 emissions scenario, mean of pasture simulations using six downscaled-GCMs for the periods 1971-2000 to 2071-2100.

	Woolnorth	Flowerdale	Merseylea	Ouse	Cressy	Ringarooma
1971-2000 kg DM·ha^{-1}	7954	8847	6140	3604	3571	6399
2071-2100 kg DM·ha^{-1}	8757	10754	9250	6676	7243	9468
% change cut yield	+10	+21	+51	+85	+103	+48
% change mean annual rainfall	+0.4%	-0.7%	+4.3%	+4.6%	+5.6%	+5.2%

Growth Limiting Factors

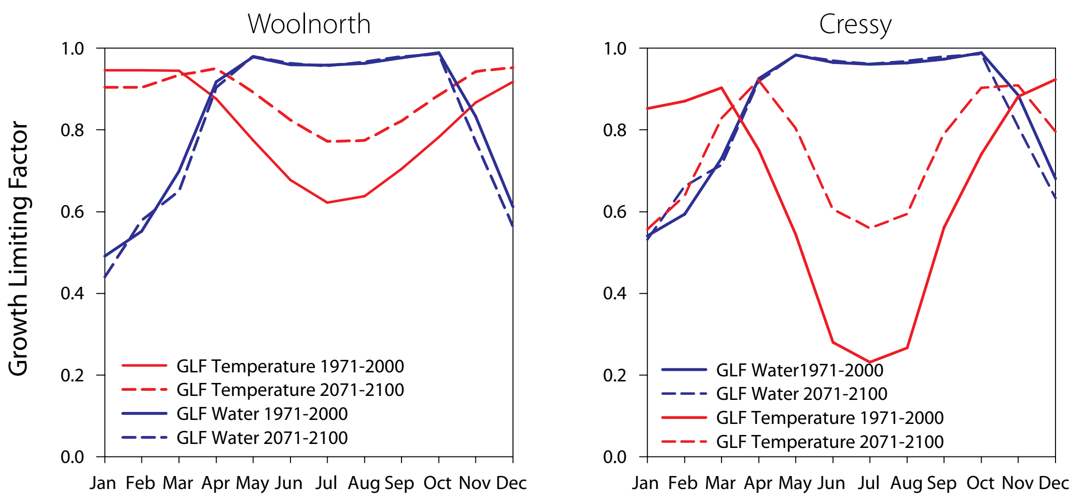


Figure 4.3 Monthly mean of Growth Limiting Factors (water and temperature) for dryland ryegrass at Cressy and Woolnorth 1971-2000 to 2071-2100, mean of pasture simulations using six downscaled-GCMs, A2 emissions scenario.

Monthly Dryland Pasture Yield

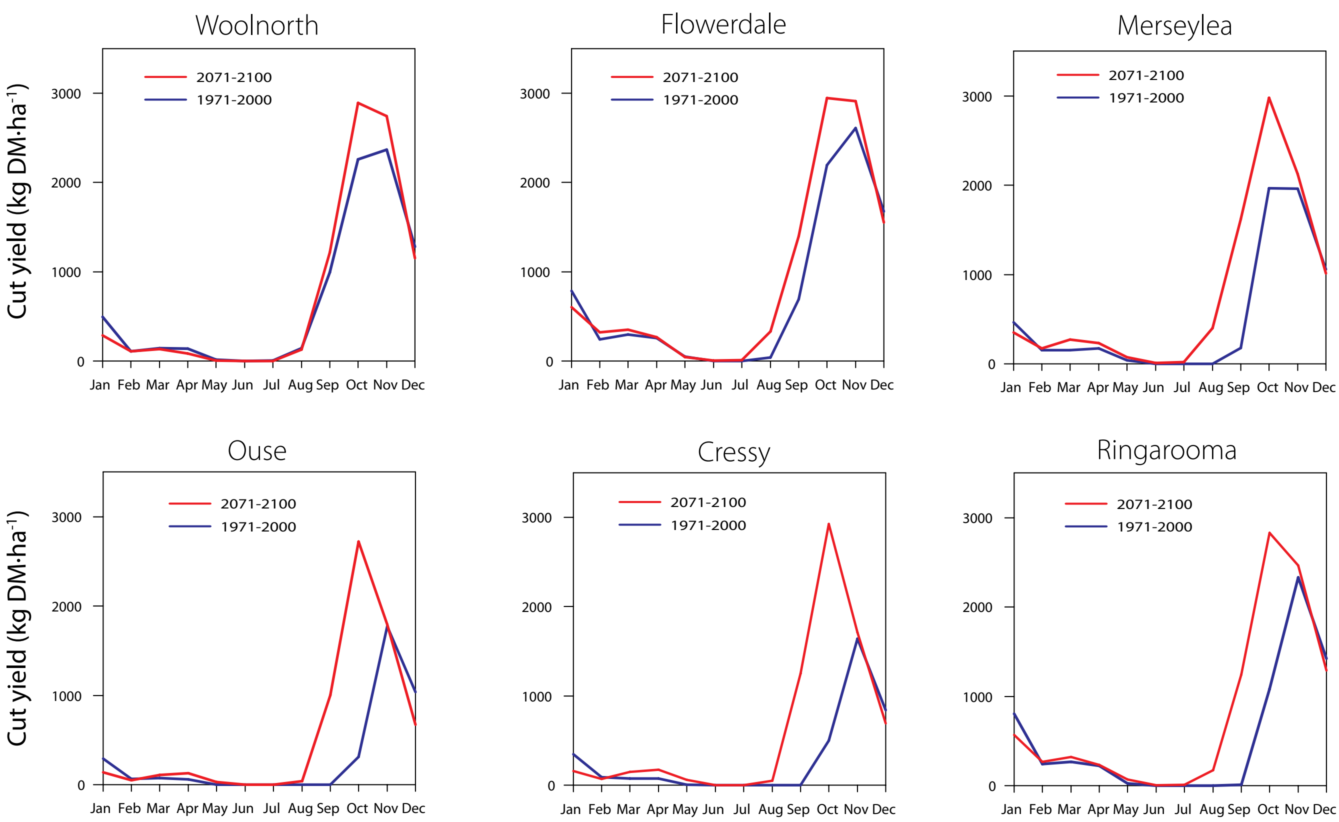


Figure 4.4 Monthly cut yield (kg $DM \cdot ha^{-1}$) of dryland ryegrass at six sites, 1971-2000 to 2071-2100, mean of pasture simulations using six downscaled-GCMs, A2 emissions scenario.

4.1.2 Irrigated pasture production

Cut yields of irrigated ryegrass are projected to increase by 20% to 25% (Figure 4.5) until around 2040 at all of the simulated sites. Thereafter, yields are projected to decrease to a level 0% to 15% above baseline by 2071-2100 (Table 4.2). Inter-annual variability is projected to increase after about 2040 (Figure 4.5).

Rising temperature is the main driver of increasing annual pasture yield to 2040. Irrigated pasture yields are projected to increase in all months to around 2020. However, after 2020, monthly yields during the summer months begin to decline (Figure 4.6). This decline is offset to 2040 by increased growth in other months, mainly spring. Yields in August to October are projected to continue to rise after 2040. The probable cause for the decrease in yields later in the century is the increase in the number of days above 28 °C (Figure 4.7), a critical upper threshold for ryegrass.

Cressy was chosen to demonstrate the impacts of higher summer temperatures. Figure 4.7 shows that at Cressy, the GLFtemperature decreases over the period 1971-2100 during summer months. Coincident with the decreasing GLFtemperature is an increase in the number of days per month in January and February above 28 °C, from 2-4 days around 1961 to 8-14 days per month by 2100. Plots of monthly cut yield and number of days above 28 °C in Figure 4.8 show that for the months with the greatest reduction in growth (January and February), monthly cut yield decreases by 240-250 kg DM·ha^{-1} for each day in December, January and February with temperatures higher than 28 °C and 200 kg DM·ha^{-1} for each day in March.

Ease of management and the high feed quality of ryegrass and white clover pastures underpin the profitability and competitive advantage of Tasmanian dairying. Under an A2 emissions scenario, yields from irrigated pastures are projected to increase to about the middle of the century. After this time, better adapted cultivars or alternative pasture species may be needed to meet summer feed demands as increasingly higher temperatures have a negative impact on ryegrass yields.

Finally in this section, some preliminary results are presented about future water demands for irrigated pastures. There are competing factors that need to be resolved when estimating future irrigation water requirements. Firstly, water demand is driven by the potential evapotranspiration of the crop. This is in part a function of the crop size or yield. In the case of ryegrass, growth projections later in the century suggest that growth of C3 pastures will be limited by increasing temperatures (Figures 4.5, 4.6 and 4.7) and these lower yields mean that there will be a reduction in irrigation water required.

Table 4.2 Annual cut yield (kg DM·ha^{-1}) of irrigated ryegrass for the periods 1971-2000, 2026-2055 and 2071-2100 and projected change from 1971-2000 at six sites across Tasmania, mean of pasture simulations using six downscaled-GCMs, A2 emissions scenario.

	Woolnorth	Flowerdale	Merseylea	Ouse	Cressy	Ringarooma
1971-2000 kg DM·ha^{-1}	17340	17308	17050	10738	13282	14450
2026-2055 kg DM·ha^{-1}	20752	21228	21321	13786	16730	18450
2071-2100 kg DM·ha^{-1}	19111	19927	19375	11220	13726	16900
% change 2026-2055	+20	+23	+22	+28	+26	+28
% change 2071-2100	+10	+15	+10	+4	+3	+17

Irrigated Pasture Yields

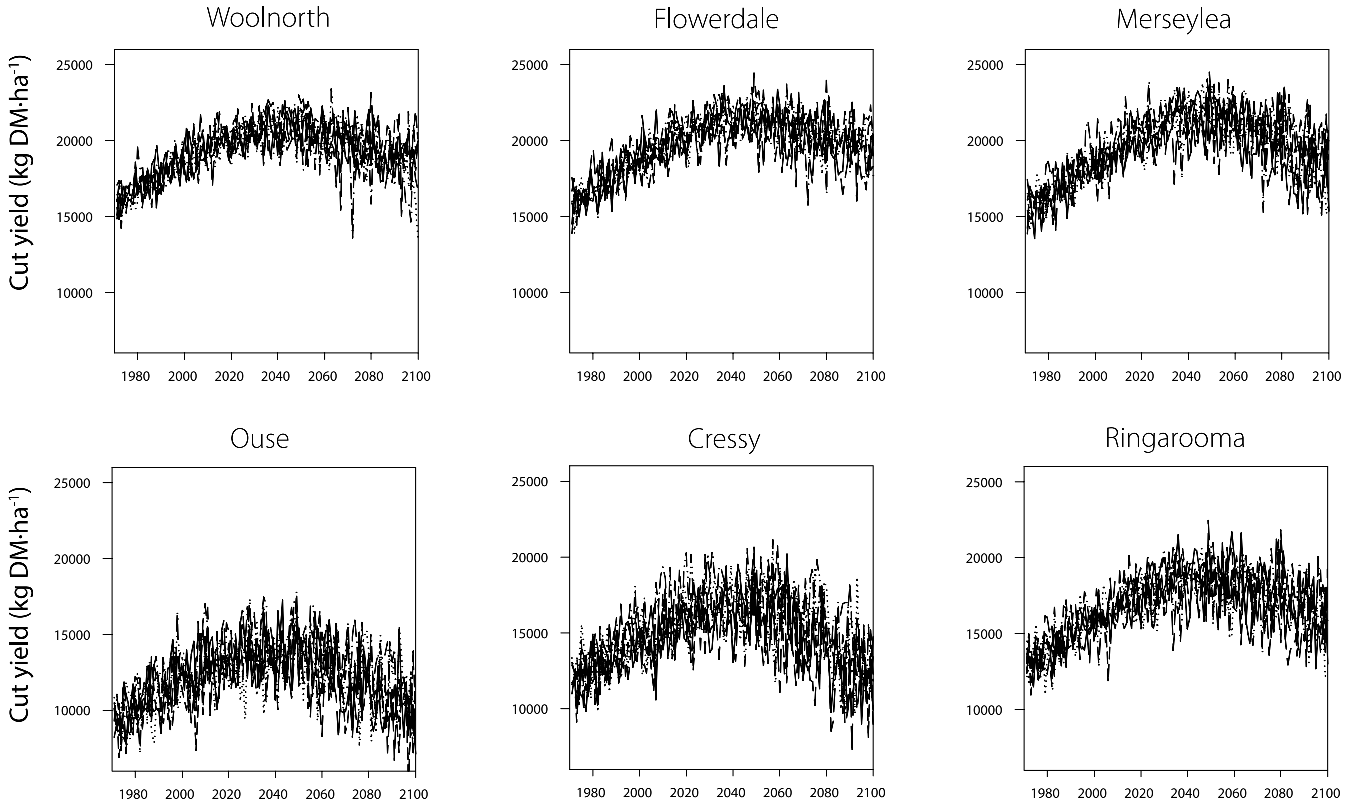


Figure 4.5 Annual cut yield (kg DM·ha⁻¹) of irrigated perennial ryegrass, 1971-2100, pasture simulations using six downscaled-GCMs, A2 emissions scenario.

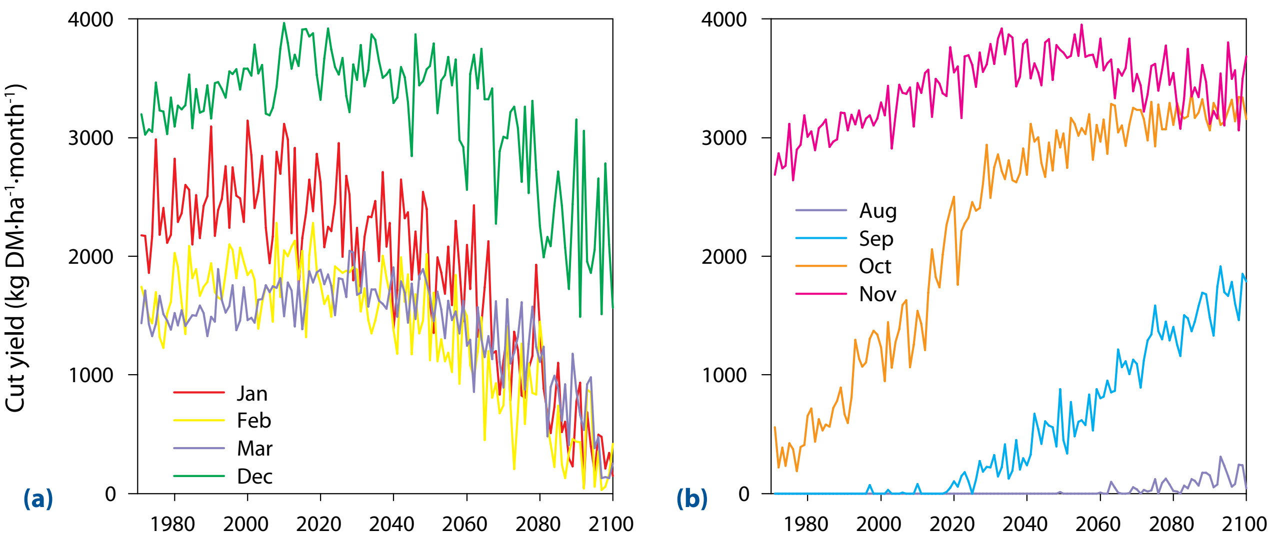


Figure 4.6 Monthly cut yield (kg DM·ha⁻¹) of irrigated ryegrass for (a) selected summer months and (b) selected spring months at Cressy, mean of pasture simulations using six downscaled-GCMs, A2 emissions scenario.

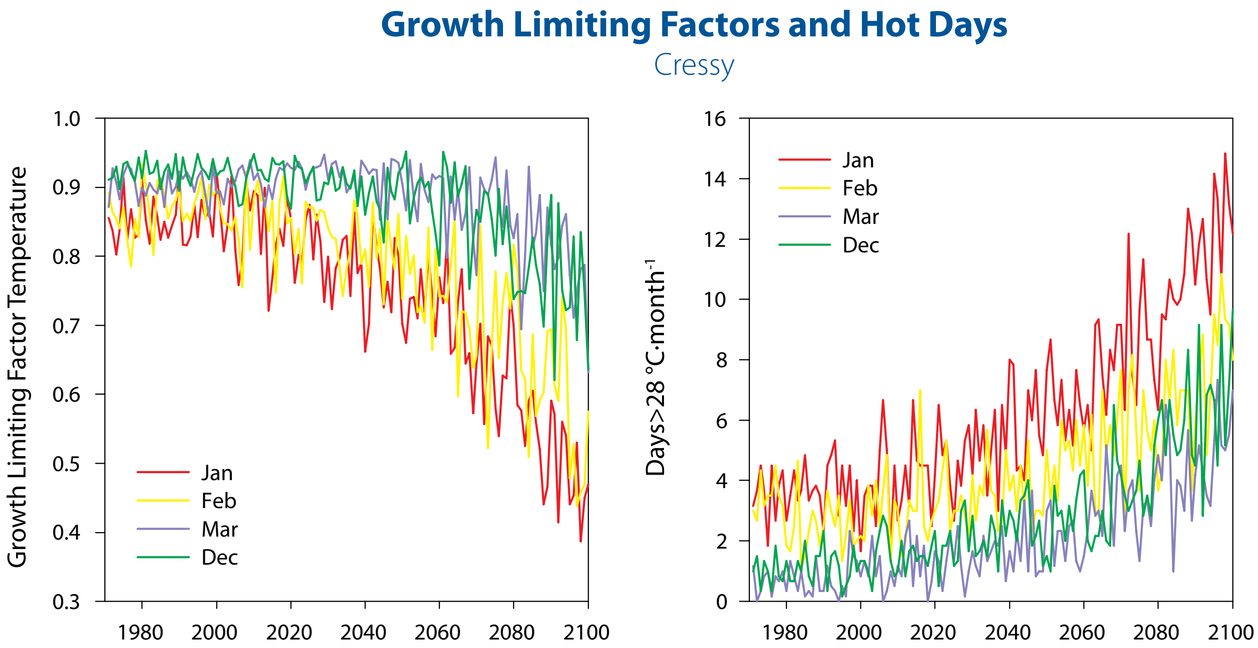


Figure 4.7 Growth Limiting Factor temperature for irrigated ryegrass and days·month^{-1} greater than 28 °C at Cressy for summer months (December to March), mean of pasture simulations using six downscaled-GCMs, A2 missions scenario.

C3 and C4 plants have different photosynthetic pathways and differences in plant anatomy. C3 plants (the most common plants) are better adapted and more efficient in cool, cloudy and moist conditions, while C4 plants are better adapted to high temperature, high light and low moisture. C4 plants have higher water use efficiencies - that is, they fix more carbon per unit of water transpired than C3 plants. Offsetting the potential increased growth of C4 plants is the generally lower digestibility and lower feed quality when compared to a C3 grass such as ryegrass.

Estimates of water use based on C3 pastures may not properly reflect future irrigation demands if farmers opt for higher productivity crops that can take advantage of the projected temperature increases. For example, replacing C3 pastures with C4 pastures means that pasture growth is less limited by high temperature, yields are maximised but potentially, more irrigation water is used. However, offsetting these demands on water supply due to higher yields is the influence of elevated CO_2 on water use efficiency. Under elevated CO_2 concentrations, C4 plants have less potential for increased yields and water use efficiency than C3 plants. DairyMod was used to quantify some of the impacts from these factors on water use efficiency and yield.

Kikuyu (*Pennisetum clandestinum*) was used to represent C4 pastures (though any C4 pasture would be suitable for this exercise). Kikuyu was modelled as an irrigated crop at Cressy using DairyMod with the same soil properties and management as used for ryegrass (that is, using six downscaled-GCMs and the A2 emissions scenario as input to the pasture simulations).

Yields of kikuyu increased linearly to the end of the century (Figure 4.9). The GLFtemperature consistently becomes less limiting as this species is not negatively affected by the higher temperatures.

Under the increasing carbon dioxide concentrations in the A2 emissions scenario, irrigation demands for kikuyu towards the end of the century are projected to remain about the same as those in the baseline period (Figure 4.9). This is despite the projected yield increases of nearly 50% above the 1971-2000 baseline.

In contrast, ryegrass yields are projected to increase by around 25% by 2040, at which time irrigation demand will remain about the same as that during the baseline period 1971-2000. Yields decrease after 2040 to be similar to those during the baseline period, but irrigation demand is projected to be also about 8% less.

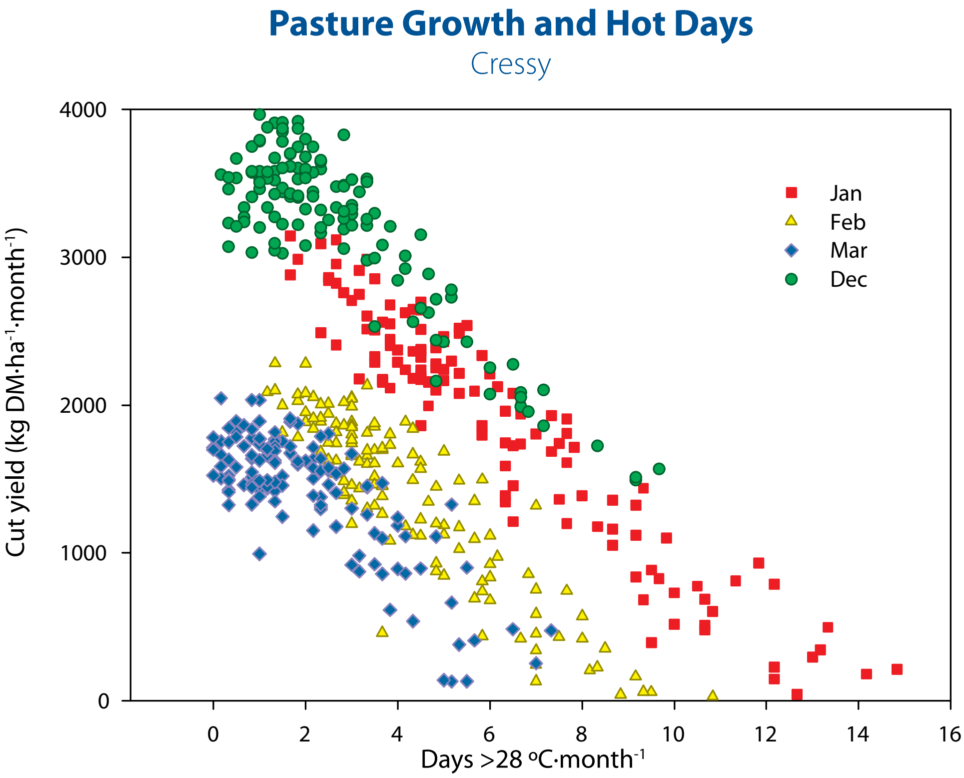


Figure 4.8 Relationship between monthly cut yield (kg DM·ha⁻¹) of irrigated ryegrass and number of days greater than 28 °C·month⁻¹ for December, January, February and March at Cressy, mean of pasture simulations from six downscaled-GCMs, A2 emissions scenario, 1971-2100.

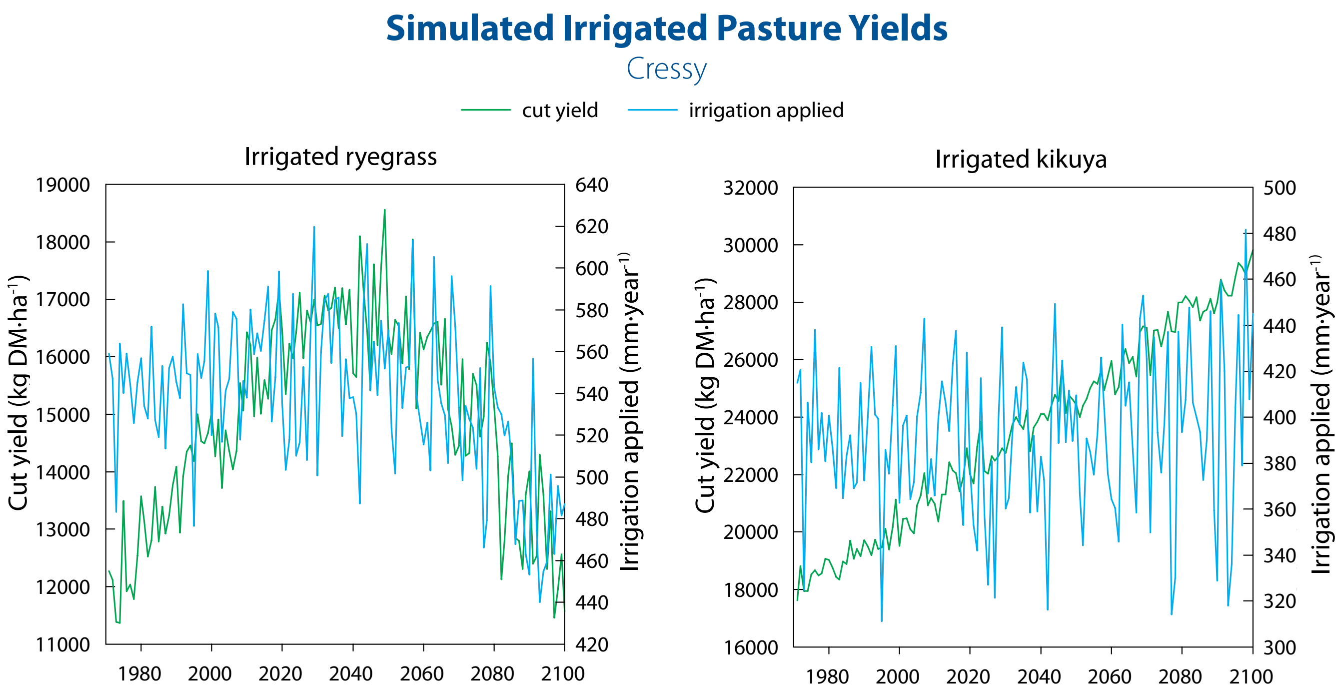


Figure 4.9 Cut yield (kg DM·ha⁻¹) and irrigation water applied (mm·year⁻¹) to ryegrass (*Lolium perenne*) and kikuyu (*Pennisetum clandestinum*) at Cressy 1971-2100, mean of pasture simulations using six downscaled-GCMs, A2 emissions scenario.

4.1.3 Extensive pasture production

Tunbridge and Bothwell were chosen to represent regions with extensive grazing farming systems. There are differing projections for the growth of phalaris at Tunbridge and Bothwell (Figure 4.10). Annual yields at Bothwell are forecast to double by the end of the century. Most of the increase in growth is projected to occur in spring, with a small contribution from increased autumn growth (Figure 4.11). The main driver of this increase in growth is increasing temperature in an area that is currently strongly temperature-limited (Figure 4.12). The increase in autumn growth is also in part due to projections of better moisture availability at this time of year, with a projected increase in monthly rainfall of 10% to 30% from February to March.

In contrast to Bothwell, yield projections of dryland phalaris at Tunbridge do not increase to 2100 but peak around mid-century and then plateau.

As with ryegrass, growth is projected to decrease in summer months due to higher daily maximum temperatures (Figure 4.12). These projections suggest changes in pasture species or cultivars may be required later in the century, though the quantity of feed should steadily improve to around 2050.

Changes in feed quality are likely with reduced protein contents and reduced digestibility, resulting primarily from the higher carbon dioxide concentrations (data not presented).

At both Bothwell and Tunbridge, the projections suggest linear increases in annual yield (45% to 60%) of subclover to 2100. Growth is forecast to increase in the months April to October but without extending the length of the growing season. There will be little change in moisture limitations on growth, with all of the yield increase coming from higher temperatures.

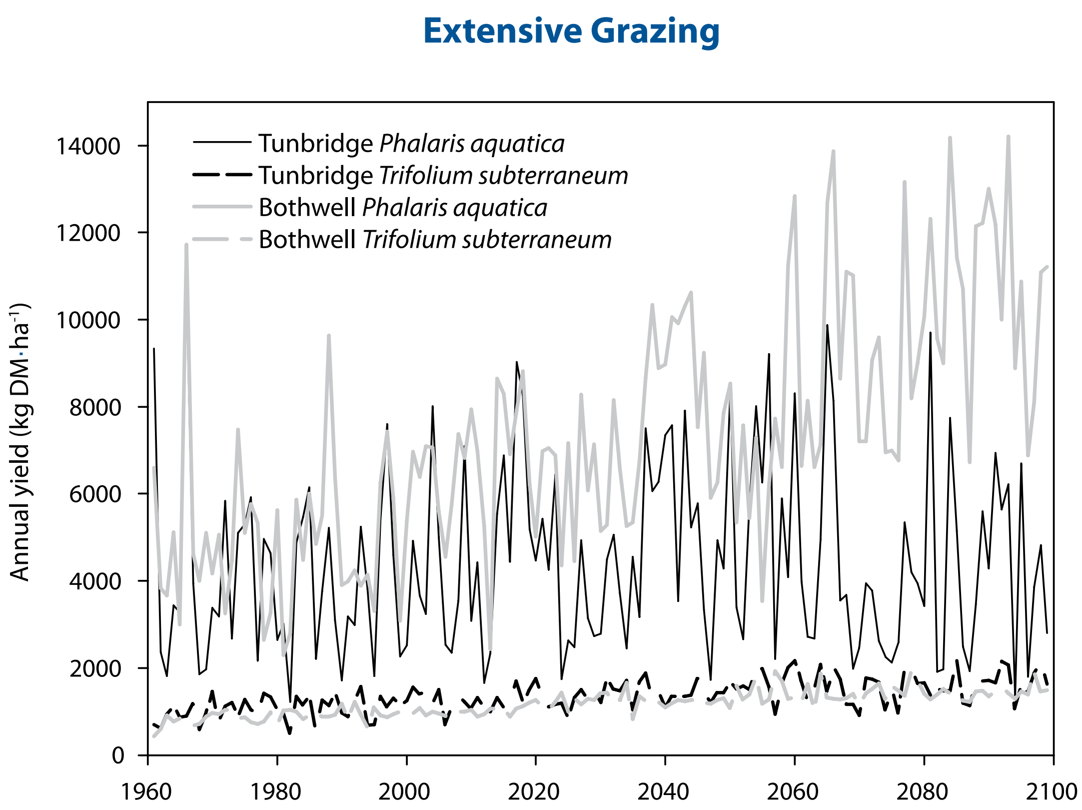


Figure 4.10 Annual yield of dryland *Phalaris aquatica* and *Trifolium subterraneum* (kg DM·ha^{-1}) at Bothwell and Tunbridge 1961-2099, pasture simulations using the downscaled-GCM GFDL-CM2.1, A2 emissions scenario.

Extensive Grazing Growth Limiting Factors

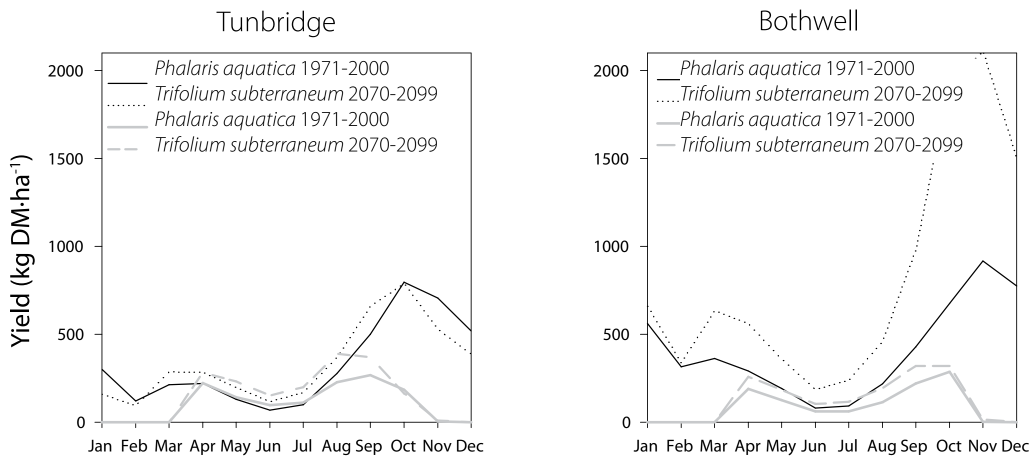
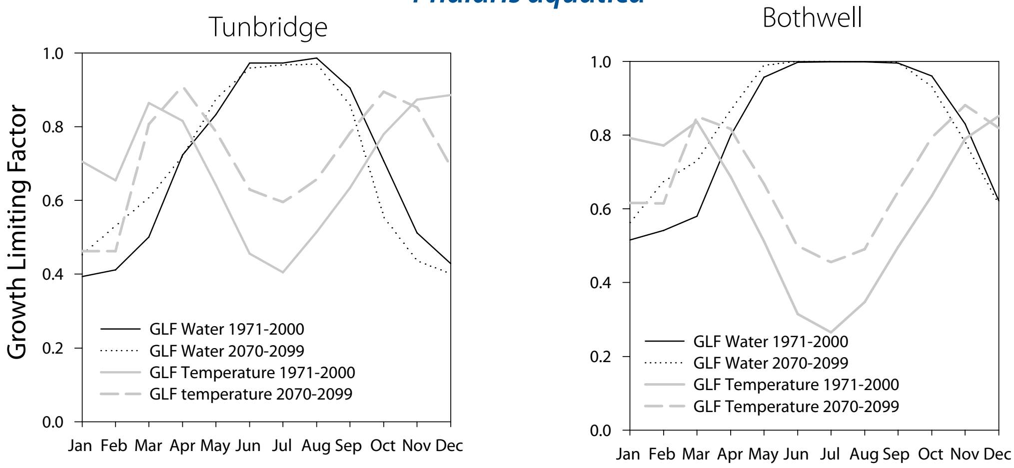


Figure 4.11 Monthly yields of *Phalaris aquatica* and *Trifolium subterraneum* (kg DM·ha^{-1}) at Bothwell and Tunbridge 1971-2000 and 2070-2099, pasture simulations using the downscaled-GCM GFDL-CM2.1, A2 emissions scenario.

Phalaris aquatica



Trifolium subterraneum

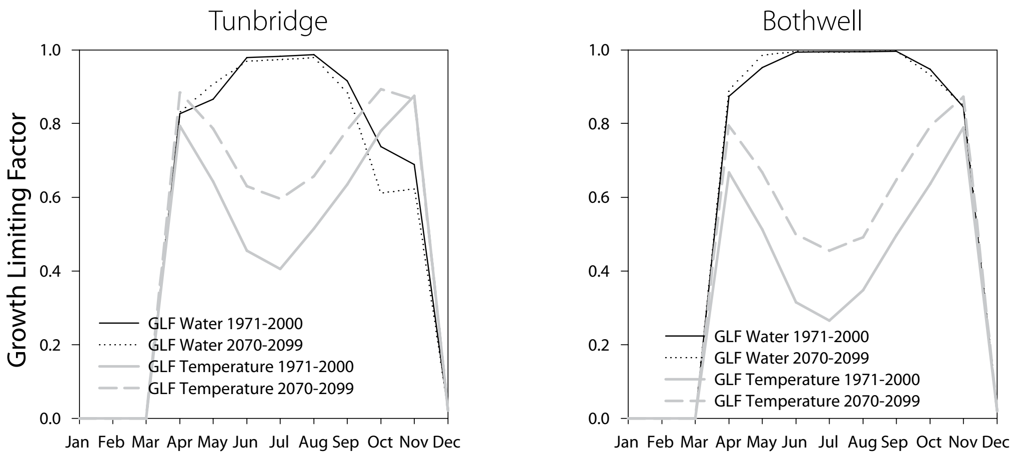


Figure 4.12 Monthly Growth Limiting Factors (water and temperature) for *Phalaris aquatica* and *Trifolium subterraneum* at Bothwell and Tunbridge for the periods 1971-2000 and 2070-2099, pasture simulations using the downscaled-GCM GFDL-CM2.1, A2 emissions scenario.

4.2 Wine grapes

Wine production is particularly sensitive to temperature. Temperature affects the length of the growing season, wine quality and wine grape variety (Jackson & Lombard 1993). There have been previous studies addressing the impact of climate change on the wine industry in Australia. Webb et al (2007) used the vine growth model VineLOGIC and climate projections from OzClim to assess the impact of climate change on budburst, ripening temperatures and harvest date. They did not use any sites from Tasmania but concluded that budburst would be earlier and time to harvest shorter. Hall and Jones (2009) used a range of temperature-based indices to evaluate the effects of warming on Australian wine growing regions, including northern and southern Tasmania. They used Biologically Effective Growing Degree Days (BEGDD) calculated for October 1 to April 30 derived using interpolated OzClim (CSIRO-Mk3.0 and A1B emissions scenario) projections and district averages to conclude that by 2070 northern Tasmania would be similar to the current conditions in the Coonawarra region of South Australia.

The thermal unit used for wine production follows Gladstones (1992) method, where biologically effective GDD (BEGDD) are calculated using the GDD equation (Equation 4) with the additional constraint of equation 5.

Equation 5

$$BEGDD = (T\ mean - T\ threshold) > 9 = 9$$

Gladstones (1992) considered temperatures above 19 °C to be no more effective to heat accumulation than 19 °C. This index may be a little controversial in the wine industry but it is useful for this report because Gladstones provided annual BEGDD requirements for different grape varieties that have been used as critical thresholds in this project. In any case, whichever thermal unit is used, the trends will be similar to those using the conventional GDD index. Gladstones (1992) calculated BEGDD from October 1 as budburst commonly occurs at this time. There is little heat accumulation prior to October 1 in the current climate in Tasmania. However, increasing future temperatures may lead to earlier budburst, so in this report BEGDD have been calculated from July 1 for both current and projected climates.

Table 4.3 Mean annual BEGDD, BEGDD October to April in brackets and mean date and range at 1100 BEGDD for six sites representing wine-producing regions in Tasmania for the periods 1961-1990, 2016-2045 and 2071-2100, mean and range of BEGDD using six downscaled-GCMs, A2 emissions scenario.

BEGDD October - April not site adjusted as per Gladstones (1992)

	1961-1990		2016-2045		2071-2100	
	Annual BEGDD	Date at target	Annual BEGDD	Date at target	Annual BEGDD	Date at target
Coal Valley	1101 (996)	2 June (30 Mar - *)	1328 (1156)	28 Mar (25 Feb- *)	1740 (1410)	15 Feb (21 Jan – 24 Mar)
Huon (95 m)	790 (733)	*	994 (893)	24 Jun (3 Apr - *)	1384 (1163)	26 Mar (22 Feb - *)
West Tamar	1058 (979)	18 Jun (10 Apr - *)	1308 (1173)	30 Mar (5 Mar – 8 Jun)	1737 (1456)	17 Feb (30 Jan – 17 Mar)
Swansea	1088 (988)	7 Jun (31 Mar - *)	1322 (1154)	29 Mar (25 Feb - *)	1765 (1427)	14 Feb (22 Jan – 24 Mar)
Glenora	794 (765)	*	977 (921)	28 Jun (13 Apr - *)	1328 (1189)	25 Mar (25 Feb - *)
Pipers Brook	1067 (987)	14 Jun (3 Apr - *)	1327 (1183)	30 Mar (5 Mar – 12 Jun)	1778 (1472)	17 Feb (28 Jan – 16 Mar)

* 1100 BEGDD not achieved.

Average annual BEGDD (Gladstones 1992) calculated in this project were not adjusted for diurnal range or site conditions. These adjustment factors tend to increase annual total BEGDD at the sites in Tasmania by around 10% (Gladstones 1992). Trends in BEGDD for many sites suggest substantial increases from 1961-1990 to 2071-2100 of 50% to 70% (Table 4.3) for the A2 emissions scenario. Time of budburst is likely to be earlier, despite budburst being a function of factors other than just temperature (for example, time since leaf fall).

Time to maturation of current varieties is projected to be much shorter by the end of the century (Figure 4.13 and Table 4.3). Harvest dates provided for pinot noir at the Kayena Vineyard in the West Tamar by Richard Smart (pers comm, 2 February 2010) over the period 2003-2009 were on average 16 April (3 May – 2 April). This harvest date lies between those calculated for the baseline period and 2030 for the West Tamar shown in Table 4.3.

There are likely to be opportunities for changes in varieties to those with higher BEGDD requirements, such as shiraz and cabernet sauvignon (Figure 4.14). High-quality cool climate varieties that require long ripening periods, such as pinot noir, may need to be moved to cooler sites such as those at higher elevations. R Menary (pers comm, 12 August 2010) suggests another option is to change from the currently favoured north-facing sites in Tasmania for wine production to the use of south-facing slopes that receive less radiation.

The current climate in the Coonawarra Region accumulates on average 1337 BEGDD from October to April, while Rutherglen in north-east Victoria averages 1567 BEGDD (Gladstones 1992). There are many meteorological components required to fully describe a viticultural climate. Using just BEGDD suggests that by the latter part of the 21st century parts of Tasmania will experience growing conditions similar to the present-day conditions in South Australia's Coonawarra Region and perhaps , Victoria's Rutherglen Region.

There may be other impacts from a changing climate. For example, the projected increased rainfall during summer and autumn in the eastern regions of Tasmania in particular could promote the development of fungal diseases at a time in the crop's development when it is particularly vulnerable.

Wine Grapes

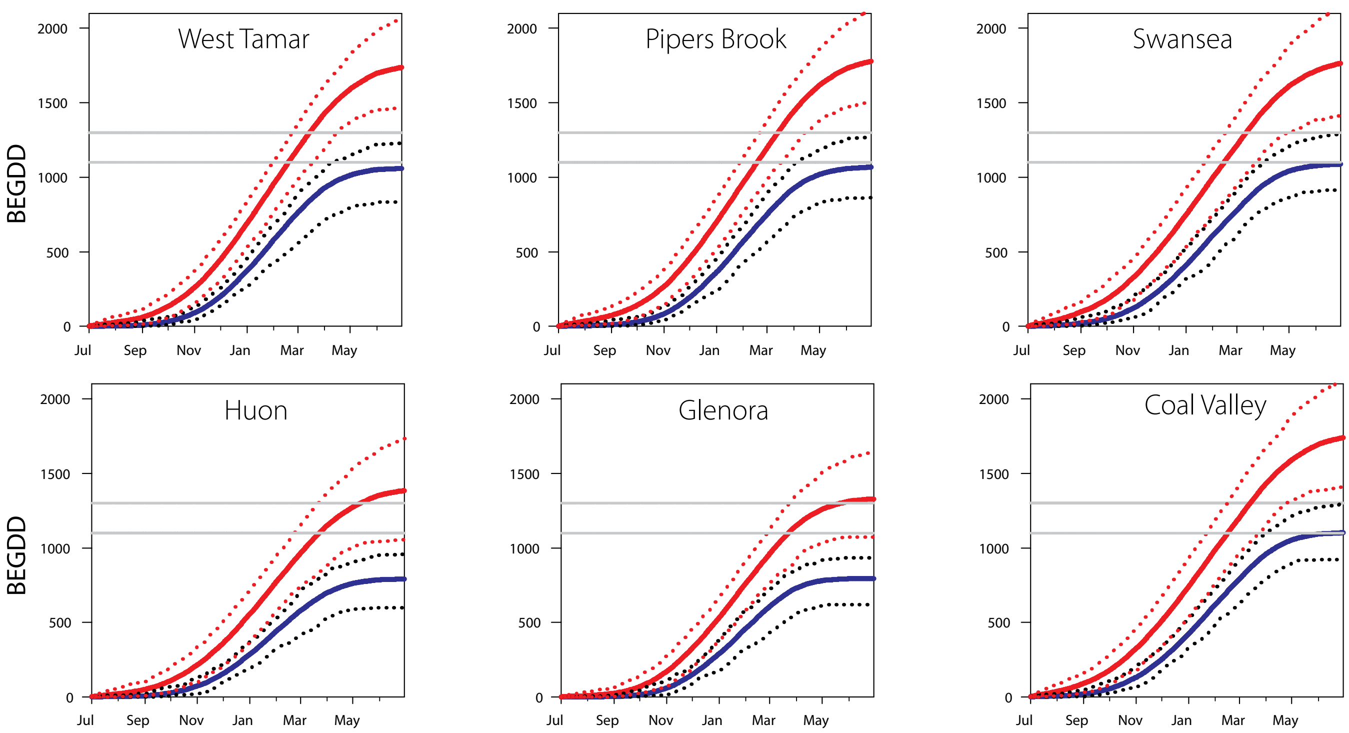


Figure 4.13 Cumulative BEGDD (10 °C to 19 °C) from July 1 for six sites representing wine-growing areas in Tasmania with mean BEGDD of 30 years for each day and six downscaled-GCMs, A2 emissions scenario (▬) 1961-1990, (▬) 2071-2100, (▪▪▪ and ▪▪▪) indicate minimum and maximum cumulative BEGDD each day and (▬) 1100 and 1300 BEGDD.

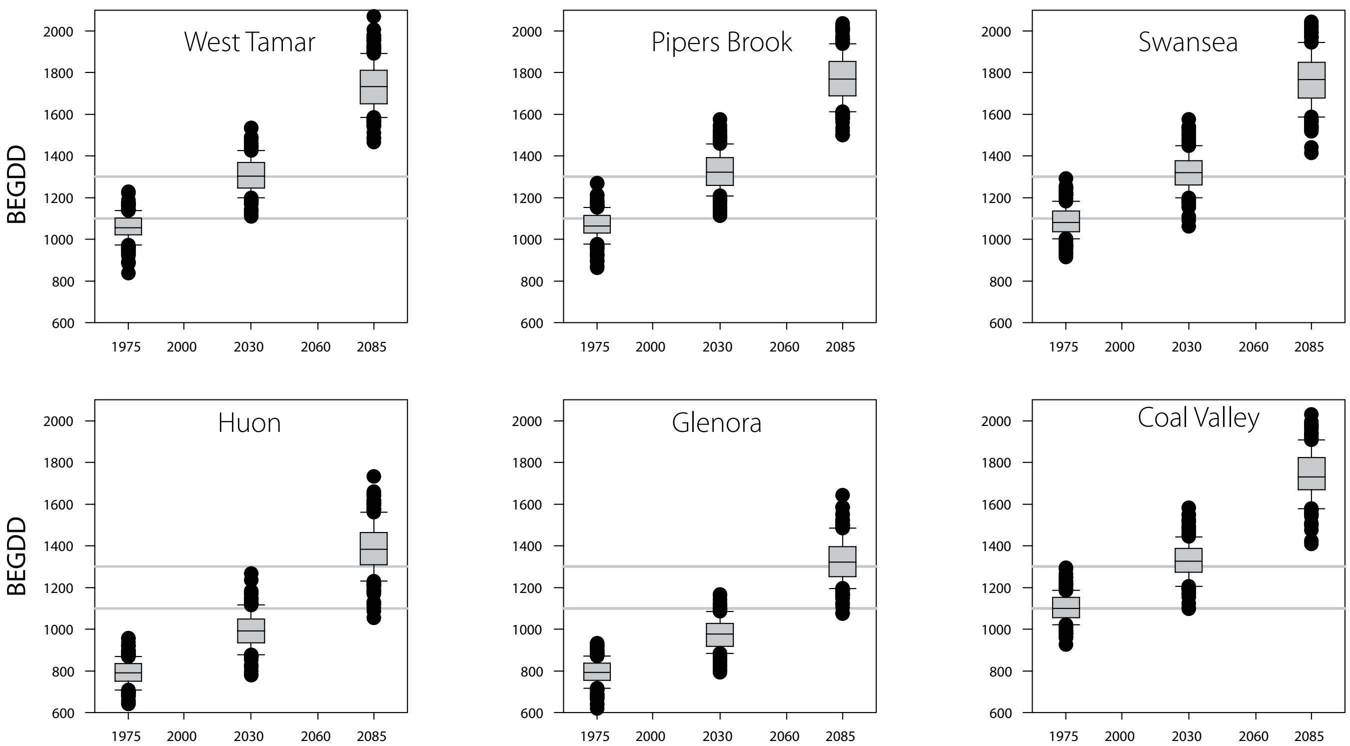


Figure 4.14 Box plots of October-April BEGDD for 30-year periods using six downscaled-GCMs for six wine regions in Tasmania for 1961-1990, 2016-2045 and 2071-2100 where the box represents the 25th, mean and 75th percentiles, the whiskers the 10th and 90th percentiles, (●) outliers and the horizontal bars (▬) 1100 and 1300 BEGDD.

4.3 Grain crops

The area planted and value of grain production in Tasmania varies from year to year based on seasonal weather and markets. To put the industry in context, there were 25,000 ha to 28,000 ha of wheat, barley and triticale between 2005 and 2007 (www.abs.gov.au/). Assessing the impact of a changing climate on annual crops is complex because of the effects of the many management decisions that farmers make each year that are in part due to the climate they are experiencing. For example, interactions between planting date, nitrogen management, water availability and crop variety profoundly influence crop yield.

To better understand the impact of a changing climate, it is best assessed farm by farm, farming system by farming system. This includes the impact of increases in temperature, decreases in frost, changes in the seasonal distribution of rainfall and increases in carbon dioxide concentrations.

Indicative climate-change impact on wheat production is presented below for two regions, Cressy and Bothwell, where the crop is currently grown in Tasmania. Crop yields were modelled using the crop model APSIM (Keating et al 2003). There are many potential cropping regimes that could have been simulated but the two cropping regimes presented in this report for growing the wheat cultivar Tennant are limited and nutrient and water unlimited. The limited regime included 25 kg $N{\cdot}ha^{-1}$ applied at planting and 46 kg $N{\cdot}ha^{-1}$ applied on September 1 each year. The rainfed crop was planted on 15 May, with the cropping system attributes reset each year so that there was no carryover from year to year. The unlimited regime was similar to the above except that sufficient fertiliser and water were applied to make these non-limiting to crop growth.

Assuming no adaptation or improved technology, simulated wheat yields under the limited regime are projected to decrease by 5% to 8% at both sites by the end of the century, after a slight increase to around 2000 (Figure 4.15 and Table 4.4).

The main drivers for the reduction under this modelling regime are an increase in nitrogen stress and a shorter time to crop maturity. Cumulative stress indices for the limited cropping regime are shown in Figure 4.16. The cumulative water and nitrogen stress indices increase as the respective stresses increase. Conversely for temperature, the cumulative temperature stress index increases as temperature stress decreases. The projected increase in nitrogen stress is common to cropping (Howden et al 2010) and pasture production

and suggests that there will be an increase in demand for nitrogen fertiliser.

The crop modelling outputs (Figure 4.16) suggest there will be less temperature stress, particularly at Bothwell, as the number of days less than 0 °C decreases. Water stress decreases due to an increase in water use efficiency resulting from the elevated carbon dioxide concentrations in the A2 emissions scenario. Increased water use efficiency offsets a decrease of around 8% to 10% in the amount of rain that occurs over the duration of the simulation using the GFDL-CM2.1 projections (Table 4.4). The number of days to flowering decreases by around 21 days at Bothwell and 16 days at Cressy (Figure 4.16). A shorter crop life means less time to assimilate photosynthate.

The yield of wheat grown with unlimited resources of water (irrigation) and fertiliser increases to around 2050 and thereafter remains relatively constant. Temperature stress decreases throughout the period to 2100, albeit less towards the end of the century. The probable cause of the flattening of the yield curve for wheat after 2050 (Figure 4.15) is the shorter time to crop maturity (Figure 4.16). An impact that may be resolved by later maturing varieties.

There are many other impacts of a changing climate on cropping and cultivated land that are not dealt with in this report and that require more investigation. There is a projected increase in the frequency of high-rainfall intensity events (White et al 2010) that could potentially change the nature of soil erosion on cultivated land and thus change the measures used to control erosion. Interactions between changes in seasonality and intensity of rainfall, water use efficiency and cropping regimes are likely to change the dynamics of salinisation, leaching and runoff of nutrients. Protein levels in grains are very likely to decrease unless fertiliser rates are increased with consequent implications for the quality of stock feed.

Changes to the timing and quantity of runoff (Bennett et al 2010) will have an impact on farm water storage and irrigation management. These are just some of the issues affecting agricultural production as a farming system. The impact on the natural environment also requires further examination.

Simulated Wheat Yields

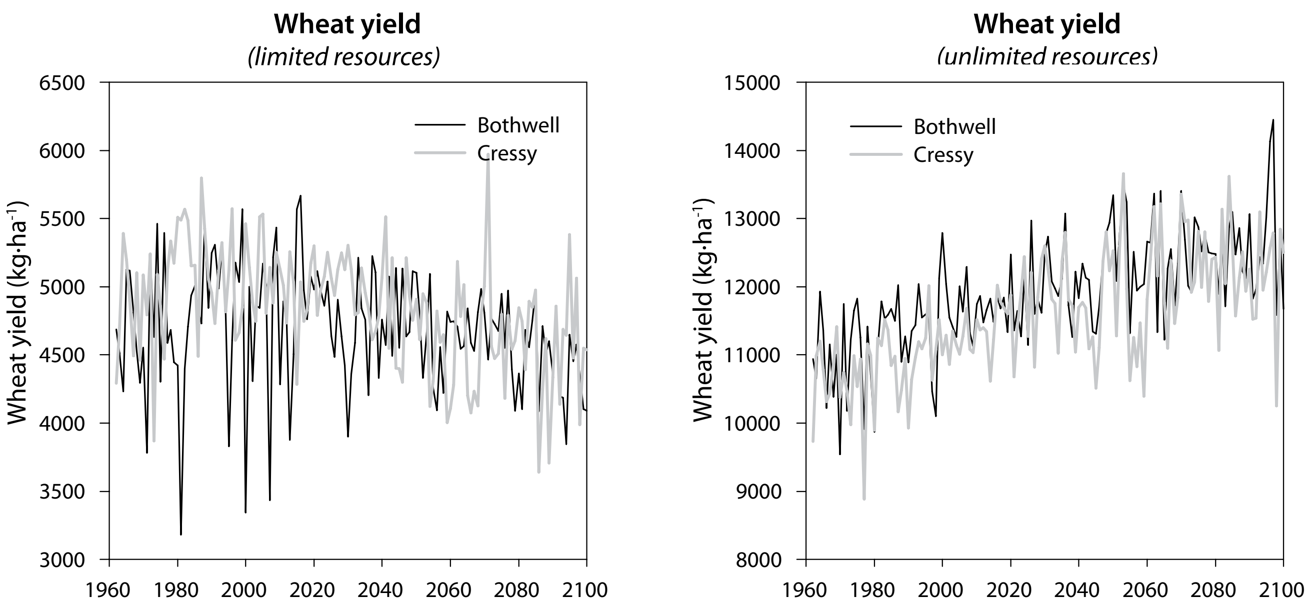


Figure 4.15 Wheat yield (Tennant) at Bothwell and Cressy 1961-2100 as simulated by APSIM grown under limited and unlimited resources using the downscaled-GCM GFDL-CM2.1, A2 emissions scenario.

Cumulative Stresses

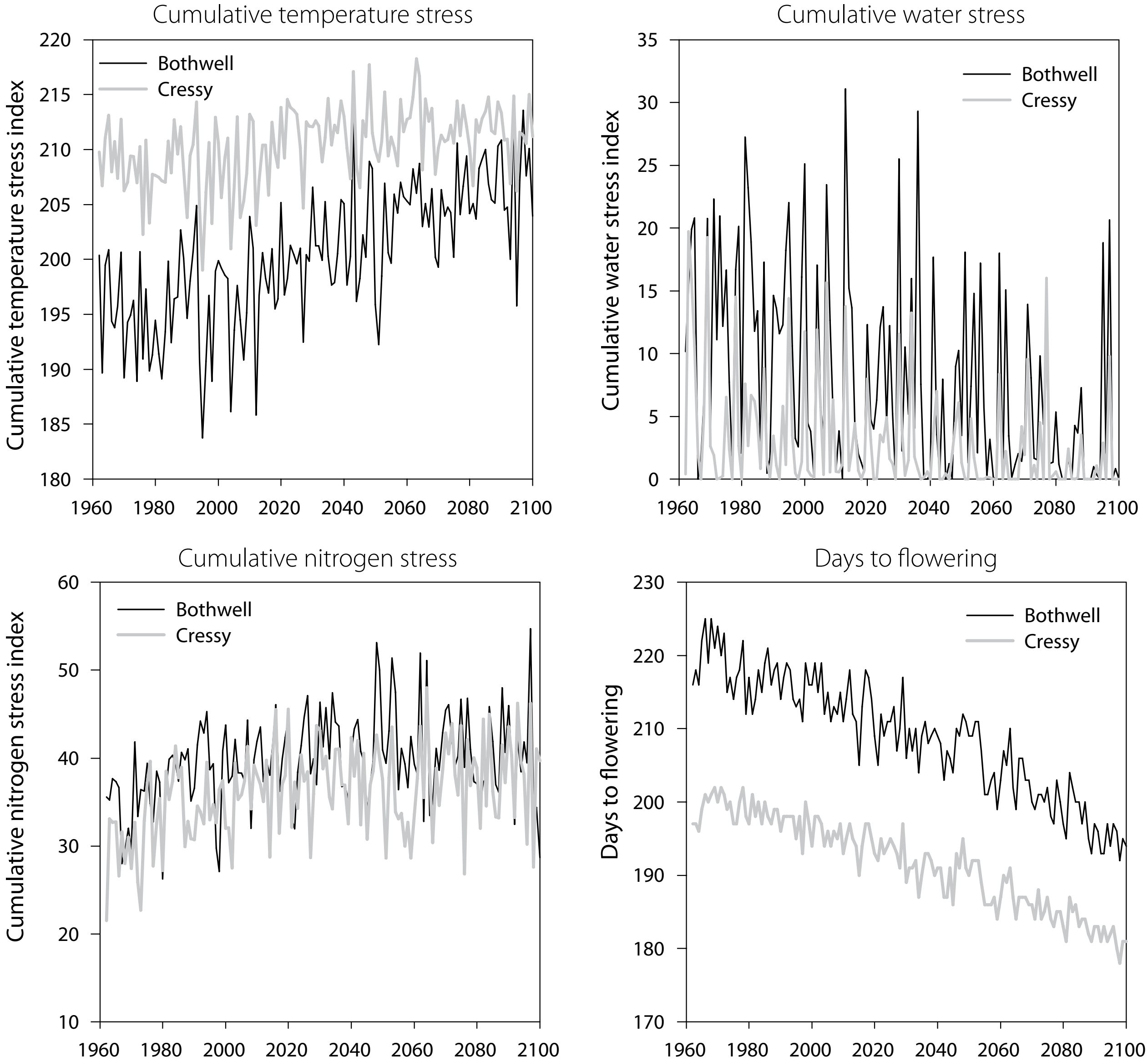


Figure 4.16 Cumulative temperature, water and nitrogen stresses and days to flowering as simulated by APSIM for wheat grown under resource-limited conditions at Cressy and Bothwell 1961-2100 using the downscaled-GCM GFDL-CM2.1, A2 emissions scenario. Note, cumulative temperature stress index increases as actual temperature stress decreases. Nitrogen and water stress indices increase as stress increases.

Table 4.4 Wheat yield and percent change in yield 1962-1991 to 2071-2100, as simulated by APSIM (limited and unlimited resources) and rainfall and percent change in rainfall (over the same periods) for the duration of the simulation, Bothwell and Cressy using the downscaled-GCM GFDL-CM2.1, A2 emissions scenario.

	Bothwell			Cressy		
	Yield limited (kg·ha-1)	Yield unlimited (kg·ha-1)	Crop rain (mm)	Yield limited (kg·ha-1)	Yield unlimited (kg.ha-1)	Crop rain (mm)
1962-1991	4693	11077	480	5012	10664	567
2071-2100	4482	12554	441	4600	12278	506
% Change	-4.5	+13.3	-8.1	-8.2	+15.1	-10.7

4 .4 'Up the hill' and land use change

In natural ecosystems, there is evidence that species have already responded to increases in temperature by moving poleward and upward in elevation (Hughes 2000, 2003; Root et al 2003). Parmesan and Yohe (2003) report on a systematic poleward shift of species of around 6.1 km per decade. In Tasmania, there are limited options to respond to changes in temperature profiles through latitudinal shifts (though shifts from the mainland are possible). However, increases in temperature at low elevations can be offset by shifting to higher, cooler elevations. Correspondingly, increased temperatures and more growing degree days at higher elevations (Figure 4.17) provide opportunities for crops and pastures that historically have been unsuited to the cold conditions in those areas.

Opportunities for 'up the hill' to higher elevation land depend not only on changed temperature profiles but also on adequate rainfall, suitable soils and a workable topography. Agricultural production in many elevated areas in Tasmania is limited by unsuitable soils (for example, shallow and stony) and steep slopes. However, there are some areas that are currently primarily temperature-limited but with soils and topography capable of supporting higher intensity agricultural production under warmer temperatures. Some of these areas include a strip along the north-west coast, parts of the north-east above Ringarooma, parts of central Tasmania from Bothwell across to Tarraleah and limited areas in the Huon. A transect across an altitudinal gradient from Burnie to Waratah on the north-west coast provides an example of the impact and potential for land use change resulting from temperature increases (Figure 4.18).

There are a number of factors that make the north-west coast suitable for expansion of agricultural production 'up the hill'. Ferrosols (red soils), developed on Tertiary basalt, are widespread along the north-west coast at elevations from sea level to above 700 m. Ferrosols with deep soil profiles in the lower, warmer elevations adjacent to the coast are arguably the best cropping soils in Tasmania. At higher elevations the Ferrosols are generally reddish-brown in colour and their physical properties are not as suitable for cropping, being generally shallower and with more stone (Loveday & Farquhar 1958). However, there are substantial areas with gently sloping topography that are currently used for eucalypt and pine plantations, native forests or

Growing Degree Days and Elevation

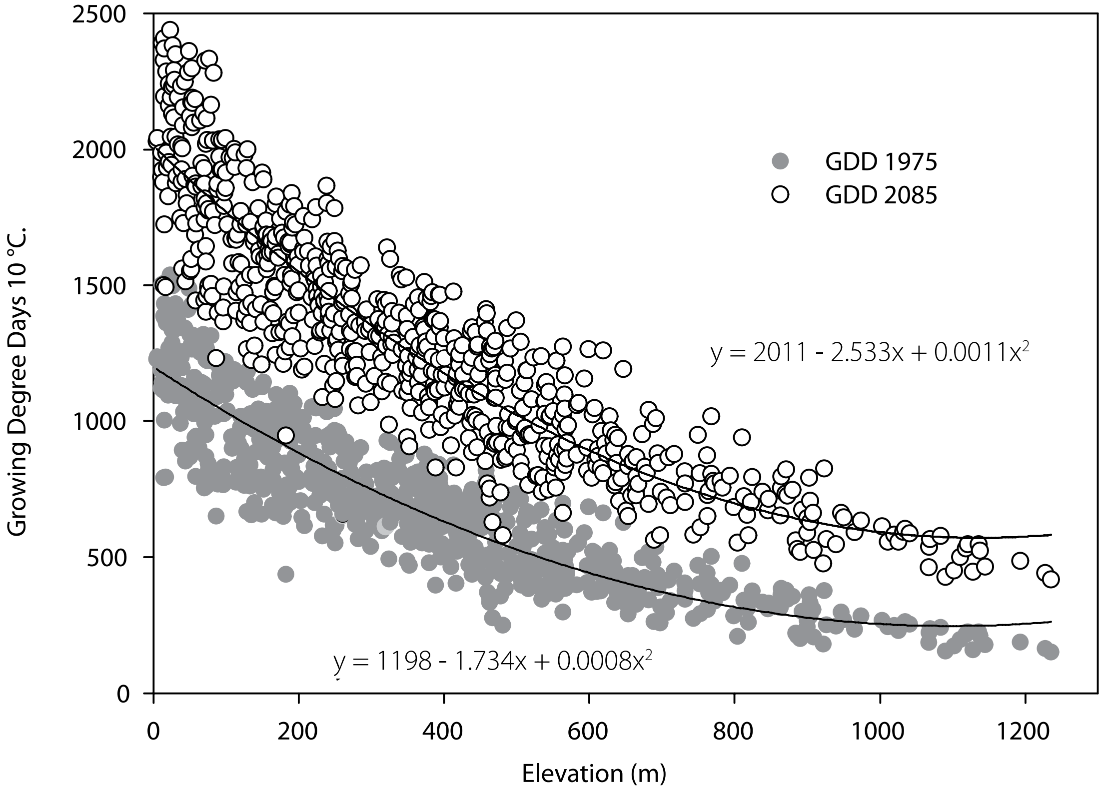


Figure 4.17 Growing Degree Days (10 °C) and elevation for 1961-1990 (1975) and 2071-2100 (2085) for all grid cells across Tasmania, downscaled-GCM GFDL-CM2.1, A2 emissions scenario.

grazing, and that have potential for higher intensity land uses under a warmer temperature regime.

The current climate for a transect from Burnie on the coast to Waratah at around 600 m (ASL) is shown in Figures 4.19 and 4.21. The mean annual rainfall along this transect (using data from grid cells representing the stated locations) increases from around 1000 mm per annum to around 2000 mm per annum. The mean annual temperature decreases from around 13 °C to 9 °C.

Currently most of the intensive cropping along the north-west coast is at elevations of less than 300 m due mainly to the shorter growing season and lower temperatures at higher elevations. The zone between 300 m to 500 m above sea level is used for crops such as turnips and seed potatoes, and grazing, and is highly suited to plantation forestry. There is little agricultural production on suitable soils above 500 m, though there are extensive areas of plantations, predominantly shining gum (*Eucalyptus nitens*).

Growing degree days along the altitudinal transect have been calculated for thirty-year periods 1961-1990, 2016-2045, 2036-2065 and 2071-2100 using the downscaled modelling outputs from the mean of the six downscaled-GCMs and the A2 emissions scenario (Figure 4.20). The elevation of lands suitable for cropping in the future can be extrapolated from experience using 300 m as a baseline upper boundary. This approach suggests that cropping will be possible to altitudes of 450 m ASL by 2030 and greater than 500 m ASL by 2050.

Rainfall trends as projected by the mean of the climate simulations (Figure 4.21) suggest that the currently high rainfall in this environment is likely to remain high. This means there will be an adequate rainfall regime for many cropping and pasture enterprises, together with higher temperatures. It is possible then that along the north-west coast, potentially arable land that is currently temperature-limited will be suitable for more intensive land uses by 2085.

Another example of potential land use change in Tasmania is at Bothwell, where the projections suggest an increase in potential for cropping and intensive agriculture. Mean annual temperature increases from 9.3 °C to 11.5 °C and a marginal increase in mean annual rainfall (Figure 4.22) will lead to a doubling of 10 °C GDD (Figure 4.23), accompanied by an increase in cropping and pasture growth potential.

Intensive horticulture and other forms of cropping may take advantage of the warmer climate, but for the present discussion, changes in the potential for agricultural production across an altitudinal gradient from Burnie to Waratah can be illustrated using a pasture growth model. The pasture growth model DairyMod 4.7.5 (Johnson et al 2008) was parameterised to simulate a perennial ryegrass pasture. The model was nutrient non-limited, included increases in carbon dioxide concentrations consistent with the A2 emissions scenario and had the same soil parameters (Ferrosol) across all sites. The differences among sites were therefore due to climate. Projections from all six downscaled-GCMs and the A2 emissions scenario were used in the presented pasture growth simulations. The model was run from 1961-2100 and the first 10 years of results discarded to allow the model to equilibrate.

The metric used to measure and explain changes in productivity was cut yield (annual total yield and monthly growth rate) where the pasture was harvested to a residual of 1400 kg DM·ha^{-1}. Climate modelling outputs used were representative of Burnie, Tewkesbury and Waratah.

DairyMod indicates that pasture growth will increase in the future at all sites (Figure 4.24), reaching a maximum at Burnie around 2070, Tewkesbury around 2080 and Waratah around 2090. The increase in pasture growth from 1971-2000 to 2071-2100 is greater at the higher, colder sites than the lower, warmer sites. Growth is forecast to increase at Burnie over this period from 9,545 kg DM·ha^{-1} to 10,613 kg DM·ha^{-1} (11%), at Tewkesbury from 9,219 kg DM·ha^{-1} to 12,246 kg DM·ha^{-1} (34%) and at Waratah from 8,535 kg DM·ha^{-1} to 13.210 kg DM·ha^{-1} (54%).

The annual mean temperature growth-limiting factor (GLFtemperature) increases approximately linearly from 1971 to 2100 (Figure 4.24). This means that temperature as a limiting factor on plant growth decreases over this period. Between the 30-year periods 1971-2000 and 2071-2100 temperature as a limiting factor decreases by approximately 10% at Burnie, 20% at Tewkesbury and 30% at Waratah. In

Transect from Burnie to Waratah

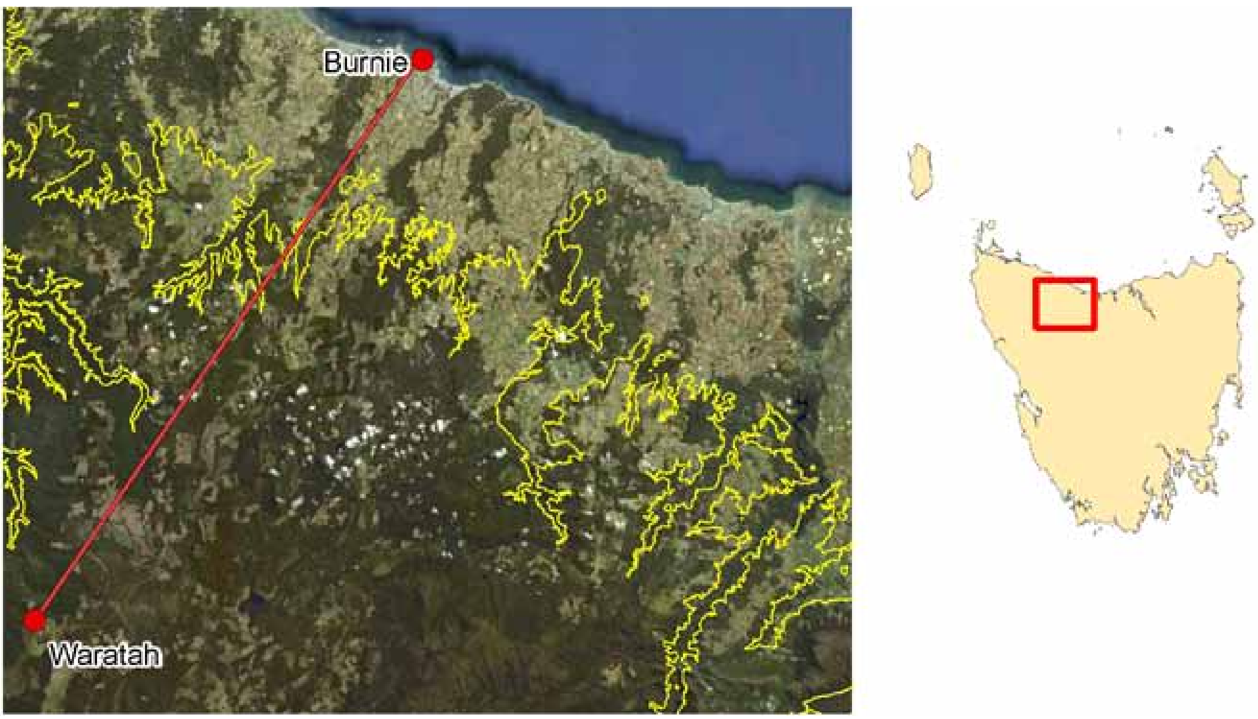


Figure 4.18 A map showing a transect (red line) along an altitudinal gradient from Burnie to Waratah on the north-west coast of Tasmania with the 300 m contour (yellow line) (Image © Google 2010).

Altitudinal Transect

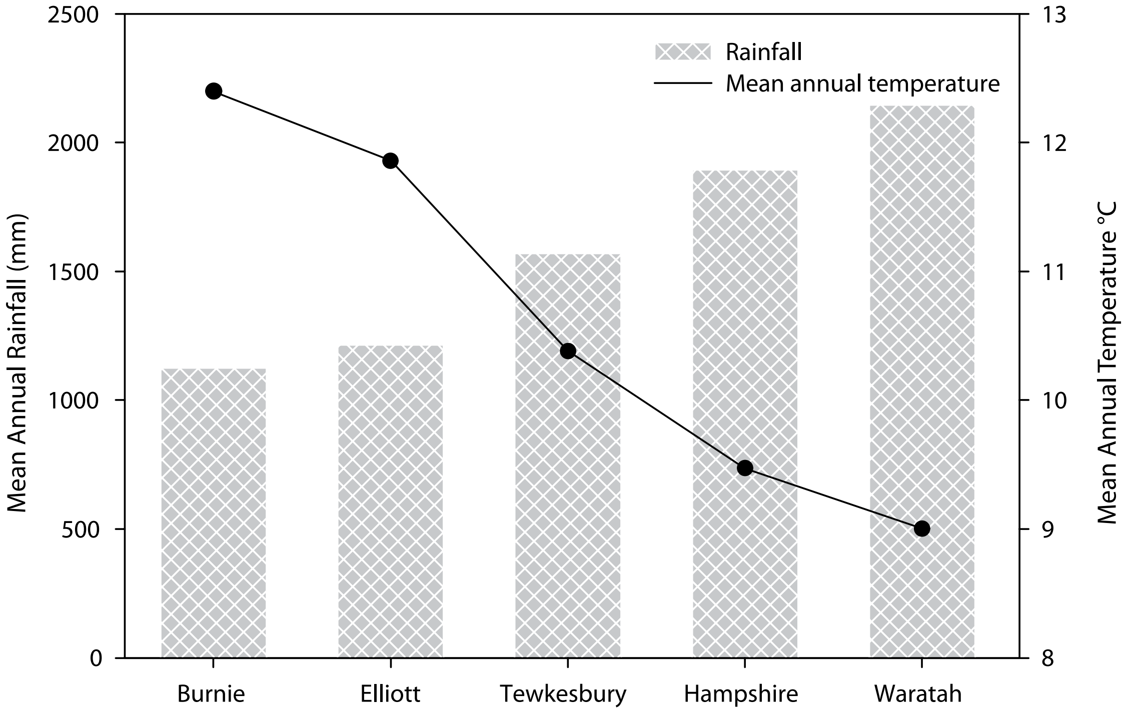


Figure 4.19 Mean annual temperature (°C) and mean annual rainfall (mm) for AWAP 0.1-degree grid cells represented by townships along an altitudinal transect from Burnie to Waratah.

Growth Potential at Elevation in North-West Tasmania

north-east to south-west transect

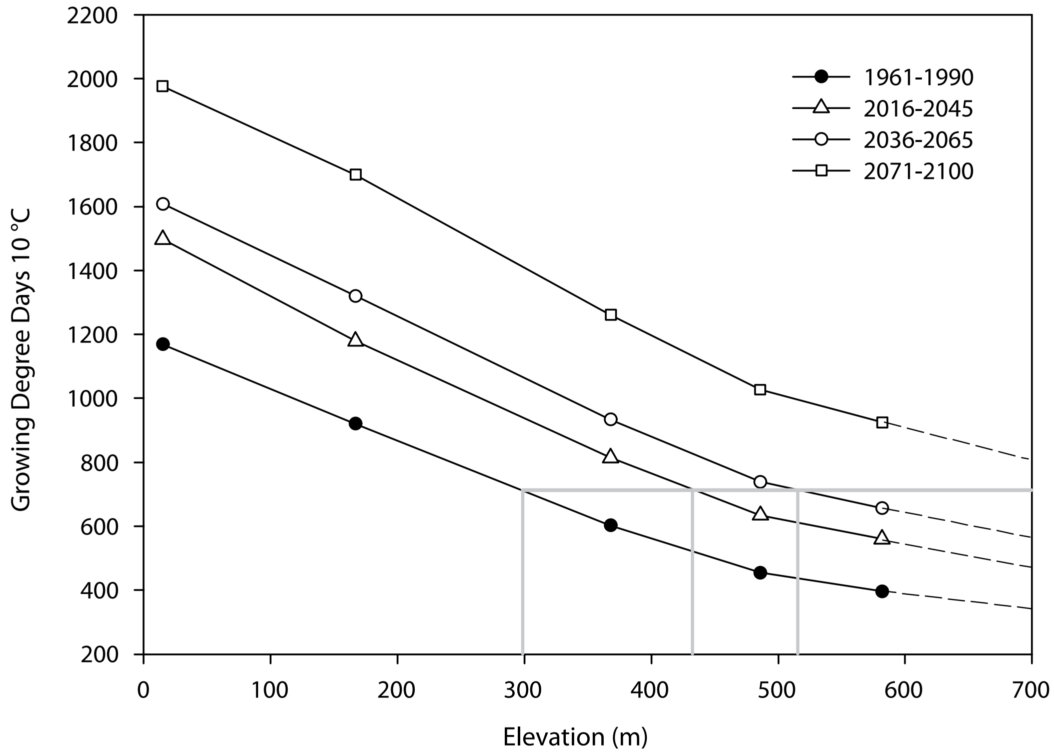


Figure 4.20 Growing degree days (10 °C) and elevation for 1961-1990, 2016-2045, 2036-2065 and 2071-2100 future climates along a transect on the north-west coast of Tasmania. Mean growing degree days calculated using six downscaled-GCMs, A2 emissions scenario. In the baseline period, most cropping was undertaken below 300 metres elevation.

contrast, at each site there is a slight trend of increasing water limitation over time, which is responsible for a plateau in pasture growth potential later in the century. Water is less limiting to pasture growth with increasing altitude and increasing rainfall (Figure 4.25) and the mean water growth limiting factor (GLFwater) for the baseline period increases from approximately 0.85 for Burnie, 0.89 for Tewkesbury to 0.92 for Waratah.

There are likely to be significant changes in seasonal pasture production under future climate. Monthly cut yield growth rates (Figure 4.25) under the current climate are highest at Burnie during the period from August to December, after which the GLFwater declines, indicating that the pastures are water-limited. In contrast, pasture growth at Waratah begins much later in spring (October) and peaks in December and January, with significant autumn growth reflecting better moisture availability in this higher rainfall environment.

In a future climate (2071-2100), spring growth rates are projected to be higher across all sites, with Waratah spring growth similar to that in Burnie but remaining high further into summer due to the lower moisture stress.

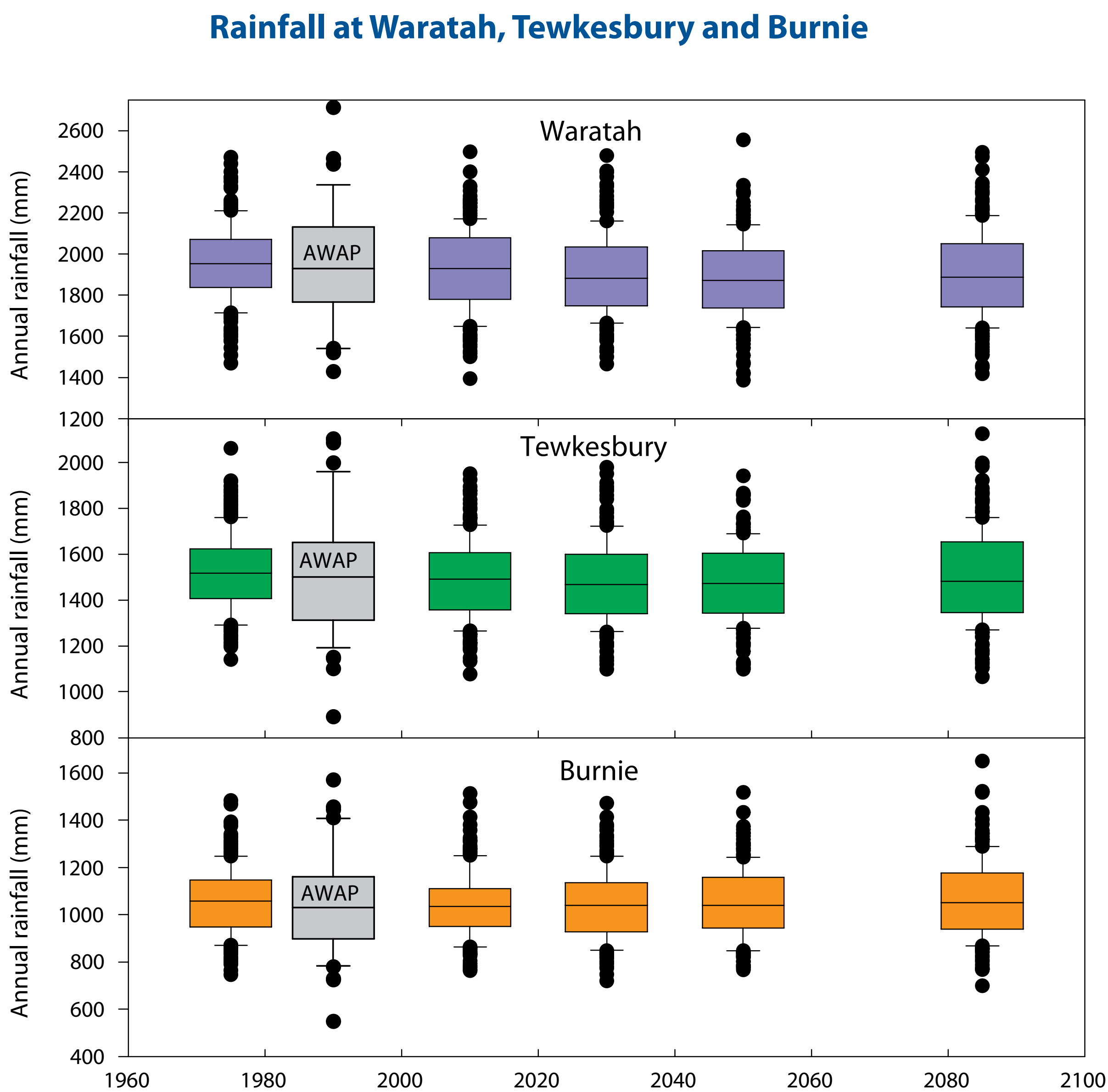


Figure 4.21 Annual rainfall for Burnie, Tewkesbury and Waratah for 1961-1990, 1996-2025, 2016-2045, 2036-2065 and 2071-2100, where the box represents the 25th, mean and 75th percentiles, the whiskers the 10th and 90th percentiles, (●) outliers, annual rainfall using six downscaled-GCMs, A2 emissions scenario. AWAP annual rainfall 1961-2007.

Bothwell Rainfall and Temperature

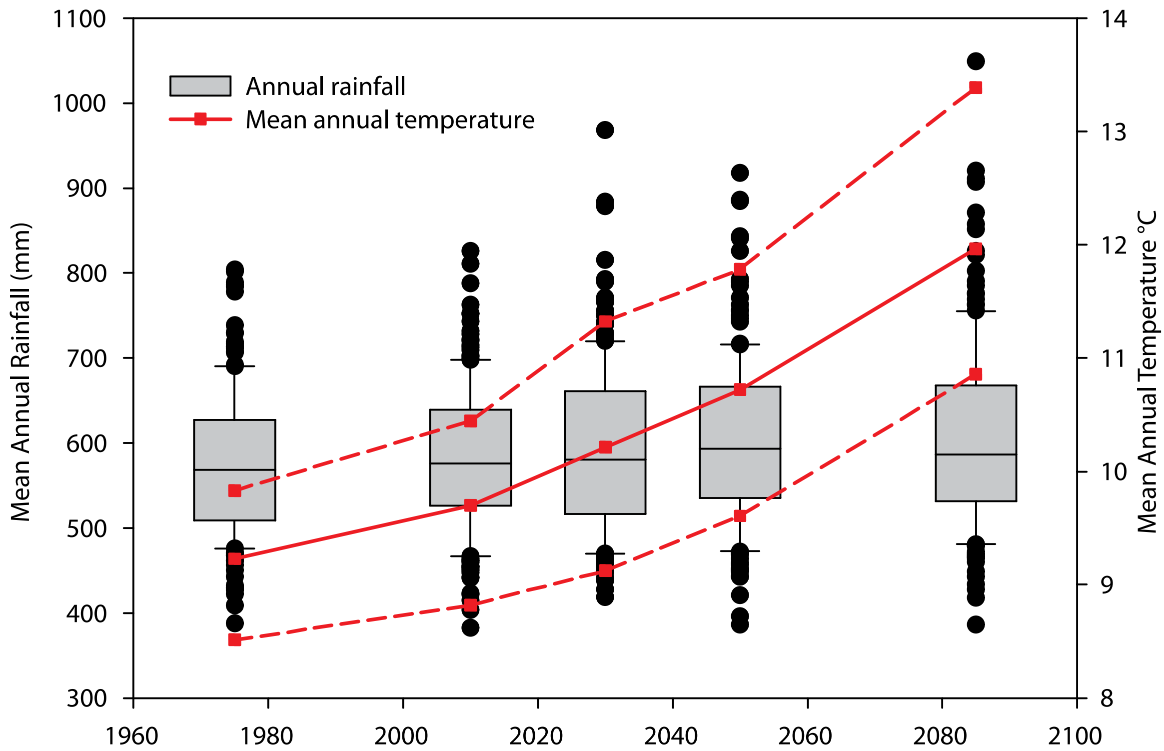


Figure 4.22 Mean annual temperature (°C) and box plots of annual rainfall for Bothwell for 1961-1990, 1996-2025, 2016-2045, 2036-2065 and 2071-2100. The box represents the 25th, mean and 75th percentiles, the whiskers the 10th and 90th percentiles, (●) outliers, mean of temperature and annual rainfall are from six downscaled-GCMs, A2 emissions scenario.

Bothwell Growing Degree Days

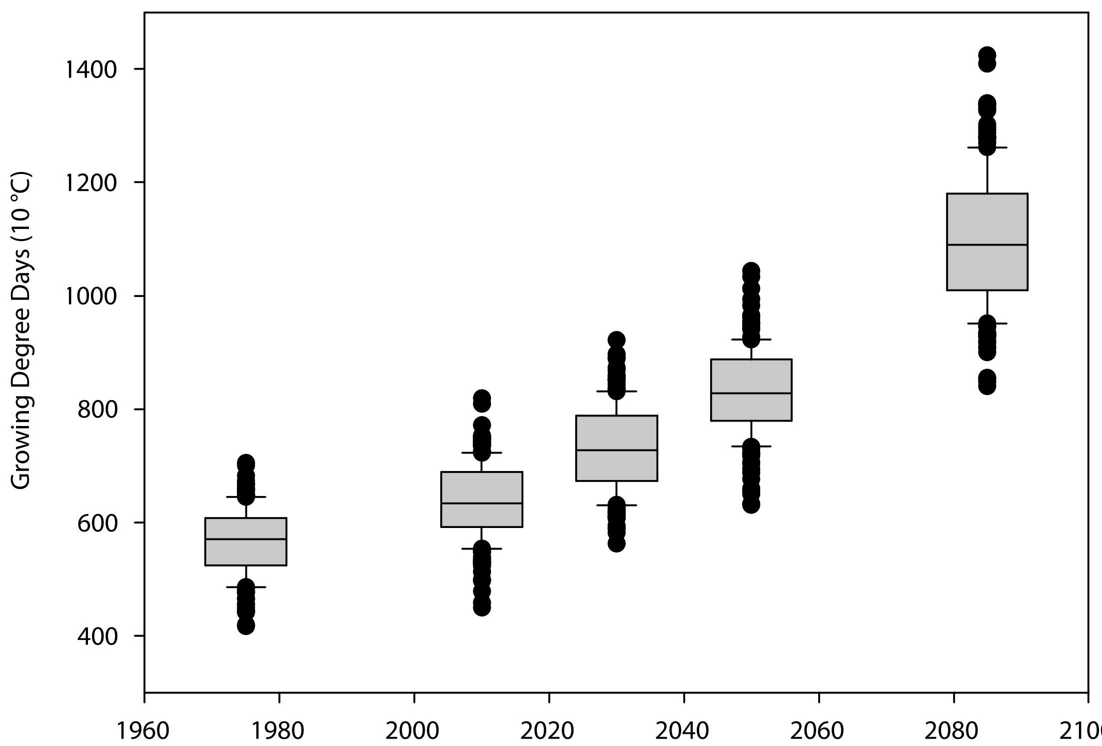


Figure 4.23 Growing degree days (10 °C) for Bothwell 1961-1990, 1996-2025, 2016-2045, 2036-2065 and 2071-2100, where the box represents the 25th, mean and 75th percentiles, the whiskers the 10th and 90th percentiles, (●) outliers, using six downscaled-GCMs, A2 emissions scenario.

Pasture Growth and Growth Limiting Factors

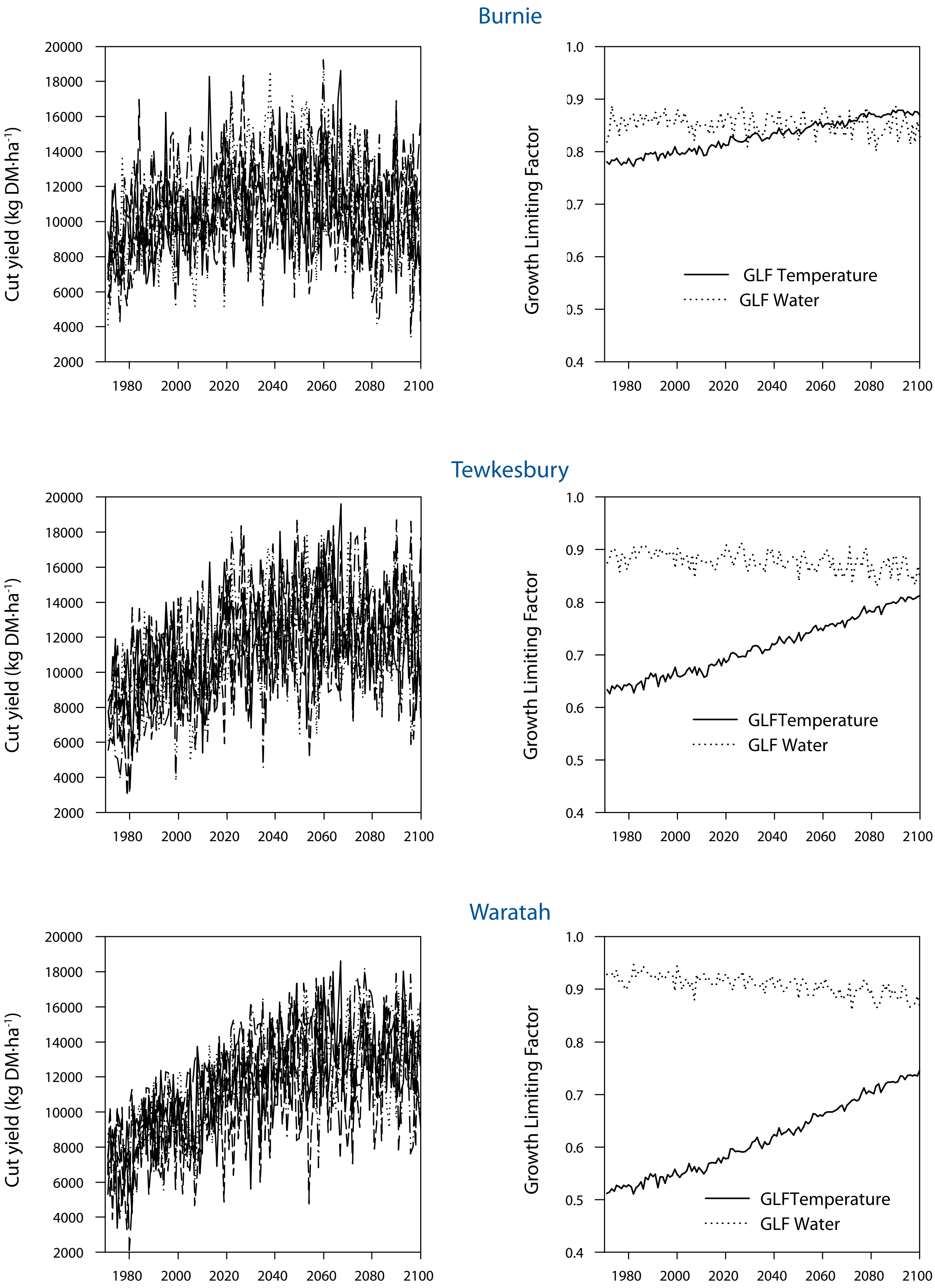


Figure 4.24 Annual cut yield (kg DM·ha^{-1}) and growth-limiting factors for temperature (GLFtemperature) and water (GLFwater) simulated by DairyMod for Burnie, Tewkesbury and Waratah 1971-2100, mean yield and mean GLFs using six downscaled-GCMs, A2 emissions scenario.

Pasture Growth and Growth Limiting Factors

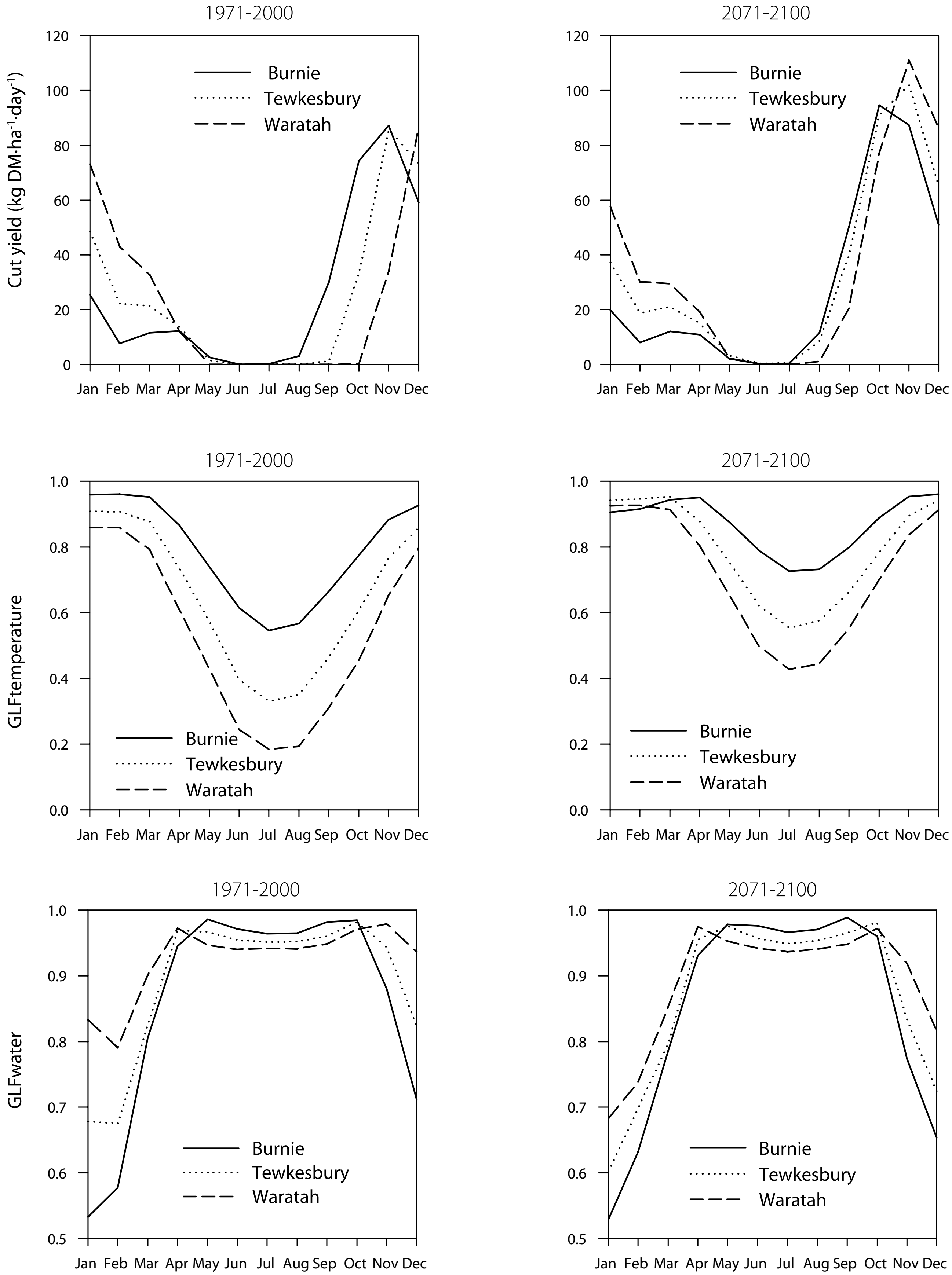


Figure 4.25 Monthly cut yield growth rate (kg DM·ha^{-1}·day^{-1}) and growth-limiting factors for temperature and water for each month 1971-2000 and 2071-2100 simulated by DairyMod at Burnie, Tewkesbury and Waratah, mean of six downscaled-GCMs, A2 emissions scenario.

5 Biosecurity

There is no doubt that changing climate, in particular increasing temperatures, will result in changes to Tasmania's biosecurity threats. Biosecurity threats for the state include invasive weeds, insects and pathogens. It is likely that some agents not currently in Tasmania, in part due to the presently unfavourable climate, will find future conditions more suitable for persistence if introduced.

Of the many potential agents that could be considered in this report, only one has been presented as an example of the methods and tools available to plan for and manage possible incursions. The likelihood of Queensland fruit fly (*Bactrocera (Dacus) tryoni)* becoming established in Tasmania has been assessed using the model CLIMEX™ (Sutherst & Maywald 1985; Sutherst et al 2007b) and the dynamically downscaled simulations.

5.1 Queensland fruit fly

Queensland fruit fly (QFly) is one of Australia's most damaging horticultural pests. It is a tropical and subtropical species with a wide host range (Yonow & Sutherst 1998). Endemic populations extend along the eastern seaboard of the Australian mainland from Cape York Peninsula in north Queensland to Gippsland in Victoria (Osborne et al 1997). Queensland fruit fly attacks a wide range of host plants, lowering production and making fruit inedible, with severe consequences for local and international trade (DPIPWE 2010b). Tasmania has national and international recognition for 'Area-Freedom' from all fruit flies - that is, persistent populations do not occur. This status decreases crop production costs as fewer pre-harvest and post-harvest treatments are required. Pesticide residue problems are reduced and most importantly, Tasmanian producers have a significant advantage in key international markets, including Japan, Korea, USA, Taiwan and China, when compared to exporters that do not enjoy Area-Freedom. It is estimated that Tasmania's fruit fly-free status adds around $90m a year to the export income earned by Tasmania's horticultural industries (DPIPWE 2010b).

Climate change has been identified as a factor that will affect the potential geographic range of species. Evidence for this comes from both empirical observations (Parmesan et al 1999), and modelling studies based on theoretical expectations (Kriticos et al 2003; Potter et al 2009; Yonow & Sutherst 1998). The ability of mobile pest species to expand their range from tropical and subtropical areas into temperate regions that previously were too cold has been projected for some time (Sutherst et al 2007). As species' altitudinal and poleward distribution limits are relaxed under a warming climate, threats to industries increase and biosecurity measures must therefore be strengthened. CLIMEX is a model used to explore the effects of climate on species distribution and relative abundance (Sutherst & Maywald 1985; Sutherst et al 2007b). This model has been successfully applied to plants, pathogens, mammals and insects (Ganley et al 2009; Kriticos et al 2007; Potter et al 2009; Sutherst et al 2007a). Its strength lies in its ability to project a species response in new regions or to future climates. CLIMEX can address questions relevant to managing invasive species. It can help authorities understand whether a pest incursion is likely to become established in an area or whether it represents only a transient threat. This insight can temper the potential response to an incursion. There is little point in mounting an expensive eradication effort against an unwanted species if it is likely that unsuitable weather conditions will preclude it from establishing.

CLIMEX uses climate data with a set of fitted growth and stress functions to assess the potential for a species to persist and grow at each location. It calculates an overall annual index of climatic suitability, the Ecoclimatic Index (EI), for each location. The EI is scaled between zero (completely unsuitable) and 100 (perfect climate year round) and gives an overall measure of the potential of a given location to support a permanent population of the species. In practice however, a score of 100 is rarely achieved. Annual heat sum is a thermal index calculated in growing degree days, and the population degree days (PDD) is that required for one generation. The annual growth index is a measure of the potential for population growth. Projections of species distribution from CLIMEX indicate the maximum range that a species may occupy. Within that climate envelope, other factors such as soil type and host availability will restrict the distribution of the species (Yonow & Sutherst 1998).

A CLIMEX model for QFly was published in 1998 by Yonow and Sutherst (Table 5.1). This model was developed using distribution maps and information on infestations in specific towns in Australia (Yonow & Sutherst 1998), as well as the results of laboratory studies. The projected distribution under current climate included the northern and eastern coast of Australia, and extended south to the mid-New South Wales coastline (Yonow & Sutherst 1998). Inland and high-altitude New South Wales, most of Victoria, South Australia and central Australia were indicated to be unsuitable. While all of Tasmania was climatically unsuitable for persistence of QFly populations using this model, it did indicate that there was the potential for a transient population at some locations in Tasmania if it were introduced into the area. At the time of publication of Yonow and Sutherst's work, there was speculation as to whether QFly could persist throughout the winter in some southern locations or needed to be re-introduced each year. Of particular interest was whether Melbourne was too cold for persistence (Yonow & Sutherst 1998). The number of fruit fly detections and declared outbreaks in both Victoria and the southern Riverina of NSW increased markedly between 2003 and 2008 (Kalang et al 2008). It is now evident from trapping data that QFly has the ability to establish in regions of Victoria once thought too cold for this species to persist. Two reasons for the change in persistence of QFly populations that were proposed by the Kalang review include climate change affecting adult fly survival during the winter months and a possible increase in the level of cold tolerance of adult flies. The recent warming trend experienced in these areas suggests that climate change is a more parsimonious explanation for the observed QFly persistence in Victoria.

The project's fine-scaled modelling outputs provide a special opportunity to study projected pest distributions. Fine-scale projections are particularly important for Tasmania where rainfall and temperature vary considerably over relatively short distances. These gradients cannot be adequately simulated by climate models that use larger grid sizes of 1-degree to 2-degree or even 0.5-degree (Corney et al 2010; Kriticos & Leriche 2010). This study assessed the present and future risk posed by QFly to the Tasmanian horticultural industry using 0.5-degree and 0.1-degree gridded downscaled modelling outputs.

CLIMEX requires monthly means of climate variables. The 0.1-degree grid simulations used downscaled modelling outputs. These included bias-adjusted rainfall, minimum and maximum temperatures and raw (unadjusted) relative humidity from three GCMs (CSIRO-Mk3.5, ECHAM5/MPI-OM and UKMO-HadCM3) and the A2 emissions scenario. The 0.5-degree gridded simulations used a gridded climate dataset developed by the Australian Bureau of Meteorology (BoM) (Kriticos & Leriche 2010).

The affect of grid size on CLIMEX projections was assessed by comparing the 0.5-degree BoM gridded simulations with 0.1-degree gridded downscaled modelling outputs for CSIRO-Mk3.5 A2 emissions scenario.

Climate projections were assessed in intervals of 30 years and were classified as historical (1961-1990), 2030 (2016-2045), 2050 (2036-2065), 2070 (2056-2085) and 2085 (2071-2100). CLIMEX model outputs include the potential distribution of QFly, numbers of generations and stress factors.

There is a clear improvement in the visual definition of QFly distributions from 0.5-degree to 0.1-degree gridded climate datasets (Figure 5.1). This improvement is particularly evident where they occur in topographically complex areas of Tasmania and along the coastline.

Projections of the risk of QFly establishing in Tasmania under climate change are shown in Figure 5.2. There are four categories of risk. Areas in red are defined as '*suitable climate*' for permanent populations of QFly. Areas in orange are defined as '*marginal climate*', where QFly could establish permanent populations in some years but extreme climatic conditions may cause local extinctions. Areas in light green are defined as '*transient risk ≥ 1 generation*'. Queensland fruit fly could not establish a permanent population, but persistence beyond one generation would occur if the fly was imported into the area. The final category in dark green shading is defined as '*transient risk < 1 generation*'. At these locations, QFly could not establish a permanent population or persist beyond one generation if individuals were imported into the area. While some individuals may be able to complete part of their lifecycle in these areas, CLIMEX predicts that cold stress would eradicate the population within one generation.

The pattern of risk under the projected climate is similar for all three downscaled GCMs for the A2 emissions scenario. The risk maps for the historical climate (1961-1990) indicate there is a '*transient risk*' of QFly establishing in Tasmania, with some areas suitable for multiple generations but not permanent populations.

There is an increasing risk along the north and east coastlines, Flinders Island and Cape Barren Island from 2030 to 2085. These areas are projected to be climatically suitable for the establishment and persistence of populations of QFly in the future. At

Table 5.1 CLIMEX parameter values for Queensland fruit fly from Yonow and Sutherst (1998). An explanation of the role and meaning of parameters is given by Sutherst (2007a).

Temperature	DV0 = lower threshold	12 °C
	DV1 = lower optimum temperature	25 °C
	DV2 = upper optimum temperature	33 °C
	DV3 = upper threshold	36 °C
Moisture	SM0 = lower soil moisture threshold	0.1
	SM1 = lower optimum soil moisture	0.5
	SM2 = upper optimum soil moisture	1.75
	SM3 = upper soil moisture threshold	2
Heat stress	TTHS = temperature threshold	36 °C
	THHS = stress accumulation rate	0.005 or
	DTHS = degree-day threshold (stress accumulates if the weekly number of degree-days above 36 °C exceeds this value)	0.4375
	DHHS = stress accumulation rate	0.01
Cold stress	TTCS = temperature threshold	2 °C
	THCS = stress accumulation rate	0.1
	DTCS = degree-day threshold (stress accumulates if the weekly number of degree-days above is below this value)	20 °C
	DHCS = stress accumulation rate	0.00025
Dry stress	SMDS = soil moisture dry stress threshold	0.1
	HDS = stress accumulation rate	0.005
Wet stress	SMWS = soil moisture wet stress threshold	2
	HWS = stress accumulation rate	0.002

the same time, larger areas of Tasmania are projected to be suitable for multiple generations of transient populations of QFly.

The presence of permanent populations of QFly in Tasmania would have a significant impact on the export advantages currently enjoyed by the state's horticultural industries due to Tasmania's QFly area-free status. It is important to note however, that due to the uncertainty around future greenhouse gas emissions and the variability of results from different downscaled-GCMs, the timeline for the changing invasion threat is more imprecise than may be suggested by the presented results. The projections shown for 2085 might be realised sometime earlier this century, or early next century. At the present time, the A2 emissions scenario is tracking slightly below current patterns of emissions. A reduction in emissions rates could delay the progression of the pest risk, while high emissions could move the timeline forward. Hence this research does not provide a base for the development of a rigid biosecurity plan, but rather should be used to support and guide policy makers and industry stakeholders to develop adaptive management options for the future.

Meats et al (2003) suggested that the unassisted long-distance flight of QFly would be no more than 6 km, and while wind assistance may increase that distance, it is extremely unlikely QFly would be able to disperse naturally from Victoria to Tasmania. The key invasion pathway into the state is likely to be through the import of infested fruit. QFly larvae have occasionally been detected in fruit imported into Tasmania from mainland Australia (ABC Rural, 2010). If such an incursion went undetected, the CLIMEX modelling suggests that Tasmania is already climatically suitable for transient populations of QFly, with some areas suitable for more than one generation. Studies by Dominiak et al (2006) indicate that towns can also provide an oasis of microclimates suitable for development and survival of QFly, as could glasshouses and supermarkets.

There are a number of potential foci for managing the future risk of permanent populations of QFly in Tasmania. A fruit fly-trapping program already exists in Tasmania with a total of 906 Lynfield-type Mediterranean and Queensland fruit fly traps distributed throughout the 'high risk' locations (ports where visitors, fruit and vegetables arrive from

Effect of Grid Size on Modelled QFly Distribution

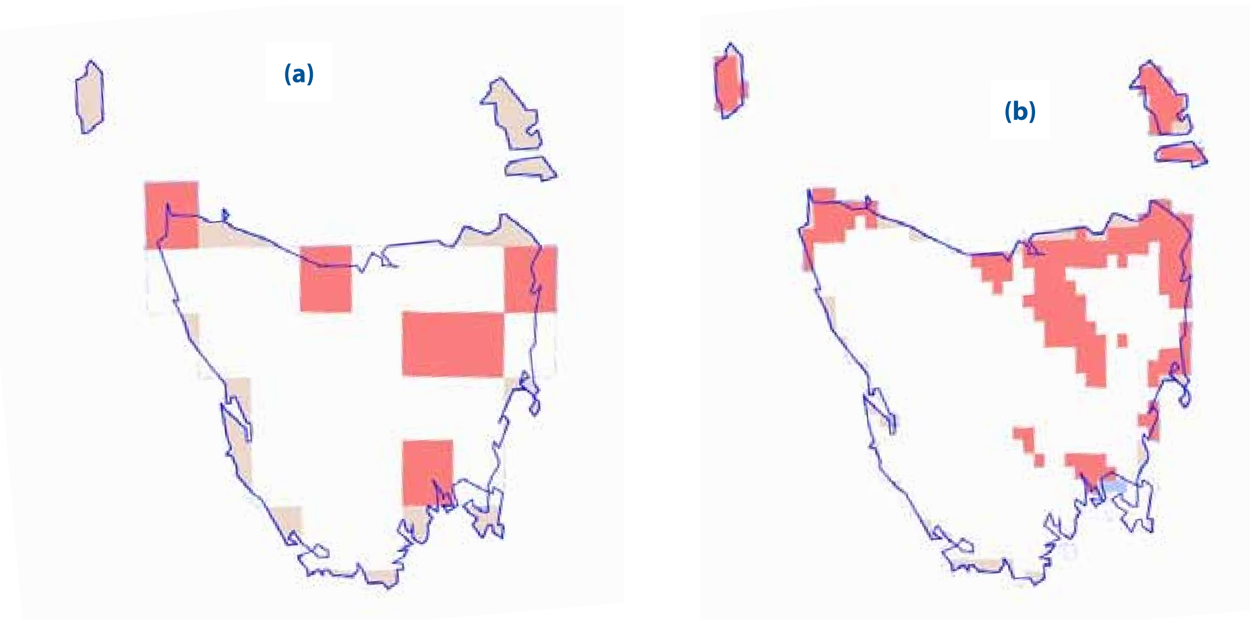


Figure 5.1 The number of generations of QFly projected to occur for 1961-1990.
a) 0.5-degree grid and
b) CSIRO-Mk3.5 0.1-degree grid,

0 generations
1 to <2 generations per annum
2 to 3 generations per annum.

Potential Distribution of Queensland Fruit Fly

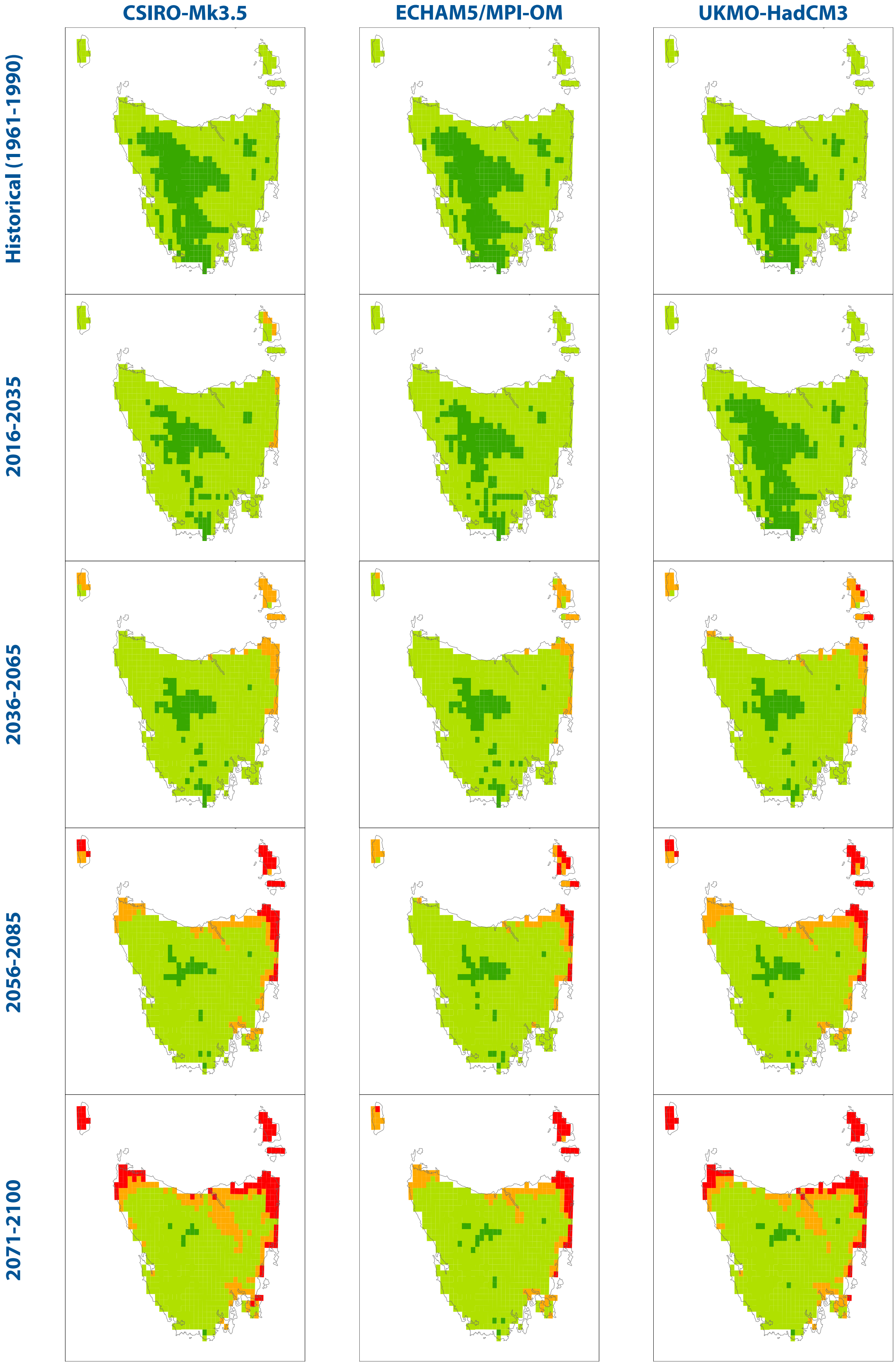


Figure 5.2 Climatic risk of Queensland Fruit Fly (Bactrocera tryoni) establishing in Tasmania using three downscaled-GCMs for the periods 1961-1990, 2016-2035, 2036-2065, 2056-2085 and 2071-2100. CLIMEX results classified for establishment risk are as follows:

- *Suitable Climate* (Ecoclimatic Index ≥ 10);
- *Marginal Climate* (10 > Ecoclimatic Index > 0);
- *Transient Risk ≥1 generation* (Ecoclimatic Index = 0 and Annual Growth Index >0 and Annual Heat Sum ≥ PDD);
- *Transient Risk <1 generation* (Ecoclimatic Index = 0 and Annual Growth Index >0 and Annual Heat Sum < PDD).

other states) and 'low risk' locations (where fruit fly hosts are grown) of the state (DPIPWE 2010b). The results of this research could assist in a review of the trapping network to ensure that not only were high and low risk regions surveyed, but fruit fly would also be monitored in those areas that are likely to be climatically suitable for permanent populations. The early detection of QFly in an endangered area significantly advantages the management of the biosecurity risk. Early detection means more management options are available at lower costs.

The 0.1-degree downscaled climate modelling outputs as used in CLIMEX have provided a useful tool to explore likely areas at risk of QFly establishing permanent populations in Tasmania. Areas at risk of supporting permanent QFly populations have been delimited. The improved precision of the downscaled simulations allows policy makers to be more strategic in their planning of surveillance networks and in the design of fruit fly management strategies for the future.

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Appendices

Table A.1 List of locations referred to in this report, including grid coordinates and elevation of each location.

Name	Easting	Northing	Elevation
Bothwell	147	-42.3	537 m
Bronte Park	146.5	-42.1	864 m
Burnie	146	-41.0	62 m
Campania	147.4	-42.7	160 m
Campbell Town	147.5	-41.9	260 m
Coal Valley	147.5	-42.8	56 m
Cressy	147	-41.6	162 m
Deloraine	146.7	-41.5	259 m
Elliott	145.8	-41.1	167 m
Flinders Island	148.1	-40.1	79 m
Flowerdale	145.6	-41	119 m
Hampshire	145.6	-41.3	486 m
Huon 39 m	147.1	-43.3	39 m
Huon 95 m	147.1	-43.2	95 m
Huon 394 m	147.1	-43	394 m
Kindred	146.2	-41.2	112 m
King Island	144	-39.8	33 m
Meadowbank	146.8	-42.6	262 m
Merseylea	146.5	-41.3	119 m
Ouse	146.7	-42.5	234 m
Pipers Brook	147.2	-41.1	99 m
Ringarooma	147.7	-41.2	321 m
Sassafras	146.5	-41.3	119 m
Scottsdale	147.5	-41.2	249 m
Smithton	145.1	-40.9	66 m
Spreyton	146.4	-41.2	38 m
Swansea	148.1	-42	87 m
Tewkesbury	145.7	-41.2	368 m
Tunbridge	147.4	-42.1	264 m
Waratah	145.6	-41.4	582 m
West Tamar	146.9	-41.3	136 m
Woolnorth	144.8	-40.8	17 m

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