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The Effects of Climate Change and Variation in New Zealand

An Assessment Using the CLIMPACTS System

R.A. Warrick, G.J. Kenny and J.J. Harman
(editors)

June 2001

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Printed by: Waikato Print
The University of Waikato
Private Bag 3105
Hamilton
New Zealand

ISBN 0-473-07988-7

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Acknowledgements

Since 1993, there have been a number of CLIMPACTS team members who have contributed substantially to its development, but who are now no longer actively involved in the Programme. These include G. Sims (who originally engineered the software for the CLIMPACTS system), M. Camillieri and J. de Ruiter.

In addition, there have been a number of external individuals and organisations, while not formally part of CLIMPACTS, have graciously contributed their time, ideas, models and/or data to its development, including: T.M.L. Wigley (National Centre for Atmospheric Research, USA); M. Hulme (University of East Anglia, UK); A.B. Pittock, P. Whetton and R. Jones (CSIRO Division of Atmospheric Research); J. Leathwick (Landcare); M.A. Semenov (IACR Long Ashton Research Station, BBSRC, UK); the Ministry for the Environment; Environment Canterbury and Environment Waikato.

The research that provided the basis for the present volume would not have been possible without the support provided to the CLIMPACTS Programme by the New Zealand Foundation for Research, Science and Technology.

To all, the authors of this report extend their gratitude.

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June 2001

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Introduction:
The CLIMPACTS Programme and Method

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Introduction to the CLIMPACTS Assessment Report

It is a decade since the publication of the first national assessment of the impacts of climate change on New Zealand (Ministry for the Environment, 1990). This assessment provided a comprehensive review, based primarily on expert judgement, of likely scenarios of climate change in New Zealand and the biophysical, economic and social impacts of these scenarios across a range of sectors. It concluded with a set of recommendations, including a need for more in-depth research to better explain and predict the impacts of climate change. Since this report was published, a number of research programmes have been supported by the Foundation for Research, Science and Technology (FRST) aimed at:

- Increasing understanding of New Zealand's climate and how it might change in future;
- Increasing understanding of the environmental responses of a range of plant and animal species;
- Developing and refining crop and soil models (Ministry for the Environment, 1997).

The 1990 assessment was a major achievement. However, it was also a time consuming exercise that cannot be repeated easily. Thus, along with a need to better understand the climate and biophysical systems of New Zealand, the need to develop an improved capacity for evaluating possible changes in climate and their effects on the New Zealand environment has also been recognised. Since the middle of 1993 the CLIMPACTS programme, described in more detail below, has been focussed on the development of such a capacity, in the first instance for the agricultural sector.

Based on this development, the goals of this present assessment are:

1. To present current knowledge on likely scenarios of climate change and associated uncertainties in New Zealand;
2. To present current knowledge, based on quantitative analyses using a consistent set of scenarios, on the likely effects of climate change on a range of agricultural and horticultural crops of economic importance;
3. To demonstrate, by way of this report and the associated technical report (Kenny *et al.*, 2001), the capacity that has been developed for ongoing assessments of this kind in New Zealand.

The CLIMPACTS Programme

The CLIMPACTS Programme is a collaborative research effort between two Universities and five Crown Research Institutes (CRIs) that began in 1993. The broad goal of the CLIMPACTS Programme is to enhance the understanding of the sensitivity of New Zealand's natural and managed environments to climate variability and change, by:

1. Enhancing the means for determining the environmental effects of climate change and variability;
2. Improving the basis for decision-making and sustainable management in avoiding adverse consequences of such changes;

3. Building a base of multi-skilled expertise in New Zealand for better understanding climate-environment relationships.

In order to address this goal a research strategy was developed, the focus of which was the development of an integrated assessment model (IAM), the CLIMPACTS system.

Why Use an Integrated Assessment Model?

From an international perspective, most model-based assessments of the impacts of climate change have proven to be cumbersome and computationally inefficient[1]. This is largely because the required data and models are not linked in a manner that facilitates rapid, and repeated, assessments in order, for example, to examine the effects of different climate scenarios or model assumptions. These difficulties are compounded when attempts are made to conduct assessments that encompass different spatial and temporal scales (e.g. from sites to regions and from time series of daily weather to monthly climate averages), and different sectors or exposure units. In such cases it proves a significant challenge to provide some sense of coherence and consistency to analyses and interpretation of results. Furthermore, the demands for informed policy decisions, as required under the United Nations Framework Convention on Climate Change (UNFCCC), have increasingly required a re-evaluation of the approach to impact assessment.

These circumstances have contributed to the emergence of integrated assessment models (IAMs). IAMs have been characterised, in the climate change literature, as encompassing inter-linkages and feedbacks between global changes in climate, sectoral effects, socio-economic effects, and responses. Such models have tended to be global in scale, and focussed heavily on socio-economic effects and responses, particularly mitigation strategies (see Weyant *et al.*, 1996). Often this precludes the requirements for integrated assessment of impacts at the nation scale. In New Zealand, the CLIMPACTS system was devised as a means to address the need for a more integrated approach to impact assessment at the national and sub-national scales where the effects of climate change will be felt most directly.

The CLIMPACTS System

The CLIMPACTS system and its component models are described in detail in the accompanying description and user's guide (Kenny *et al.*, 2001). In the initial stage of development, the CLIMPACTS system built upon work carried out in Europe, in particular the ESCAPE model (CRU and ERL, 1992). As discussed above, the CLIMPACTS system was developed to enhance New Zealand's capability to examine environmental sensitivities to climate change, as a basis for informed policy decisions. Importantly, the system was developed as an evolving platform that could be readily extended to other sectors (e.g. water resources or health) and updated to account for improvements in scientific understanding, datasets, or models. The development of the CLIMPACTS system has had a very strong focus on system design, which has brought together a number of key requirements, including:

- User accessibility;
- Capability to handle spatial and non-spatial data;
- Integration of a flexible climate change scenario generator with data and sectoral impact models;
- Capacity to be readily updated with new models and data and to account for advances in climate change science.

---

[1] Nevertheless, a number of successful studies of this kind, the majority of which have focussed on agriculture, have been made (e.g. Parry *et al.*, 1988a,b; Kenny *et al.*, 1993; Rosenzweig and Iglesias, 1994).

The key system components of the CLIMPACTS system (see Figure 1.1) are:

- A global climate model, known as MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change, Wigley, 1994);
- Patterns of climate change for New Zealand;
- Historical climate and land use data for New Zealand;
- Sectoral impact models;
- Weather generators and an extreme event analysis tool.

The application of these components at different assessment scales is described briefly below. A common feature at all scales of assessment, and an integral part of the research capability provided by the CLIMPACTS system, is the climate change scenario generator. This links together output from MAGICC (an energy-balance, box-diffusion-upwelling climate model that provides projections, from 1990 to 2100, of global temperature changes from greenhouse gas emissions with patterns of climate change and historical climate data for New Zealand. The manner in which these components are combined is described by Kenny *et al.* (1995) and Warrick *et al.* (1996). The most important characteristic is that the CLIMPACTS system provides flexibility to specify numerous combinations of GHG emissions scenarios, climate sensitivity, time horizon, and climate change patterns (as derived from general circulation models (GCMs)). Thus it is possible to explore environmental sensitivities to a wide range of scenarios.

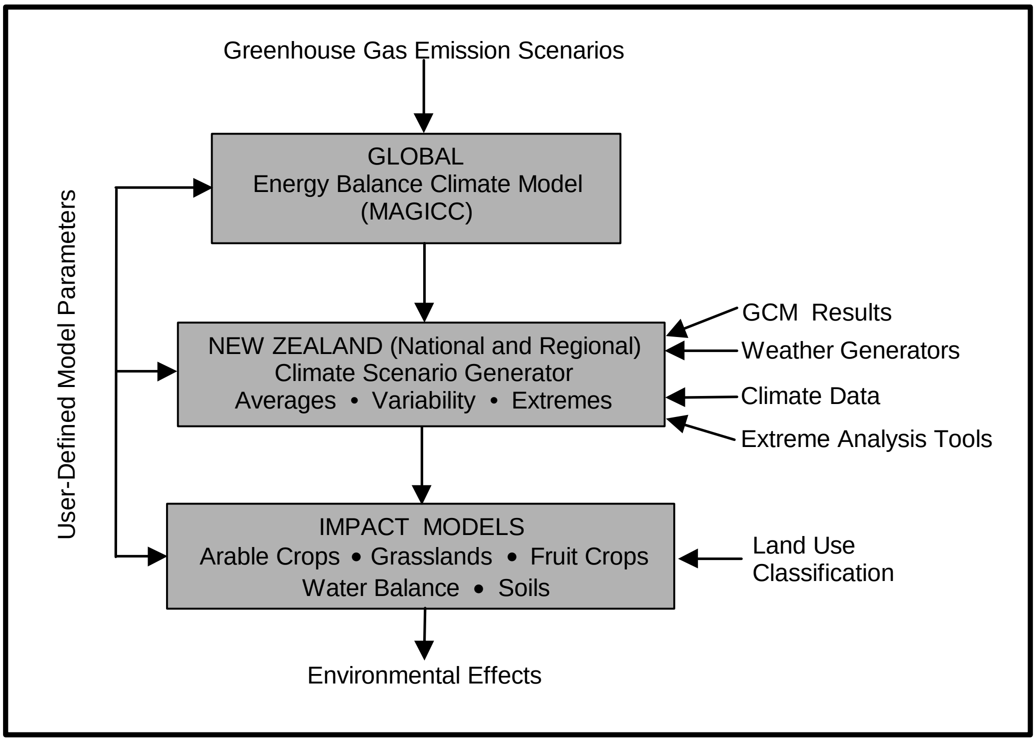

Figure 1.1: Conceptual structure of the CLIMPACTS system

The CLIMPACTS system was designed to address issues at national, regional and local scales through four stages of development (Table 1.1). In the first stage of development, the focus was on designing and developing the CLIMPACTS system to address questions at the *national* scale, such as "what changes in crop distribution might occur under climate change?" The second stage was focussed at the *site* scale, with an emphasis on more detailed impact models, along with weather generators and statistical tools for examining climatic risks. Thus, the type of question addressed at this scale is "how might frost risk for a particular crop vary or change at a given site?" The third stage involved development and implementation of models and tools for analysis at the *regional* scale within New Zealand. The purpose of this development has been to examine questions such as "how does the risk of frost vary within the region and how might this change in the future?" Currently work is underway to develop tools for assessing the *economic* effects of climatic change and variability, the fourth stage of development. These developments of the CLIMPACTS system are discussed in greater detail below.

Table 1.1: CLIMPACTS research strategy

	Stage 1 Develop CLIMPACTS System, NZ-Wide Applications	**Stage 2 Develop Site-Specific Capacity**	**Stage 3 Develop Regional Capacity**	**Stage 4 Develop Economic and Land Use Analysis Capability**
Spatial Scale (Resolution)	North or South Island (~5 km x 5 km)	~10 sites (nonspatial)	Canterbury and Waikato regions (~1 km x 1 km and data for 20 sites in each region)	Combination
Time Scale of Climate Forcing	Monthly/seasonal /annual	Daily	Combinations	Model dependent
Environmental Modelling Approach	Simplified impact models and indices	Complex biophysical process models	Mix of models	Production, land use models
Uses	Broad-scale sensitivity analyses; national impact assessments	Detailed analyses of biophysical responses; evaluation of management options	Sensitivity analyses at local level; resource management and planning	Sectoral sensitivity analyses; economic assessments and management
Potential Users	Government	Private sector; modellers	Local authorities; planners	Industry; local government

The National-Scale Capacity

The early development of the CLIMPACTS system focussed on the national scale (Kenny *et al.*, 1995; Warrick *et al.*, 1996) and was aimed at addressing broader questions related to relative changes in climate in different parts of New Zealand and the sensitivity of different agricultural crops to those changes. The principal system components for national-scale applications are:

- Interpolated monthly climate data, derived from the 1951-80 climate normals;
- Times series of monthly climate data, for selected sites;
- Land use capability (LUC) data, from the New Zealand Land Resources Inventory (LRI);
- Patterns of climate change, derived from GCMs;
- Models, for kiwifruit (Salinger and Kenny, 1995), grain maize, Paspalum dilatatum (Campbell and Mitchell, 1996), wheat, and barley.

The spatial data (climate, soils and GCM patterns) were all interpolated (or sampled in the case of the LUC data) to a 0.05° lat/long grid for North and South Islands. The LUC data are used in the CLIMPACTS system to identify arable and non-arable land classes, and thus reduce computation time for particular applications. The integration of these components within the CLIMPACTS system has provided the capability for spatial analyses of the effects of climate change in New Zealand (e.g. Kenny *et al.*, 2000).

The Site-Scale Capacity

The development of a site-scale capacity in the CLIMPACTS system formed the second stage of the research programme. This was designed to address more detailed questions related to effects of climate change on agricultural and climatological risk. The principal system components for site-scale applications are:

- Time series of daily weather data;
- Weather generators;
- A climate risk analysis tool;
- Simulation models for pasture production, wheat and maize yield, kiwifruit phenology, and soil carbon.

A significant part of the site-capacity development was the development and incorporation of *weather generators* and an *extreme event analysis tool*, which are described in more detail by Ye *et al.* (1999). An important issue in climate change science is the matching of space and time scales between output from GCMs and input requirements for impact assessments (Semenov and Barrow, 1997). GCM output is provided at a coarse spatial (tens of kilometres) and temporal (monthly or seasonal) resolution. On the other hand, site assessments, such as risk analysis, often require high-resolution data. This includes information on changes in both mean climate and its variability. Weather generators are models that provide realistic simulations of changes in daily weather that may be associated with mean changes in climate (Barrow and Hulme, 1996; Barrow *et al.*, 1997; Semenov and Barrow, 1997). Four different weather generators were incorporated within the CLIMPACTS system to enable evaluation of differences in their performance under different conditions (Ye *et al.*, 1999).

In addition to the weather generators, an extreme event analysis tool was also incorporated. This tool fits a generalised extreme event (GEV) distribution curve to observed extreme daily values from time-series data. With this tool, one can thereby estimate the return periods of extreme events and how they might change under future climates.

The Regional-Scale Capacity

While the national capacity in the CLIMPACTS system focussed more on issues of spatial scale, and the site capacity focussed more on issues of temporal scale, the requirements for the regional capacity were for both spatial and temporal-scale issues to be addressed. For this purpose a separate regional version of the CLIMPACTS system was developed, focussing in the first instance on the Waikato and Canterbury regions. This incorporates the components described for both the national and site scale capacities, with several refinements including:

- Spatial data interpolated to the New Zealand map grid at a 1 km x 1 km resolution, with the addition of available water holding capacity (AWC) data;
- Time series of daily weather data for 21 sites in Waikato and for 20 sites in Canterbury;
- A water balance model, as the basis for developing a capacity for drought risk assessment.

The spatial climate data used for these two regions were developed by Leathwick and Stephens (1998). The use of finer resolution data at the regional scale allows for much closer examination of sensitivities to change within regional boundaries (e.g. spatial changes in the regional water balance). Likewise, the addition of time series of daily weather data for a wider network of sites enables more detailed characterisation of within region changes (e.g. changes in drought risk at selected sites within the region). This capability has been extended by the development of methods for linking coarse resolution GCM output to the finer resolution required by a weather generator (Thompson and Mullan, 1999).

The Advantages of the CLIMPACTS System

In summary, as a tool for impact assessment, the CLIMPACTS system has a number of distinct advantages, including:

- The system is integrated, linking together a number of analytical tools and models, allowing a range of assessments of climate variability and change to be made;
- The system is flexible, allowing the user to examine effects for a range of climate change scenarios;
- The system can be easily updated as new information becomes available and the accuracy of the models improves;
- The outputs for a specified scenario are generated quickly, and thus comprehensive analyses are possible in a short space of time;
- The system allows both spatial and temporal analyses to be conducted;
- The multi-scale nature of the system means an analysis can be made separately on a national, regional, or site basis, or in an integrated manner across these scales;
- Various types of analyses can be undertaken including sensitivity analyses, an examination of uncertainties, extreme event analyses, or a combination of the above;
- The system can be used as a training tool or as an instructional tool to assist with policy and plan formulation.

Given these advantages, the CLIMPACTS system served as the primary tool for the assessment presented in the remainder of this Volume.

Contents and Structure of this Assessment Report

This report has been prepared for both the science and policy communities in New Zealand. There are two main components:

1. The detailed findings of the assessment, presented in a series of chapters;
2. An annex, which contains technical details on models used in the assessment.

A synthesis of the report has been produced as a separate document.
The chapters are ordered as follows:

Chapter 1 provides an introduction, including: the goals of the assessment; a description of the CLIMPACTS programme and the CLIMPACTS system, the integrated model used in the assessment; a summary of the scenarios used; and important limitations.

Chapter 2 provides a review of historical climate trends, examines extremes and variability, and describes the predominant patterns of change arising from the scenarios used throughout the assessment.

Chapter 3 examines effects on arable crops, focussing on wheat and grain maize.

Chapter 4 examines effects on fruit crops, in particular kiwifruit and apples.

Chapter 5 examines effects on pasture production and possible changes in distribution of sub-tropical pasture species.

Chapter 6 examines effects on soil organic matter and discusses possible consequences in terms of effects on pasture production.

Chapter 7 provides a regional perspective, focussing on effects on regional water balance and drought frequency in Canterbury and Waikato regions.

Each chapter, aside from the first and to some degree the second chapter, address four key questions:

1. What is known?
2. What do results from the CLIMPACTS system show?
3. What are the links to policy and adaptation?
4. What are the key uncertainties, gaps in knowledge and methods, and future directions?

Accompanying this assessment report is a companion volume, which contains a detailed technical description of the CLIMPACTS system used for this assessment along with a CD which contains a demonstration version of this system (Kenny *et al.*, 2001).

Scenarios Used in this Assessment Report

Within the CLIMPACTS system there is the flexibility to select from a wide range of GCM patterns, GHG emissions scenarios, and climate sensitivities. There is also the capability to select variability options associated with the southern oscillation index (SOI), to enable users to examine effects of El Niño and La Niña events.

Within the scope of this assessment it was not feasible, nor necessary, to analyse and compare every possible scenario combination. Those GHG emissions scenarios and GCM patterns used provide the most up-to-date results on global and regional changes that may occur over the next 100 years as a result of the enhanced greenhouse effect. A number of combinations of emissions scenarios and GCM patterns were made to reflect the range of uncertainty in current climate change science.

The scenario options used were:

- The most recent transient GCM patterns from the Hadley Centre in the United Kingdom (HadCM2) and the CSIRO Division of Atmospheric Research in Australia (CSIRO9). These were selected because they are widely recognised internationally, are two of the GCM patterns being used in the latest IPCC assessment, and have validated well for the New Zealand region;
- A new set of GHG emission scenarios was developed by the IPCC Special Report on Emissions Scenarios (SRES). These are referred to as the SRES marker scenarios. The preliminary SRES marker scenarios A2, A1, and B1 have been chosen for the IPCC 2000 assessment to represent the high, mid-range, and low levels of GHG emissions respectively (Carter and Hulme, 1999). On the basis of this recommendation they were chosen for use in this assessment of effects on

New Zealand agriculture and horticulture;
- High, mid and low climate sensitivity options were also selected to represent the range of uncertainty in climate response to an equivalent doubling of atmospheric CO2;
- Positive and negative SOI values were identified to examine effects of enhanced El Niño and La Niña conditions under climate change.

These options were selected in the following combinations to create a range of climate change scenarios in order to express, as well as possible, the range of uncertainty:

1. The uncertainty with greenhouse gas emissions scenarios was examined using the HadCM2 GCM pattern with:
    - SRES A2, high climate sensitivity;
    - SRES A1, mid climate sensitivity;
    - SRES B1, low climate sensitivity.

2. The uncertainty between GCM patterns was examined using the SRES A1, mid climate sensitivity scenario with:
    - CSIRO9 transient GCM pattern;
    - HadCM2 transient GCM pattern.

3. The effects of positive and negative SOI conditions were examined using the HadCM2 GCM pattern and the SRES A1, mid climate sensitivity scenario with:
    - A “typical” La Niña (positive SOI) pattern;
    - A “typical” El Niño (negative SOI) pattern.

Important Limitations to this Assessment

The results presented in this assessment are for the agriculture and horticulture sectors only. The CLIMPACTS system is an evolving platform for facilitating integrated assessment of the effects of climate change in New Zealand. While its current application is limited to the agriculture and horticulture sectors, there are already developments underway for human health and water resources, which will provide a basis for cross-sectoral assessments.

This assessment does not provide the definitive answers on effects of climate change for the agriculture and horticulture sectors in New Zealand, for two important reasons:

1. The scenarios used represent the current state of knowledge, but GCMs are still relatively poor at predicting changes at regional and local scales. Thus, while a range of uncertainty has been captured in the scenarios used, there is still the likelihood of surprises. The capacity for surprise, in terms of future changes in climate and its effects, relates particularly to ongoing uncertainty about possible changes in variability and extremes.
2. The array of models that have been incorporated are in various stages of development. The most reliable and best validated models, for as representative a range of crops and species as possible, have been used in this assessment. However, results are provided for only a relatively small number of crops, they are not comprehensive for all of New Zealand, and they are wholly focused on first order effects. No account has been made, for example, for effects on pests and diseases.

What this assessment does provide is a state-of-the-art, and in-depth, evaluation of the possible effects of climate change on agriculture and horticulture in New Zealand. Importantly, it reflects the capacity that has been established, through both the CLIMPACTS system and the team of collaborators who have worked on this development, for ongoing assessments of this kind.

References

Barrow, E.M., and Hulme, M. (1996). Changing probabilities of daily temperature extremes in the UK related to future global warming and changes in climate variability. *Climate Research*. 6, 21-31.

Barrow, E.M., Hulme, M., and Semenov, M. (1997). Effect of using different methods in the construction of climate change scenarios: examples from Europe. *Climate Research.* 7, 195-211.

Campbell, B.D., and Mitchell, N.D. (1996). *Report on the development of climate profiles of subtropical grasses for CLIMPACTS.* AgResearch Internal Report, 5 pp.

Carter, T. and Hulme, M. (1999). *Interim Characterizations of Regional Climate and Related Changes up to 2100 Associated with the SRES Emissions Scenarios: Guidance for lead authors of the IPCC Working Group II third assessment report.*

CRU and ERL (Climatic Research Unit and Environmental Resources Limited), (1992). *Development of a framework for the evaluation of policy options to deal with the greenhouse effect: A scientific description of the ESCAPE model.* Report to the Commission of the European Communities.

Kenny, G.J., Harrison, P.A., and Parry, M.L. (1993). *The effect of climate change on agricultural and horticultural potential in Europe.* Research Report No. 2, Environmental Change Unit, University of Oxford, England.

Kenny, G.J., Warrick, R.A., Mitchell, N.D., Mullan, A.B., and Salinger, M.J. (1995). CLIMPACTS: An integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography*. 22(4/5), 883-895.

Kenny, G.J., Warrick, R.A., Campbell, B.D., Sims, G.C., Camilleri, M., Jamieson, P.D., Mitchell, N.D., McPherson, H.G., and Salinger, M.J. (2000). Investigating climate change impacts and thresholds: an application of the CLIMPACTS integrated assessment model for New Zealand agriculture. *Climatic Change.* 46, 91-113.

Kenny, G.J., Harman, J.J., and Warrick, R.A. (2001). *CLIMPACTS Description and Users' Guide.* IGCI, University of Waikato. 45 p. and CD-rom.

Leathwick, J.R., and Stephens, R.T.T. (1998). *Climate surfaces for New Zealand*. Landcare Research Contract Report: LC9798/126.

Ministry for the Environment, (1990). *Climatic Change: Impacts on New Zealand, Implications for the Environment, Economy, and Society*. Ministry for the Environment, Wellington.

Parry, M.L., Carter, T.R., and Konijn, N.T. (eds), (1988a). *The impact of climatic variations on agriculture. Volume 1. Assessments in cool temperate and cold regions.* Kluwer, Dordrecht, The Netherlands.

Parry, M.L., Carter, T.R., and Konijn, N.T. (eds), (1988b). *The impact of climatic variations on agriculture. Volume 2. Assessments in semi-arid regions*. Kluwer, Dordrecht, The Netherlands.

Rosenzweig, C., and Iglesias, A. (eds), (1994). *Implications of climate change for international agriculture: crop modeling study, U.S.* Environmental Protection

Agency, Office of Policy, Planning and Evaluation, Climate Change Division, Adaptation Branch, Washington D.C.

Salinger, M.J., and Kenny, G.J. (1995). Climate and kiwifruit cv. 'Hayward': 2. Regions in New Zealand suited for production. *New Zealand Journal of Crop and Horticultural Science*. 23, 173-184.

Semenov, M.A., and Barrow, E.M. (1997). Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change*. 35, 397-414.

Thompson, C.S., and Mullan, A.B. (1999). *CLIMPACTS 1998/1999: Applying the Richardson weather generator to climate change studies*. NIWA Internal Report No. 55.

Warrick, R.A., Kenny, G.J., Sims, G.C., Ericksen, N.J., Ahmad, Q.K., and Mirza, M.Q., (1996). Integrated model systems for national assessments of the effects of climate change: Applications in New Zealand and Bangladesh. *Journal of Water, Air and Soil Pollution*. 92, 215-227.

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, E.A., Richels, R., Rotmans, J., Shukla, P.R., and Tol, R.S.J. (1996). Integrated assessment of climate change: an overview and comparison of approaches and results. In: Bruce, J.P., Lee, H., and Haites, E.F. (eds.). *Climate Change 1995: Economic and Social Dimensions of Climate Change, Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, New York, Melbourne. p. 367-396.

Wigley, T.M.L. (1994). *MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) User's guide and reference manual*.

Ye, W., Kenny, G.J., Sims, G.C., and Warrick, R.A. (1999). *Assessing the site-scale effects of climate variability in New Zealand: developments with the CLIMPACTS integrated model system*. MODSIM 99 Conference Proceedings.

Chapter 2:
The New Zealand Climate - Present and Future

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National Institute of Water and Atmospheric Research

Observed Climate

New Zealand lies in the mid-latitude zone, with southern New Zealand in the current of Southern Hemisphere westerlies, and northern New Zealand protruding into the subtropical belt of migratory anticyclones. The prevailing circulation over New Zealand is from the west to southwest. The alpine axial ranges lie southwest/northeast, forming an orographic obstacle to the prevailing circulation over the North and South Islands. Thus, sheltered eastern areas of the North Island, and eastern and inland areas of the South Island, are much drier than the exposed western areas. Annual precipitation varies from as little as 300 mm in Central Otago to over 8000 mm in the Southern Alps. For a greater part of New Zealand, precipitation varies between 600 and 1500 mm. Areas of below 600 mm of precipitation are found in the South Island east of the main ranges in Central and North Otago and South Canterbury. In the North Island the driest areas are central and southern Hawke's Bay, Wairarapa and coastal Manawatu with 700-1000 mm annually.

Mean temperature at sea level varies from 16°C in the far north to 10°C in the far south, with temperatures decreasing as altitude increases. Being a maritime climate, extreme temperatures are less common than in continental areas, but these do occur in the central North Island and Central Otago.

The sunniest locations in New Zealand are at the northern end of the South Island and eastern Bay of Plenty with more than 2350 hours per annum. The remainder of the Bay of Plenty and Hawke's Bay are only slightly less sunny. A large portion of the country has at least 2000 hours, with Westland at 1800 hours. The locations with the least sunshine are Southland and coastal Otago, and the Southern Alps.

The climate of a region in New Zealand is a result of New Zealand's location in the general atmospheric circulation, and the interaction of the country's orography with the climate patterns. CLIMPACTS has used 1951-80 as the baseline climate from which to assess change. However, climate is not constant, and the following sections in this chapter will describe how observed climate has changed during the 20th century, and outline scenarios of future climate for the 21st century.

Observed Climate Trends

Global mean surface temperatures have increased by about 0.6ºC this century (Nicholls *et al.*, 1996), a finding that is consistent with evidence from nineteenth century ocean temperatures (Parker and Folland, 1991). Since 1880, the overall temperature increase of the Southern Hemisphere between the 20-year period 1880-1900 and the decade 1981-90 has been 0.48ºC (Nicholls *et al.*, 1996). Folland and Salinger (1995) have compared homogenized series of mean air temperature averaged over New Zealand with high quality marine temperature data for the period 1871-1993. A warming in all three data series (surface air temperature, sea surface temperature, night marine air temperature) of 0.7ºC is detected between 1900 and the 1990s.

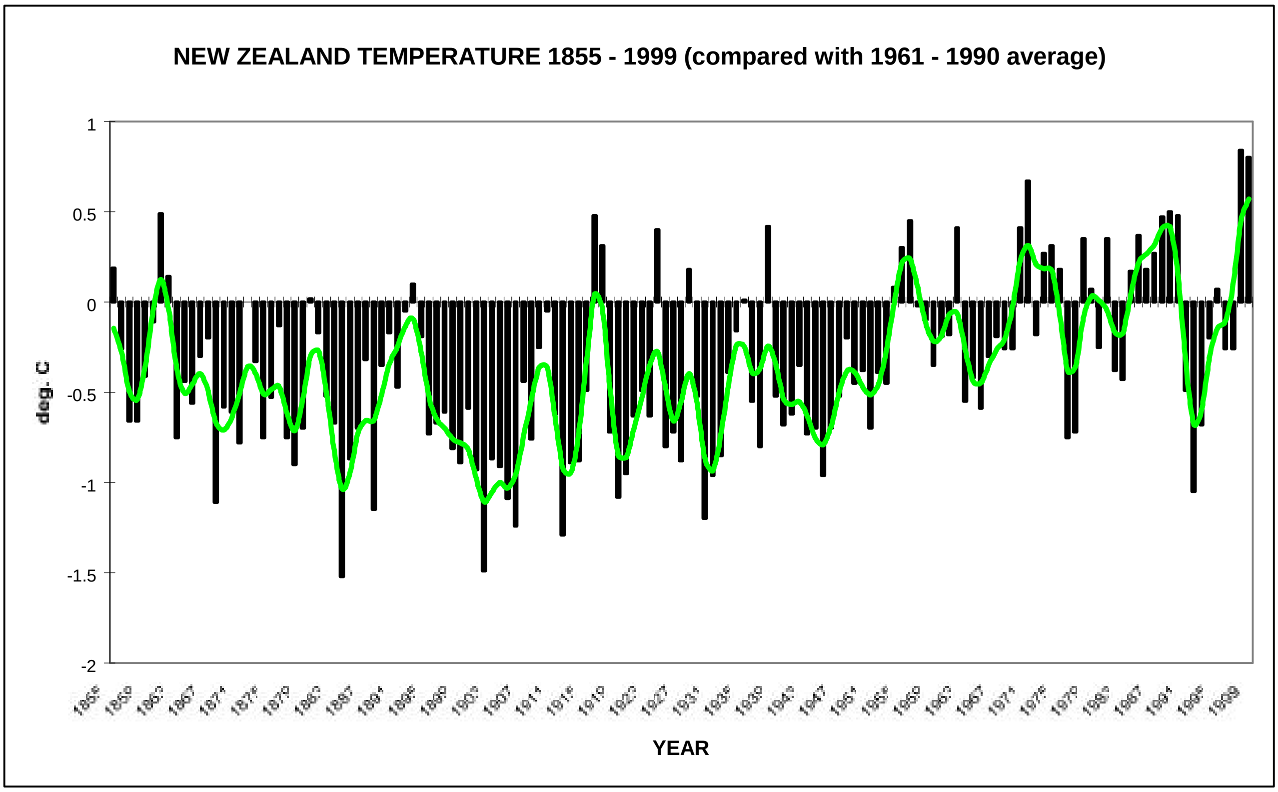

Figure 2.1: Annual mean surface temperature anomalies 1855-1999
as departures from the 1961-90 average. Bars represent annual anomalies,
and the line smoothed values over several years.

In the New Zealand observed surface temperature record to 1999 (Figure 2.1), the 1900s were the coolest decade, with rapid warming between the 1940s and 1950s, and warming reaching a peak by 1990. The early 1990s cooled slightly. The 1980s were the warmest decade and 1998 and 1999 the warmest individual years. In New Zealand, site temperature and rainfall trends have been documented for the period 1920-90 by Salinger *et al.* (1992a, 1992b) for records from 21 stations with rigorously quality controlled measurements. These showed increases in annual mean temperatures between the decades 1941-50 and 1981-90 of 0.8ºC for the North Island, and 0.7ºC for the South Island. Thus, the warming trend since 1900 is dominated by the changes since the 1940s. Since the mid-1970s there has been a drying trend in many North Island stations, whilst stations in the north, west and south of the South Island became wetter. Thompson (1984) has also calculated rainfall trends for some sites with a longer period of observations.

New Zealand's orography plays a significant role in determining the spatial response of regional temperature and rainfall anomaly patterns to circulation. This gives distinct regional responses to variations in atmospheric circulation.

During the 20th century substantial fluctuations in circulation over the New Zealand region have occurred. These are shown in the time series of the regional indices of meridional (M1) and zonal (Z1) flow (Figures 2.2 and 2.3).

In the period 1930-1994, two main circulation changes have occurred in the New Zealand area - around 1950 and 1975 (Salinger and Mullan, 1997, 1999). This

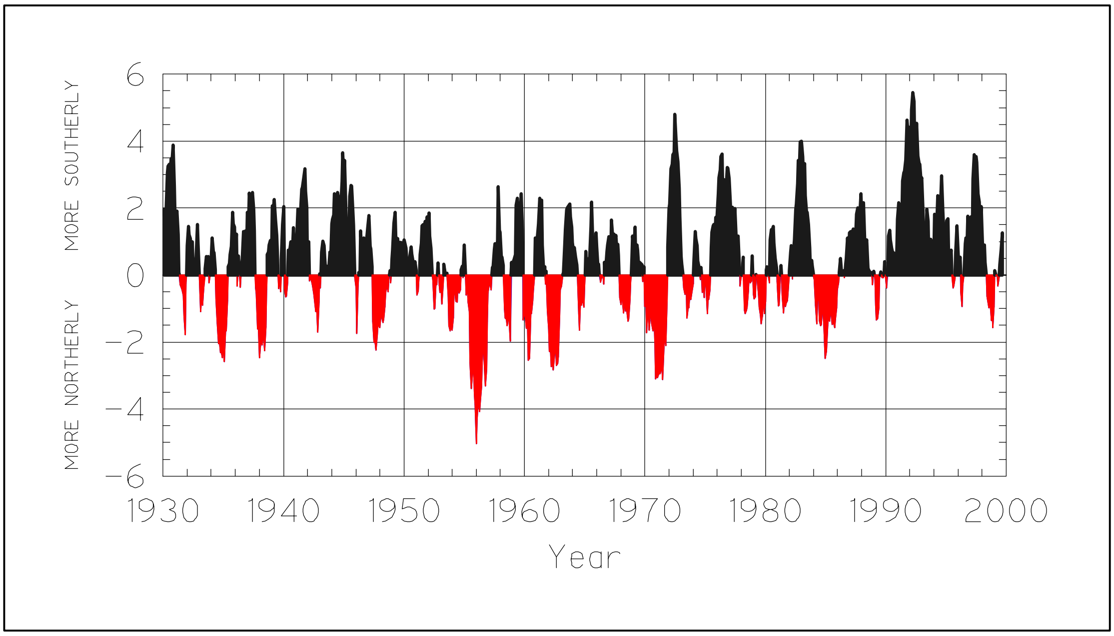

Figure 2.2: Time series of 12-month running averages of the M1 (Hobart-Chatham Island) meridional circulation index 1930-1999, compared with the base period 1951-1980.

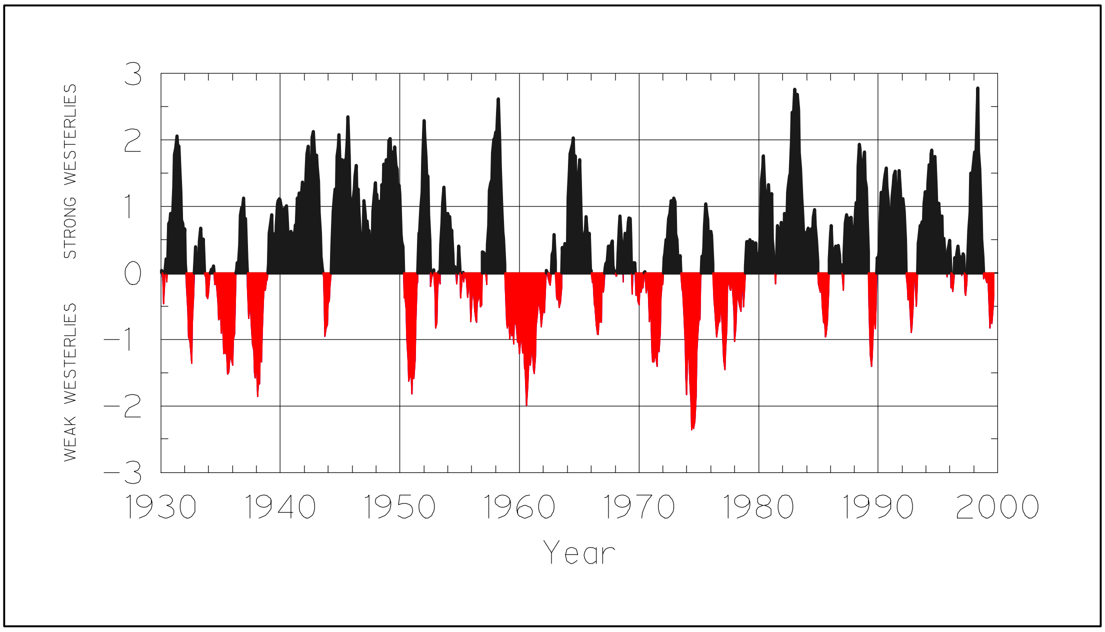

Figure 2.3: Time series of 12-month running averages of the Z1 (Auckland-Christchurch) zonal circulation index 1930-1999, compared with the base period 1951-1980.

breaks the record into three distinct periods of climate: 1930-50, 1951-75 and 1976 onwards.

The period from 1930-50 was one of more south to southwest flow over the New Zealand region, particularly in the 1940s (Figures 2.2 and 2.3). Temperatures in all the regions were lower in this period, with wetter conditions in North Canterbury, particularly in summer, and drier conditions in the north and west of the South Island. This was a consequence of more southerly quarter airflow.

In the 1951-75 period increased airflow from the east and northeast occurred, compared with the earlier period. Mean temperatures in all regions increased in this period. The main trends in rainfall were towards wetter conditions in the north of the North Island, particularly in autumn, yet drier conditions in the southeast of the South Island, especially in summer. More northeasterly flow accounts for all these trends. Figures 2.2 and 2.3 show more northerlies and weaker westerlies at this time.

The latest period from 1976 onwards is notable for more frequent circulation from the west to southwest over New Zealand (see more southerlies and stronger westerlies in Figures 2.2 and 2.3). Temperature trends in all the three areas were similar, with little overall warming from the 1951-75 period. However, the circulation changes produced significant trends in rainfall. The north of the North Island became drier, the only part of the country to do so on an annual basis. Seasonal rainfall trends are apparent too. Summers became drier in the east of the North Island. Winters became wetter in the north of the South Island, summers wetter in the southeast of the South Island, and both seasons wetter in the west and south of the South Island.

Recently shifts in climate have been detected in the Pacific basin, driven by a newly described atmospheric feature, the Interdecadal Pacific Oscillation (IPO), which modulates climate on time scales of one to three decades (Power *et al.*, 1999). The IPO causes significant shifts in climate, that can affect New Zealand (Salinger and Mullan, 1999). Three phases of the IPO have been identified during the 20th century: a so-called “positive phase” (1922–1946), a negative phase (1947–1977) and the most recent positive phase (1978–1998). The phase reversals of the IPO, particularly the more recent one in 1977, coincide to some degree with the circulation changes in the New Zealand region described above.

The CLIMPACTS base period of climate (1951-80), selected for the period of most comprehensive climate data coverage, is representative of the negative phase of the IPO when the prevailing westerly and southwesterly circulation over New Zealand was weaker. On top of this background decadal climate variability, El Niño and La Niña episodes provide major additional variations from year to year. During El Niño events, westerly and southwesterly circulation intensifies over New Zealand; temperatures are normally cooler than normal in the west and south, with above average rainfall there, and below average rainfall in the north and east. La Niña events bring approximately the reverse climate anomaly patterns across the country.

Daily Temperature and Rainfall Extremes

Highest temperatures are recorded east of the main ranges, usually in foehn nor’westerly conditions, and in inland Otago, where 30°C is exceeded on a few days in most summer seasons. Local variation in low temperatures is quite variable, with no days of air frost (<0°C) in parts of Northland and Auckland. In contrast, inland areas of the North Island on the central Plateau, inland north Canterbury, the MacKenzie Basin, Central Otago and much of Southland, can experience more than 50 days per year of air frost. (See Table A1.1 in Annex 1).

The regional increase in surface temperatures that occurred during the 20th century, coupled with changes in circulation, alters the incidence of extremes. The first such change saw a regional temperature increase of the order of 0.5°C around 1950, coupled with increased airflow from the east and northeast. Over all of the North Island, and over the majority of the South Island except inland Otago and South Canterbury, the frequency of days below 0°C decreased by 5 to 10 days per annum. In contrast, the incidence of days below 0°C increased in these latter areas because of more sheltered conditions and clearer skies in winter. In response to the changed circulation, the frequency of days above 30°C decreased fractionally in the northeast of the North Island, and increased slightly in the northeast of the South Island (Figure 2.4), because of more north to northeast flow.

The second period of circulation change, around the mid 1970s, produced a climate with circulation of more regional west to southwest circulation. There was slight warming. In this period the incidence of days below 0°C again decreased, in response to continued warming of the regional oceans and winter temperatures, by between 5 and 10 days per annum. Only on the South Island west coast, and at higher elevations, was there no decrease. The higher frequency of foehn westerly winds brought small increases in the frequency of days above 30°C for the 1976-94 period, compared with earlier years in the east of the North Island and eastern Marlborough. The changes noted in temperature extremes are a direct result of regional warming and circulation changes interacting with the local orography.

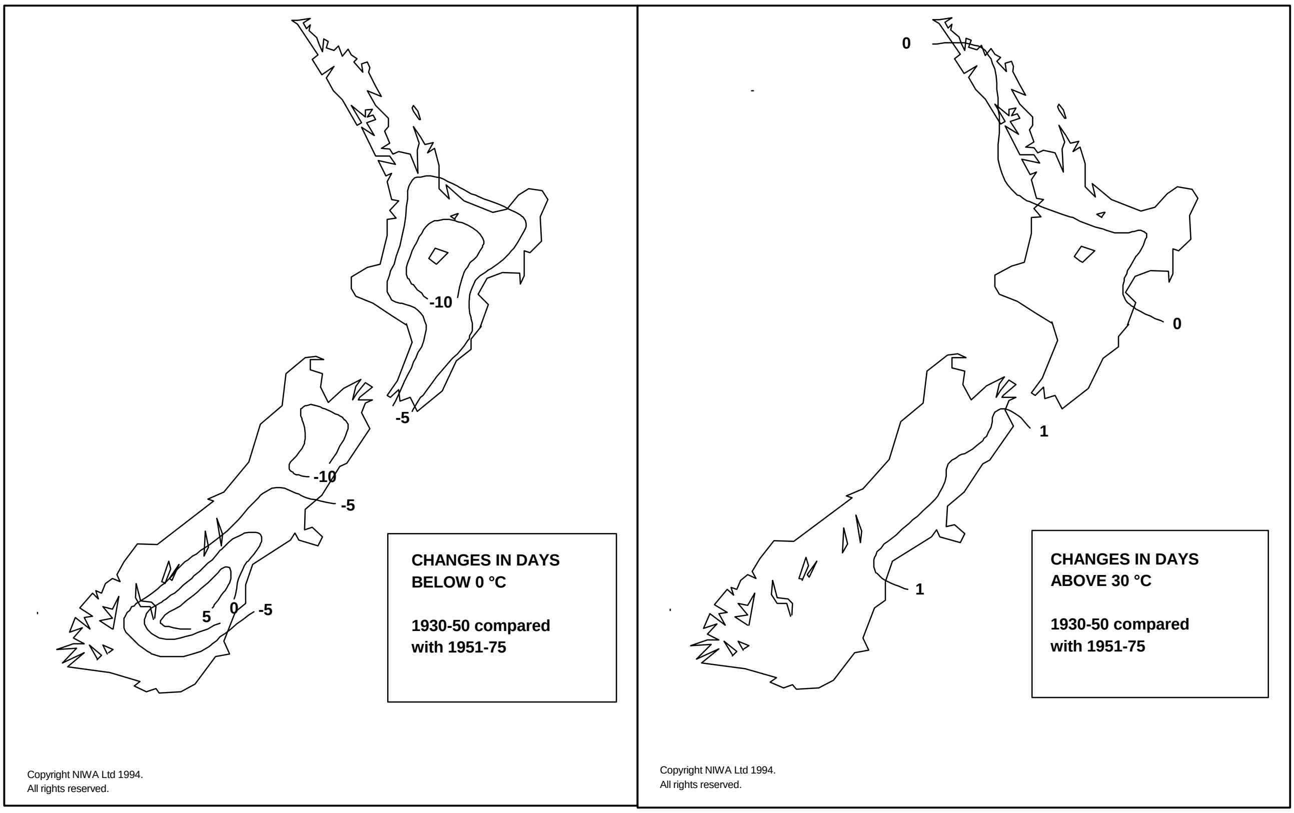

Figure 2.4: Changes in (a) days below 0°C and (b) days above 30°C, from the period 1930-50 to the period 1951-75.

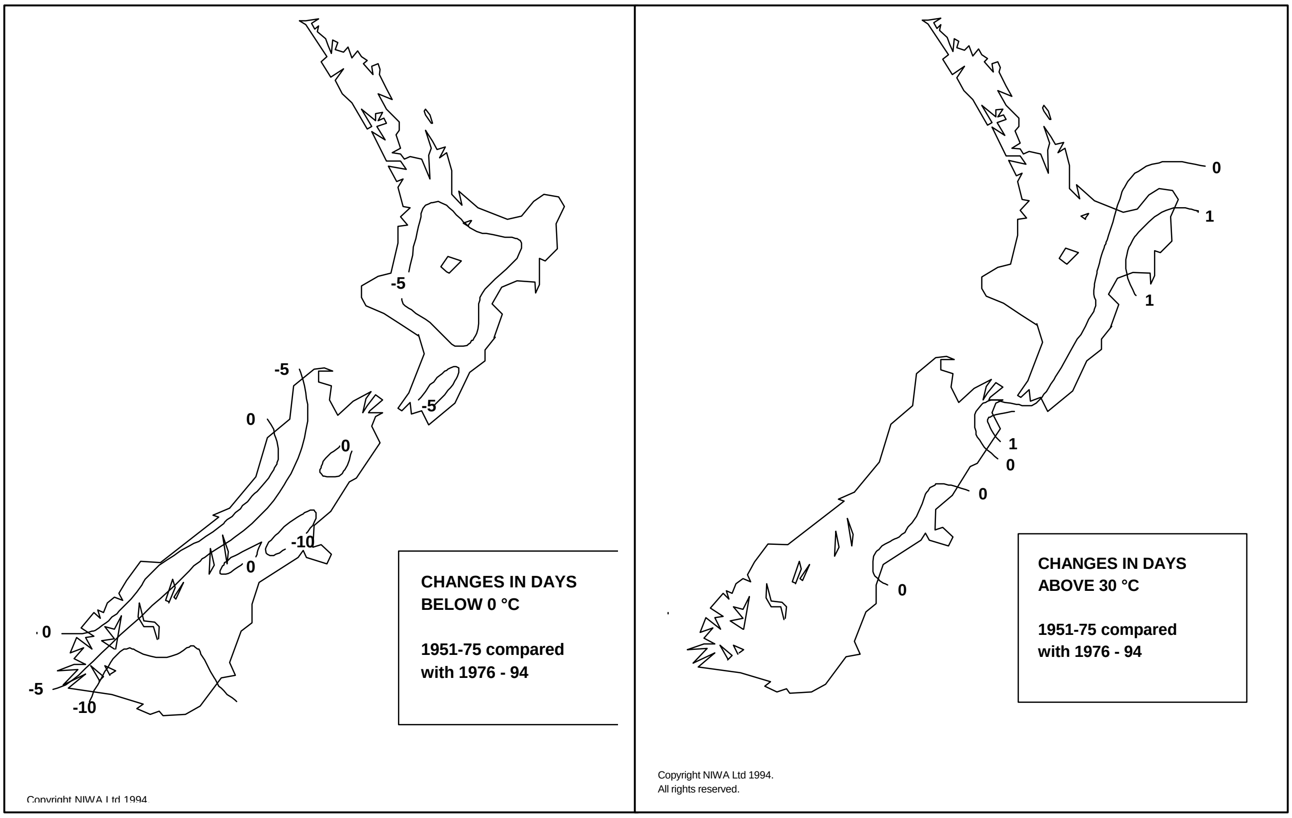

Figure 2.5: Changes in (a) days below 0°C and (b) days above 30°C, from the period 1951-75 to the period 1976-94.

With the 20th century regional warming and changes in circulation, daily rainfall extremes are expected to vary in response. The change in frequency of the annual 1-day 95th percentile, a measure of heavy rainfall intensity, has been quantified at 22 locations over New Zealand for the period 1950-96. In the west of the North Island from the Waikato to the Horowhenua, and in the west and south of the South Island, the 95th percentile daily rainfall amount has increased between 5 and 15 percent over this period. In contrast, decreases are seen in this index of extreme rainfall in the north and east of the North Island, Wellington and Canterbury by between 5 and 20 percent. These changes are consistent with the trend to more anticyclones over northern New Zealand and stronger westerlies further south.

Scenarios of Climate Change and Variability

The simple climate model MAGICC (Chapter 1) generates a time series of global-average temperature for a selected emission scenario. However, the sectoral impact models (Chapters 3-8) require high resolution patterns of precipitation and temperature change over New Zealand in order to calculate ecosystem responses. The link from a single number (the global-average temperature at some future time) to detailed patterns of precipitation and temperature is provided by a “scenario generator”. Depending on the particular impact model, patterns of change may be required at either monthly or daily time scales. This section describes the basic approach taken to derive these scenario patterns. Further technical details are provided in the Annex 2.

Monthly Scenario Patterns

Within the CLIMPACTS system there is the facility for selecting from a range of climate change and climate variability scenario patterns. All these patterns have been generated "off-line" and supplied to CLIMPACTS as data files. These patterns are scaled appropriately and added to the baseline (1951-1980) climate normals. The variability patterns are based on observed past data representing, in particular, Southern Oscillation Index (SOI) variations and Interdecadal Pacific Oscillation (IPO) changes. For the SOI scenario, the user selects a desired future SOI value, ranging from –1 (representing a permanent El Niño) to +1 (permanent La Niña). Figure 2.6 shows an example of changes in precipitation and mean temperature for the El Niño scenario, for the 3-month winter and summer seasons. Figure 2.6 shows the typical El Niño pattern of cooler conditions and a changed west-east rainfall gradient.

For the low frequency IPO scenario, the user has the option of selecting either "no change" which effectively assumes the negative phase of the IPO that is implicit in the baseline data, or selecting the "+ phase" for the pattern of change subsequent to 1978. The sectoral impact models described in this assessment report do not examine IPO effects, so they will not be considered further. However, additional information on both the IPO and SOI scenarios can be found in Salinger and Mullan (1997).

The climate change patterns are based on "downscaling" various general circulation model (GCM) simulations. Downscaling is a procedure that allows local scale climate changes to be inferred from the raw data provided by the GCM at a much coarser spatial scale. All the downscaled GCM patterns are stored as a change per degree global warming. The global-average temperature increase value from MAGICC is thus used to scale the pattern for the year under consideration. There are currently seven GCM patterns available for selection, named as: Greenhouse 94 Rank 2 and Rank 4, DARLAM, CCC, CSIRO9, HadCM2 and Japan.

The patterns of precipitation and temperature change for all models, with the exception of DARLAM, were generated by a statistical downscaling method from the coarse grid-scale data of the GCM. DARLAM is a so-called "limited area" high resolution model for the Australasian region, nested within the coarser CSIRO9 global model. Because the DARLAM output is available directly at approximately 50km resolution (similar to station site separation used in statistical downscaling), the direct model output is used. Annex 2 provides additional technical details on all these models and the downscaling approach.

The first three of the 7 GCM patterns come from equilibrium GCM simulations, where a comparison is made between a current climate control run and a doubled carbon dioxide run. The latter four patterns come from more recent transient GCM simulations, where atmospheric CO_2 concentration is incremented year by year and ocean-atmosphere interactions are taken into account more realistically. The basic difference between equilibrium and transient results, as they affect the New Zealand scenarios, is that equilibrium simulations show maximum warming at the poles, whereas transient models predict a much slower warming of Southern Hemisphere high latitudes. Thus, for transient models the latitudinal temperature gradient across the New Zealand region strengthens in a future climate, and therefore the strength of the mid-latitude westerlies also increases. This difference between generally weaker westerlies (equilibrium) and stronger westerlies (transient) has a major effect on changing rainfall patterns over the country. New Zealand temperatures also tend to increase more slowly in the transient scenarios.

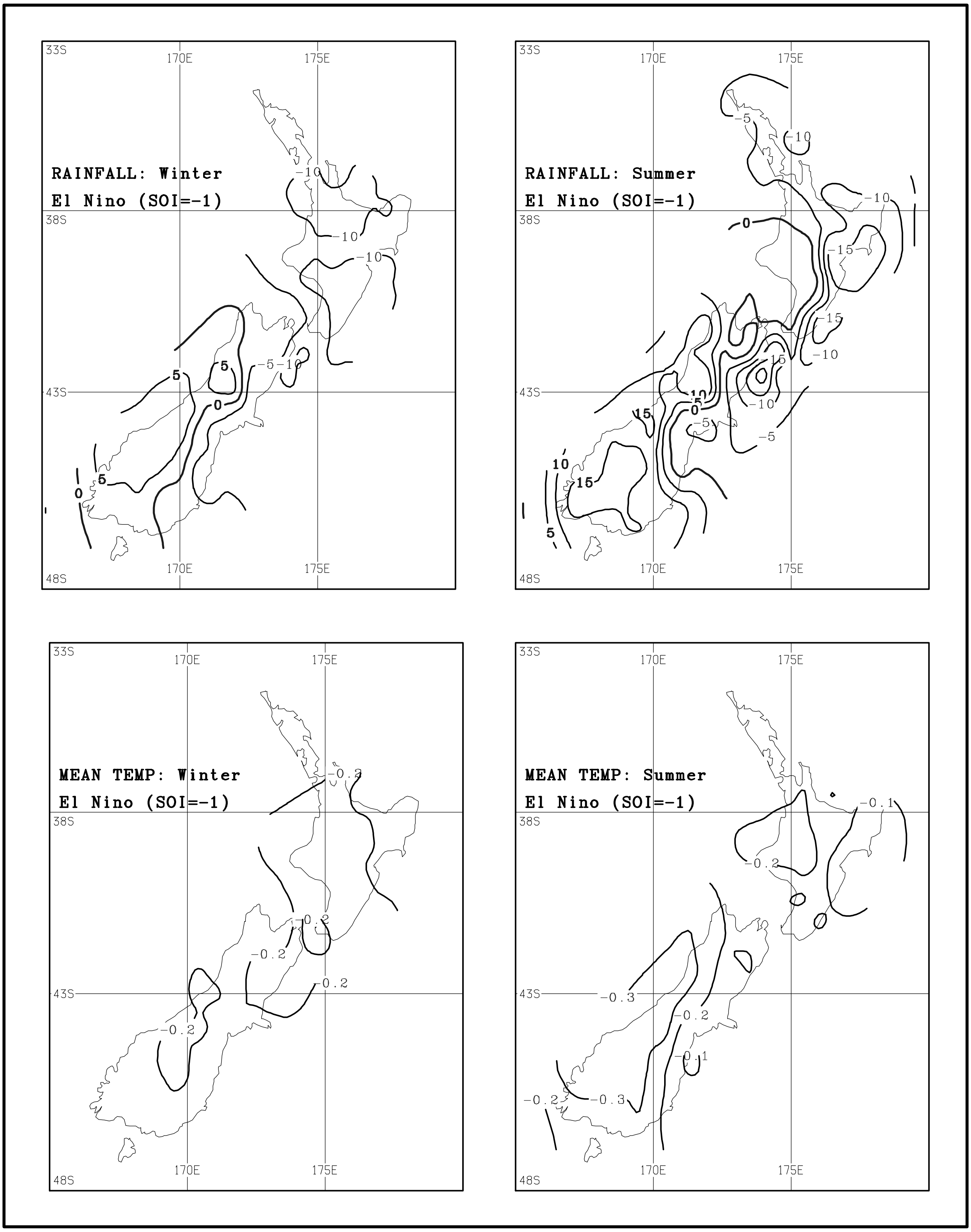

Figure 2.6: El Niño (SOI = -1) changes, for precipitation (upper panels, contours in %) and mean temperature (lower panels, contours every 0.1C): Winter (Jun-Aug), left-hand panels; Summer (Dec-Feb), right-hand panels.

Figures 2.7 and 2.8 show the downscaled rainfall and mean temperature changes per degree global warming for the HadCM2 and CSIRO9 transient GCMs. These are the two GCMs that the National Assessment focusses on. Corresponding patterns from all the other models that are available within the CLIMPACTS system are shown in Figures A2.1-A2.5 in Annex 2. Figure 2.7 gives the HadCM2 pattern for winter (April to September) and summer (October to March) half-years, and the influence of intensified westerlies simulated by that model is readily apparent. Rainfall increases in the west, particularly for the South Island, and decreases in the east. The magnitude of the changes are in the order of 10% per degree global warming, and intensify the existing rainfall gradient (wet in the west, dry in the east) across New Zealand (note the different contour intervals for winter and summer). The temperature scenario also shows an east-west gradient. Temperature increases are largest in the winter season and in the northeast of the country.

By comparison, the CSIRO9 pattern (Figure 2.8) is much more uniform (see Annex 2 for discussion of reasons). An increased west-east rainfall gradient is seen in the summer half-year, but is much weaker than the HadCM2 pattern. Temperature increases are close to 0.7C per degree global warming: the warming is least in the southern half of the South Island, and slightly less in winter than summer, although the seasonal and latitudinal variation is weak.

Daily Scenarios

Daily time series of precipitation, minimum and maximum temperature and solar radiation are produced by a stochastic model known as a "weather generator" (see Annex 3 for technical details and validation of the Richardson weather generator for current climate). Three weather generators are available to CLIMPACTS but all use the basic idea of separating weather elements according to whether it is a wet or dry day. Day to day variations in weather elements are calculated as departures from a climatology, which will be different for a dry day compared to a wet day. Observed cross-correlations between weather elements and lag-correlations are also taken account of. The weather generators differ in how they calculate rainfall amounts or distributions over time. The only weather generator used in this report is based on the Richardson model (Richardson, 1981; Thompson and Mullan, 1997).

The weather generator parameters are initially fitted to the observed distributions (see daily weather data, Annex 1). For future climate simulation, the climatological annual cycle is adjusted according to the prescribed changes in the monthly scenario patterns (Thompson and Mullan, 1999). At present, the same adjustment is made for wet and dry days, since the GCM data was not partitioned on the basis of daily rainfall occurrence. It is possible, also, to make manual changes to the variance structure of future climate.

Future Climate

This section examines the consequences of a range of scenarios for New Zealand future climate, and considers changes in both mean and extreme values. This is important background information to assist interpretation of the sectoral impact model results. Many combinations of emissions scenarios, sensitivities, and GCM scenario patterns are possible. Presentation of future changes thus follows a few standard options used throughout this National Assessment report.

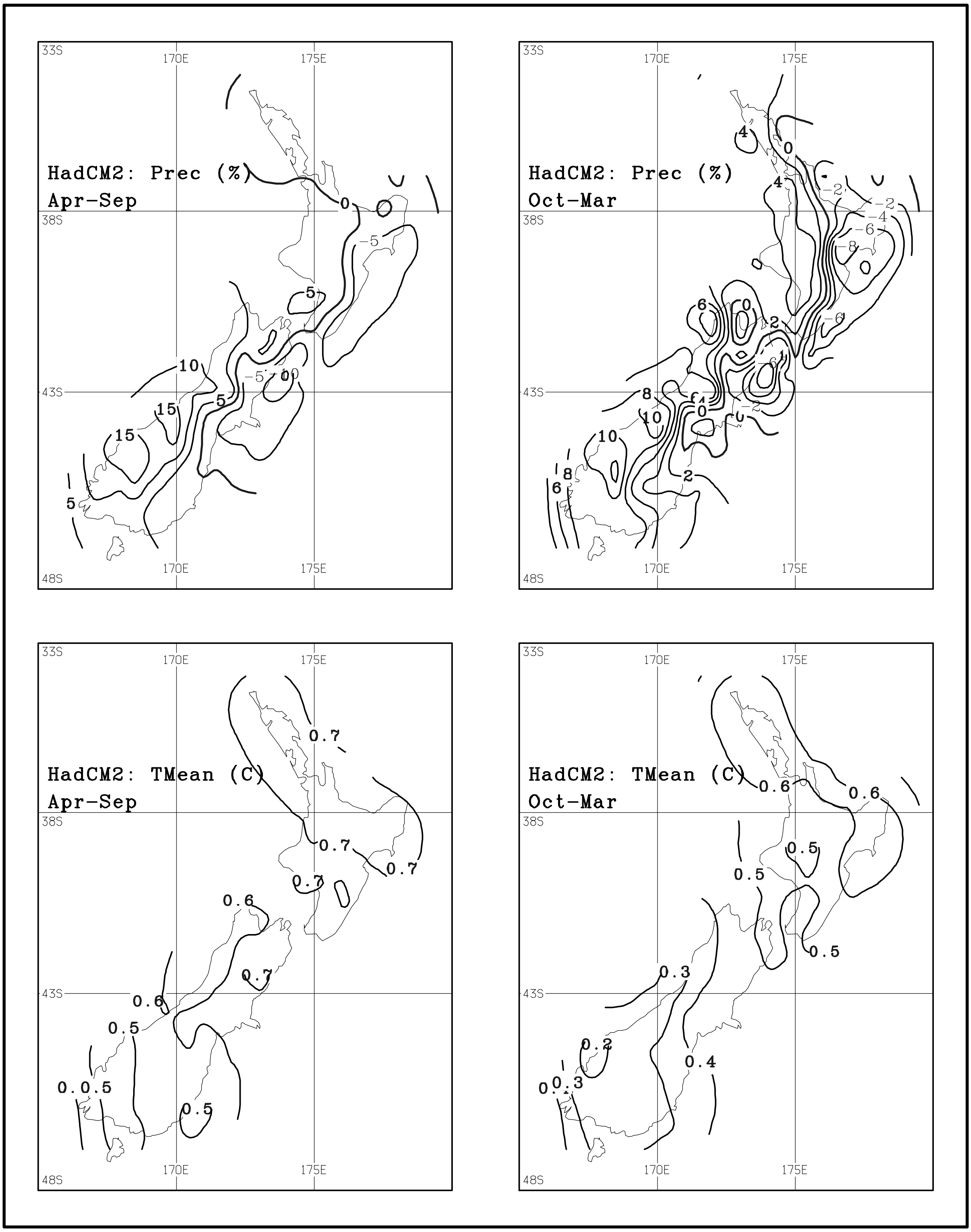

Figure 2.7: HadCM2 model downscaled changes per degree global warming, for precipitation (upper panels, contours in %) and mean temperature (lower panels, contours every 0.1C): Winter (Apr-Sep), left-hand panels; Summer (Oct-Mar), right-hand panels.

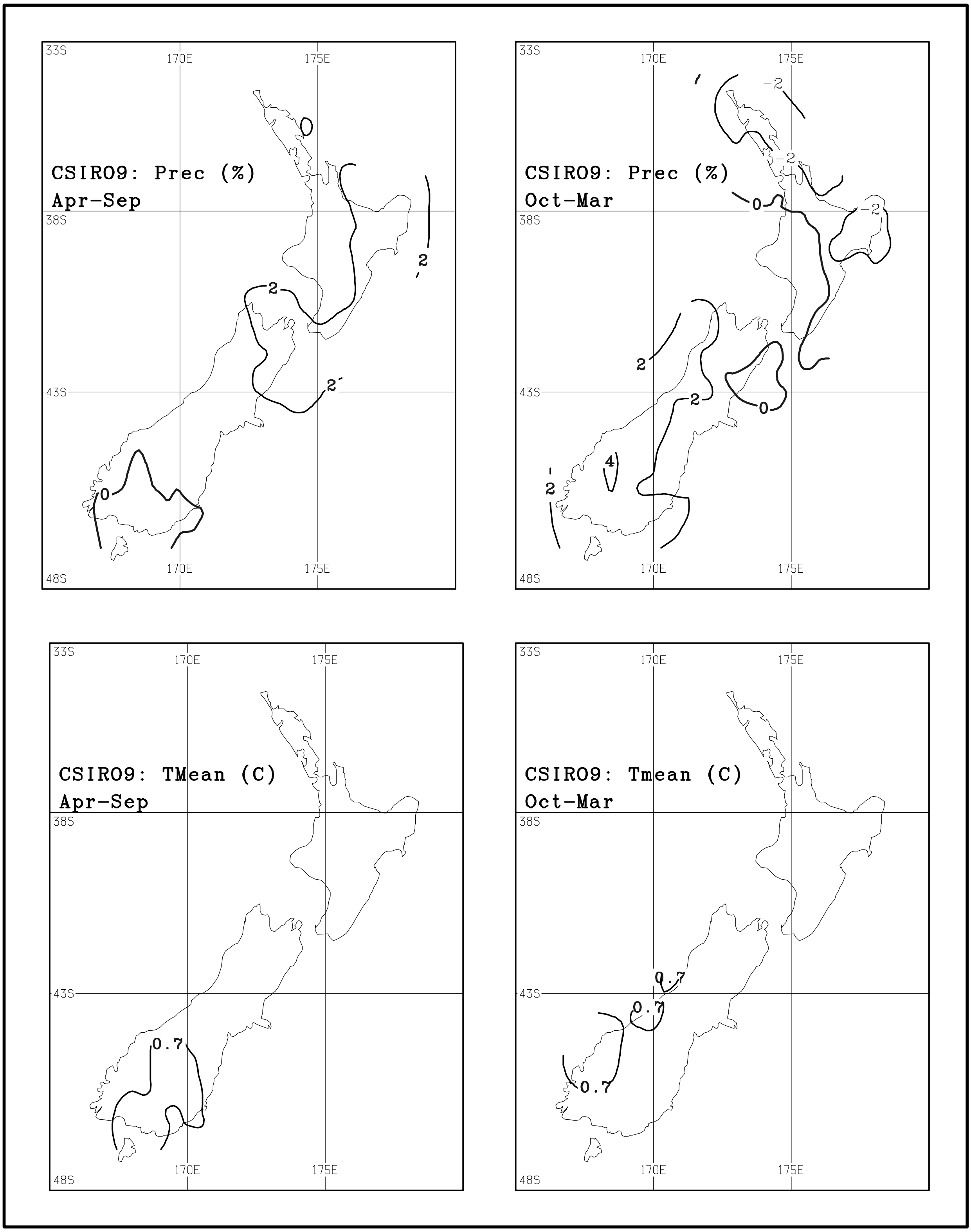

Figure 2.8: CSIRO9 model downscaled changes per degree global warming, for precipitation (upper panels, contours every 2%) and mean temperature (lower panels, contours every 0.1C): Winter (Apr-Sep), left-hand panels; Summer (Oct-Mar), right-hand panels.

Future Mean Changes

The mean climate change at any future time is determined by multiplying the scenario pattern by the MAGICC value of the global-average surface temperature change since 1990. This temperature change depends on the assumed emissions scenario and climate sensitivity. Figure 2.9 shows the global temperature curves for three combinations of SRES marker greenhouse gas emissions scenarios and sensitivities. The global temperature change is then used to scale the appropriate GCM pattern, either HadCM2 or CSIRO9 (Figures 2.7 and 2.8 respectively).

The following four combinations are taken:

1. SRES A2 emissions, "high" climate sensitivity, HadCM2 transient scenario (A2H);
2. SRES A1 emissions, "mid" climate sensitivity, HadCM2 transient scenario (A1H);
3. SRES B1 emissions, "low" climate sensitivity, HadCM2 transient scenario (B1H);
4. SRES A1 emissions, "mid" climate sensitivity, CSIRO9 transient scenario (A1C).

The global temperature changes diverge markedly after about 2030. The temperature increase in the B1 Low scenario by 2100 is reached by about 2045 in the A1 Mid scenario. A1 Mid at 2100 corresponds approximately to A2 High at about 2063. The HadCM2 patterns will tend to magnify the rainfall changes (plus or minus) and scale down the temperature changes (particularly for the South Island in summer), relative to CSIRO9.

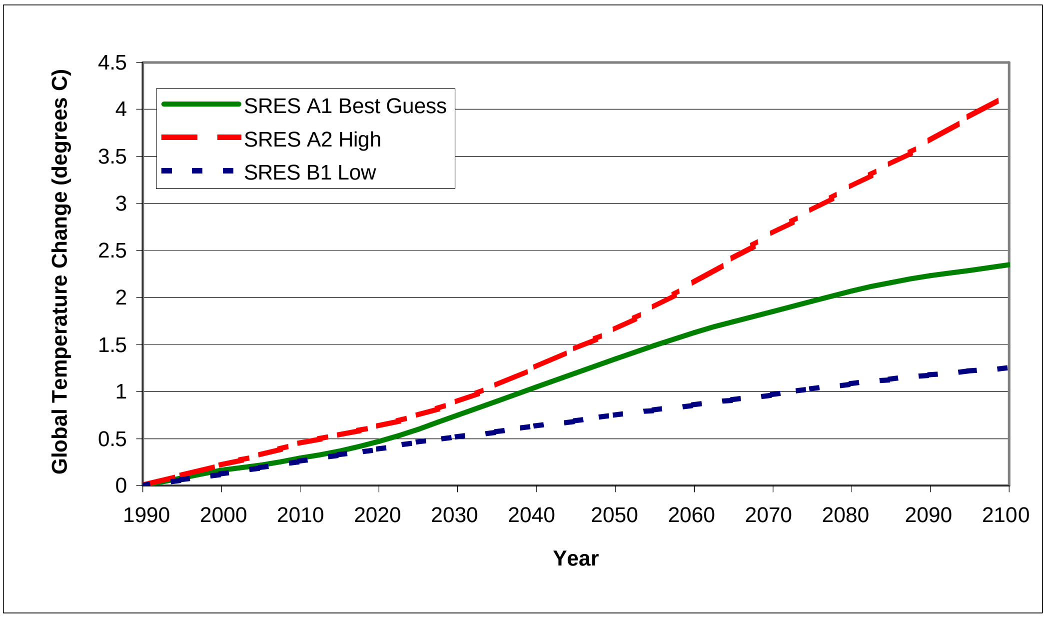

Figure 2.9: High, low, and mid-range global temperature curves for the SRES marker greenhouse gas emissions scenarios.

Future Changes in Extremes

To illustrate future changes in daily weather extremes, it is necessary to run the weather generator in combination with the selected emissions scenario, global climate sensitivity, and GCM scenario pattern. The four scenario combinations (A1H, A1C, B1H and A2H) were run for years 2050 and 2100 at 13 sites where current daily data were available to tune the weather generator. (Note that two further sites, Appleby and Whakatu, which lie very close to Motueka and Havelock North, respectively, were not used).

Figures 2.10a,b to 2.12a,b show changes in the extremes of low temperature (frosts) and high temperature, as follows:

- Number of days per year below 0°C (Figure 2.10a,b);
- Number of days per year above 25°C (Figure 2.11a,b);
- Number of days per year above 30°C (Figure 2.12a,b).

The maps are for changes at two future times: for 1990 to 2050, and for 1990 to 2100. The contours need to be interpreted with some caution, given the small number of daily data sites across the country (sites shown in B1L 2050 panel of Figure 2.11b). Since there are no sites on the West Coast of the South Island, contours have been blanked out for this portion of the country. However, the figures are useful in interpreting the impact model results of the subsequent chapters in this report.

Figures 2.10a,b show the changed frequency of frosts at the two future times of 2050 and 2100. For the mid-range scenario (A1), Figure 2.10a shows changes are insensitive to the GCM pattern used. The greatest reduction in frosts occurs in the South Island, exceeding 10 fewer days by 2050 and 20 fewer days by 2100. This would approximately halve the number of frosts in this part of the country. We would expect smaller reductions on the West Coast, where contours are suppressed (see Figure 2.5). Least change, of course, occurs in Northland where frosts are already very rare (averaging less than 0.3 days per year in the recent record at Kerikeri, for example). Figure 2.10b shows the range of changes possible with the two extreme scenarios of minimal warming (B1) and large warming (A2). Under the B1 scenario, changes by 2100 are similar to the A1 changes 50 years earlier (2050), and likewise A2 changes by 2050 are as large as A1 changes by 2100.

Changes in the frequency of days with temperature maxima exceeding 25°C are shown in Figures 2.11a,b. In this case, there is a difference with the GCM pattern used, with the more rapid warming of CSIRO9 resulting in 5-10 more days above 25°C by 2100 than HadCM2. Again, there is a strong regional pattern to the changes, with much larger increases in the north of the country. In Northland, the number of days above 25°C typically doubles by 2100, and increases by 30-50% in the far south of New Zealand. The minimal warming scenario B1 shows modest increases in numbers of warm days in the North Island, but no significant changes in Otago and Southland during the 21st century. The extreme high scenario (A2) shows a very large increase in days above 25°C in the north and east of the North Island.

Many places in New Zealand rarely experience days above 30°C, and this makes it difficult for the weather generator to simulate results there. What Figures 2.12a,b do show, though, is that an increasing number of very hot days are likely in Gisborne, Hawkes Bay, Wairarapa and Marlborough. Changes by 2050 in the low B1 scenario are very similar to recent observed changes (Figure 2.5 for 1951-75 to 1976-94). Stronger warming scenarios (A1 and A2) show progressively greater effects. In the recent record, Havelock North has experienced about 3 days per year above 30°C, and Gisborne 6 days. For the extreme high A2 case, there is a dramatic increase in very hot days. By 2100, maximum temperatures in Gisborne could exceed 30°C on about 20% of summer days.

Conclusions

- New Zealand climate has changed since 1950, most likely due to a combination of both a greenhouse warming trend and "shifts" in Pacific circulation. Since 1940, New Zealand has warmed at a rate averaging between 0.1 and 0.2°C per decade.

- We expect New Zealand climate to continue warming, at a rate determined by a number of global factors. At the low end of the scale (B1 low sensitivity scenario), changes by 2050 would be similar to observed 30-year trends. Changes much more rapid than this are possible, particularly after 2050.

- Temperature changes in both means and extremes (such as days of frost or days above 30°C) are relatively insensitive to the GCM scenario used, at least out to 2050. On the other hand, precipitation changes are very dependent on the climate model used for downscaling.

- Weather generators are a valuable tool to simulate the daily weather variations required by many impact models, and to give a guide to changes in extremes under future climates. The climate changes apply strictly only at the sites simulated, but the interpolated regional patterns appear sensible.

Gaps and Future Directions of CLIMPACTS

- Weather generators do not simulate sufficient interannual variability in climate elements. This is a common deficiency in weather generators, because the statistical models concentrate on producing realistic day-to-day variations. Improvements will be made in this area in the 2000-2002 programme. A further development of the weather generators will allow the simulation of daily weather series at any point over the regional model grid, whether or not site data exist there. This will greatly improve the utility of the weather generator and impact models at the regional scale.

- Patterns of New Zealand climate variation on an interannual and interdecadal scale are available within the CLIMPACTS system, but have not been fully explored in this assessment. Further work is planned to refine these patterns of higher frequency change and explore their consequences.

- A fundamental uncertainty in the CLIMPACTS scenarios is the long-term pattern of rainfall change. This pattern is very dependent on the GCM used for downscaling, and there appears little prospect of narrowing this source of uncertainty in the near future.

- A deficiency in the current CLIMPACTS system is the absence of a sophisticated hydrological model, although some inferences can be drawn from predicted rainfall changes and simple water balance calculations. In 2000-2002, a hydrological model for South Canterbury will be validated, and incorporated into the regional version of CLIMPACTS. This will allow changes in future water use and land management to be analysed.

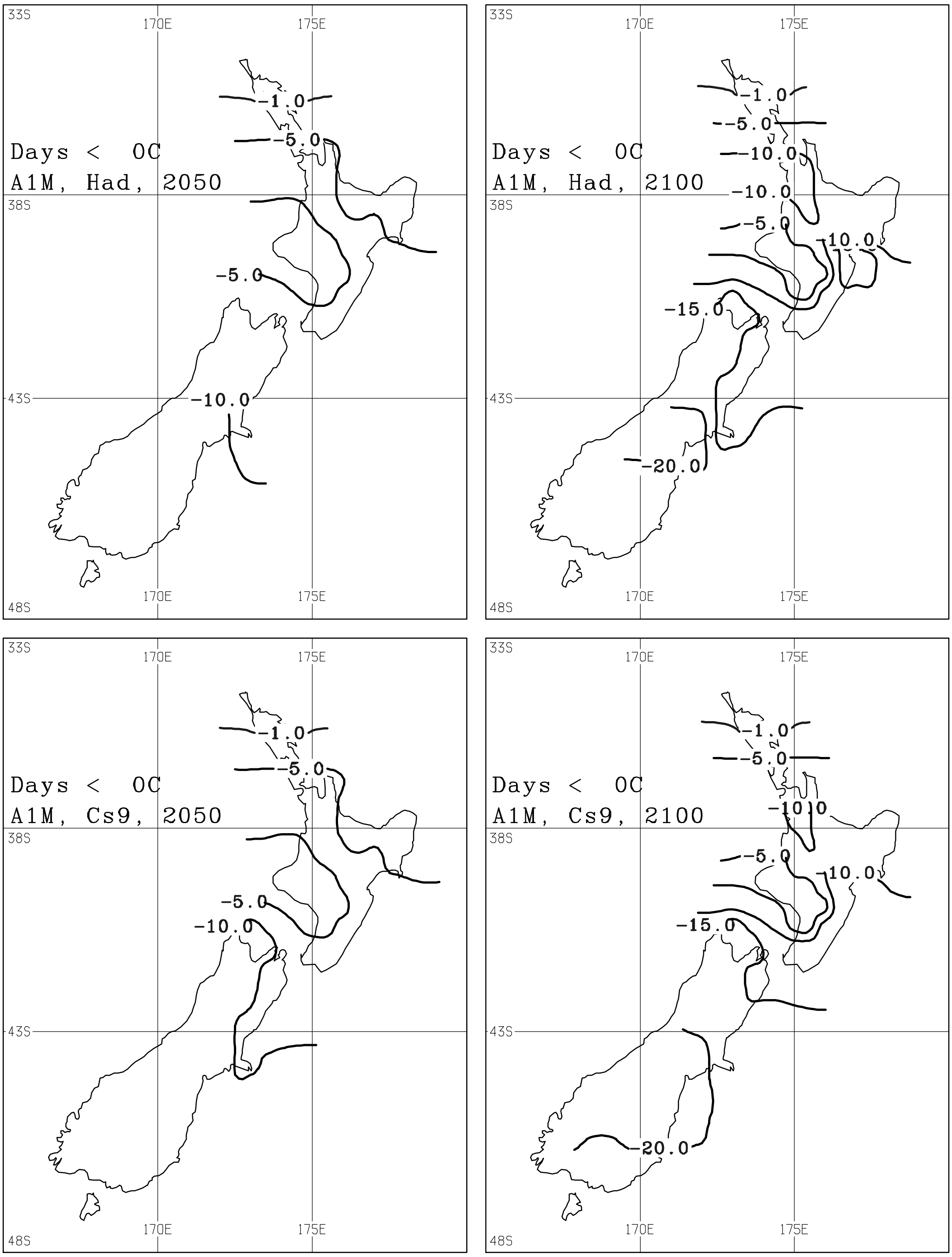

Figure 2.10a: Changes between 1990 and 2050 or 2100 in the number of days per year below 0^{o}C, for the A1 mid sensitivity emission scenario, and for the HadCM2 and CSIRO9 downscaled GCM patterns. Contours at –1, -5 days, and thereafter at -5 day intervals.

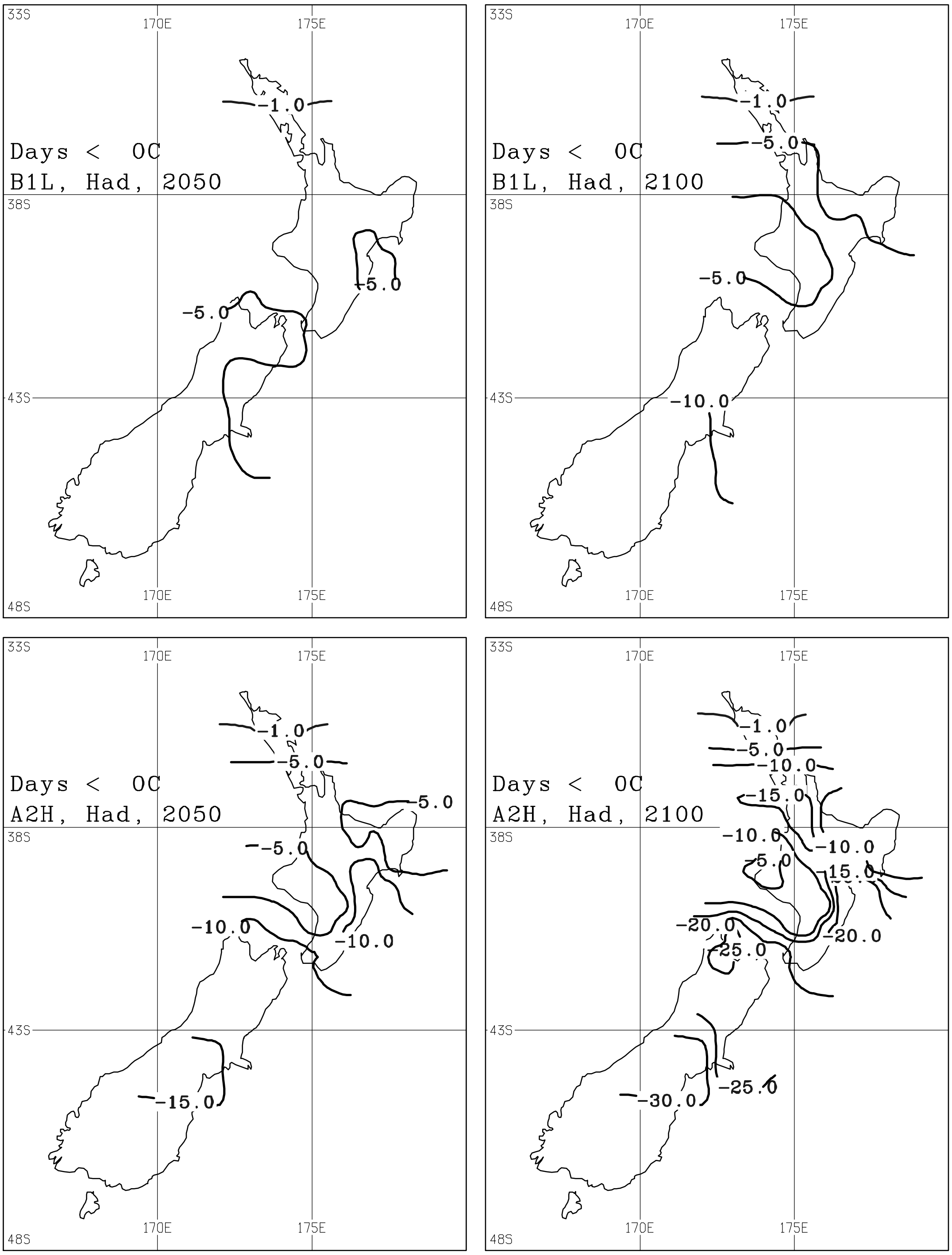

Figure 2.10b: As Figure 2.10a, but for B1 low sensitivity and A2 high sensitivity emission scenarios, with the HadCM2 GCM pattern.

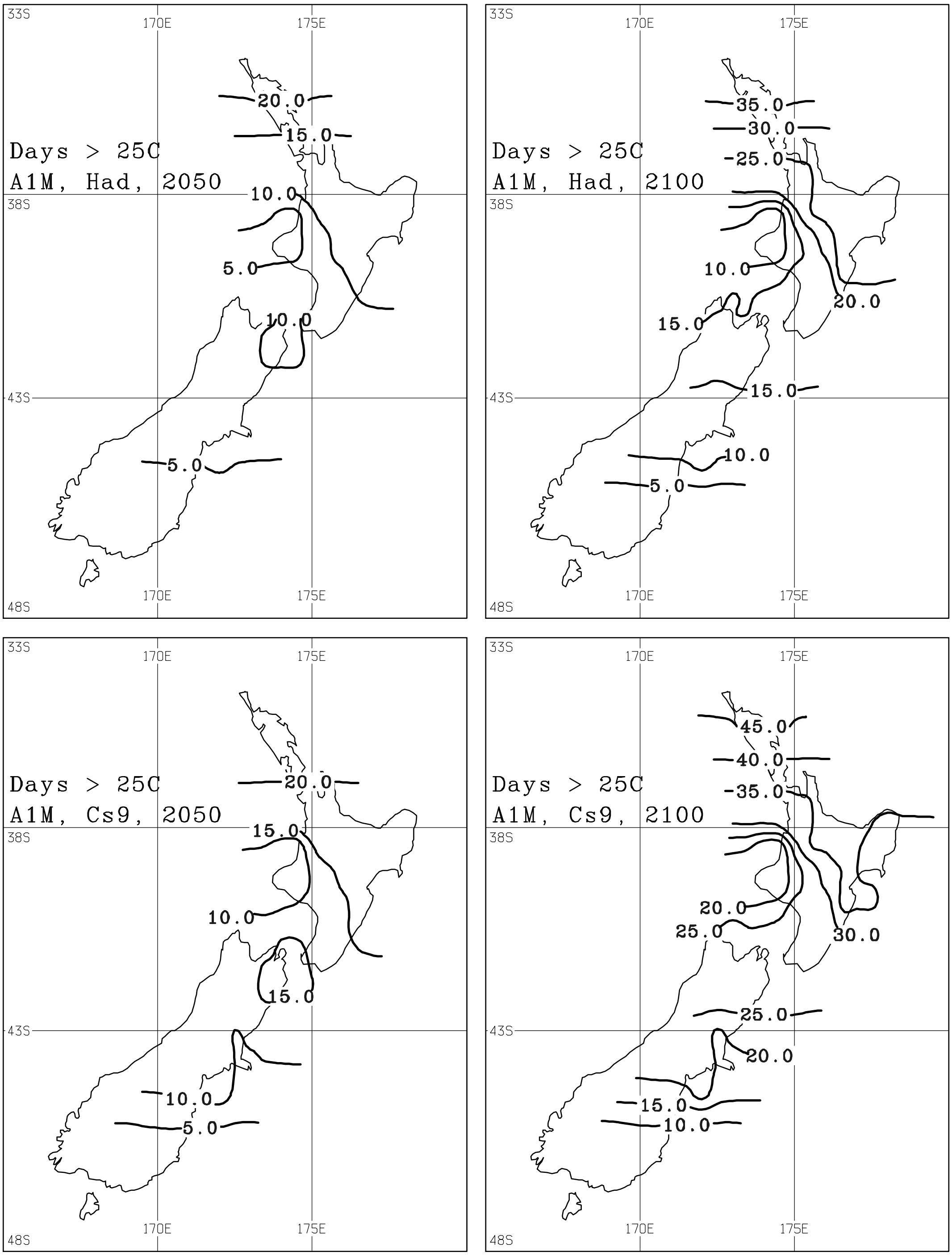

Figure 2.11a: Changes between 1990 and 2050 or 2100 in the number of days per year above 25°C, for the A1 mid sensitivity emission scenario, and for the HadCM2 and CSIRO9 GCM patterns. Contours at 0.5, 1, and 5 days, and thereafter at 5 day intervals.

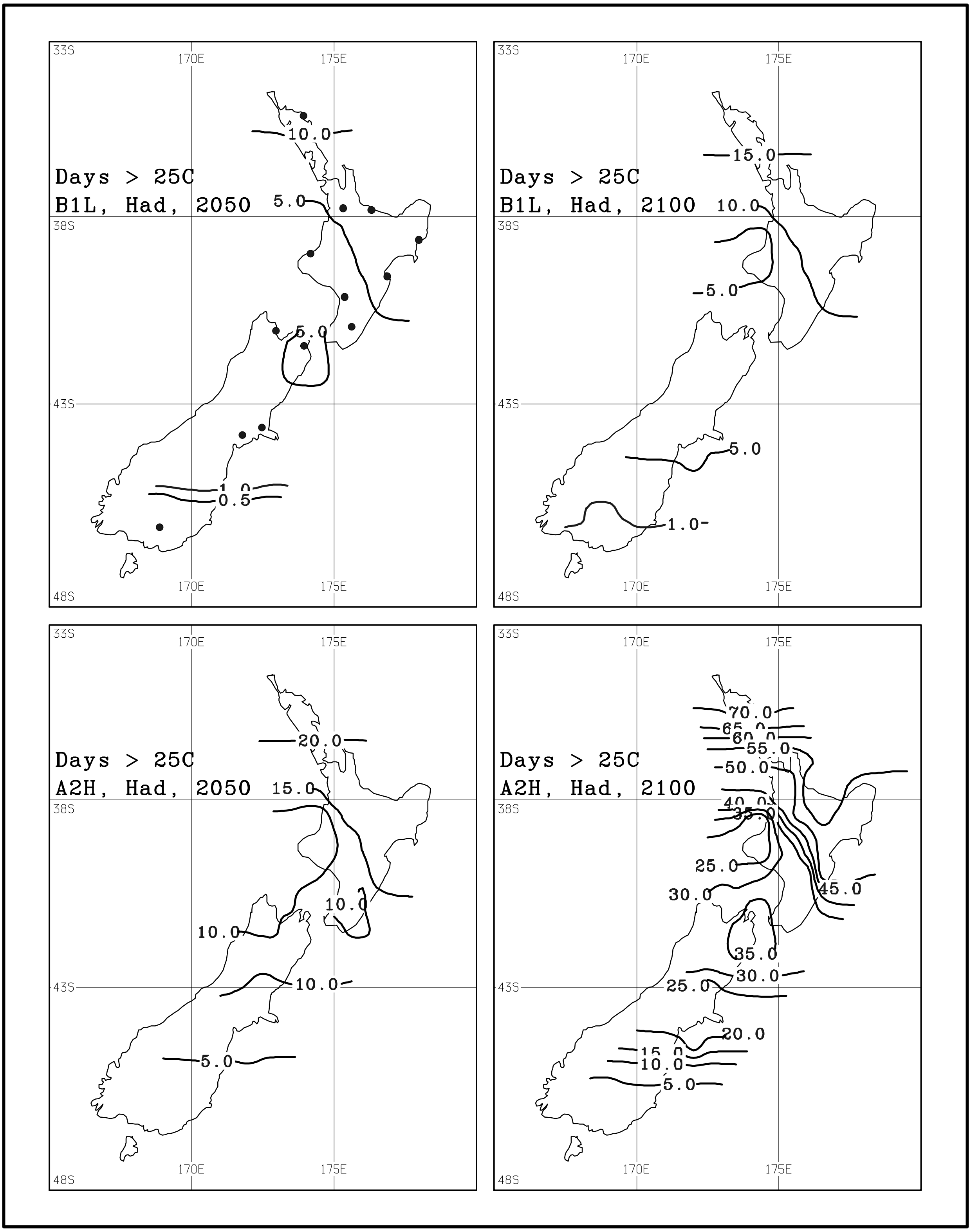

Figure 2.11b: As Figure 2.11a, but for B1 low sensitivity and A2 high sensitivity emission scenarios, with the HadCM2 GCM pattern.

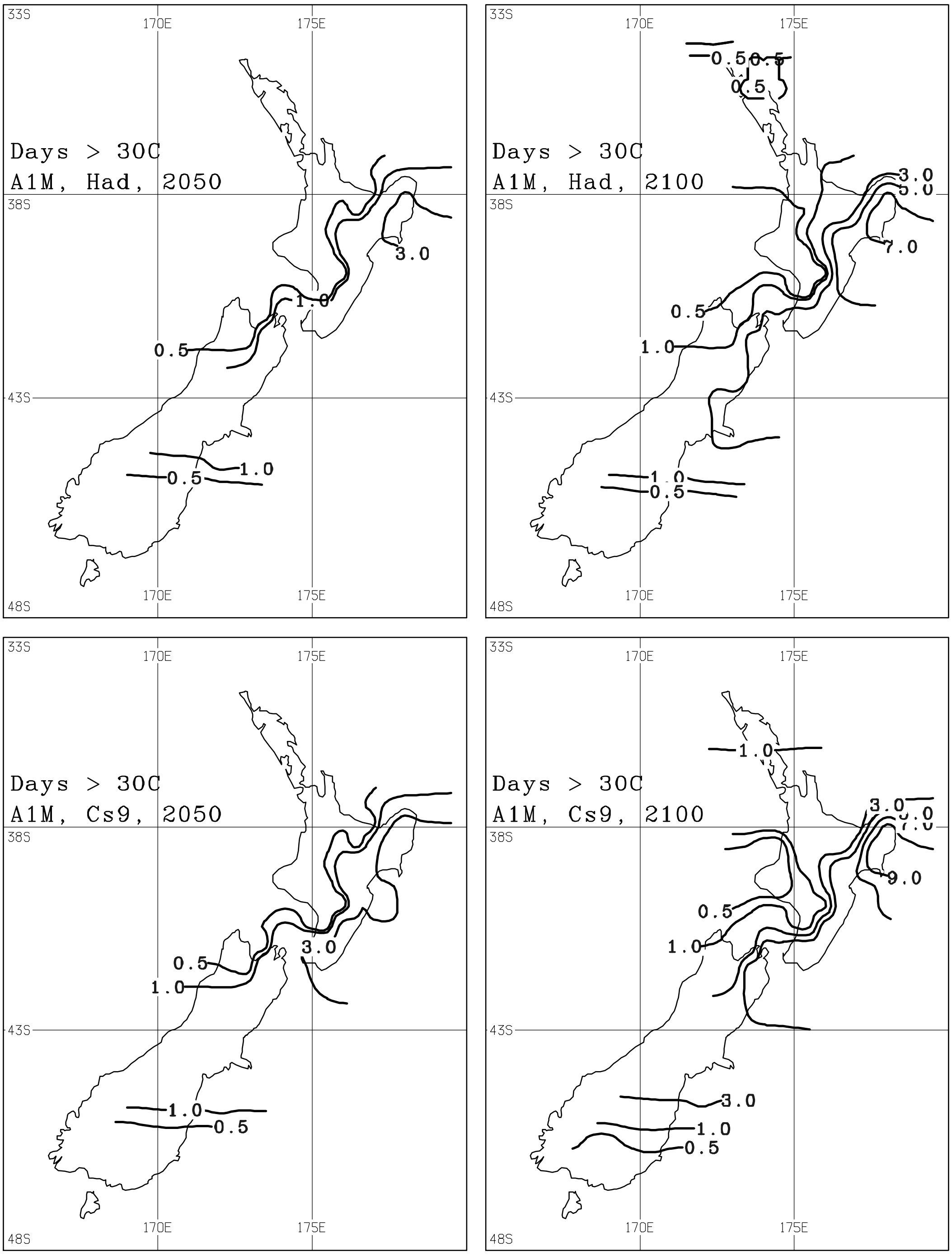

Figure 2.12a: Changes between 1990 and 2050 or 2100 in the number of days per year above 30°C, for the A1 mid sensitivity emission scenario, and for the HadCM2 and CSIRO9 GCM patterns. Contours at 0.5 and 1 day, and thereafter at 2 day intervals.

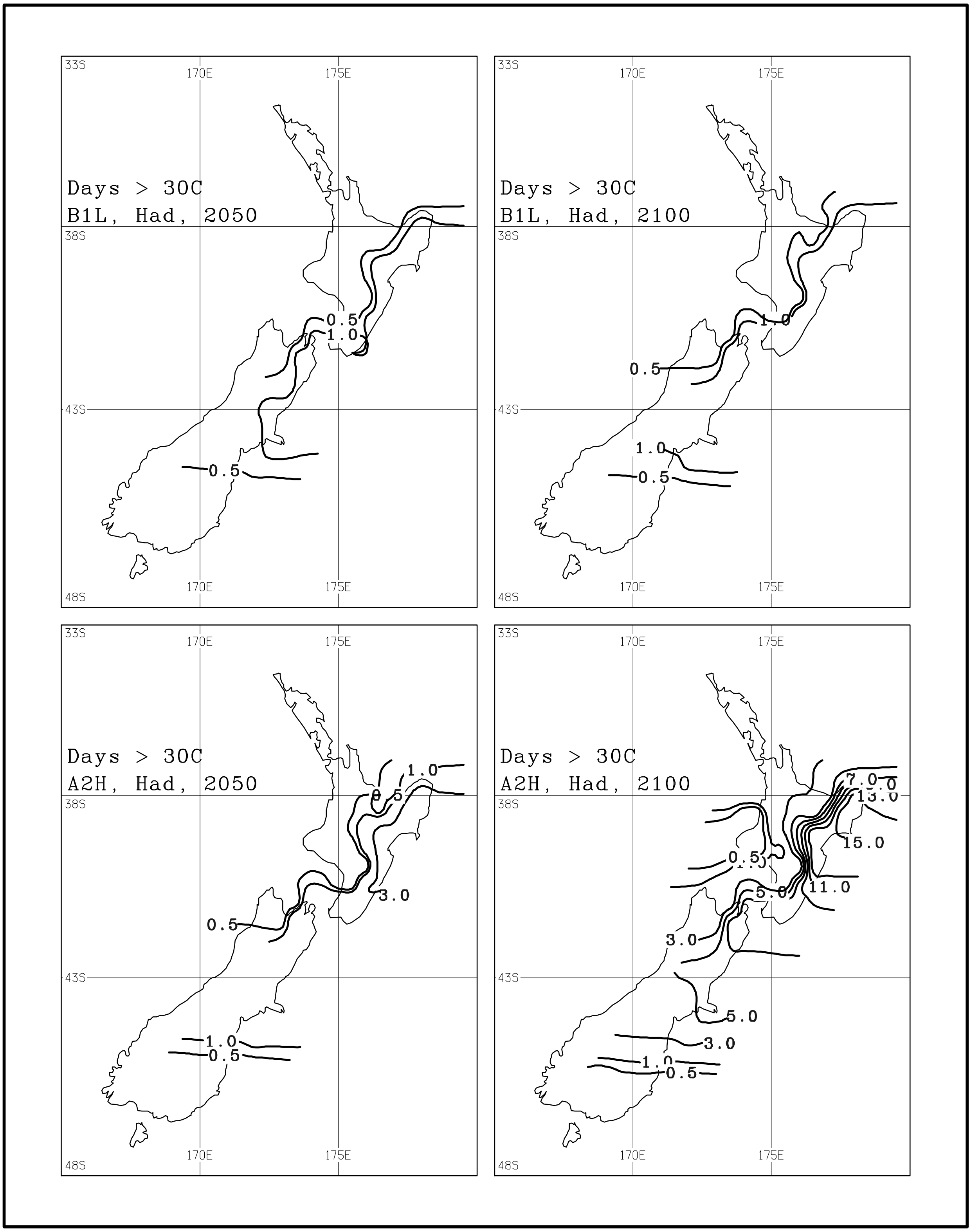

Figure 2.12b: As Figure 2.12a, but for B1 low sensitivity and A2 high sensitivity emission scenarios, with the HadCM2 GCM pattern.

References

Folland, C.K., and Salinger, M.J. (1995). Surface temperature trends in New Zealand and the surrounding ocean, 1871 – 1993. *Int. J. Climatol.* 15, 1195-1218.

Mullan, A.B., and Salinger, M.J. (1994). *CLIMPACTS 1993/94: Climate change scenarios from GCM output and palaeoclimate data.* NIWA Report, February 1994. 44p.

Mullan, A.B., and Salinger, M.J. (1995). *CLIMPACTS 1995/96: Variability of daily temperatures and of monthly temperatures, sunshine and rainfall patterns.* NIWA Report. 42 pp.

Nicholls, N., Gruza, V., Jouzel, J., Karl, T.R., Ogallo, L.A., and Parker, D.E. (1996). Observed climate variability and change. In: J. H. Houghton, L.G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell. (eds.). *Climate Change 1995: The Science of Climate Change.* Cambridge University Press, Cambridge. 133-192.

Parker, D.E., and Folland, C.K. (1991). Worldwide surface temperature trends since the mid-19th century. In: M.E. Schlesinger (ed.). *Greenhouse-gas-induced climatic change: a critical appraisal of simulations and observations.* Elsevier, Amsterdam. 173 - 193.

Power, S., Casey. T., Folland, C., Colman, A., and Mehta, V. (1999). Inter-decadal modulation of the impacts of ENSO on Australia. *Climate Dynamics.* 15, 319-324.

Richardson, C.W. (1981). Stochastic simulation of daily precipitation, temperature and solar radiation. *Water Resources Research.* 17, 182-190.

Salinger, M.J., McGann, R., Coutts, L., Collen, B., and Fouhy, E. (1992a). *Temperature trends in New Zealand and outlying islands.* New Zealand Meteorological Service, June 1992. 31pp.

Salinger, M.J., McGann, R., Coutts, L., Collen, B., and Fouhy, E. (1992b). *Rainfall trends in New Zealand and outlying islands.* New Zealand Meteorological Service, June 1992. 33pp.

Salinger, M.J., and Mullan, A.B. (1997). *CLIMPACTS 1996/97: Climate change and variability scenarios for temperature, rainfall and sunshine, based on observed changes and a nested GCM.* NIWA Report AK97083, July 1997.

Salinger, M.J., and Mullan, A.B. (1999). New Zealand climate: temperature and precipitation variations and their link with atmospheric circulation 1930-1994. *Int. J. Climatol.* 19, 1049-1071.

Thompson, C.S. (1984). Homogeneity analysis of rainfall series: an application of the use of a realistic rainfall model. *J. Climatol.* 4, 609-619.

Thompson, C.S., and Mullan, A.B. (1997). *CLIMPACTS 1997/98: Models for generating daily weather variables.* NIWA Internal Report No. 4. 99 pp + floppy disk.

Thompson, C.S., and Mullan, A.B. (1999). *CLIMPACTS 1998/99: Applying the Richardson weather generator to climate change studies.* NIWA Internal Report No. 55, June 1999. 17 pp.

Chapter 3:

Changes in Kiwifruit Phenology with Climate

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What is Known?

'Hayward' Kiwifruit is currently grown commercially in a wide range of locations in New Zealand, primarily in the Northern and Eastern parts of the North Island, and the North of the South Island. Over 75% of the national crop is produced in the Bay of Plenty region. In this work we focus solely on the predominant 'Hayward' variety, although it is clear that new cultivars such as Hort16A ('Zespri Gold') are becoming increasingly important.

'Hayward' kiwifruit in New Zealand has so far shown itself by horticultural standards to be relatively free of pests and disease, apart from a susceptibility to botrytis and scale, so questions of where it can be grown are largely affected by the crop's physiology, driven by soil and climate factors. The physiological models discussed here are driven by temperature alone, as irrigation is typically used to compensate for inadequate rainfall. The ability to irrigate is not affected by rainfall per se, but rather by the availability of river and ground water. No attempt has been made yet to include the effect of climate change on the latter in these models. An important requirement of the soils seems to be that they be relatively free-draining, as appropriate fertiliser application can overcome many other problems. Orchards typically have high shelter to prevent wind damage, and this tends to create a microclimate which may differ considerably from "standard meteorological site" conditions, so some models have had to be refitted in terms of "standard" temperatures for use here.

Budbreak in 'Hayward' kiwifruit occurs in the spring, after sufficient cool temperatures have occurred to break dormancy, then sufficient spring warming to allow the buds to expand and break open. The model used here is that of Hall and McPherson (1997a), refitted to standard met site data (rather than measurements made in the local microclimate) (Annex 4). In this model, there is no "fixed" chilling (cool temperature) requirement, but the rate of bud development can be very slow if insufficient chilling has been accumulated.

The rate of development from budbreak to flowering is enhanced by warm temperatures. In the model applied here (Annex 4), flowering is assumed to occur after a fixed heat sum has been accumulated following budbreak (McPherson *et. al.*, 1992). For simplicity, we have chosen to ignore the complications due to apical dominance discussed in McPherson *et al.* (1992).

Fruit are considered ready for picking when soluble solids reach around 6.2% (also called 6.2° brix). Fruit picked before this stage do not store well. In a new development in the last few years ("Kiwistart"), some fruit have been picked before this stage is reached (provided they satisfy other criteria), for immediate export and sale. The date of maturity discussed here is the date of the "main harvest", when fruit reach 6.2° brix. This date is strongly dependent on late-season temperatures, as cool temperatures are required to trigger the conversion of starch to soluble sugars. The model used here (Annex 4; Hall and McPherson, 1997b) ignores temperatures in the first three months after flowering, then allows the soluble solids level to increase at a rate dependent on both fruit age and temperature, with lower temperatures corresponding to higher rates of increase. As the original model required hourly data rather than simply maximum and minimum temperatures, daily integration is carried out assuming a daylength-dependent quadratic frequency distribution between the maximum and minimum (Annex 4).

The models outlined above enable us to predict the dates of budbreak, flowering, and maturity for ‘Hayward’ kiwifruit. However, these dates are not of themselves indicators of whether this crop will flourish in a particular climate. Of more importance are various quantitative measures of crop performance, which can be estimated by accumulation of appropriate weather variables between pairs of these dates. Two important indicators of crop performance are the number of “king” flowers per winter bud (KFWB), and the proportion of the fruit which is dry matter (i.e. not water) (DM%). While fruit size is also important, the relationship between fruit size and climate is complex (Hall *et al.*, 1996) and useful models have not been developed.

In winter, orchardists prune vines and tie down canes containing the number of buds they hope will give adequate flowering in the spring. While an anticipated low number of flowers can be compensated for to a certain extent by laying down extra buds in winter, it is generally agreed that with less than about 1 KFWB (Annette Richardson, pers. comm.; Bill Snelgar, pers. comm.), growing ‘Hayward’ kiwifruit becomes uneconomic. It should be noted that when winter temperatures are high enough to significantly depress the number of buds which break, the number of flowers on those shoots also drops considerably. In the model of Hall and McPherson (1997a), the bud development can be expressed as a sum of development due to chilling, and that due to warming. The expected number of flowers per winter bud (KFWB) can be estimated from the proportion of the development due to chilling (Annex 4). Note that in the data set used to develop this relationship, the lowest number of KFWB observed was about 0.5, so estimated values below this threshold should be treated with caution. However, as we will be focussing on the proportion of years for which KFWB<1, this is not too great a problem.

In warm growing areas, hydrogen cyanamide (HC) is often used to alleviate the effects of warm winters and therefore inadequate flowering. A different relationship with accumulated winter chilling applies when HC is applied (Annex 4). On average, flowering when HC is applied will exceed 1.0 KFWB under conditions where when untreated vines would produce less than 0.5 KFWB. It is possible that the use of HC may become less acceptable to our markets in future, so considerable effort is being made to find a possibly more acceptable alternative.

Unlike some of the other variables discussed here, the number of king flowers per winter bud is dependent on a number of other management factors, not just the winter temperatures, so a significant proportion of the variation in this factor is unaccounted for by the model. Because the efficacy of application of HC is one of these factors, this additional variation can be a little larger when HC is applied. However, in estimating standard deviations and probabilities of dropping below a threshold, we have included an approximate average variance, additional to that attributable to the climatic data, of 0.04 in both cases (corresponding to a standard deviation of about 0.2 KFWB about the prediction line).

The times of budbreak, flowering, and maturity given here are those that would apply without HC application. HC application advances budbreak, and therefore the other phenological dates too. Predictions of the date of “natural” budbreak are important even where HC is applied, because the time of application needs to be determined relative to the crop’s natural state of development.

The percentage of dry matter in fruit (DM%), is an important determinant of fruit quality, as the "sweetness" of a ripened fruit can be directly related to DM%. However, in developing models relating DM% to climate, a real problem exists in that there is a paucity of quantitative measurements for locations where average DM% drops below the accepted standard. The New Zealand 'Hayward' kiwifruit industry is currently considering the use of DM% as a quality standard, with suggestions that fruit would need dry matter levels above a threshold of at least 14% to be called "grade 1". Despite the lack of a "model" for DM%, it is recognised that in cooler climates, fruit are less likely to reach this threshold. We have chosen to use a "degree day total" or "heatsum" between flowering and harvest, with a base temperature of 10^{o}C (HU10) as a measure of the warmth of the growing season. Using the small amount of data currently available, we estimate that when HU10 is greater than 1000, mean DM% is likely to be at least 14.5%, so most fruit are likely to reach the grade 1 standard. However when the heatsum is less than 850 there is a good chance that mean DM% will be less than 14%. Given the uncertainty in exactly where the threshold should lie, and its relationship to DM%, we have simply presented HU10 values in the results rather than DM%, so the interpretation can be easily changed once more information becomes available. Note that the dates of flowering and harvest are for vines not treated with HC, so HU10 would be slightly different if a dormancy-breaking chemical is used, advancing both flowering and harvest.

What does CLIMPACTS Show?

Method

Because of the problem of local, artificially created microclimates, we have not attempted a full spatial analysis of New Zealand based on the physiological models outlined above. Instead we have focused on four regions where 'Hayward' kiwifruit are currently grown, and looked at how crop development at selected "indicator" orchards within those regions is likely to change with time. The regions and sites selected were: Northland (Kerikeri); Bay of Plenty (Te Puke); Hawkes Bay (Havelock North); and Nelson (Riwaka).

In assessing whether 'Hayward' kiwifruit are likely to perform well in a particular climate, the "average" performance is less important than the proportion of years when production may be uneconomic. For this reason we have chosen to analyse 'Hayward' kiwifruit performance under various climate change scenarios by applying adjustments to the historical data record only, rather than using weather generators. At the present stage of development, weather generators seem to capture the mean performance of temperature-driven models well, but underestimate the variability which gives meaning to proportions of years. Both the historical baseline, and the projections forward for various climate change scenarios, were based only on years for which the relevant meteorological site was operational in each location, which means the number of years is quite small in places, leading to projections which do not change particularly smoothly. Years used were: Kerikeri (A53191) 1972-1986; Te Puke (B76836) 1973-1994; Havelock North (D9668B) 1972-1993; and Riwaka (G12191) 1972-1995. This "baseline" is shown on all graphs as "1990".

Simulations have been run for this 1990 base year, then at 25-year intervals over the period 2000-2100. For each of the models discussed above, we present outputs using the HadCM2 GCM pattern, coupled with three different greenhouse gas emission scenarios to obtain a range of predictions from conservative to extreme: SRES marker scenario A2, high climate sensitivity; SRES A1, medium sensitivity; and SRES B1, low sensitivity. For selected outputs, we then discuss the effect of different GCM patterns (a comparison of the HadCM2 and CSIRO9 models for the SRES A1, medium sensitivity scenario). Finally, the effect of different phases of the southern oscillation (comparing SOI values of +1, 0, and –1 for the HadCM2 GCM with SRES A1, medium sensitivity) is discussed.

Results

Dates of Budbreak, Flowering, and Maturity

For unadjusted climatic data (1990), the phenological models used produce patterns of dates reasonably consistent with those observed in the four New Zealand regions (Figures 3.1 to 3.3), except that the date of flowering is a little late in Kerikeri, and the date of harvest is late at Kerikeri and Riwaka. The late flowering dates in Kerikeri are likely to be because we have ignored the complications due to apical dominance and the suppression of late buds. This problem is particularly important in very warm climates, so is likely to affect Kerikeri and may also have some effect on predictions in Te Puke. The late harvest dates at Kerikeri and Riwaka perhaps show that we have not adequately solved the problem of turning daily maximum and minimum temperatures into the hourly data required by the model. In what follows we focus on changes in model predictions with time, rather than absolute dates, and the changes should not be too sensitive to the exact starting point. However, the fact that model predictions are most in error at the warmest site means that predicted changes under the more extreme scenarios may be exaggerated.

Note that for the year 2100, predictions for two years in Kerikeri have been omitted in Figures 3.1 to 3.3, as by that time the date of budbreak had “wrapped around” into the following year.

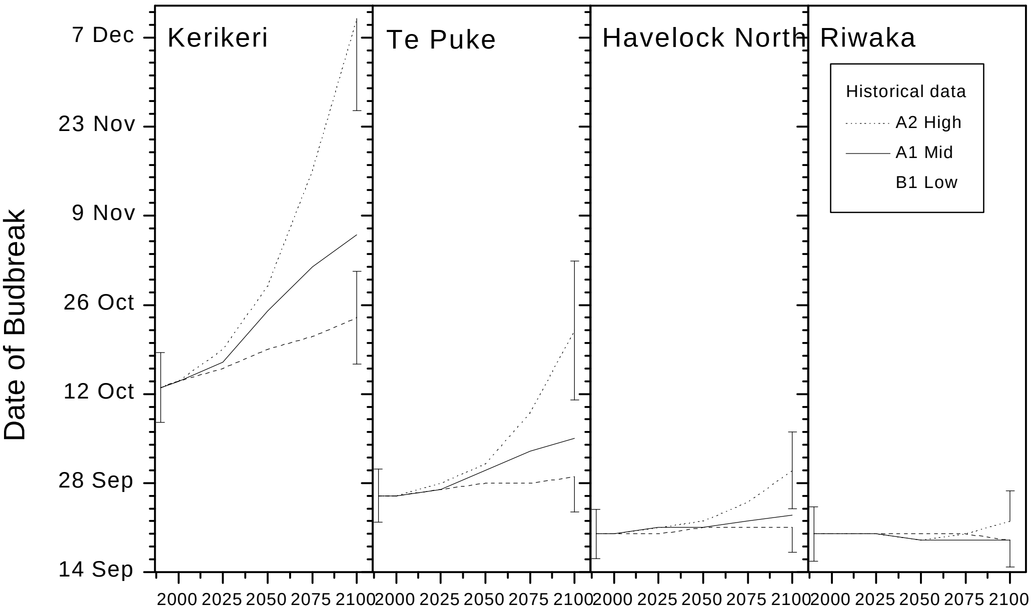

Figure 3.1: Change in the date of budbreak for ‘Hayward’ kiwifruit in four NZ production regions. Simulations are based on the application of three climate scenarios (SRES marker scenario A2, high climate sensitivity; SRES A1, medium sensitivity; and SRES B1, low sensitivity) to historical temperature data.

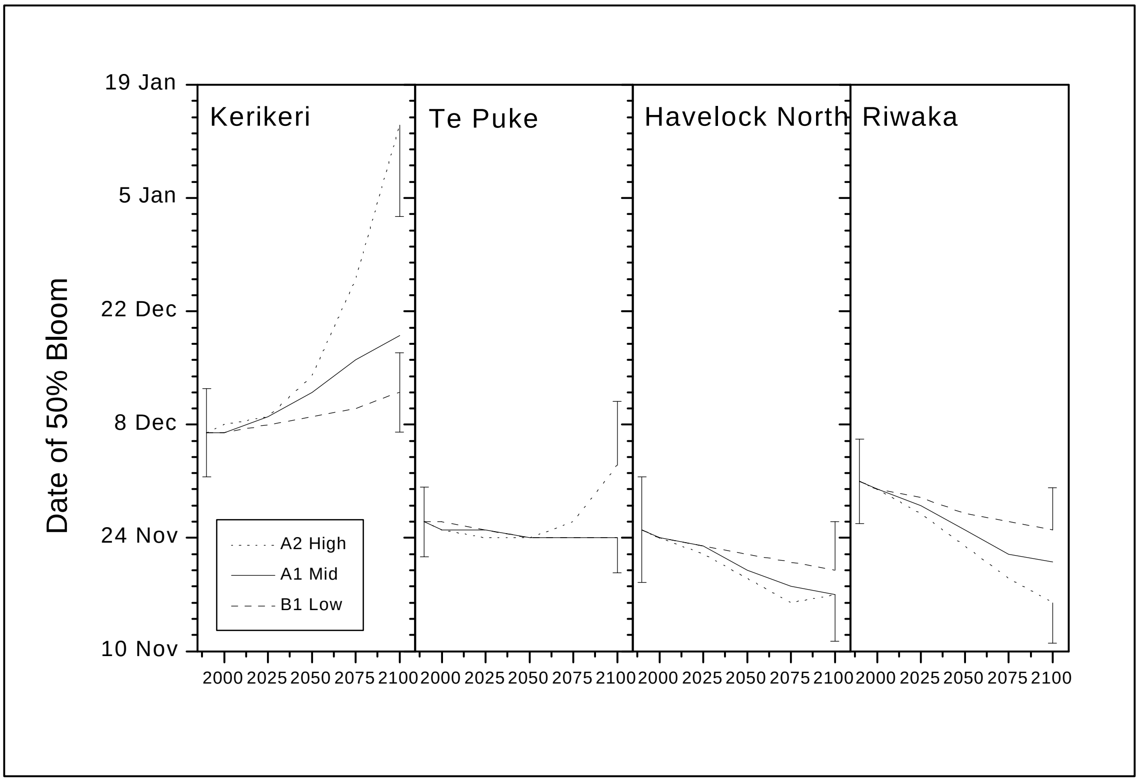

Figure 3.2: Change in the date of flowering for 'Hayward' kiwifruit in four NZ production regions. Simulations are based on the application of three climate scenarios to historical temperature data.

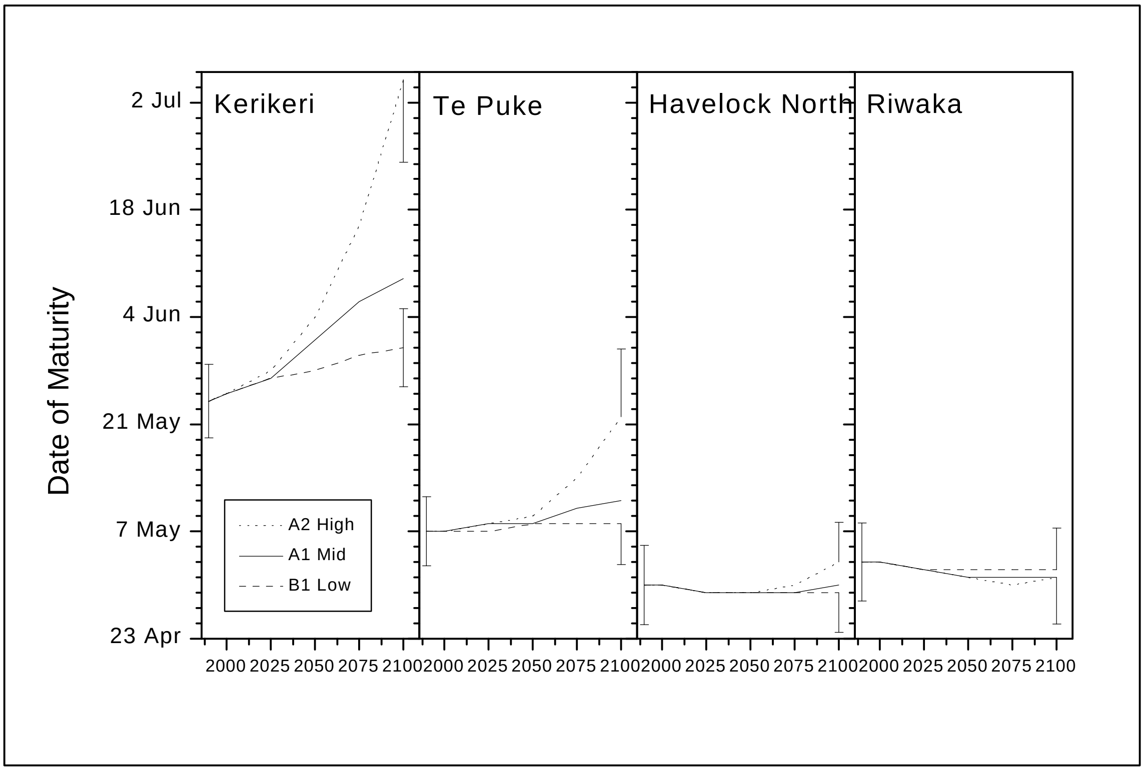

Figure 3.3: Change in the date of harvest maturity for 'Hayward' kiwifruit in four NZ production regions. Simulations are based on the application of three climate scenarios to historical temperature data.

At the two warmer sites, all three scenarios show the date of budbreak getting consistently later as the century progresses, but at the other two sites little change can be expected. In the next 25 years, little change is expected, but by 2050 under either the "A1" or "A2" scenarios, it can be seen (Figure 3.1) that the mean predicted date for Kerikeri lies outside the standard deviation shown at the baseline. Remembering that about 2/3 of all occurances lie within 1 standard deviation of the mean, with 1/6 above and 1/6 below, this means that on average budbreak will be as late as what is currently the latest year in six. In Te Puke, this does not happen until 2075.

The date of flowering (Figure 3.2) tends to change less over the period shown than the date of budbreak, because late budbreak is associated with following warm conditions, leading to a reduced duration between budbreak and flowering. A tendency to earlier flowering in Havelock North and Riwaka is evident under all scenarios, with Kerikeri in contrast getting later because of its much later date of budbreak.

The date of maturity (Figure 3.3) is relatively unaffected by climate change except at Kerikeri, and under the "A2" scenario at Te Puke. The change at Kerikeri can be attributed to a combination of later flowering (Figure 3.2), which may in part be an artifact due to the simplified model, and delayed conversion of starch to sugars because of a lack of cool temperatures.

The magnitude of the changes shown (Figures 3.2 and 3.3) at Kerikeri, and using scenario "A2" at Te Puke, may be exaggerated because of the problems with the flowering model (no consideration given to the lack of flowers on late buds) and the harvest time model (lack of hourly data). There is a natural negative feedback built into the harvest time model, as if warmer temperatures push the starting point of the process (flowering) later in the spring, then maturation will be pushed into a later period of the autumn, when cooler temperatures will accelerate maturation.

Flowering: Requires Cool Winters

As expected, the predicted number of flowers per winter bud drops with climatic warming, both without dormancy-breaking chemical application (Figure 3.4) and with HC (Figure 3.5). The effect is very consistent across all sites and years, with the greatest decrease in mean flower numbers occurring at the warmest site, Kerikeri. These quantitative predictions of flowering are unaffected by errors in predicted dates of flowering and maturity referred to earlier.

Of most interest is the lower half of Figures 3.4 and 3.5, showing the proportion of years in which flower production is likely to fall below the estimated threshold for economic production of 1 KFWB. Without HC, 'Hayward' kiwifruit production is known to fall below this threshold most years in Kerikeri already, and this situation will only get worse (Figure 3.4). With HC (Figure 3.5), 'Hayward' kiwifruit currently produce adequate flower numbers 9 years out of 10 in Kerikeri, but this situation is likely to change drastically by the middle of the 21st century if any but the "B1" scenario is used. It is likely that new cultivars will replace 'Hayward' before this time. In Te Puke, most years it is currently possible to grow 'Hayward' kiwifruit successfully without the application of dormancy-breaking chemicals, but this situation may well change in the future (Figure 3.4). As long as HC application is seen as acceptable to consumers, few problems are likely to arise due to climate change this century as long as sufficient buds are tied down in winter. In Havelock North, some problems may be experienced with chemical-free flower production by the end of the century, but whatever scenario is used flower production is not likely to be a problem in Riwaka (Figures 3.4 and 3.5).

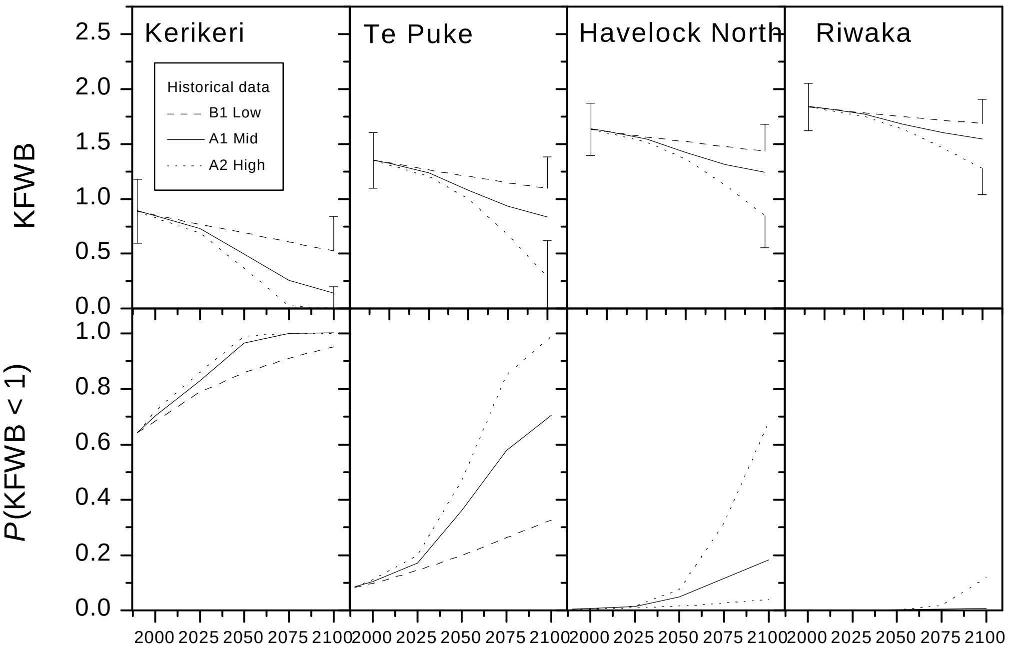

Figure 3.4: (a) Change in the mean number of flowers per winter bud (KFWB) for ‘Hayward’ kiwifruit in four NZ production regions, without the use of dormancy-breaking chemicals. Simulations are based on the application of three climate scenarios to historical temperature data. (b) The proportion of year when the number of king flowers per winter bud can be expected to drop below 1.0.

Fruit Dry Matter: Requires Warm Growing Season

The heat unit sum during the growing season can be expected to increase at all sites during the coming century (Figure 3.6(a)). However, of the four sites it is only at Riwaka where this is likely to make much difference to the proportion of years in which satisfactory fruit, with DM%>14%, can be produced. Remembering that the connection between the heat sum and dry matter production is not yet well established, it still appears likely that the difficulties sometimes experienced at that site currently are likely to diminish with time. Only with the “B1” scenario is there a significant probability of ‘failure’ in this sense beyond about 2075.

Effect of GCM

The choice of GCM had little effect on model outputs at the selected sites. At Kerkeri, results when using the CSIRO9 model were almost indistinguishable from those using HadCM2. At Te Puke and Havelock North, the difference was slightly greater (with the CSIRO9 model predicting slightly more change than HadCM2), but still very small compared with the difference between say the A1 mid and A2 high scenarios. At Riwaka, the effect was slightly greater, but in general the difference between the output obtained from the HadCM2 and CSIRO9 models (using the A1 mid scenario) was still not as large as that between the A1 mid and A2 high scenarios with the HadCM2 GCM.

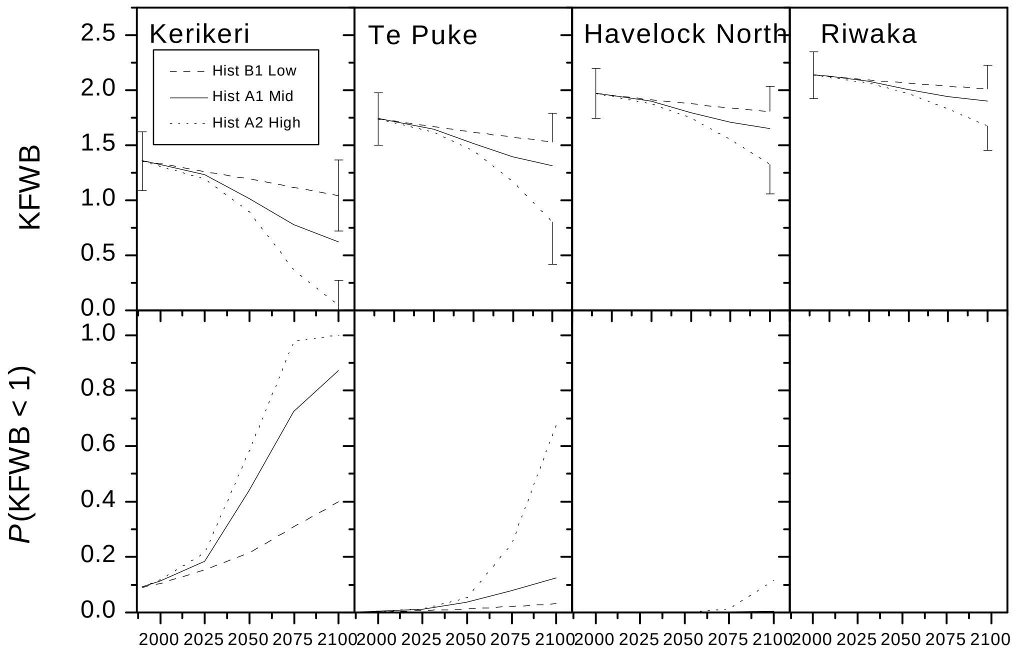

Figure 3.5: (a) Change in the mean number of flowers per winter bud (KFWBHC) for 'Hayward' kiwifruit in four NZ production regions, with HC applied. Simulations are based on the application of three climate scenarios to historical temperature data. (b) The proportion of year when the number of king flowers per winter bud can be expected to drop below 1.0.

Even at Riwaka, the difference between the two GCMs in the predicted flowering is very small compared to the year-to-year variation (Figure 3.7).

Effect of SOI

The southern oscillation index (SOI) is an important factor in determining the year-to-year variability about the long-term trends discussed above. This aspect of the climatic variability is perhaps the most amenable to seasonal prediction, so the magnitude of this effect determines the degree to which seasonal variability can be predicted and therefore more easily managed.

La Niña conditions (SOI>0) on average lead to warmer conditions in the selected sites, so flower numbers tend to be correspondingly lower (Figure 3.8 shows the change when no dormancy-breaking chemical is applied). Heat unit sums (HU10) also tend to be bigger (data not shown). The difference between the two extremes is significant, but because of the dependence of KFWB on factors other than simply climate, the proportion of the overall variability accounted for by the SOI is quite small. The same is true if HC is applied.

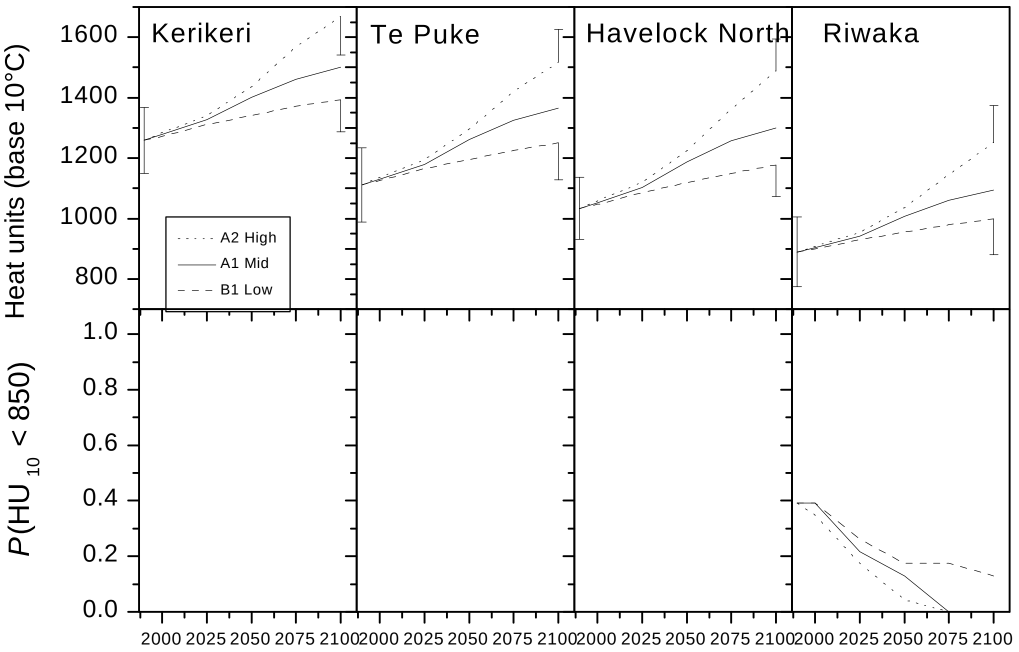

Figure 3.6: (a) Change in the heat unit sum between flowering and harvest (HU10) for 'Hayward' kiwifruit in four NZ production regions. Simulations are based on the application of three climate scenarios to historical temperature data. (b) The proportion of year when the heat unit sum can be expected to drop below 850.

Spatial Analysis

Spatial analysis by Kenny *et al.* (2000) used a 'Hayward' kiwifruit suitability model with a range of scenarios in the CLIMPACTS system to predict the changing area in the Bay of Plenty likely to be suitable for 'Hayward' kiwifruit. The model used reflects the same features as the more detailed models described in Annex 4, but uses monthly aggregated climatic variables so that it can be applied within the CLIMPACTS system spatially. An area is defined as "optimally" suitable for 'Hayward' kiwifruit if the average temperature from May to July is less than 11°C; the heat sum (base 10°C) from October to April exceeds 1100 degree-days; and annual rainfall exceeds 1250 mm (Salinger and Kenny, 1995). The analysis of Kenny *et al.* (2000) was re-done, using the CLIMPACTS system, to generate a new set of results for the revised scenarios prepared for this report. The area suitable for 'Hayward' kiwifruit production in the Bay of Plenty is predicted to decline rapidly, beginning about 2040 or 2050, for all but the lowest case B1 emissions scenario (Figure 3.9).

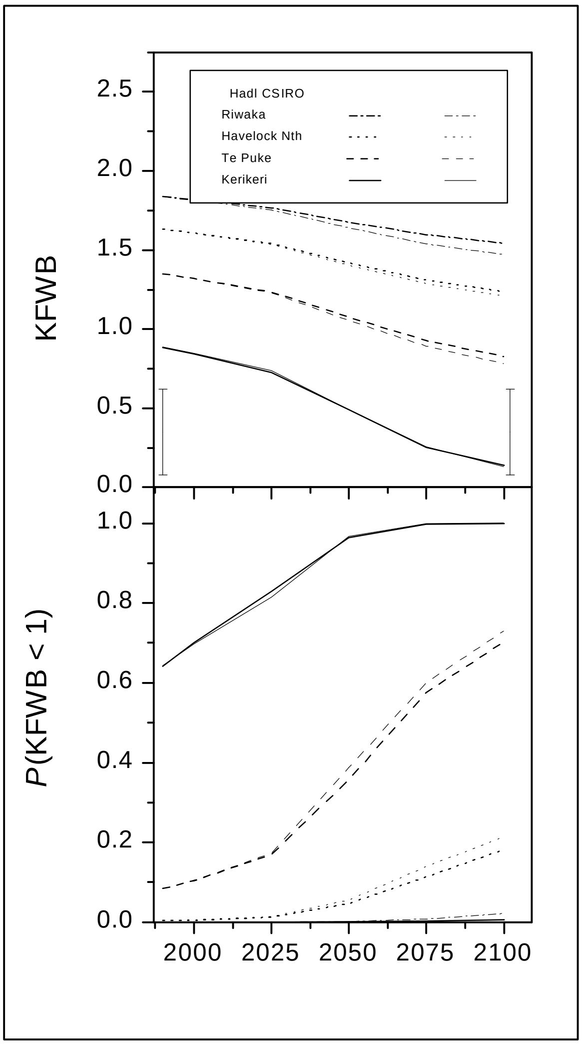

Figure 3.7: (a) Change in the mean number of flowers per winter bud (KFWB) for 'Hayward' kiwifruit in four NZ production regions, without the use of dormancy-breaking chemicals. Simulations are based on the application of two GCMs (HadCM2 and CSIRO9) to historical temperature data for the same change scenario (SRES A1, medium sensitivity). (b) The proportion of year when the number of king flowers per winter bud can be expected to drop below 1.0.

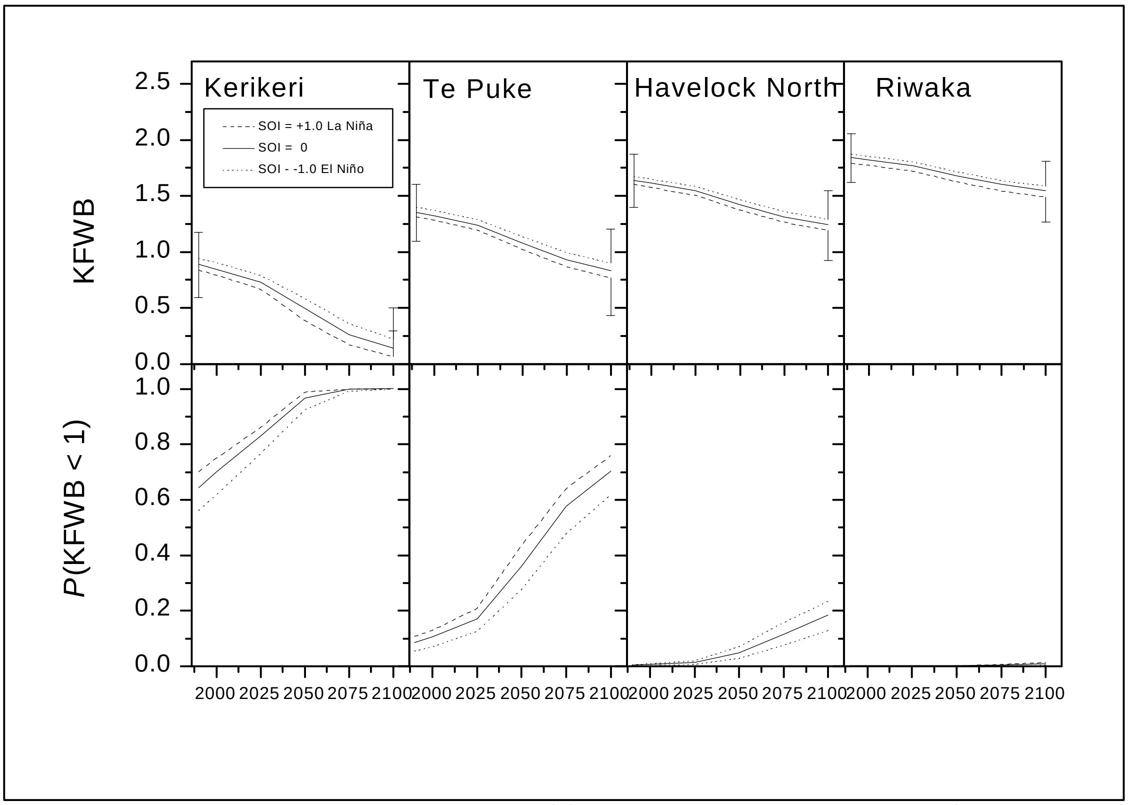

Figure 3.8: (a) Change in the mean number of flowers per winter bud (KFWB) for 'Hayward' kiwifruit in four NZ production regions, without the use of dormancy-breaking chemicals, for three different values of the SOI. (b) The proportion of years when the number of king flowers per winter bud can be expected to drop below 1.0.

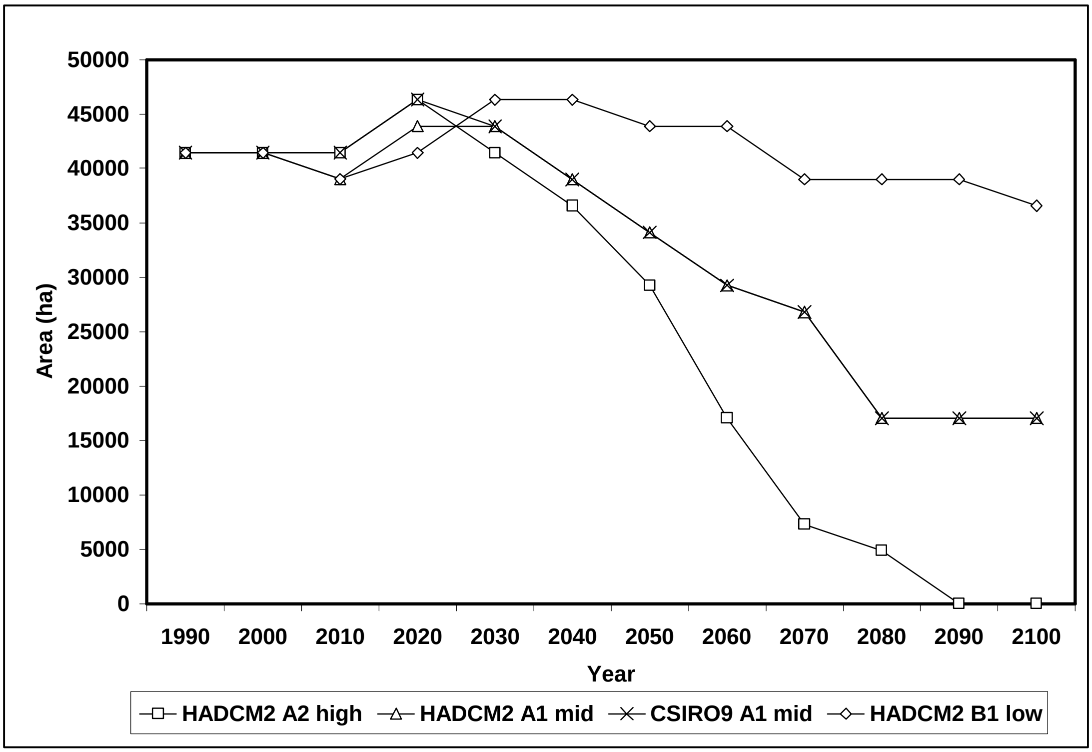

Figure 3.9: Changes in 'Hayward' kiwifruit suitability for Bay of Plenty (optimal areas) for two different GCM patterns (CSIRO9 and HadCM2) and three GHG emissions scenarios (A2 high, A1 mid, B1 low). Revised from Kenny *et al.* (2000).

The main restriction on 'Hayward' kiwifruit production in the Bay of Plenty reflected in Figure 3.9 is the requirement for winter temperatures to average below 11°C, and the most important effect of winter temperatures is on the number of flowers produced. A comparison of Figure 3.9 with Figure 3.4 shows that the aggregated suitability model and the more detailed phenological model are in agreement about when the critical time for the 'Hayward' kiwifruit industry in the Bay of Plenty is likely to be. Without the use of dormancy-breaking chemicals, 'Hayward' kiwifruit production is not likely to be viable in that region by the middle of the 21st century. A comparison with Figure 3.5 however suggests that chemical intervention may well extend the period of economic production beyond the end of the century.

Summary

Effect of climate change on 'Hayward' kiwifruit production

- Timing of phenological events may change significantly in warmer regions.
  - Budbreak is likely to occur later;
  - Shortcomings in current models mean that the effects on dates of flowering and maturity are less clear.
- The most important effect will be a drop in flower numbers in warmer regions. Because of this, we can expect that by around 2050:
  - Production may become uneconomic in Northland, even when "HC" is applied;
  - Production in the Bay of Plenty without dormancy-breaking agents will be uneconomic.
- In cooler regions, problems with low dry matter due to cool summers will become less important over the next 50 years.

Effect of Different Scenarios and GCMs on Model Predictions

- The "A2 high" scenario leads to dramatic change, but even under the "B1 low" scenario significant change can be expected over the next 100 years;
- The choice of GCM had little effect on predicted crop performance.

Effect of SOI

- Average flower numbers are higher under 'La Niña' conditions than under 'El Niño'.

Links to Policy and Adaptation

It is clear that in Northern parts of New Zealand, for which we have used the Kerikeri research orchard as an "indicator" site, there are likely to be ongoing problems in maintaining adequate flower numbers with 'Hayward' kiwifruit, particularly if use of dormancy-breaking chemicals such as "HC" is limited.

A number of possible adaptations to this threat of warm winters leading to poor flowering in the Northern parts of New Zealand need discussion. All are already happening.

The first adaptation is simply to tie down more buds (either through more canes or longer canes) when it is thought flower numbers could be low. However, the fixed canopy area of each vine places a natural limitation on how far this can be taken, and the suggested lower limit for commercial viability of 1 KFWB has already taken this into account. It should also be pointed out that this does not get around the problem of climatic variability – unless the weather over the next winter can be predicted with some reliability, it is hard to decide how many buds to leave. Recent improvements in estimating the effects of early-winter temperatures on flowering, and the ability to use the SOI in long-term forecasts, are improving this position but there is still a long way to go.

The next adaptation is technological, a search for a chemical (or even better, a "natural" agent) which can reliably force buds to break and flowers to be produced even after a relatively warm winter, and which is seen as acceptable by consumers. Consumer resistance to chemicals is increasing, so this route may not prove fruitful; also even if a chemical with the same efficacy as HC is used, 'Hayward' kiwifruit production may well become uneconomic in the Northern parts of New Zealand by the middle of this century (Figure 3.5).

The third form of adaptation is simply to change cultivars to those more suited to warmer climates. The industry is currently making a heavy investment in the new "Zespri Gold" cultivar. This cultivar may be just as sensitive as 'Hayward' to warm winters, but its natural flowering habit is more prolific so there is a greater margin available before flower numbers drop too low. It is yet to be shown which, if any, of the new Actinidia cultivars being developed by HortResearch are more tolerant of warm winters, but given the stated intention of the industry to introduce a major new cultivar every 5-10 years it can be expected that adaptation will occur at a rate adequate to deal with climate change issues.

Finally, it may be that over the next century more 'Hayward' kiwifruit will be grown in cooler regions such as Nelson and Hawkes Bay, and less in Northland and the Bay of Plenty. Cool-temperature limitations on crop development are likely to become less important in the cooler regions.

In summary,

- Dormancy-breaking agents will become increasingly important in warmer production areas;
- In future, one selection criterion for new cultivars may need to be the production of adequate flower numbers following a warm winter;
- We should anticipate some movement in 'Hayward' kiwifruit production from warmer to cooler regions.

Key Uncertainties, and Future Research Directions

To improve this assessment of the likely consequences on 'Hayward' kiwifruit production in New Zealand, we need to move forward on a number of fronts.

Aspects of the impact of climate change not directly related to 'Hayward' kiwifruit physiology, have not been considered here. These include the possibility of establishment of new pests or diseases in New Zealand, and the effects of changing ground-water availability for irrigation.

We need to improve our models of the effects of climate on 'Hayward' kiwifruit physiology. Two areas highlighted here are the need to modify predictions of flowering date to incorporate the effects of warm winter conditions, and the need for a good model of the effect of summer temperatures, radiation, and water availability on fruit quality. Further work is also needed to "tailor" models developed using hourly weather data to applications when data is available only on daily or monthly time scales.

Because the reliable historical record at the sites used above is relatively short (for example, only 12 years at Te Puke), the probability of low-frequency events should really be estimated using a more "continuous" tool such as a weather generator, rather than as a simple fraction of historical years. However, the weather generators currently available do not reflect inter-annual variation well, so improvements are needed.

The following possible future research directions are therefore identified:

- Implement an improved model for the time of flowering;
- Develop and implement a more robust weather-driven model for fruit quality;
- Improve methods for using temporally averaged data in models;
- Integrate the effects of ground water supply and water availability into the models;
- Investigate the possibility of including relevant pest and disease models;
- Improve weather generators so they adequately reflect inter-annual variability.

References

Hall, A.J., McPherson, H.G., Crawford R.A., and Seager, N.G. (1996). Using early-season measurements to estimate fruit volume at harvest in kiwifruit. *New Zealand Journal of Crop and Horticultural Science.* 24: 379-391.

Hall, A.J., and McPherson, H.G. (1997a). Modellingthe influence of temperature on the timing of budbreak in kiwifruit. *Acta Horticulturae.* 444(1), 401-406

Hall, A.J., and McPherson, H.G. (1997b). Predicting fruit maturation in kiwifruit (Actinidia deliciosa). *Journal of Horticultural Science.* 72(6), 949-960.

McPherson, H.G., Hall, A.J., and Stanley, C.J. (1992). The influence of current temperature on the time from budbreak to flowering in kiwifruit (Actinidia deliciosa). *Journal of Horticultural Science.* 67(4), 509-519.

Kenny, G.J., Warrick, R.A., Campbell, B., Sims, G.C., Camilleri, M., Jamieson, P.D., Mitchell, N., and McPherson, H.G. (2000). Investigating climate change impacts and thresholds: an application of the CLIMPACTS integrated assessment model for New Zealand agriculture. *Climatic Change.* 46(1/2), 91-113.

Salinger, M.J., and Kenny, G.J. (1995). Climate and kiwifruit cv. ‘Hayward’: 2. Regions in New Zealand suited for production. *New Zealand Journal of Crop and Horticultural Science.* 23, 173-184.

Chapter 4:
Temperature Impacts on Development of Apple Fruits

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Introduction

This chapter provides an analysis of the implications for New Zealand apple production of predicted global warming. It was prepared using the CLIMPACTS suite of models to assess the potential impact of global climate change on New Zealand primary production systems. It uses results from a model of early season temperature effects of rates of apple fruit development and growth, integrated as part of the CLIMPACTS system, as an index of the sensitivity of apple production to long-term climate change.

What is Known?

Climatic conditions influence the characteristics of apples important to consumers. These include fruit appearance (size, shape and colour); its flavour and texture; its storage ability; and how chemical and other methods have been used to control pests and diseases.

For marketers, these characteristics (especially fruit size and colour, but recently, texture characteristics such as firmness, and management regime) are significant since they influence consumer choice and therefore fruit value. For growers also, knowledge of climatic impacts of these properties is increasingly significant for orchard management, to ensure fruit produced achieves optimal distributions of size and other parameters. The climatic impacts of global warming are therefore potentially of significant interest to the apple industry.

Sensitivity to Climate

Production of apple fruits is an extended process, which begins the year before fruit are harvested. It starts with the formation of flower buds in the preceding summer and concludes with harvest 15-18 months later. It displays two periods characterised by active growth (the first and second summers), interrupted by a dormant period over the intervening winter. Climatic conditions, notably day length and temperature, but also water availability, are important signals controlling this process.

Climatic conditions during this period therefore affect its final outcome, especially since development occurs in an open orchard environment. Internationally, this can be seen in the factors that limit apple production in major overseas fruit-producing regions. These include high temperature stress (e.g. South Africa, Chile), lack of winter chilling (e.g. South Africa, Brazil), and drought stress in conjunction with high temperature. Predicting the potential impact of these factors under different climate change scenarios represents an important modelling application.

By comparison, the climate of New Zealand apple regions is generally favourable for successful apple production. However, given the dependence of fruit development on climatic conditions, changes due to predicted global warming may still affect New Zealand apple production. These impacts could occur via:

- Climatic effects on flower initiation, dormancy, bloom and pollination;
- Effects on rates of fruit growth, maturation and subsequent postharvest quality;
- Effects of elevated CO_2 on photosynthesis and production efficiency;

- Impacts of changed rainfall patterns on irrigation requirements and disease.

These factors, and other impacts such as those via changes to the incidence of cold-temperatures (e.g., frost), hail and cyclonic storms, could all influence the suitability of existing apple cultivars for current production regions.

What Kinds of Changes in Climate Would Imply Substantial Changes?

The impact of early-season temperature on apple fruit size provides an example of how change to climatic conditions could affect a key fruit property. This is because conditions during the 4-6 weeks post-bloom strongly influence fruit development. The impact of temperature during this period is now well defined. For instance, the correlation between length of growing season and temperature in the first 30-50 days after bloom is stronger ($R^2 > 0.90$) than that with average temperature over the entire season (Stanley, *et al.*, 2000). Controlled environment work, in which temperature is precisely controlled, confirms field studies and shows that early season temperatures strongly influence potential fruit size for some cultivars (Warrington *et al.*, 1999). These results therefore suggest a warming of 1-2°C which could be expected to alter fruit development directly, irrespective of other effects on orchard performance.

What does CLIMPACTS Show?

Methods

We have used the direct impact of temperature on fruit size to gauge the possible impact of climate change on New Zealand apple production. We therefore report how predicted trends in global temperature may affect potential fruit size in three New Zealand apple production regions. To do so we use a model integrated within the CLIMPACTS suite to simulate fruit growth under a selected range of climate change scenarios.

The CLIMPACTS apple fruit growth model is a composite model of a mid-season apple and consists of three components. These describe the effect of temperature on: i) the date of bloom; ii) the date of fruit maturity; and iii) the rate of fruit growth between these two dates. It is run for a site using daily max-min temperature data.

Date of bloom is predicted using a correlation equation, derived from multiple regression of past dates for ‘Delicious’ apple (Havelock North, 1987-97 and Nelson, 1969-87) against daily temperature averages, and is used to predict a date at which to start the fruit growth component. The best relationship was with maximum temperatures immediately prior to bloom. Thus

$$Day\,of\ Full\,Bloom = 367 - 5.5\overline{T}_{x\,Aug-Sep}$$

where *Day of Full Bloom* is days from Jan 1 ($R^2 = 0.58$, n=28, p<0.05).

Date of maturity for ‘Delicious’ (at which simulated growth ceases) is estimated using a correlation function relating average daily temperature for the period 0-50 DAFB) to the duration from Full Bloom to maturity (Stanley, *et al.*, 2000). This relationship is

$$\begin{aligned} &Days\ from\ Full\ Bloom\ to\ Maturity \\ &\qquad = 263.2 - 7.62\overline{T}_{0-50DAFB} \end{aligned}$$

where $T_{0\text{-}50\mathrm{DAFB}}$ is calculated from ‘true’ daily means (i.e., means calculated from $(T_{\max} + T_{\min})/2$ were adjusted for bias from the seasonally varying duration spent near Tmax and Tmin).

The fruit growth component (Austin *et al.*, 1999) simulates the changing impact of temperature on fruit growth rate by a set of differential equations describing transfer of tissue from one conceptual compartment, which contributes to setting a potential size, to one that does not. Its development used data describing growth of ‘Delicious’ apple fruits growing under controlled environment conditions.

To test performance under field conditions, the model was re-parameterised for daily mean temperature ((T_{max} + T_{min})/2), and used to predict the diameter of 'Royal Gala' apples growing in Hawke's Bay. The change of cultivar also required re-estimation of non-temperature related model parameters.

In this survey, the model was run using data series for three New Zealand regions. These were: Hawke's Bay (D9668B Havelock North), Nelson (G12191 Motueka) which together represent 80% of New Zealand's apple production (NZAPMB, 1998), and Canterbury (H32642 Lincoln), chosen as a site whose present climate is marginal for commercial apple production.

Simulations were run for the 1990 base year, and then at 25-year intervals over the period 2000-2100. They examined the sensitivity of model predictions to uncertainties in three areas: i) Greenhouse gas emissions (IPCC SRES marker scenario A2, high climate sensitivity; SRES A1, mid sensitivity; SRES B1, low sensitivity); ii) GCM patterns (HadCM2 and CSIRO9 models); iii) positive, neutral and negative SOI conditions (+1.0 La Niña, 0, -1.0 El Niño).

All results presented are based on the application of climate change scenarios to the 30-year historical database for each of the three sites surveyed. All results are the means of 30 simulations with the current inter-annual variability presented as ± 1 sample standard deviation. This statistic has the characteristic that 1 in 6 values can be expected to fall outside 1 standard deviation from the mean.

All fruit size results are presented in relation to the simulated mean fruit size at Havelock North for the 1990 base year. This relative basis is used since actual fruit size depends heavily on factors such as past yields, crop load, nutrition and irrigation. Here, all model runs assumed a light crop without competition between fruits, or interactions between climate and factors such as disease and pests. Hence, the survey does not simulate different crop load levels, which would have pronounced effects on actual fruit size. Results therefore represent the effect of temperature changes in isolation from other interacting or compensating effects on fruit development.

Results

Dates of Bloom and Maturity

The model, when applied to adjusted historical temperature data, reproduced patterns in dates of bloom and maturity consistent with those currently observed in the three survey regions (Figure 4.1 and Figure 4.2). Dates of bloom and maturity were earliest at Havelock North (Hawke's Bay), slightly later at Motueka (Nelson), and substantially later at Lincoln (Canterbury). This pattern remained the same throughout the 2000-2100 prediction period and was unaffected by the choice of climate change scenario.

At each site, dates of bloom and maturity became progressively earlier over the 2000-2100 survey period. Full bloom was advanced by about a week under the SRES marker scenario A1, medium climate sensitivity scenario and maturity by about two weeks. Date of maturity showed greater sensitivity to the superimposed climate change but also displays greater year-to-year variability.

The results, however, indicate that the climate-induced advancement in bloom and maturity is not likely to be significant within the next 25 years. In all cases, the climate-induced shift in the mean dates was small compared to the model's prediction of present inter-annual variation in size due to seasonal temperature variability. Only under the SRES A2 high sensitivity scenario did the predicted change in bloom and maturity dates become significant, and this was only at the latter end of the survey period. This situation applied at all three sites investigated.

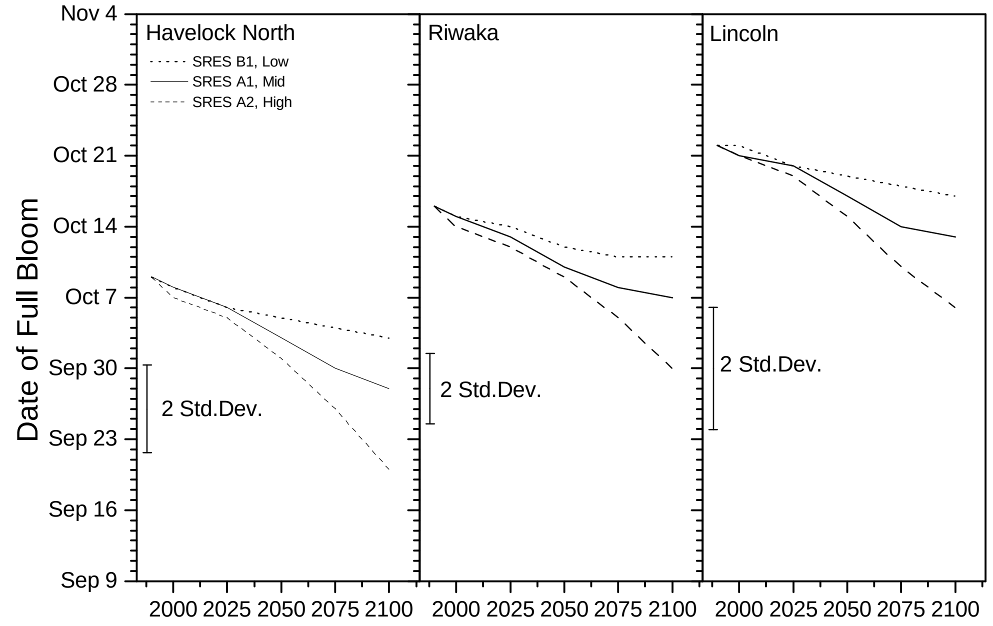

Figure 4.1: Change in date of full bloom for a standard mid-season apple in three NZ production regions. Simulations are based on application of three climate scenarios (SRES marker scenario A2, high climate sensitivity; SRES A1, medium sensitivity; SRES B1, low sensitivity) to 30 years historical temperature data. Bars equal ± 1 population std. dev.

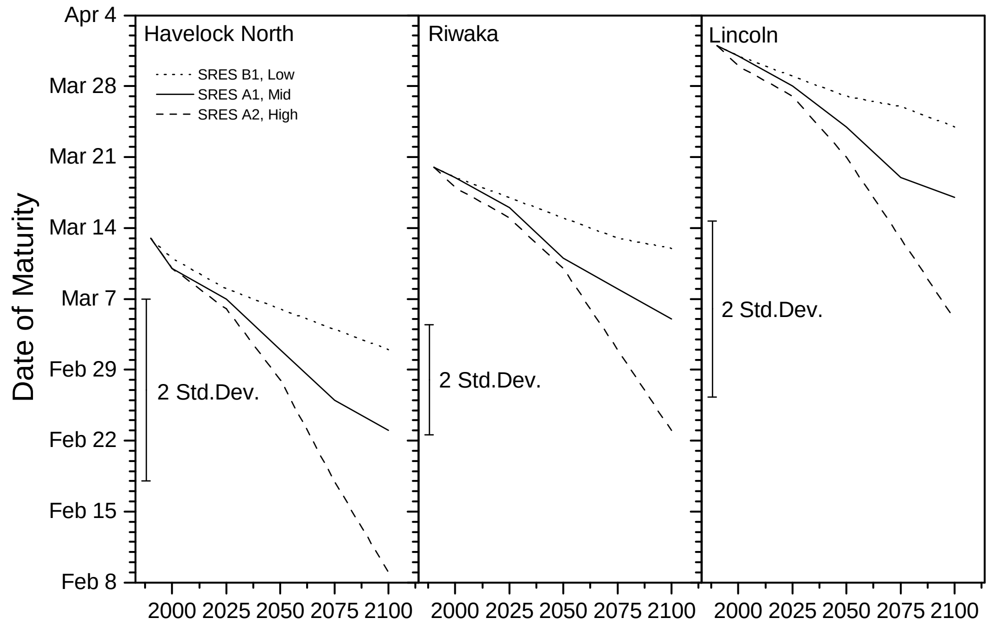

Figure 4.2: Change in date of maturity for a mid-season apple in three NZ regions. Simulations apply three climate change scenarios (SRES A2, high sensitivity; SRES A1, medium sensitivity; SRES B1, low sensitivity) to 30 years historical temperature data.
Bars equal ± 1 population std. dev.

Apple Fruit Size at Maturity

Application of the model to climate-adjusted historical data produced trends in apple fruit size consistent with the relative performance of the three production regions represented in the survey (Stanley *et al.*, 2000). Fruit size was largest at Havelock North, slightly smaller at Motueka, and substantially smaller again at Lincoln (Figure 4.3). This overall pattern remained the same throughout the survey period and was not altered by the choice of climate change scenario. At each site, apple size increased over the survey period, although the increase was greatest under the SRES marker scenario A2, high climate sensitivity scenario.

The results indicate climate-induced trends in fruit size are not likely to become significant before 2050, at any of the sites investigated. The induced change in size over the 2000-2100 period was negligible under the SRES B1, low sensitivity scenario. Only under the SRES A2, high sensitivity scenario did the change in size become significant, and this only at the latter end of the survey period. In all cases, the induced shift in the mean associated with long-term climate change was small compared to the model's prediction of present inter-annual variation in size due to seasonal temperature variability.

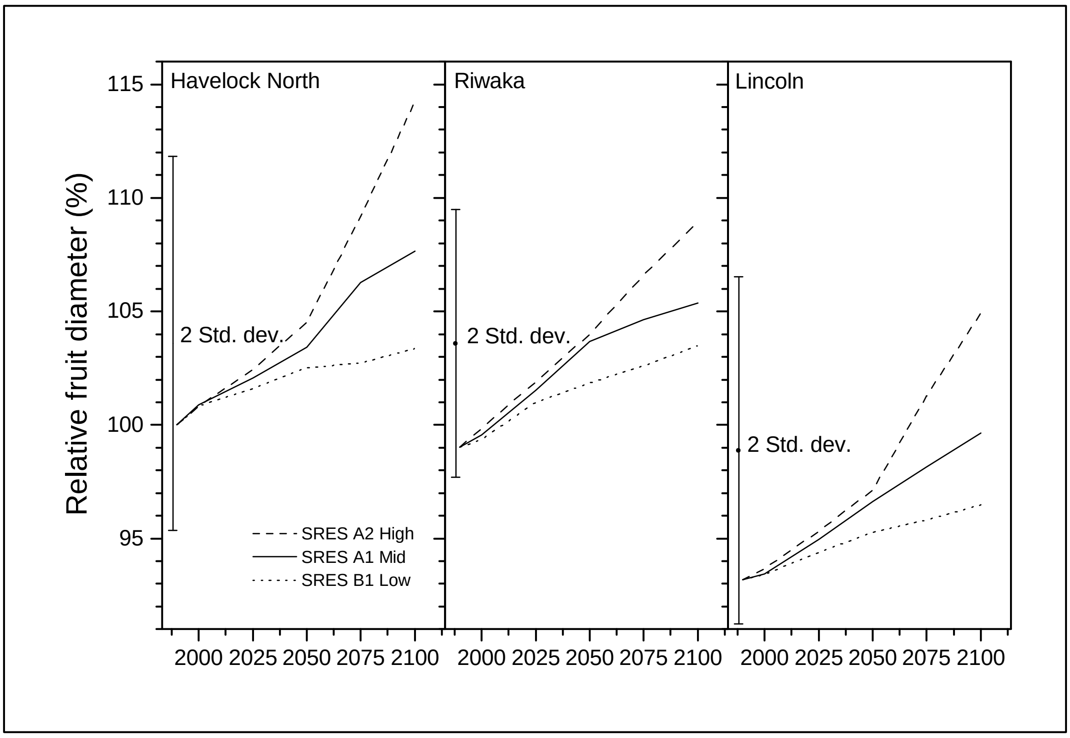

Figure 4.3: Change in relative fruit size (based on diameter at maturity at Havelock North) for a mid-season apple in three NZ regions. Simulations apply three climate change scenarios (SRES A2, high sensitivity; SRES A1, medium sensitivity; SRES B1, low sensitivity) to 30 years historical temperature data. Bars equal ± 1 population std. dev.

Other Factors

Predicted fruit size at maturity showed a small effect of choice of GCM. The effect varied between sites but overall, the upward trend was slightly lower using the Hadley model (Figure 4.4).

At Havelock North, there was no difference between predictions using the HadCM2 or CSIRO9 models, whereas at Motueka and Lincoln, the Hadley model resulted in a smaller increase in size than the CSIRO GCM. However, in both cases, the climate-induced trend in fruit size was small relative to normal seasonal variability.

The sensitivity of the potential size of apple fruits to SOI-related seasonal variability differs between regions (Figure 4.5). The effect is small at Havelock North, and remained small throughout the forecast period. At Motueka and Lincoln, however, fruit are on average potentially larger under 'La Niña' conditions than under 'El Niño', reflecting the effect of normally warmer early-season (spring) conditions during the 'La Niña' phase. The difference between phases remained the same throughout the survey period. It did not override the long-term climate-induced trend towards increased fruit size.

When do the Scenarios Indicate Major Changes?

The globally-induced trend towards earlier bloom and maturity in major New Zealand apple production regions will initially be perceived as a higher frequency of “early” years. However, the results suggest producers are unlikely to observe a consistent and pronounced change in fruit development over the next 25 years, even under the IPCC SRES A2, high climate sensitivity scenario. This is because predicted changes in dates and potential size are small relative to present year-to-year variability. The predicted changes in average dates of bloom and maturity, and potential fruit size are not significant before 2050, which is beyond the economic life-span of existing commercial orchards, or of presently-grown cultivars (both ~20 years).

Summary of Results

Date of Bloom and Maturity

- Warmer temperatures bring forward dates of bloom and maturity;
- Date of maturity appears more sensitive to changes than bloom;
- Advancement of dates is limited before 2050.

Potential Fruit Size

- Choice of climate change scenario strongly affects how fruit size changes (greatest under SRES A2, high sensitivity, negligible under SRES B1, low sensitivity);
- Climate changes are unlikely to affect the relative performance of existing apple producing regions;
- The predicted impact of temperature on fruit size is limited before 2050.

Other Factors

- Choice of GCM has a small effect on model predictions, and which varies between sites;
- SOI-related variability is comparable in scale to long-term effects, but small for Hawke’s Bay;
- The 'La Niña' phase favours larger fruit than 'El Niño'.

We conclude that the New Zealand apple industry is unlikely to observe major changes in apple production due to global warming. Changes are more likely to be driven by marketing requirements than by the impacts of predicted climatic changes.

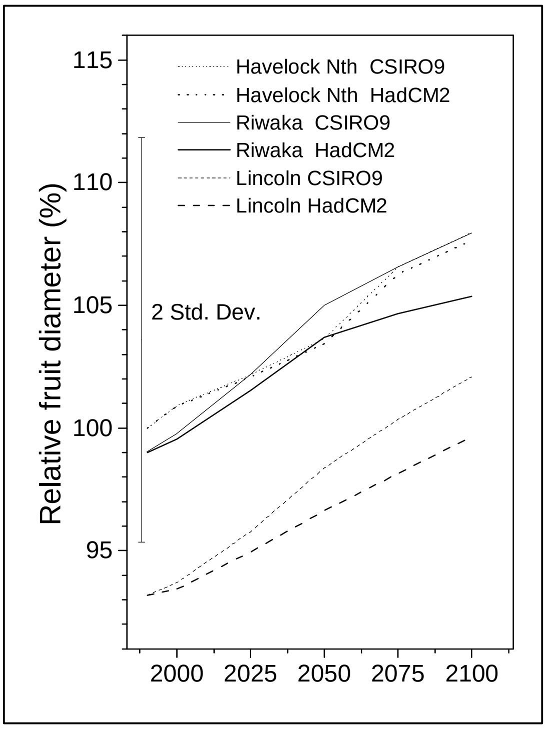

Figure 4.4: Effect of GCM on relative fruit diameter at maturity in three NZ regions based on application of a single scenario (SRES A1, medium sensitivity) to 30 years temperature data. Bar equals ± 1 population std. dev.

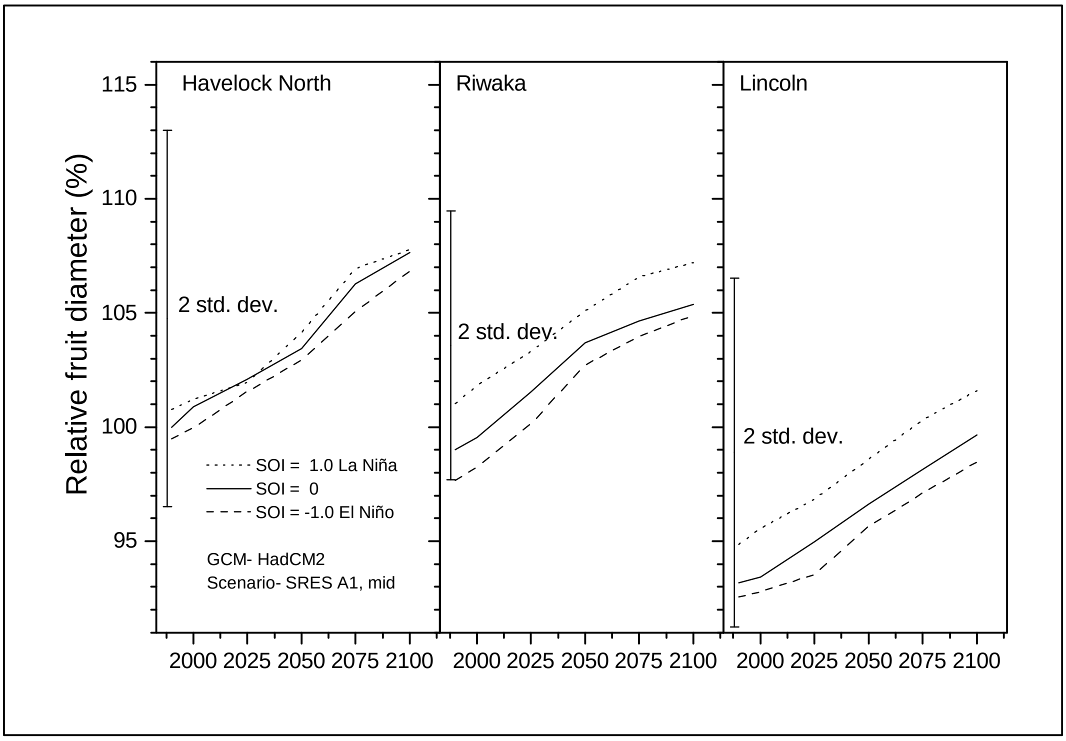

Figure 4.5: Effect of Southern Oscillation Index (SOI) on potential fruit diameter at maturity in three NZ regions, relative to the average diameter for a 1990 base year at Havelock North. All simulations apply a single scenario (SRES A1, medium sensitivity) to 30 years temperature data. Bars equal ± 1 population std. dev.

Key Uncertainties and Future Directions

The key uncertainty associated with results presented is a reflection of the exclusive focus here on direct temperature effects on fruit growth. The present model does not consider the potential impacts of other amplifying or compensating effects from other processes also sensitive to climatic conditions, as highlighted in the introduction.

For instance, the impact of warmer winter conditions on time of budbreak (and hence flowering) is not treated in detail by the model. This is because the bloom date component is based on data for the major production regions, which presently have enough winter chilling for satisfactory budbreak and flower development. If winter chilling were to be sufficiently reduced during warmer winters so that budbreak and flowering were delayed, then there could be flow-on effects for subsequent fruit growth.

Whether fruit size would increase under this scenario (later bloom => warmer conditions during early fruit growth), or fall (warmer conditions during early fruit growth => earlier maturity) is not clear. However, the interaction between bloom and maturity dates indicated under the scenarios explored does suggest that consequent changes to fruit size would be limited.

A further reason for conservatism in our interpretation of the results is the absence of simultaneous modelling of changes in possible crop-load (fruit number per tree) management strategies that could be applied to mitigate effects of climatic changes. Crop load has a profound impact on actual fruit growth, and is manipulated as a standard management practice to optimise fruit size distributions. This is because apple trees (like other pip- and stonefruit species) normally begin the season with many more flowers than are ultimately required for a commercial crop.

For this reason, all results are presented in relation to the simulated mean fruit size at Havelock North for the 1990 base year. All model runs assumed no competition between fruits, which would have a pronounced effect on actual fruit size. A more comprehensive approach to fruit development, for instance incorporating competition impacts demand, is required.

The results also predict the effect of temperature changes in isolation from other possible interacting or compensating effects of climate on tree growth and fruit development such as past yields, nutrition, irrigation and pest/disease management. Thus, changes in rainfall patterns caused by climatic trends are very likely to alter the incidence of diseases such as ‘black spot’ (or apple scab, caused by Venturia inequalis). Models are available that can predict weather related disease risk and could provide a basis for future analysis of likely climate change impacts.

Market-driven trends in management practices and fruit quality specification levels provide a further source of uncertainty. These trends, for instance towards higher levels of fruit colour, better fruit storage performance and lower levels of chemical inputs all have potential climatic interactions. In particular, alternative disease management regimes, which are acceptable under organic production codes, often come at a cost of tree performance and fruit size. The impact of large-scale movement to such regimes under climatic conditions that may present a greater risk of diseases such as ‘black spot’ (or apple scab, caused by Venturia inequalis) has not been considered here. Modelling the production consequences of such factors is also a significant challenge for the future.

Links to Policy and Adaptation

The climatic impact results presented by this report suggest that New Zealand apple producers are unlikely observe major changes in apple development due to predicted climatic warming under global climate change scenarios. Any alterations to cultivar selections and production systems are more likely to be driven by marketing requirements than by the impacts of predicted climatic changes.

This conclusion is consistent with that drawn from a general comparison of the climates of New Zealand apple production regions (Hawke's Bay and Nelson) with those of major overseas regions. The climates of the New Zealand regions have a significant maritime influence and are therefore relatively mild. Summers, in particular, are relatively cool (daily maximum around 5ºC less than overseas production regions), while winters, although warmer, are still sufficiently cool to satisfy dormancy-breaking chilling requirements. It is speculated that the superior performance of New Zealand orchards (which produce yields of up to twice those of overseas regions) may be attributable to this difference, in conjunction with the long period after harvest before leaf-fall.

The strong focus of the New Zealand apple industry, and its research providers such as HortResearch, towards developing new cultivars suited to New Zealand conditions and to world markets also means the industry will be able to adapt to long-term climatic change, should it induce any adverse impacts. This is the case whether the effects considered are direct impacts on fruit development and quality, or indirect impacts on pests and diseases and their management. The New Zealand industry is innovative in its approach to cultivar introduction, which is occurring within a market-led context, and with a timeframe much shorter than anticipated climate changes. This process simultaneously offers the opportunity to respond to changes in climatic conditions.

References

Austin, P.T., Hall, A.J., Gandar, P.W., Warrington, I.J., Fulton, T.A., and Halligan, E.A. (1999). A compartment model of the effect of early-season temperatures on potential size and growth of 'Delicious' apple fruits. *Annals of Botany.* 83, 129-143.

NZAPMB, (1998). *Annual Report of the New Zealand Apple and Pear Marketing Board for 1998.*

Stanley, C.J., Tustin, D.S., Lupton, G.B., McArtney, S., Cashmore, W.M., and De Silva, H.N. (2000). Towards understanding the role of temperature in apple fruit growth responses in three geographical regions within New Zealand. *Journal of Horticultural Science and Biotechnology.* 75(4).

Warrington, I.J., Fulton, T.A., Halligan, E.A., and DeSilva, H.N. (1999). Apple fruit growth and maturity are affected by early season temperatures. *Journal of the American Society for Horticultural Science.* 124, 468-477.

Chapter 5:
Impacts of Climate Change on Wheat Production

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Wheat in New Zealand

The area of wheat grown in New Zealand peaked at about 130 000 ha in 1969 (Logan, 1983), declined to 37 000 ha in 1991, and has been gradually rising since, to reach nearly 60 000 ha in 1997 (Petrie and Bezar, 1997). There has been some swapping between wheat and barley production, so that when wheat area declines, it is usually because barley area is increasing. Wheat yields have been slowly increasing over the years, from a mean of 3.56 t ha^{-1} in 1980 (Logan, 1983) to 5.4 t ha^{-1} in 1997 (Petrie and Bezar, 1997). Despite the low average yields, some Canterbury farmers are now regularly achieving yields of 10 t ha^{-1} or more (Jamieson and Munro, 1999). Canterbury is the main production area, with 97% of the nation's production in 1996. The remainder of the crop is evenly split between Southland and Manawatu-Wanganui.

Sensitivity to Climate

Sunlight, temperature, water supply and atmospheric CO_2 concentration ([CO_2]) all influence crop production. Variations in these, whether just from natural interannual variation or a systematic change associated with increasing greenhouse gases, will cause variations in crop performance. Plant growth rates are enhanced as [CO_2] increases, provided that other factors (such as soil water or nitrogen) are not limiting. The increases are rather larger in C_3 crops like wheat than in C_4 crops such as maize.

Physiological and physical theory of responses to these stimuli at the process level has been summarised and included in simulation models of crop growth. The wheat model Sirius (Jamieson *et al.*, 1998c) has been included in the CLIMPACTS framework so that site based assessments of climate change can be made. Sirius itself has been extensively tested at a wide variety of sites (Jamieson *et al.*, 1998b,c; Jamieson and Semenov, 2000) and, in particular, has been validated in situations where the weather was warm and [CO_2] was enhanced (Jamieson *et al.*, 2000).

In this chapter we describe the sensitivity of wheat to climate change, through a brief description of how processes are described in Sirius, and report on some of the validation testing. We then use it to predict the likely consequences for wheat production in the main wheat growing areas (Southland, Canterbury and Manawatu) of a set of future scenarios of climate change.

The Model

Sirius simulates the growth, development and water use of wheat on a one-day time step. The model consists of interlinked modules that simulate phenological development (the life-cycle of the crop from sowing to harvest), development of the canopy and interception of light by it, the accumulation of biomass, and the partitioning of biomass among plant parts, particularly important in the production of grain. The following description sets out the major climate responses of wheat, and how they are implemented in Sirius.

Phenological Development

Wheat development can be divided into a number of phenophases of varying duration. The ones used in Sirius are: sowing to emergence (SE), emergence to flag leaf ligule appearance (EFL), flag ligule to anthesis (FLA), anthesis to end of grain filling (AEG), end grain filling to maturity (EGM). All phases except EFL are near constant in thermal time (base 0°C). The main source of variation among cultivars and in response to sowing date is in the phase EFL (Jamieson *et al.*, 1998a), because the number of leaves produced on the mainstem varies (Brooking *et al.*, 1995), as does the rate at which they are produced (Jamieson *et al.*, 1995). The result is that varieties sown in autumn may produce 11 or 12 mainstem leaves (and therefore take 1100-1200°C days to complete EFL), whereas the same varieties grown in spring will produce only eight leaves, so that EFL is shorter by 300-400°C days. This means that the complete life-cycle of wheat crops may vary from 1900-2400°C days according to location, sowing time and variety. Water stress may shorten the duration of the later phases, particularly grain filling, because the canopy can senesce early (Moot *et al.*, 1996).

Canopy Development

Although a wheat canopy is made up of a population of tillers each bearing leaves with finite lifetimes, calculations in Sirius are aggregated to the canopy level and characterised by green area index (GAI), the area of green tissue (one side of leaves) per unit ground area. GAI is calculated as a function of thermal time in four phases, and is closely linked to phenological development (Jamieson *et al.*, 1998c). GAI is sensitive to temperature, so that canopy development is more rapid in warmer conditions. The link to phenology will also mean that in warm conditions phases are of reduced duration, so that the total amount of light collected during a season (the seasonal light integral) will reduce in warmer conditions. Water stress can reduce the rate of increase of GAI during canopy expansion and limit the maximum GAI attained. Water stress also accelerates loss of green area through premature senescence later in the life of the crop.

Biomass Accumulation

Sirius calculates biomass accumulation as a linear function of the amount of light intercepted by the crop. The light use efficiency (LUE) is constant at 2.2 g MJ^{-1} of photosynthetically active radiation (PAR), except when reduced by severe water stress. Increased atmospheric CO_2 concentration increases the LUE, so that for a doubling of [CO_2], the LUE increases by 30%. Between current levels and doubling, the increase is assumed to be linear. The daily growth rate is then determined by the amount of light captured by the canopy, water stress, and [CO_2]. Phenological responses to daylength and temperature determine the duration of growth and the exposure of the crop to the climate during its lifecycle.

Partitioning to Grain

The potential duration of grain growth is constant in thermal time, so any increase in temperature will decrease the duration. Any factor that decreases grain growth duration will tend to decrease yield. In Sirius, grain grows assuming that all new biomass from the beginning of grain filling is partitioned to the grain, plus a proportion of the biomass that existed at anthesis. This latter portion is transferred at a constant rate in thermal time so that it is all transferred by the potential end of grain filling. Hence, if grain filling is curtailed early because of water stress, then not all the extra biomass is transferred.

Drought Effects

Drought indices are calculated from the ratio of water availability to water demand (Jamieson, 1999). The most important effect of drought is to reduce canopy expansion during the early growth phase, and to accelerate canopy senescence. An important consequence can be the reduction of the grain growth duration (Moot *et al.*, 1996). A secondary effect, applied only when drought is severe, is to reduce the LUE (Jamieson *et al.*, 1998b).

Validation of the Model

To have confidence that Sirius can simulate the impacts of climate change adequately in the CLIMPACTS environment, it is necessary to confirm that it can provide accurate simulations of water stress and variation in [CO_2] in a variety of environments. The environments tested in detail are Canterbury, New Zealand (variation in water supply), Rothamsted, UK (cooler than New Zealand, variation in nitrogen and water supply), and irrigated production in the Arizona desert environment (substantially warmer than New Zealand, variation in nitrogen and [CO_2]). In this last environment [CO_2] around the crop was increased by 200 ppm over ambient using free air CO_2 enhancement (FACE). The tests were reported in Jamieson *et al.* (1998b), Jamieson and Semenov (2000) and Jamieson *et al.* (2000). Generally, Sirius accurately simulated the effects of experimental treatments on the time courses of GAI, above ground and grain biomass accumulation, final biomass and yield. Comparisons of simulated with observed final biomass are given in Figure 5.1, and for grain in Figure 5.2.

The results of the validation studies made where experimental conditions were well known and the crops were monitored in detail show that Sirius is a reliable estimator of the likely performance of wheat crops in very variable environments. Importantly, it performed well in conditions warmer than New Zealand at present and with elevated [CO_2]. Hence we can have some confidence in its ability to simulate climate change impacts from future scenarios.

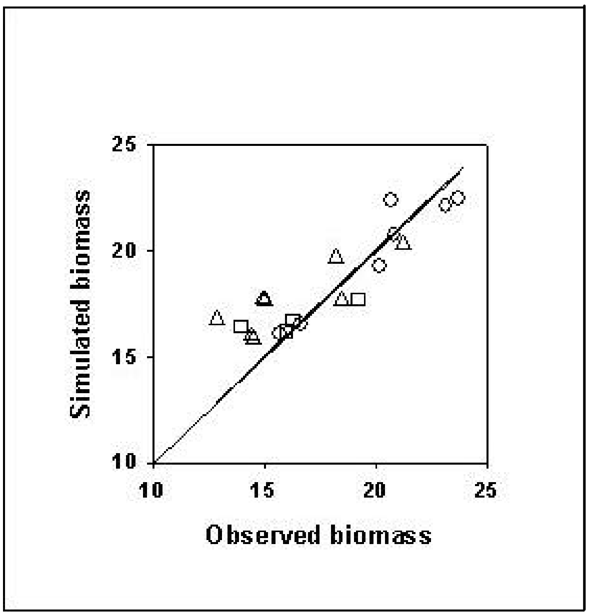

Figure 5.1: Observed and simulated biomass (t ha^{-1}) from experiments in New Zealand, the UK and Arizona.

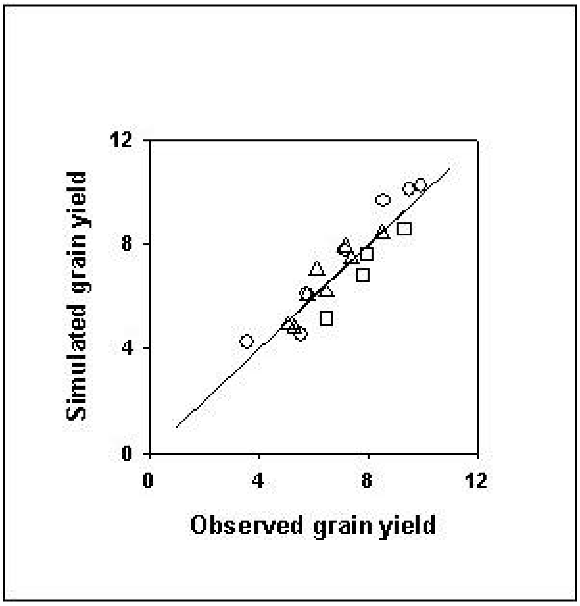

Figure 5.2: Observed and simulated grain yield (t ha^{-1}) from experiments in New Zealand, the UK and Arizona.

CLIMPACTS Simulations

The wheat chosen for the CLIMPACTS simulations has characteristics typical of common varieties grown in New Zealand. Two sowing times were chosen – a typical autumn sowing time (1 May) and a typical late spring sowing time (1 August). Simulations were done for three soil types:

1. Deep soil, available water holding capacity (AWC) 225 mm – where in many years there would be sufficient water for near potential yields to be achieved;
2. Medium soil, AWC 98 mm – typical of many cropping soils;
3. Shallow soil, AWC 75 mm – typical of stony Canterbury soils.

The simulations were run for sites in Southland (Gore weather), Canterbury (Lincoln weather) and Manawatu (Ohakea weather). In the first part of this analysis we examine the response of Sirius to changes in climate given by the SRES marker scenarios A2, A1 and B1 with the HadCM2 GCM pattern. The response of Sirius to a change in the GCM pattern is then examined, where the HadCM2 GCM pattern is changed to the CSIRO9 GCM pattern, coupled with the SRES A1 marker scenario. These examinations were conducted by applying the climate changes to the site specific historical data to predict the climate for the years 1990, 2000, 2025, 2050, 2075 and 2100.

Changes in Maturity and Yield

In all scenarios, maturity dates were predicted to become earlier over time, with some scenarios changing this somewhat more than others (Figure 5.3 a,b,c). There are a number of competing consequences of increased earliness, and these are further modified by CO_2 fertilisation. In medium to shallow soils particularly, yield can be improved through earliness by avoiding some drought. Warm conditions decrease the duration of grain filling, and this tends to decrease yields. The balance of the effects of drought avoidance, decreased grain growth duration and CO_2 fertilisation is that in all scenarios wheat yields tend to increase, and the dominant effect is CO_2 fertilisation – the highest CO_2 scenario gave the highest predicted yields (Figure 5.3 d,e,f).

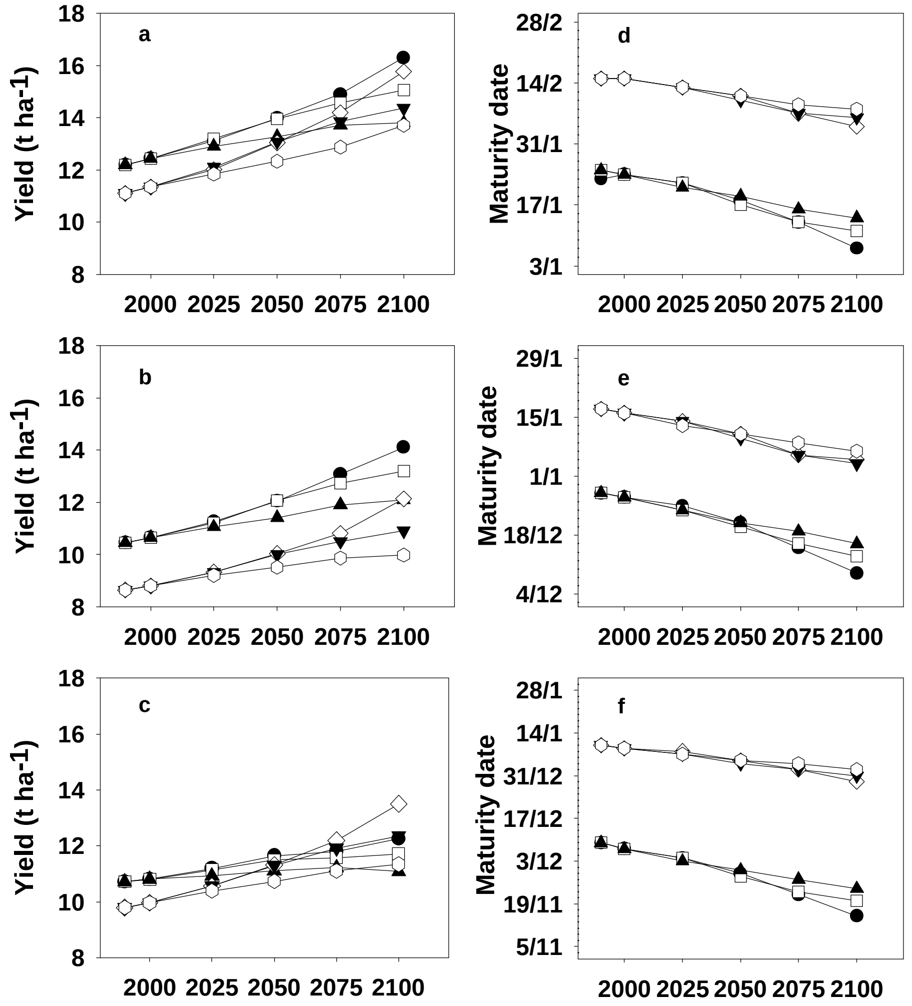

Figure 5.3: Yield and maturity date outputs of simulations for the deep soil type at Gore (a,d), Lincoln (b,e) and Ohakea (c,f). Winter sown, A2 marker scenario ●; A1 marker scenario ☐; B1 marker scenario **p** ; Spring sown, A2 marker scenario ¯ ; A1 marker scenario **q** ; B1 marker scenario ⬡;)

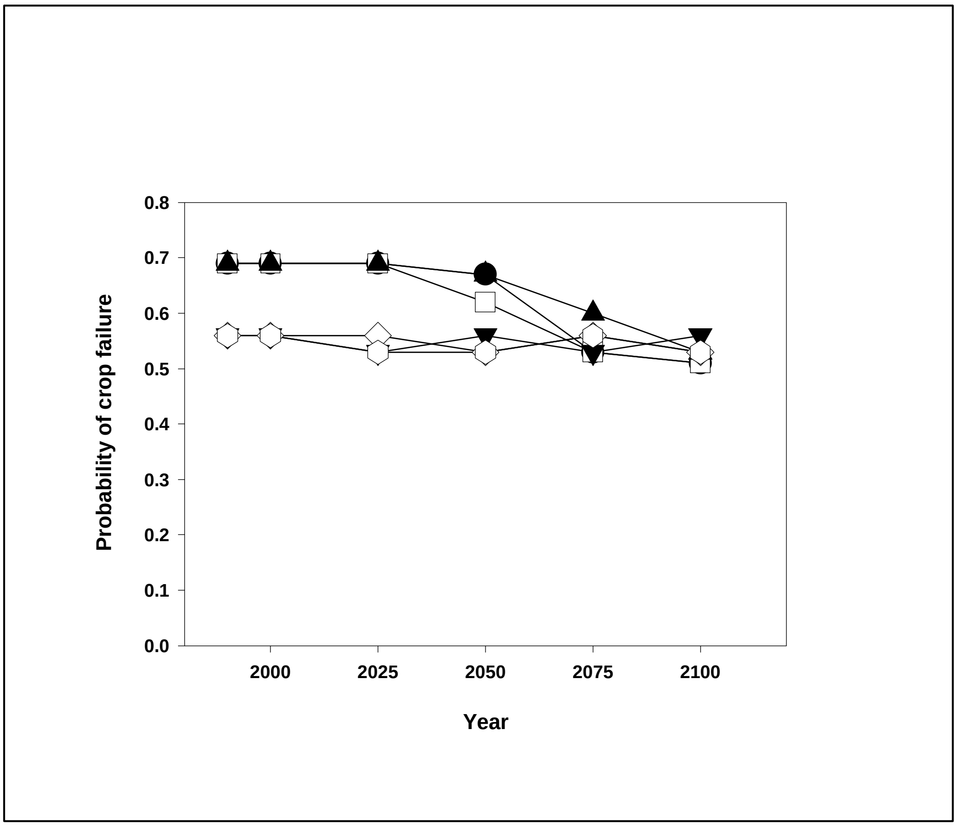

Figure 5.4: Crop failure Probabilities for simulations run on the shallow soil type at Lincoln. Symbols as for Figure 5.3.

Changes in Probability of Crop Failure

Crop failure was defined for the purposes of the exercise as occurring if the predicted yield fell below one t ha^{-1}. It was considered solely for dryland conditions. In the context of this study, it is an index of the need for irrigation, rather than a prediction of widespread crop failure. With these constraints, the simulations showed that when there is a risk of crop failure, this decreases over time when the climate changes according to the scenarios examined, because earlier maturing crops succeed in avoiding drought to some degree. Furthermore, the simulations show that for all scenarios, all soil types and both sowing times, that risk of crop failure in Southland crops was zero. For Lincoln the same simulations showed that there would be a significant likelihood of crop failure for both the shallow and medium soil types of both sowing dates (Figure 5.4), along with a wide range of maturity dates. Spring sown wheat in the Manawatu in the shallow and medium soil types showed significant likelihood of crop failure, while for the winter wheat there would be only a low probability of crop failure if it is sown in a shallow soil type. The high levels of crop failure observed in the simulations indicate for the considered scenarios that, in the lighter soil regions of Canterbury and the Manawatu, irrigation will continue to be a vital part of winter/spring wheat cropping, but is unlikely to be important in Southland.

When the differences between the GCM patterns HadCM2 and CSIRO9 with the SRES marker scenario A1 were evaluated, the differences in crop outputs were minimal. The yield differed at most by 0.3 t/ha while the maturity dates were different by only a day or two. It is apparent from this that, although there are responses of wheat to the climate change scenarios tested, there was only minor sensitivity to choice of scenario.

Conclusions

For wheat production, most of the implications of climate change are positive. CO_2 fertilisation is large enough to overcome reductions in crop duration caused by warming, and the increasing earliness of crops caused by climate warming to some extent reduces their exposure to drought risk by avoiding the driest time of the year. Irrigation will remain a substantial need in New Zealand's breadbasket of Canterbury. The realisation of increased yield potential with CO_2 fertilisation will doubtless increase the need for nitrogen fertiliser (Jamieson *et al.*, 2000). Future development of the wheat and maize models within CLIMPACTS, and the addition of models describing other crops, mean that in future the system will be able to be used to assess the impacts of climate change and seasonal variations on demand for water and nitrogen fertiliser, and on the productive capacity of a wider range of crops.

References

Brooking, I.R., Jamieson, P.D., and Porter, J.R. (1995). The influence of daylength on the final leaf number in spring wheat. *Field Crops Res.* 41, 155-165.

Jamieson, P.D. (1999). Drought effects on transpiration, growth and yield in crops. *J. Crop Production.* 2, 71-83.

Jamieson, P.D., Brooking, I.R., Porter, J.R. and Wilson, D.R. (1995). Prediction of leaf appearance in wheat: a question of temperature. *Field Crops Res.* 41, 35-44.

Jamieson, P.D., Brooking, I.R., Semenov, M.A., and Porter, J.R. (1998a). Making sense of wheat development: a critique of methodology. *Field Crops Res.* 55, 117-127.

Jamieson, P.D., Porter, J.R., Goudriaan, J., Ritchie, J.T., van Keulen, H., and Stol W. (1998b). A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. *Field Crops Res.* 55, 23-44.

Jamieson, P.D., Semenov, M.A., Brooking, I.R., and Francis, G.S. (1998c). *Sirius*: a mechanistic model of wheat response to environmental variation. *Eur. J. Agron.* 8, 161-179.

Jamieson, P.D. Munro, R.L., and Butler, R.C. (1999). Strobilurins increase production in high yielding wheat crops. *Proc. NZ Agron Soc.* 29, 97-100.

Jamieson, P.D., Berntsen, J, Ewert, F., Kimball, B.A., Olesen, J.E., Pinter, P.J., Jr, Porter, J.R., and Semenov, M.A. (2000). Modelling CO_2 effects on wheat with varying nitrogen supplies. *Agric. Ecosys. Environ.* 82, 27-37.

Jamieson, P.D., and Semenov, M.A. (2000). Modelling nitrogen uptake and redistribution in wheat. *Field Crops Res.* 68, 21-29.

Logan, L.A. (1983). *Crop production and utilisation in New Zealand.* Report No. 81, Crop Research Division, DSIR. 210 pp.

Moot, D.J., Jamieson, P.D., Henderson, A.L. Ford, M.A., and Porter, J.R. (1996). Rate of change of harvest index during grain filling in wheat. *J. Agric. Sci., Camb.* 126, 387-395.

Petrie, P.R., and Bezar, H.J. (1997). *Crop profiles 1997.* CropInfo Report No. 16, New Zealand Institute for Crop and Food Research. 161pp.

Chapter 6:

The Sensitivity of New Zealand's Managed Pastures to Climate Change

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Introduction

Pastoral agriculture is the major activity on more than 50% of New Zealand's land. Dairy, meat and wool exports make up close to 40% of New Zealand's export of goods. Therefore a knowledge of the likely impact of climate change on New Zealand's pastures is of more than academic interest. Two features that distinguish grasslands from other agricultural crops are the range of species present (nitrogen fixing legumes, C_3 grasses, C_4 grasses) and the wide range of conditions under which pasture species can be grown and utilised. When considering the effect of climate change this leads to two linked questions: how will climate change affect the productivity of pastures in different regions of the country and will it change the species composition of these pastures?

The determinants of productivity and botanical composition in New Zealand pastures that are likely to be affected by climate change are temperature, rainfall and CO_2 concentration.

Temperature influences a range of plant processes (e.g. net photosynthesis, leaf appearance, leaf extension and tiller production) with the optimum temperature for these individual processes differing within and between species. In pasture communities that contain a range of species, a single optimum temperature for growth is impossible to quantify, but for New Zealand pastures it is likely to be in the 16-20°C range for the dominant C_3 species, a temperature band that is common to most of lowland New Zealand only in the summer months. Therefore a general increase in temperatures within the range predicted by GCM models (1 – 3°C over the next century, IPCC, 1996) would be expected to result in an increase in annual pasture yields with the biggest effect occurring outside the summer months. Modelling studies conducted in a previous study on the effects of climate change on pasture and animal productivity in New Zealand (MAF Technology, 1990) reported annual increases of 20-50% in pasture productivity assuming a 3°C increase in temperature, all of this increase being attributable to growth outside the summer period. Temperature also influences the botanical composition of pastures. In parts of the North Island (north and north east) temperatures are such that C_4 species, which have a higher temperature optimum for certain processes (e.g. photosynthesis and leaf extension), are highly competitive with C_3 species and can become major components of pastures (Field and Ford, 1990). Although productive in the summer months these grasses are often low yielding in the cooler months and are generally regarded as having poorer animal performance characteristics (Minson, 1990). Higher temperatures resulting from climate change should favour C_4 species at the expense of C_3 species and may result in an increase in the area in which C_4 species are commonly found in pastures. A key area of uncertainty, affecting both the yield and botanical composition of pastures, is how they will respond to any changes in the variability of temperatures, e.g. frequency of frosts and hot days.

Inadequate water supply places a major limitation on pasture production. For example in long term trials at Winchmore, a site where warm summer temperatures are accompanied by a low summer rainfall, irrigation was found to almost double annual pastures yields (Coop, 1986).

Moisture shortages tend to be seasonally based in general in New Zealand, occurring between late-spring and mid-autumn. Therefore changes in the seasonal pattern of rainfall, as well as changes in the total rainfall received, have to be considered when assessing the effect of climate change. Botanical composition is also influenced by moisture supply. Legumes are generally less tolerant of water shortages than grasses and C_4 species are more water use efficient than C_3 species (Thomas and Norris, 1981; Morrison and Gifford, 1983). Variability of rainfall between years is also high and any changes in this variability could have profound impacts. For example, changes in the frequency of El Niño patterns and the consequent higher probability of drought conditions in the east of the country, are likely to have a greater impact on pastures in these areas than small changes in the annual mean rainfall. Plant water supply also cannot be considered in isolation from water demand. If temperatures rise, the crop demand for water will change due to the influence of temperature on evapo-transpiration. Increases in atmospheric CO_2 levels may also interact with moisture supply as it enhances the water use efficiency per unit of leaf in pasture plants (Kirkham *et al.*, 1991). However, the implications of this for water use per unit area are problematic because of the greater leaf area developed under elevated CO_2 concentrations. In the 1990 climate assessment (MAF Technology, 1990) changes in rainfall had little effect on pasture production when assessed using a regression based model of pasture productivity. This was principally because the predicted changes were small and evenly distributed through the year. The model used was also unable to take account of interactions between rainfall, temperature and CO_2. In common with temperature effects, the key area of uncertainty is the impact of changes in rainfall variability rather than mean annual rainfall. Severe droughts are of particular concern as they can result in plant mortality and so have yield and botanical composition implications which extend beyond the period of drought itself.

The concentration of carbon dioxide in the atmosphere has a strong positive influence on photosynthesis in C_3 plant communities but a smaller influence on harvested yield (Newton, 1991). On balance, legumes are stimulated more than grasses (Newton, 1991), which should therefore be positive for New Zealand's legume-based pastures, but the lack of predictive models that take environmental variables and species balance into account limit our ability to quantify this. Atmospheric CO_2 concentration has less of a direct effect on photosynthesis and yield in C_4 species but it does influence water use efficiency and may therefore influence the competitive interactions between C_3 and C_4 species (Owensby *et al.*, 1993). In the 1990 assessment (MAF Technology, 1990) a rise in CO_2 concentration from 330 to 600 ppm, without any concurrent change in climate, increased pasture production by 40%. This rose to between 60 and 70% when climate change scenarios were coupled with CO_2 increases. Since that time our knowledge of plant responses to CO_2 has improved and these estimates, which were based primarily on the response of photosynthesis to atmospheric CO_2, may be too high.

The rest of this chapter is devoted to assessing the sensitivity of New Zealand pastures to a range of climate change scenarios. In this assessment two complementary approaches were taken. One approach was to look at how changes in the climate might affect the geographic distribution of C_4 grass species in pastures and the other was to look at how potential pasture productivity in different areas of the country could change.

Sensitivity of Invasive Subtropical Grasses to Climate Change

Neil D. Mitchell and Bruce D. Campbell

This study investigates the potential for two sub-tropical grasses, Paspalum (*Paspalum dilatatum*) and kikuyu (*Pennisetum clandestinium*) to become invasive throughout the country. Paspalum is already quite widespread, and a more detailed regional investigation is presented.

Why Paspalum and Kikuyu?

These two species are representative sub-tropical grasses that can cause pasture management problems within the pastoral sector. Campbell *et al.* (1999) showed that with respect to response to climate, both species are representative of the response of other C_4 grasses present in New Zealand. Paspalum is more widespread in the North Island than kikuyu. Kikuyu is potentially more of a management problem than paspalum due to its more invasive growth habit and poorer forage quality.

Present Day Distribution

At present, both species have a predominantly northern distribution, with kikuyu being strongly confined to the northern North Island. Paspalum is primarily found in Northland and Auckland, but extends in coastal regions down the west coast of the North Island and into the northern South Island.

Potential for Future Spread Southwards

Both species are found in a variety of situations and appear to spread quite easily. This study concentrates on them as they occur in managed pastures; however, they widely occur elsewhere (e.g. roadsides and sand dunes) and given suitable conditions could readily spread into managed pastures.

Methods

Data Source

The species data used to develop the models are as described in Campbell *et al.* (1999). The data consisted of presence/absence records from 583 pasture sample sites distributed throughout New Zealand. The use of climate data was as described in Campbell *et al.* (1999) based on the approach of Mitchell (1991).

Analytical Methods

To derive a model to describe the relationship between the distribution of paspalum and kikuyu to selected climate parameters, logistic regression techniques applied as a general additive modelling approach were used (Yee and Mitchell, 1991). This technique was preferred over general linear modelling, as it appears to provide solutions that are more robust.

The basic approach was to first regress individual climate variables with the

Equations developed to explain the relationship between the species and climate parameters

kikuyu $p=1-(1/(1+\exp^{(-32.0341\ -\ (\ -2.2144\ \text{mean min monthly temp}\ -1.0488\ \text{mean monthly range temp}))}))$

paspalum $p=1/(1+\exp^{(-14.3\ -\ (\ -1.09\ \text{mean annual daily solar radiation}\ +2.87\ \text{mean minimum monthly solar radiation}\ -1.08\ \text{mean minimum monthly temperature}\ +1.96\ \text{mean temperature of the coldest quarter}))})$

p = probability that the climate at a location is suitable species data. Those climate variables that explained the greatest amount of deviance were then regressed in all combinations to derive the optimal solution. The equation derived from this analysis was then used within the CLIMPACTS system.

These models were then applied to the base climate data to generate databases of the probability that the climate in a given grid cell was suitable for paspalum and kikuyu. The results can be displayed as a mapped set of probability values (and re-displayed with different climate scenarios) and/or extracted for further analysis.

Scenario Analysis

All these analyses were based on the HadCM2 transient 1% compounding CO_2 climate change pattern and then tested against the following global temperature change scenarios: SRES marker scenarios A1, A2, B1. In this analysis, for each scenario, we assessed the potential distribution pattern every ten years from 1990 to 2100. The data was then extracted and a set of sub-regions chosen for more detailed analysis. To simplify interpretation, the probability data was divided into four categories: (1) 0.0 – 0.25; (2) 0.26 – 0.50; (3) 0.51 – 0.75; (4) 0.76 – 1.0. Grid cells re-coded to 1 have a low probability of containing locations suitable for paspalum or kikuyu, a code of 4, indicating a high probability. The extraction of data, the regional sub-setting, re-coding and some analysis was carried out using IDRISI.

Results for kikuyu are only discussed for the North Island; paspalum is used to illustrate the regional effects as well as national.

Results

North Island

For the more extreme scenario, the model predicts a general increase in the probability of finding both paspalum and kikuyu over time. For example, there is an increased probability of finding kikuyu, with the area of land which has a probability >0.5 of being suitable for kikuyu increasing from ca. 2,800 to 41,300 km^2.

In managed pastures the model for scenario A2 predicts that as at 1990, ca 27,000 km^2 of the North Island have a probability (>0.5) of being suitable for paspalum, which would increase to ca. 74,000 km^2.

Scenario B1 shows the least change for both species, with an intermediate increase for A1. However, at the most intense scenario, the proportional change is greatest for kikuyu, which increases ca eight-fold as compared to ca two-fold for paspalum.

South Island

The model predicts that the current, limited distribution of paspalum will change little, except under scenario A2. At present, almost no kikuyu is present. Under scenario A2 some increase of paspalum is observed up to ca. 9,000 km^2.

Regional Distributions

A more detailed analysis is presented of the changing distribution pattern of paspalum in sub-regions of the North Island (kikuyu shows a similar, but less pronounced, pattern of change). The five regions chosen were: Northland, Waikato, Bay of Plenty, Taranaki and Manawatu. These regions were chosen partly for their economic significance, but also to illustrate a range of current distribution patterns and how these may change. Paspalum is currently common in Northland, whereas it is quite rare in Manawatu. The other three regions all have important pasture based industries that could be affected by spread of these sub-tropical grasses.

In each of the following regional analyses the results are presented for each scenario.

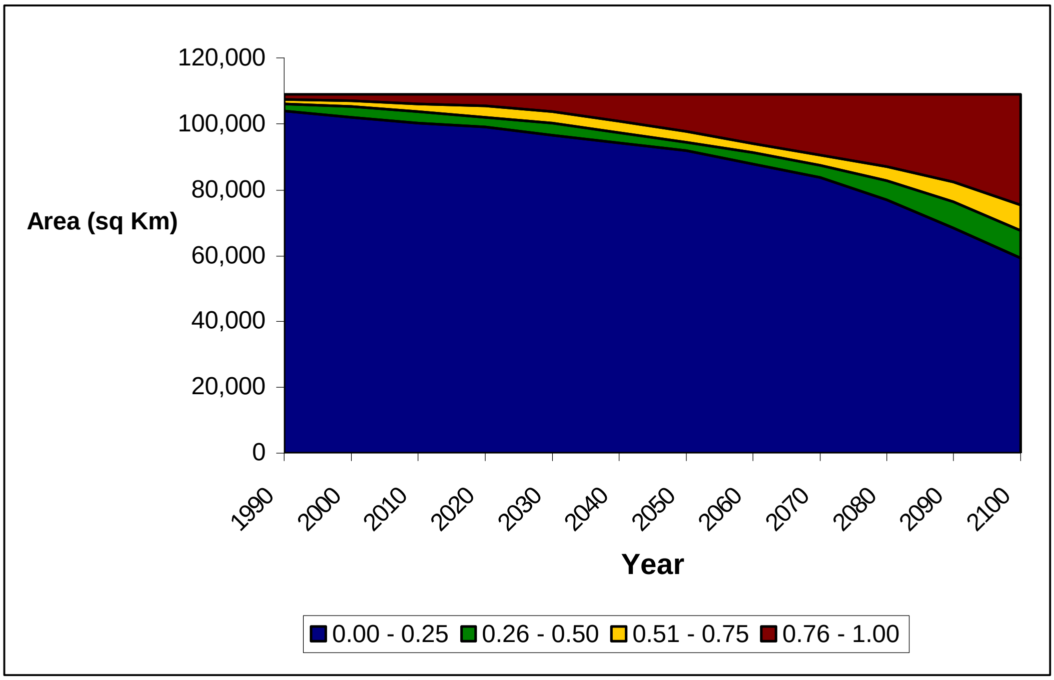

Figure 6.1: Probability of the occurrence of Kikuyu in the North Island, assuming a high case scenario (HadCM2 GCM, SRES A2 high scenario).

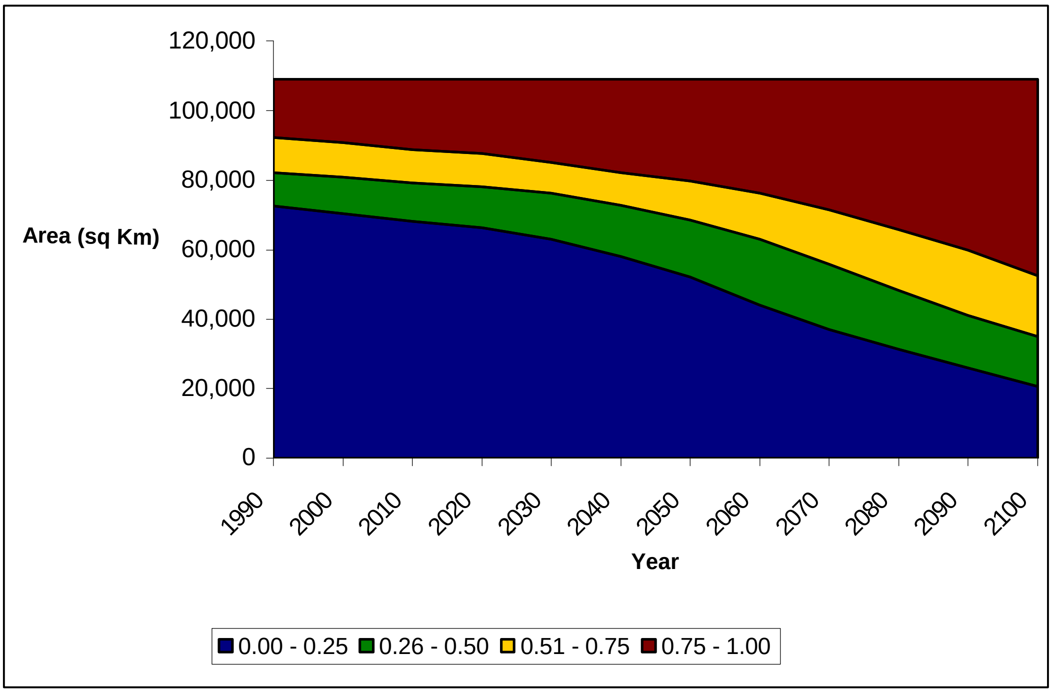

Figure 6.2: Probability of the occurrence of Paspalum in the North Island, assuming a high case scenario (HadCM2 GCM, SRES A2 high scenario).

Northland

In Northland, the generally suitable conditions for paspalum will continue to improve. It is already common, but an increased prevalence could have additional impacts on pastoral farming in areas where there is still a strong reliance on C_3 grasses.

Waikato

In the Waikato, the results for all scenarios suggest that large areas will become suitable for paspalum. In the case of scenario B1, the increase will be gradual, but in the case of both A1 and A2, there appears to be a rapid change in conditions between 2020 and 2040. By 2040 these results suggest that paspalum could become widespread in the region.

Bay of Plenty

Conditions in the region are not at present particularly suitable for paspalum. The results suggest that there will only be a slow change to more suitable conditions, although in the case of A2, this change will accelerate after 2050.

Taranaki

Paspalum is quite uncommon in the region at present and seems likely to stay so, if warming is not very intense (B1). However, if warming follows the A2 scenario, then between 2060 and 2080, there would be a very rapid spread to become a problem in large areas of the region.

Manawatu

Except under the warmest scenario, paspalum will stay an uncommon species of managed pastures in the region. However, in the warmest scenario, the species could start to become more common by the end of the 21st century.

Summary

In the northern regions, paspalum can be expected to steadily spread southwards as climate warms. The extent and rate of this spread will depend upon the intensity of the warming. Under scenarios A1 and B1, the spread is relatively gradual; however, under scenario A2, after a period of relatively steady increase, there could then be a period of 'explosive' spread through a region. The timing of this 'explosive' spread would vary with the regions. This has potentially serious implications for the pastoral sector in some of the regions. The rapid spread of paspalum could make some activities less economic. Under all scenarios kikuyu becomes more widespread in the northern regions but in general seems likely to still remain a local rather than a national problem.

The Sensitivity of Pasture Yields to Climate Change

Harry Clark and Paul Newton

Pasture yields in CLIMPACTS were estimated using a model based on the mechanistic physiological model of pasture growth developed at Hurley by Johnson and Thornley (1983, 1985). It was developed originally to explore the relationship between temperature, radiation and growth in vegetative swards amply supplied with moisture and nutrients. Modifications to the model mean that it now also takes into account the influence of: (1) atmospheric CO_2 concentration on photosynthesis and assimilate partitioning; (2) reproductive development on sward processes; and (3) variable moisture supply.

Site Locations

Data requirements of the model (daily temperature, solar radiation and rainfall records) mean that a pre-requisite for any site was that it must have a reliable long term weather record that included either direct measurements of solar radiation or measurements of sunshine hours. This placed severe restrictions on the potential number of sites and only 13 sites met these requirements. The final choice of sites was therefore a compromise between obtaining a good geographical and climatic spread. The sites chosen were Gisborne, Gore, Kerikeri, New Plymouth and Winchmore. Summary climatic data for these locations are presented in Annex 5.

Scenarios

At each site assessments were made of the following:

- Pasture yields using historical daily climate data perturbed according to the Hadley GCM and three different GHG emission scenarios (low, mid-range, high);
- Pasture yields using historical daily climate data perturbed according to two different GCMs (Hadley and CSIRO9) and the mid-range GHG emission scenario.

For each site the number of years for which historical data were available determined the number of years used in the calculation of average annual and seasonal yields. This was 23 years at Gisborne, Kerikeri and New Plymouth, 40 years at Gore and 44 years at Winchmore. Soil and fertility conditions were assumed to be the same at each location.

Results

Hadley GCM, Three Emission Scenarios

Mean of Five Sites

Under the mid-range and high emission scenarios yields increase by an average of between 4 and 5% per decade up to 2030, reducing to 3% per decade by 2050 (Figure 6.3). Yields obtained using the low emission scenario follow a similar pattern but the increases are considerably smaller with a peak value of just over 3% in the early decades falling to 2% by 2050. This implies that yields rise from 12000 kg ha^{-1} now to approximately 15000 kg ha^{-1} in 2050 for the high and mid-range scenarios

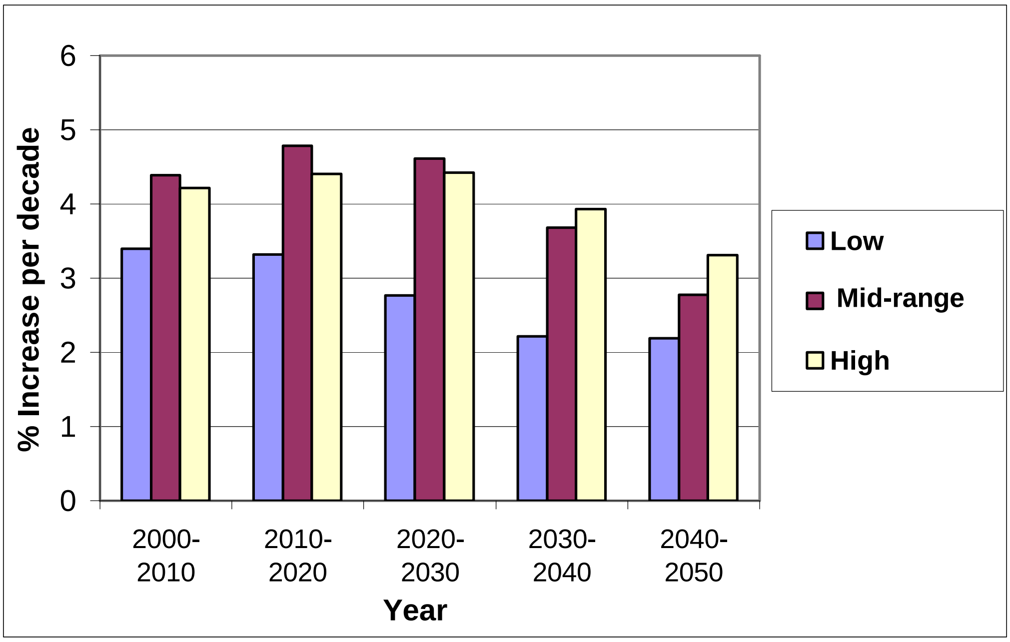

Figure 6.3: Percent increase in yield per decade obtained using the HadCM2 GCM and three emission scenarios (mean of five sites).

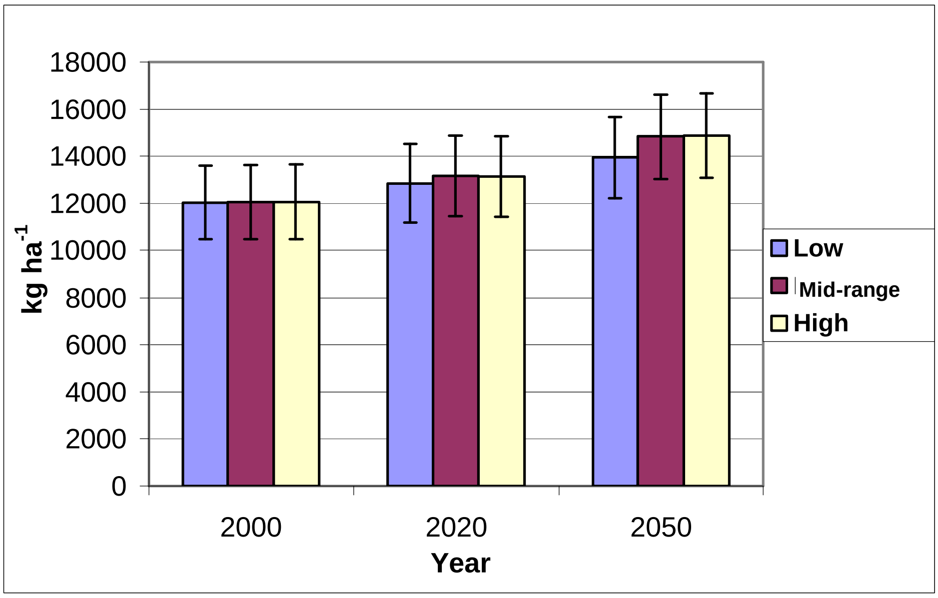

Figure 6.4: Annual dry matter yields obtained using the HadCM2 GCM and three different emissions scenarios (mean of five sites).

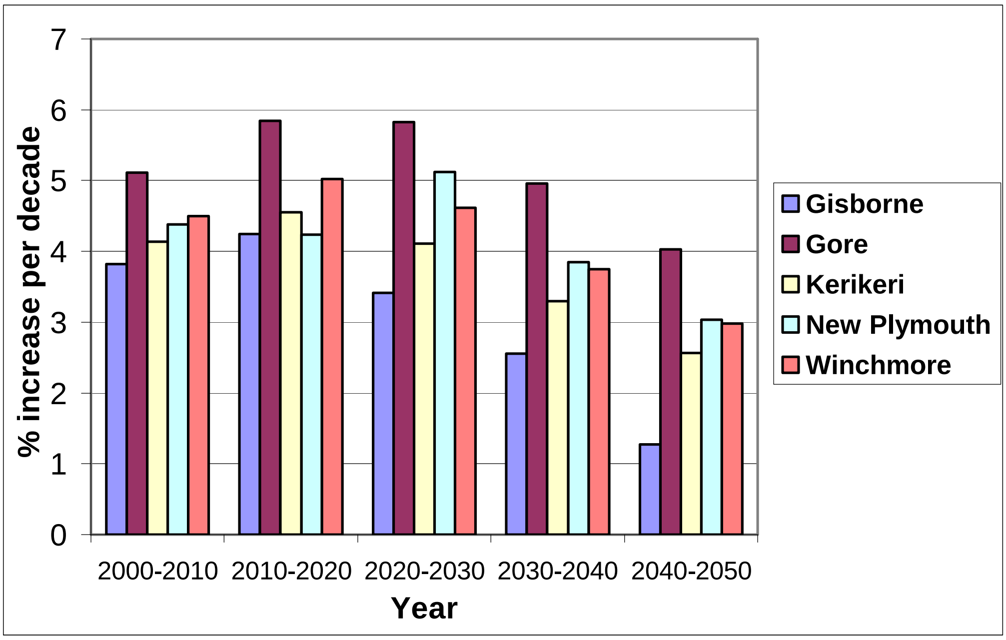

Figure 6.5: Percent increase in yield per decade at five sites obtained using the HadCM2 GCM and the mid-range emission scenario.

and to 14000 kg ha^{-1} for the low emission scenario (Figure 6.4). The size of the standard deviation for these annual yield totals (vertical lines in Figure 6.4) demonstrates that climate change induced yield increases of the magnitude shown here are small in comparison to the normal year to year variation in pasture yields.

Differences Between Sites

For all sites and emission scenarios the highest decadal rates of increase are in the early part of the century (data for the mid-range scenario only presented in Figure 6.5). The two principle features of this data are the relatively high rates of increase in yield at the Gore site and the low rate of increase at the Gisborne site. Under the present climate, yields at the chosen sites range from approximately 9000 kg ha^{-1} in Winchmore to 14500 kg ha^{-1} in New Plymouth and Kerikeri, a yield range of about 5500 kg ha^{-1} (Figure 6.6). Under the mid-range scenario this yield range increases slightly to approximately 6000 kg ha^{-1} by 2050.

Seasonal Distribution of Yield

The percentage increase in yield each season did show some differences (Figure 6.7) but the overall effect on the seasonal distribution of yield was small (Figure 6.8). Differences between sites and emission scenarios were also small (data not shown).

Different GCMs, Mid-Range Emission Scenario

Averaged over the five sites yields obtained using the different GCMs were very similar (Figure 6.9). Differences between sites were restricted to annual yields by 2050 being about one tonne ha^{-1} higher when using the Hadley GCM at New Plymouth but being lower by a similar amount at the Gisborne site (data not shown).

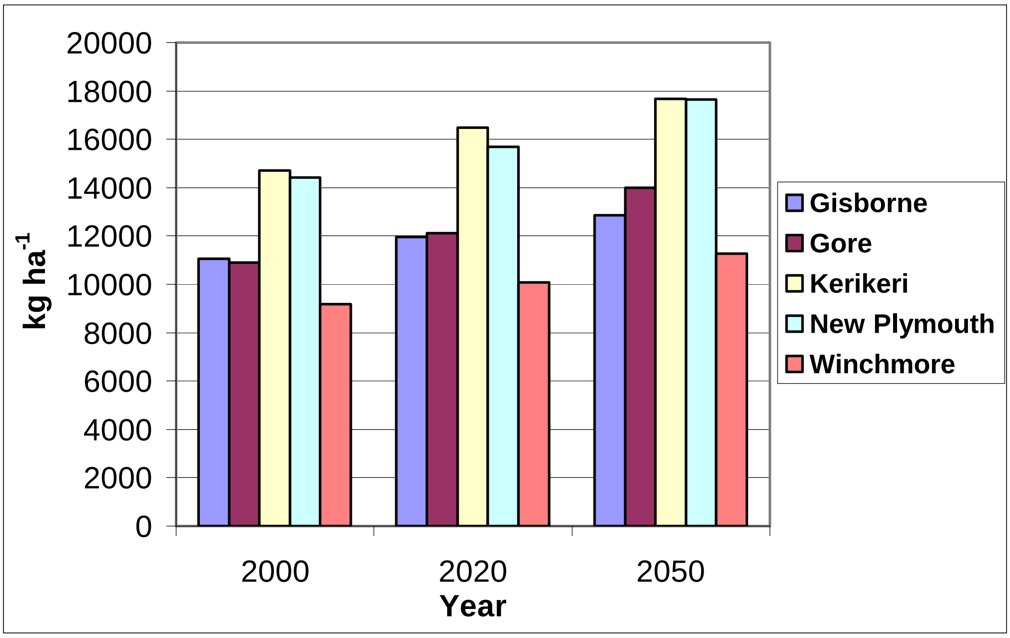

Figure 6.6: Mean annual yield at five sites obtained using the HadCM2 GCM and the mid-range emission scenario.

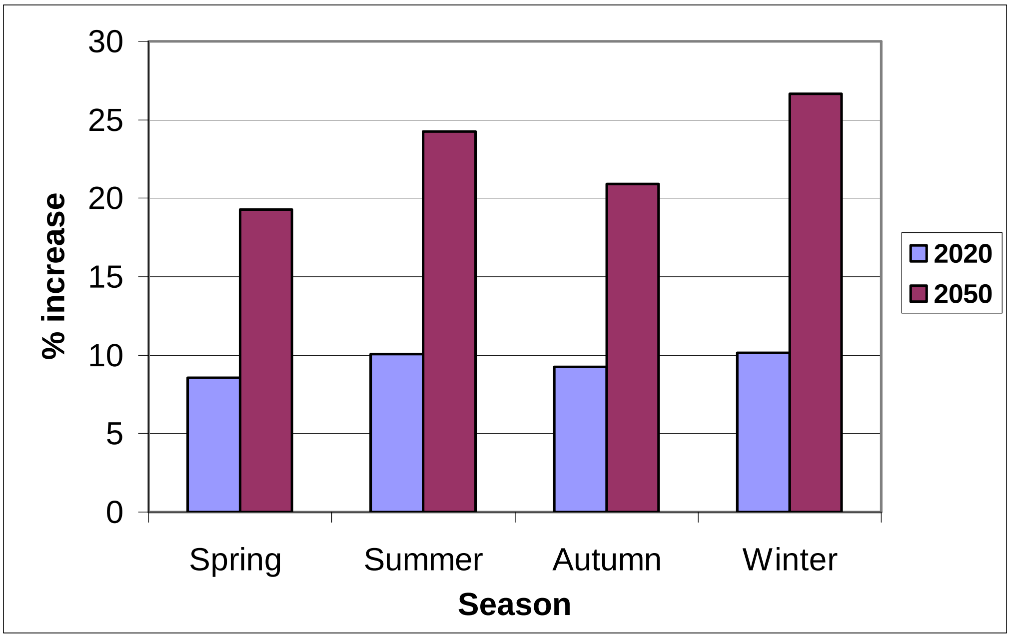

Figure 6.7: Percent increase in yield in each season obtained using the mid-range emission scenario (mean of five sites).

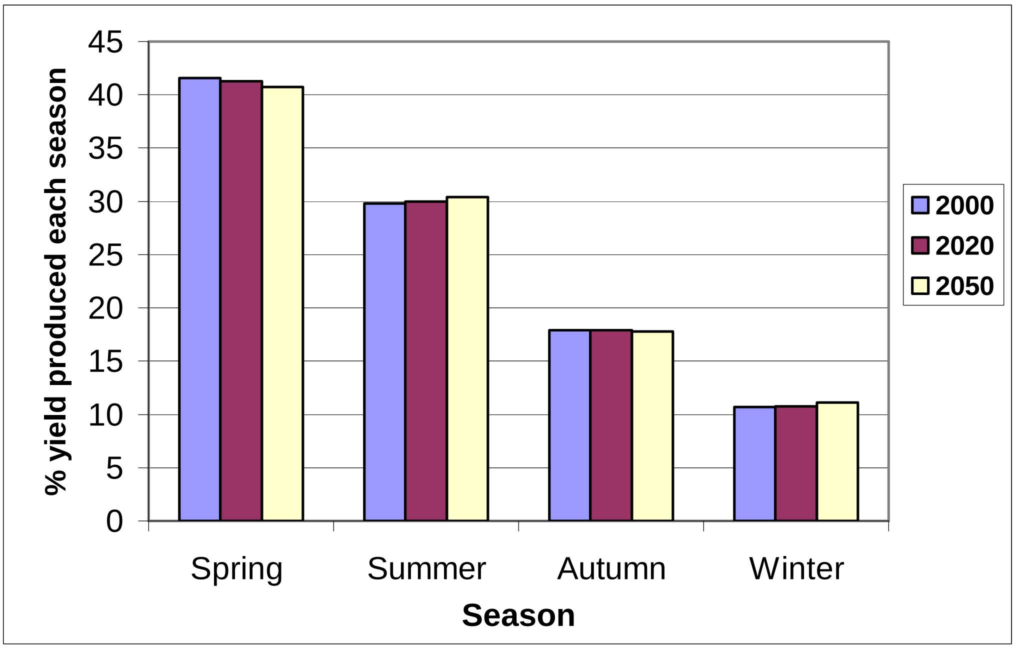

Figure 6.8: Percent of annual yield produced each season obtained using the HadCM2 GCM and the mid-range emission scenario (mean of five sites).

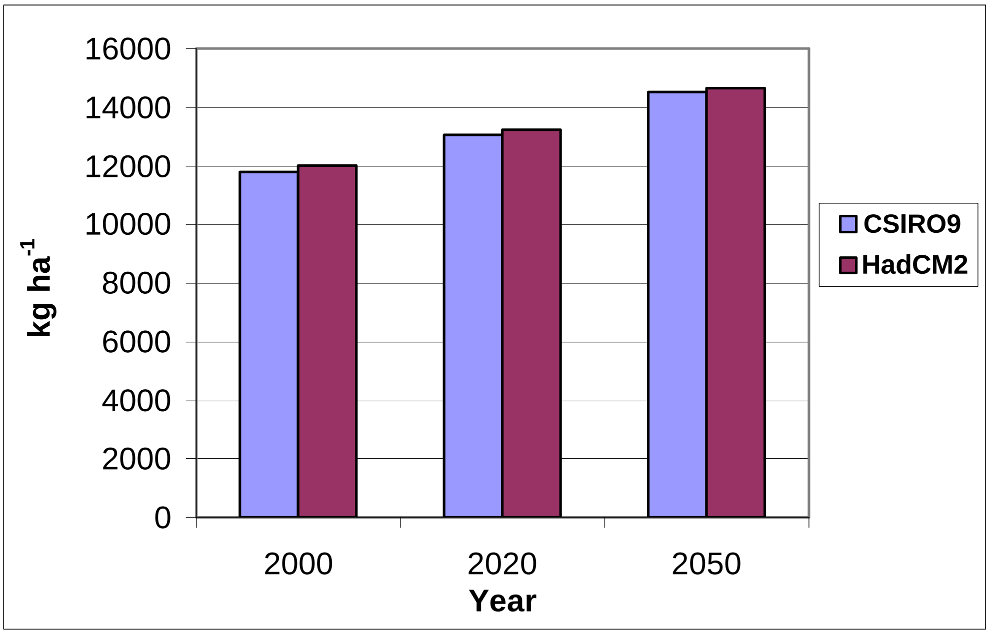

Figure 6.9: Average annual yields obtained using the HadCM2 and CSIRO9 GCMs and the mid-range emission scenario (mean of five sites)

Summary

- Yields increase whatever the GHG emission scenario, very little difference between the mid-range and high emission scenario.
- Highest rates of increase occur in the early part of this century.
- Some shifts in relative productivity between different geographical locations.
- Little change in the seasonal distribution of yield.
- No sharply defined thresholds of change.
- Projections are independent of the GCM used.
- Rate of increase manageable compared to the annual variability in yields.

Uncertainties in Model Outcomes

All models are simplifications of reality and both of the approaches outlined here include only some of the factors that will influence pasture responses to climate change. The results are best seen as giving an indication of the potential influence that climate change could have on pasture yield and C_4 grass distribution. Some important areas of uncertainty in this assessment are outlined below.

- The principle purpose of pasture grasses is to feed ruminants and some sward processes that influence animal productivity (e.g. changes in grass/legume balance and chemical composition) have not been quantified.
- Nutrient levels remain fixed in runs of the pasture model and are not considered when examining C_4 grass distribution. This is unrealistic as climate change is likely to affect soil processes and this has the potential to influence both plant growth and competition between pasture plants.

- Pests and diseases are not likely to remain unaltered by climate change and any effects these changes may have are outside the scope of either of the models.

- Sensitivity of pasture productivity and botanical composition to changes in the variability of the climate have not been tested.

Future Directions

The CLIMPACTS framework of linked models and data sets developed over the last five years opens up new possibilities for examining the impacts of climate change in a comprehensive and integrated manner at both regional and national scales. Future areas of work in relation to managed pastoral ecosystems include the following.

- Greater emphasis on the sensitivity to climate variability rather than mean, especially the influence of the frequency and severity of SOI. The continuing development of stochastic weather generators is crucial to this process.

- Integration of plant and soil models so that feedbacks between soil and plant processes become a fundamental component of the assessment process.

- Development of methodologies that will enable output from the pasture yield model to be aggregated at the regional and national scale.

- Development of models capable of determining the spread and distribution of species at a range of scales. This involves combining the climate envelope approach used for the C4 grass distribution assessment with the mechanistic approach of the grass yield model. These models will need to include both vegetative and reproductive processes, seed production and dispersal mechanisms and take into account relevant topographical and climatic data.

References

Campbell, B.D., Mitchell, N.D., and Field, T.R.O. (1999). Climate profiles of temperate C_3 and subtropical C_4 species in New Zealand pastures. *New Zealand Journal of Agricultural Research.* 42, 223-233.

Coop, I.E. (1986). Pasture and crop production. In: S.N. McCutcheon, M.F. McDonald, and G.A. Wickham (eds.). *Sheep Production, Volume II, Feeding, growth and health.* Wellington, New Zealand Institute of Agricultural Scientists.

Field, T.R.O., and Forde, M.B. (1990). Effects of climate warming on the distribution of C_4 grasses in New Zealand. *Proceedings of the New Zealand Grassland Association.* 51, 47-50.

IPCC (1996). *Climate Change 1995 – Impacts, Adaptations and Mitigations of Climate Change: Scientific-Technical Analyses.* R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds.).

Johnson, I.R., and Thornley, J.H.M. (1983). Vegetative crop growth model incorporating leaf area expansion and senescence, and applied to grass. *Plant, Cell and Environment.* 6, 721-729.

Johnson, I.R., and Thornley, J.H.M. (1985). Dynamic model of the response of a vegetative grass crop to light, temperature and nitrogen. *Plant, Cell and Environment.* 8, 485-499.

Kirkham, M.B., He, H., Bolger, T.P., Lawler, D.J., and Kanemasu, E.T. (1991). Leaf photosynthesis and water use of big bluestem under elevated carbon dioxide. *Crop Science.* 31, 1589-1594.

MAF Technology (1990). *Predictions of the impact of climate change on pasture and animal production in New Zealand* – a report prepared for MfE. May 1990.

Minson, D.J. (1990). *Forage in ruminant nutrition.* San Diego, Academic Press.

Mitchell, N.D. (1991). The derivation of climate surfaces for New Zealand, and their application to the bioclimatic analysis of the distribution of kauri (Agathis australis). *Journal of the Royal Society of New Zealand.* 21, 13-24.

Morison, J.I.L., and Gifford, R.M. (1984). Plant growth and water use with limited water supply in high CO_2 concentrations. II. Plant dry weight, partitioning and water use efficiency. *Australian Journal of Plant Physiology.* 11, 375-84.

Newton, P.C.D. (1991). Direct effects of increasing carbon dioxide concentrations on pasture plants and communities. *New Zealand Journal of Agricultural Research.* 34, 1-24.

Owensby, C.E., Coyne, P.I., Ham, J.M., Auen, L.M., and Knapp, A.K. (1993). Biomass production in an all grass prairie ecosystem exposed to ambient and elevated CO_2. *Ecological Applications.* 3(4), 644-653.

Thomas, H., and Norris, I.B. (1981). Evaluation of drought resistance of grass and clover populations grown in containers. In: C.E. Wright (ed.). *Plant physiology and herbage production.* Maidenhead, United Kingdom: British Grassland Society. 217-219.

Yee, T., and Mitchell, N.D. (1991). Generalized additive models in plant ecology. *Journal of Vegetation Science.* 2, 587-602.

Chapter 7:

The Impacts of Climate Change on Soils and Land Systems in New Zealand

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Landcare Research

Introduction

In evaluating the sensitivity of soils, the emphasis is on soil organic matter. Soil organic matter, which stabilises topsoils and stores most of the nutrients, is critically important for the sustainability of land systems. In addition to promoting water retention, infiltration, soil tilth, and reducing wind and water erosion, organic matter is a major nutrient reservoir in most soils. An understanding of the extent and timing of changes in soil organic matter under a warmer climate requires knowledge of both the inventory of carbon in soils and its turnover rate. A further requirement is an understanding of how future patterns of climate in New Zealand will change land systems in response to regional climate change scenarios.

A decrease in New Zealand's soil C of ca 6% per degree global temperature increase was suggested from a comparison of soil C storage in native tussock grasslands along a climate gradient in Otago (Tate, 1992). However, the use of this soil sequence provided only a rather crude simulation of the possible effects of climate change. Consequently, a more sophisticated modelling approach was developed to explore in more precise detail the possible responses of New Zealand's soils to climate change (Tate *et al.*, 1996), using a limited number of scenarios. In that exercise, reductions in soil carbon of about 4-6% per degree temperature increase were generally expected in the absence of effects from CO_2 fertilization and increased nutrient availability. This analysis accounted for the presence in soil of C pools that differ widely in their stability; the more stable pools are known to be relatively unresponsive to temperature changes, leading some researchers to suggest that decomposition rates of organic carbon in mineral soil do not vary with temperature (Giardina and Ryan, 2000).

This section examines the possible impacts of an enhanced greenhouse effect on soil organic matter content, with particular emphasis being given to identifying the most sensitive land systems. How might soil organic matter change in the future with climate change and CO_2 fertilisation, as compared with related changes in intensification of land use? Our objective is to investigate the effects of regional climate change and variations on land systems and soils, by testing a model adapted for New Zealand conditions. The model predicted changes in soil organic matter levels in response to climate change, within CLIMPACTS, on a number of sites. A further objective is to couple a simple plant physiological model for pastures to our soil C turnover model, to link the response of above- and below-ground components of these ecosystems more realistically to climate change.

Methods

The soil organic matter model incorporated into CLIMPACTS is the Rothamsted Soil organic matter model, adapted for New Zealand conditions (see Parshotam *et al.*, 1999). Inputs to the model are meteorological data (temperature (^{o}C), rainfall (mm), PET (potential evapotranspiration) (mm)), soil clay percent, plant residue inputs, a soil quality factor that depends on vegetation type, FYM (farm yard manure), if any, and a soil cover factor.

The rate of soil carbon turnover is modified by considering the effects of soil temperature and moisture.

Evapotranspiration is used in a water balance model to estimate moisture rate modifying factors. Average monthly temperature and rainfall are modified according to climate change scenarios built into CLIMPACTS.

The model outlined above enables us to predict the changes in soil organic matter over time with contrasting environmental conditions and to identify sites with critical thresholds.

To have confidence that the soil-C turnover model within CLIMPACTS can simulate the impacts of climate change adequately, it is necessary to confirm that it can provide accurate simulations for New Zealand in a range of current climates and soil types. To date, good correlation between observed data and simulated results is reported (see Parshotam *et al.*, 2001). The results of the validation studies where experimental conditions were well known in detail show that the soil-C model adapted into CLIMPACTS is a reliable estimator of the likely performance of soil organic matter under variable New Zealand climatic conditions and soils.

It is assumed in the model that before any temperature and moisture perturbations, the system is at steady state. The site we chose was a permanent pasture site at Kairanga, in the Manawatu, with 41% clay and 90.8 t ha^{-1} of total C. The climate data from Ohakea was used. For initial modelling runs, inert organic matter carbon (IOM-C) to a depth of 23cm was set at 10 t C ha^{-1}, based on New Zealand estimates of 'bomb' ^{14}C in specific site studies. The CLIMPACTS system allows this value to be arbitrarily chosen.

Simulations are started at monthly intervals, from the 1990 baseline year, for the years 1990-2100. We applied the HadCM2 and CSIRO9 GCMs, coupled with four global temperature change scenarios, SRES marker scenarios A1, A2, B1 and B2, with medium, low and high climate sensitivity, and also with different phases of the southern oscillation (SOI = -1, 0 and +1). For selected outputs, the effects of different GCM patterns (HadCM2 and CSIRO9 patterns), global temperature change, climate sensitivity, and different phases of the southern oscillation were assessed.

The soil C and plant production model is coupled in the following way: the pasture production model that incorporates climate impacts and CO_2 responses is used to derive soil C inputs by allocating total C to above- and below-ground C. Inputs of C into the soil model are derived from the sum of below-ground C and above-ground grassland litter C.

Results

The model reproduced patterns that were consistent with our earlier work. In all cases, a gradual decline of up to 3% of organic C was observed over the period 1990-2100, with the same level of plant input as at present.

Effect of GCM

Predicted change in soil carbon was affected by the choice of GCM. The effect of GCM on trends in soil carbon varied between sites (see Figure 7.1).

Effect of Global Temperature Change Scenarios

Predicted change in soil carbon was affected by choice of global temperature change scenarios. The effect of global temperature change scenarios on trends in soil carbon varied between sites (see Figure 7.2).

Effect of SOI

The change in SOI did not make any difference to predictions nor did the sign for interdecadal Pacific Oscillation. The effect of SOI-related variability did not override the long-term climatically induced trend towards changes in soil C.

Effect of Global Temperature Change with Climate Sensitivity Scenarios

The HadCM2 GCM with SRES marker scenario A1, appears to be an important factor in determining the long-term trends with low and high climate sensitivity scenarios (see Figure 7.3).

Coupled (Plant-Soil) Model

Preliminary runs of the coupled plant-soil model, show a considerable decline in soil C levels (not shown). This results from the two very different methods of calculating plant inputs. The Rothamsted soil-C turnover model calculates plant inputs with the assumption that the system is at steady state. The pasture production model calculates soil C inputs dynamically from the sum of below ground C and above ground grassland litter C.

Discussion

Note that the changes suggested in Figure 7.1 and Figure 7.3 are unlikely to be detected by direct measurement without extensive soil sampling. The modelling runs assume constant land management and use over 100 years. This is unlikely to occur, and we may have to factor into the model the effects of changes in land use.

Changes in land use are likely to have a much larger impact on soil organic matter than climate change. Risks of soil degradation will be high in heavily cropped arable land, and in land where changes in use have major effects on the hydrological regime. In many of the areas with soil organic C concentrations close to critical threshold levels (e.g., in parts of Canterbury), the growing of crops such as grain maize may in future not be

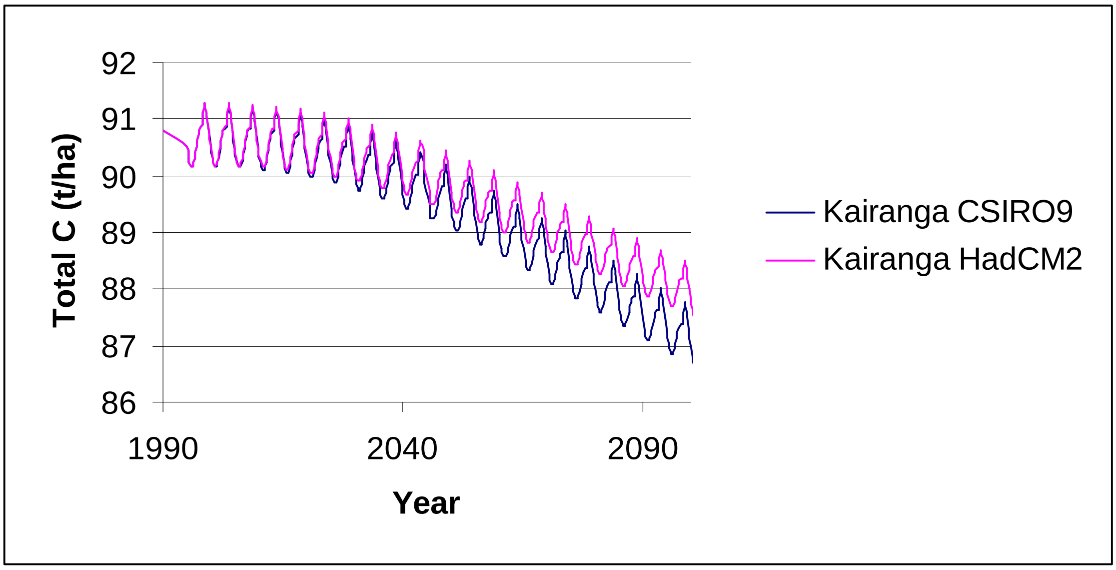

Figure 7.1: Changes in total C for Kairanga site, with 41% clay and 90.8 t ha^{-1} of soil C. Simulations are based on the application of two GCMs (CSIRO9 and HadCM2) with SRES marker scenario A1, medium climate sensitivity, and SOI = 1.0.

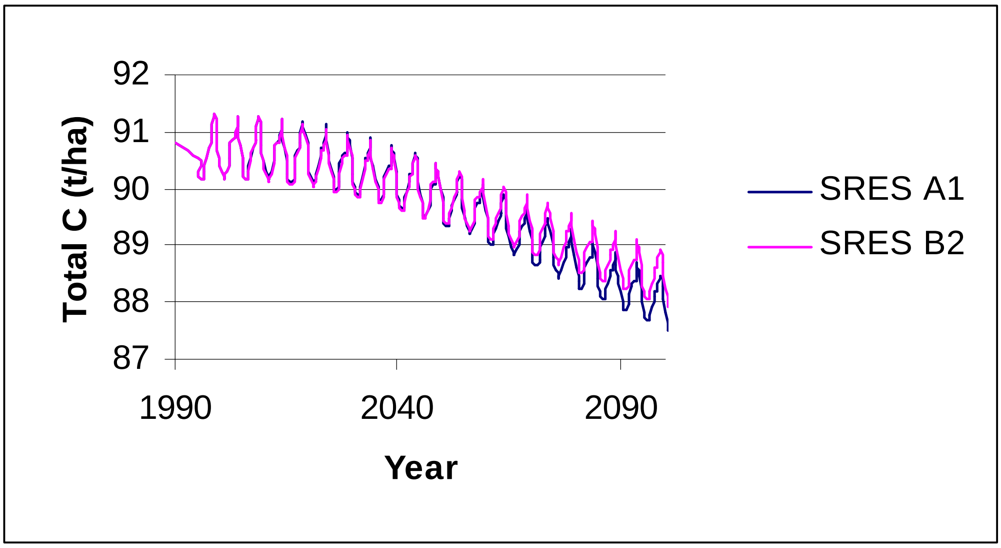

Figure 7.2: Changes in total C for Kairanga site, with 41% clay and 90.8 t ha^{-1} of soil C. Simulations are based on the application of the HadCM2 GCM with SRES marker scenarios A1 and B2 with medium climate sensitivity, and SOI = 1.0.

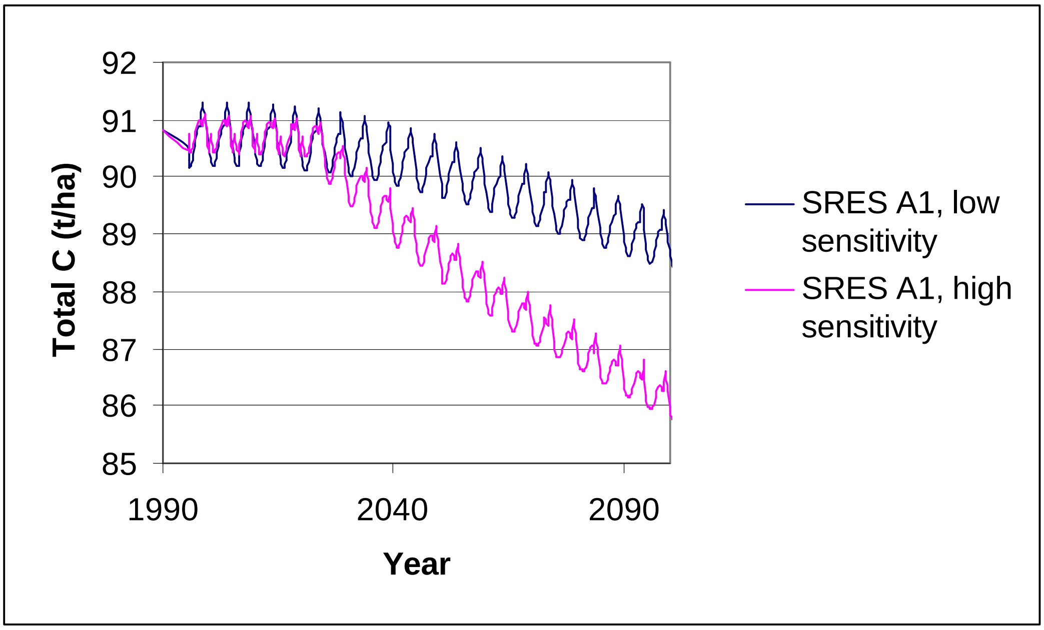

Figure 7.3: Changes in total C for Kairanga, with 41% clay and 90.8 t ha^{-1} of soil C. Simulations are based on the application of the HadCM2 GCM with SRES marker scenario A1, and low and high climate sensitivity scenarios.

sustainable, despite the suitablility of the climate. This example illustrates the need to include edaphic and other factors (e.g., hydrology) with climate when assessing the sustainability of future land uses in a warmer world.

Soils sustain a large and diverse population of organisms that contribute significantly to decomposition processes. Apart from the larger animals (e.g., earthworms), most organisms are concentrated in the dead organic matter near the soil surface, in a zone most vulnerable to the effects of changes in climate and land use.

Some future research imperatives for understanding the impacts of climate change on New Zealand's soils and land systems include:

- Quantifying the net effects of changes in climate and water balance on soil organic matter in New Zealand's major ecosystems, directly from temperature and precipitation changes, and indirectly from changes in net primary production, elevated CO_2 and increased nutrient availability. This information could then be used to identify areas and locations of the most sensitive soils.

- Determining areas and land classes potentially at risk from increased land pressure as a consequence of climate change. Analysis should include a wide range of arable, horticultural and tree crops, and their interactions with climate, soils and hydrological regimes.

- Incorporating different water balances corresponding to different land-uses. To this end, we have produced a spatial database of available water-holding capacity (AWHC) and crop rooting depth for different crop types, for national-scale applications.

- Incorporating base-line soil, climate and land-use data into the CLIMPACTS system and a management system constructed for data storage, extraction, and use.

- Understanding the effect of short-term climatic variability on soil organic matter. Although, soil C processes occur over a much longer time, they are apparently not influenced by short-term climatic variability. However, short term climatic variability will be important if our attention is shifted to the soil nitrogen (N) cycle.

- Including feedbacks in the soil model between soil organic matter content and crop available soil moisture, and work on developing similar links between soil organic matter and nutrient availability and on incorporating explicit recruitment processes (vegetative and seed) into the plant component of the model. This will contribute to the development of management strategies that minimise the influence of climate variability on pastures.

References

Giardina, C.P., and Ryan, M.G. (2000). Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. *Nature.* 404, 858-861.

Parshotam, A., Johnson, M., and Tate, K.R. (1999). *Modelling Soil C Dynamics within CLIMPACTS.* Landcare Research Report.

Parshotam, A., Saggar, S., Tate, K., and Parfitt, R. (2001). Modelling organic matter dynamics in New Zealand soils. *Environmental International* (In Press).

Tate, K.R., Giltrap, D.J., Parshotam, A., Hewitt, A.E., Ross, D.J., Kenny, G.J., and Warrick, R.A. (1996). Impacts of Climate Change on Soils and Land Systems in New Zealand. In: G. Pearman and M.R. Manning (eds.). *Greenhouse 94; Coping with Change.* Collingwood, Australia, CSIRO Press. 190-204.

Tate, K. (1992). Assessment, based on a climosequence of soils in tussock grasslands, of soil carbon storage and release in response to global warming. *Journal of Soil Science.* 43, 697-707.

Chapter 8:

The Impact of Climate Change on Regional Resources: A Case Study for Canterbury and Waikato Regions

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Introduction

New Zealand's regional councils were established with a mandate, under the Resource Management Act 1991 (RMA), to manage the land, water, and air resources within their prescribed boundaries. A principal requirement of the RMA is that planning and policy decisions are founded on the mitigation or avoidance of adverse effects on the environment and the requirement to weigh up the costs and benefits. In general, regional councils acknowledge that climate change could lead to adverse effects. However, there is limited knowledge of likely changes in climate and the possible nature of effects within regions of New Zealand and, consequently, minimal consideration of potential effects of climate change in regional policies and plans. This constitutes a significant gap in current knowledge, particularly given the wide range of responsibilities carried by regional councils including mitigation or avoidance of effects arising from natural hazards such as flooding, drought, coastal erosion and landslides and control of invasive plant and animal pests.

To address this gap, two regional councils (Environment Canterbury and Environment Waikato) were identified as case studies for development of a capacity to examine effects of climate change at the regional scale. Consultations were held with both councils to identify the range of climate-related issues that they are required to address. Out of this process, three priority areas were identified:

1. The coastal environment and possible effects of extreme events;
2. Interactions between land use and soil moisture, and impacts on water supply, particularly in relation to drought events;
3. Water resource protection and allocation, and how climate change might influence both quality and quantity of regional water resources.

There were other issues of importance, such as the potential for new invasive plant and animal pests and possible effects on native vegetation, wetland areas, as well as the general effects on climate variability and extreme events. Within the scope of the CLIMPACTS programme it was not possible to address all of the above. Thus, in the first instance, a capacity was developed to:

- Provide user-specified scenarios of climate change;
- Allow examination of effects on regional water balance, as a basis for evaluating changes in drought risk;
- Allow examination of possible changes in climate extremes at selected sites.

The following sections: describe the regional capacity in more detail; describe what is presently known in terms of effects of climate, particularly relating to drought severity and risk; present an evaluation of the possible of effects of climate change on the water balance and drought severity in Canterbury and Waikato regions; and identify links to policy and adaptation as well as future directions for research.

What is Currently Known in Canterbury and Waikato?

The Canterbury and Waikato regions are located in two quite different climatic zones in New Zealand, which are influenced very differently by local orography. These characteristics are discussed briefly below, and differences between the two regions are highlighted by a summary of possible effects of climate change on water resources in both regions, which arose from a survey of expert opinion from a decade ago (Griffiths, 1990).

Present Climate in the Canterbury Region

The Southern Alps have a strong influence on the climate of Canterbury. Annual average temperature ranges from less than 8ºC in the Alps to 10-12ºC in the plains. Rainfall gradients are very high from west to east, ranging from an annual average of 10,000 mm in the Alps to 600-800 mm on average in the Canterbury plains. Rainfall is spread fairly evenly through the year, but there are stronger temperature variations through the year than experienced in most parts of New Zealand (Ryan, 1987).

Floods and droughts, along with other natural hazards, are experienced in the plains of Canterbury with sufficient frequency for them to be taken seriously in regional planning. Environment Canterbury anticipates that the potential for adverse effects from natural hazards will increase in the future as a result of increasing development. There are also competing, and growing, demands for water resources. A plan has been developed to 2008, aimed at reducing the cost of natural hazards by implementing appropriate mitigation measures. The 1997/98 drought in Canterbury highlighted the need for such planning. This was one of the worst droughts on record in Canterbury, with extremely low river flows and low ground water levels (Horrell *et al.*, 1998). While it is anticipated that such droughts will continue into the future (Owens *et al.*, 1994), and that effects will worsen as a result of ongoing development in the region, the possible effects of climate change are not presently taken into account. Future planning for the water resources of Canterbury is perhaps the issue of highest priority for the region.

Present Climate in the Waikato Region

Annual average temperature, based on the 1951-80 period, in the Waikato ranges from 10-11ºC in the south to 14-15ºC in the north of the region. There is also a lesser gradient from the warmer west coast to cooler inland basin areas. Rainfall (mostly ranging from 1200 mm to 2000 mm) is influenced by orography and prevailing winds, with rainfall highest in the western and eastern ranges and the Coromandel peninsula and lowest in the central Waikato basin.

In general, Waikato experiences less extreme variations in climate than other parts of New Zealand. Drought, in particular, has not been regarded as a significant hazard in the region (Harman, 1999) compared to other parts of New Zealand. A move to more intensive dairy farming systems, including higher stocking rates, over the last decade or so has led to a heightened perception of drought in otherwise relatively moderate years. Coupled with these changes there have been significant climatic events, in particular the 1997/98 drought, which have impacted on the regional economy. As a consequence Environment Waikato has become more proactive in seeking to avoid adverse effects of drought, with the preparation of a Drought Risk Mitigation Plan (Environment Waikato, 2000). The areas at greatest risk from drought in Waikato, as identified by Harman (1999), are north Waikato, including the Hauraki Plains area. Areas of least risk are in the south and west.

Effects of Climate Change

A comprehensive review of expert opinion on the impacts of climate change in New Zealand was completed in 1990 (Ministry for the Environment, 1990). The water resources chapter of this report contains a summary of possible regional effects, based on the scenarios used for the study (Griffiths, 1990). Effects in Waikato – Bay of Plenty and Canterbury are provided in Table 8.1.

In general, these results suggest more flooding, greater groundwater recharge and higher erosion risk in Waikato, with less flooding, lower groundwater recharge, increased competition for water resources, and increased drought risk in Canterbury.

The final concluding statement made by Griffiths (1990) was that "improved precision in predicting the impacts of Greenhouse climate change, for given scenarios, requires comprehensive modelling of water resource systems". The following analysis provides a step towards such a capability.

The Analysis of Regional Effects – Methods

The analysis of regional effects of climate change over the next 100 years in Canterbury and Waikato regions, using the CLIMPACTS system (see Box 8.1), was aimed at:

1. Describing, briefly, changes in climate (temperature and rainfall) that may occur at the regional scale;
2. Examining the current areal extent of average (1951-80) summer water deficit and drought (based on the 1997/98 El Niño event) ;
3. Determining changes in the areal extent of average summer water deficit;
4. Using anomalies from the 1997/98 drought, together with climate change scenarios, to determine possible changes in drought severity in the future;
5. Examining changes in grain maize suitability in Canterbury, as a case study of the possible effects of land use change that may be associated with climate change and for assessing the implications in terms of changes in average water deficit and drought severity;
6. Discussing adaptation options.

Current Conditions

The summer months in New Zealand are, in most regions and years, the time of greatest evaporative demand and the least rainfall. This results in a period of water deficit, the degree of which is conditioned by the relative dryness of the preceding Spring months, the capacity of the soil to hold water, and the land management systems in place in a given region, as well as the relative amounts of evaporative demand and summer rainfall.

Box 8.1: The regional capacity of the CLIMPACTS system

The regional capacity of the CLIMPACTS system was developed for two regions, Canterbury and Waikato, incorporating the following key features:

- A climate change scenario generator (as described in Kenny *et al.*, 2000a);
- Spatial climate, land use capability (LUC) and available water holding capacity (AWC) data (at a 0.01° lat/long resolution) for the two regions;
- Time series of daily weather data for 21 sites in Waikato and for 20 sites in Canterbury;
- Models for application with spatial data, including: suitability models for grain maize and kiwifruit; an atmospheric water balance model, as a basis for developing a capacity for drought risk assessment; a crop water requirement index, as a basis for identifying the possible irrigation demands for different crops;
- An extreme event analysis tool, for use with the daily data, to analyse extreme rainfall and temperature events.

Table 8.1: Effects of climate change on water resources in Waikato – Bay of Plenty and Canterbury, drawn from Griffiths (1990).

	Waikato – Bay of Plenty	**Canterbury**
i)	More frequent and severe flooding.	Little change to groundwater recharge under either S1 or S2, but an increase in the number of days of soil moisture being below wilting point suggests greater demands for groundwater supplied irrigation.
ii)	Enhanced baseflows in rivers and streams and lake levels on the volcanic plateau would rise.	Greater incidence of drought and river reaches drying up and major aridity problems on non-irrigated downland areas.
iii)	Greater recharge of groundwater and less demand for irrigation.	Reduced baseflows in foothills and rivers on Banks Peninsula.
iv)	The increased frequency of sub-tropical cyclones might be compensated for by the lower frequency of south-easterly storms under the S1 scenario but not under S2.	Greatly increased competition for water between instream and out of stream uses.
v)	Geothermal systems would receive greater groundwater recharge.	Forested areas in the east with low rainfalls would supply a reduced water surplus to streamflow and groundwater recharge.
vi)	Waitomo Glow Worm Cave would be closed more frequently owing to flooding, and siltation in the cave would increase.	Less water in rivers in late spring and early summer where snowmelt is now important.
vii)	A significant increase in water yield from *Pinus radiata* forested basins can be expected, with more yield in summer than in winter.	Very little snow storage in South Canterbury, resulting in significant changes in the temporal runoff pattern in rivers. Snowmelt contribution would probably move forward about a month in time.
viii)	The operation of the Huntly thermal power station might be affected by increased river temperatures – discharges are already limited by temperature restrictions in the summer. Increased river flows may compensate to some degree.	Significant increase in irrigation demand.
ix)	Severe gullying could occur in highly erodible volcanic materials, leading to increased infilling of hydro dam reservoirs, thus reducing reservoir life and flood storage capacity.	Water resources of South Canterbury would no longer be able to meet demands on a run of the river basis.
x)		Possible saline intrusion to groundwater resources in South Canterbury.
xi)		Increased water use by permanent grassland and shortening of period of recharge of soil water.

The current summer water balance was determined for average conditions and high deficit areas (areas with a deficit greater than 300mm in Canterbury and greater than 250mm in Waikato) were identified. A lower threshold value was used in Waikato because the areal extent and magnitude of deficit is lower than in Canterbury.

The 1997/98 drought, which occurred in both Canterbury and Waikato regions, was simulated by increasing average temperatures by 1.0ºC and decreasing rainfall by 50%. These values were applied uniformly in both regions, using the synthetic scenario option in the CLIMPACTS system (see Kenny *et al.*, 2000a), and high deficit areas were identified. Because the 1997/98 drought already showed a summer deficit of greater than 300mm throughout the Canterbury plains, a more intensive situation (areas with a deficit greater than 400mm) was examined. Similarly for Waikato, areas with a deficit of greater than 390mm were identified.

Future Conditions

The summer water balance was calculated for future conditions, using the scenarios specified in Chapter 2, and changes in the area of greatest deficit (using the same thresholds as for current conditions) were calculated.

For future drought analysis, the 1997/98 event was used in association with average climate changes identified for each of the regions by 2050 (see Tables 8.2 and 8.3) to develop a synthetic future drought scenario. For Canterbury, the 1997/98 drought values were adjusted by scenario changes from the HadCM2 GCM pattern, and were then applied to the current climate. For 2050 the 1997/98 temperature anomaly was increased by an additional 0.5°C (based on a mid case scenario), to give a change value of 1.5°C, and rainfall was unchanged from the 1997/98 anomaly. For 2100 the 1997/98 temperature anomaly was increased by an additional 1.5°C (based on a mid to high case scenario) to give a change value of 2.5°C, and rainfall was decreased by an additional 5% from the 1997/98 anomaly, giving a total decrease of 55%.

For Waikato, contrasting drought scenarios were developed to reflect differences between the two GCM patterns used, particularly in 2100 (Table 8.3). For 2050, when differences between the GCMs are relatively small, temperature and rainfall anomalies were adjusted by the same amounts used for Canterbury, giving a 1.5°C temperature anomaly and a rainfall decrease of 50%. For 2100, based on the HadCM2 GCM pattern, the 1997/98 temperature anomaly was increased by an additional 2.0°C (a high case scenario) to give a change value of 2.5°C, and rainfall (which increases in Waikato under this GCM) was decreased by a total of only 41% (reflecting a 9% average rainfall increase across Waikato relative to the present). In contrast, the CSIRO9 GCM pattern shows warmer, drier conditions in Waikato. Consequently, for a high case scenario a second drought anomaly was developed for 2100 with a total temperature increase of 3.0°C and a total rainfall decrease of 55%.

Changes in Land Use

The preceding analysis focused on changes in the average summer water balance and drought severity. A further analysis, for Canterbury only, was carried out to examine the possible implications of changes in land use.

Maize was used as an example of a high water demanding crop that is presently marginal in Canterbury but could become more widely grown under warmer conditions. The following analyses were made:

1. For present climate, the average date of maturation of an October sown, early maturing, maize cultivar was

determined for the arable land area of central/coastal Canterbury;

2. Changes in the average date of maturation were determined for the range of scenarios presented in Chapter 2 for:
    - An October sown, early maturing cultivar;
    - An October sown, late maturing cultivar;
    - A November sown, late maturing cultivar.

This information provided the basis for a discussion on the possible implications for future water demand in relation to the drought hazard in Canterbury.

All of the spatial analyses described above were completed for arable land areas only (LUC classes 1 to 4).

Results

Canterbury Region

The climate change scenario results for Canterbury, for the years 2050 and 2100 are summarised below (Table 8.2). In general the scenarios based on the CSIRO9 GCM pattern give warmer and wetter conditions than those based on the HadCM2 GCM pattern. Based on the CSIRO9 results, the warming tends to be greatest in the northeast and least in the southwest, whereas the precipitation changes are greatest inland and least in coastal Canterbury. The temperature changes from the HadCM2 pattern show a similar northeast to southwest gradient, with greater temperature changes in the northeast. With this GCM pattern, precipitation decreases in most of coastal Canterbury, grading to very small increases towards the Southern Alps. The greatest precipitation increases are in the southwest.

Current Average Water Deficit and Drought Conditions

All of the Canterbury plains are in deficit, on average, in the summer months. Areas with greatest deficit (greater than 300mm) are in coastal mid-Canterbury (Figure 8.1), covering an area of approximately 3600 km^2. A simulation of the 1997/98 drought indicates that the entire plains area experienced a summer deficit of at least 300 mm at this time. In coastal mid-Canterbury the deficit was at least 400 mm, a significant increase on the average.

Changes in Average Summer Water Deficit

Changes in the average summer water deficit were evaluated for the different scenarios by using the CLIMPACTS

Table 8.2: Scenarios of temperature and precipitation change for Canterbury, 2050 and 2100.

			SRES A2	**SRES A1**	**SRES B1**
HadCM2	D**T**	2050	0.8 – 1.1°C	0.5-0.65°C	0.2 - 0.3°C
		2100	1.5 - 2.0°C	0.7 – 0.9°C	0.35 - 0.45°C
	D**P**	-5.0 to +2.0% per degree of temperature change			
CSIRO9	D**T**	2050	1.6 – 1.7°C	1°C	0.45°C
		2100	3°C	1.4°C	0.7°C
	D**P**	0 to 2% per degree of temperature change			

system to generate images, in 10-year increments, and then calculating the land area with a deficit greater than the 300mm threshold. Results show very little difference between the CSIRO9 and HadCM2 GCM patterns, particularly when compared to the influence of the different SRES emissions scenarios (Figure 8.2). This is due to the contrasting effects of warmer, wetter conditions with the CSIRO9 pattern and less warming coupled with drier conditions with the HadCM2 pattern, which tend to balance out to give similar results. Under the HadCM2 pattern of climate change, the land area where the deficit threshold is exceeded increases at widely different rates for the three emissions scenarios (Figure 8.2). However, even for the lowest warming scenario (B1 low) there is an increase of about 400 km^2 by 2040, with a maximum increase (under the A2 high scenario) of over 1000 km^2 by this time. These changes occur primarily southwards along the coast, with a lesser shift inland (Figure 8.2).

Changes in Drought Severity

Based on the drought anomaly described in the methods section, results show both an increase in areal extent of drought, along the coast and inland, and an intensification of drought in the most affected areas of central Canterbury (Figure 8.3). This is a

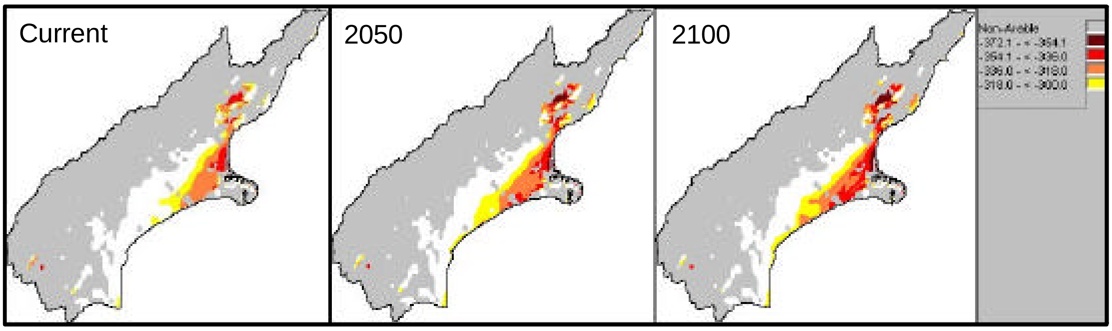

Figure 8.1: Spatial changes in average summer water deficit in Canterbury, for the HadCM2 GCM pattern and the A1 emissions scenario.

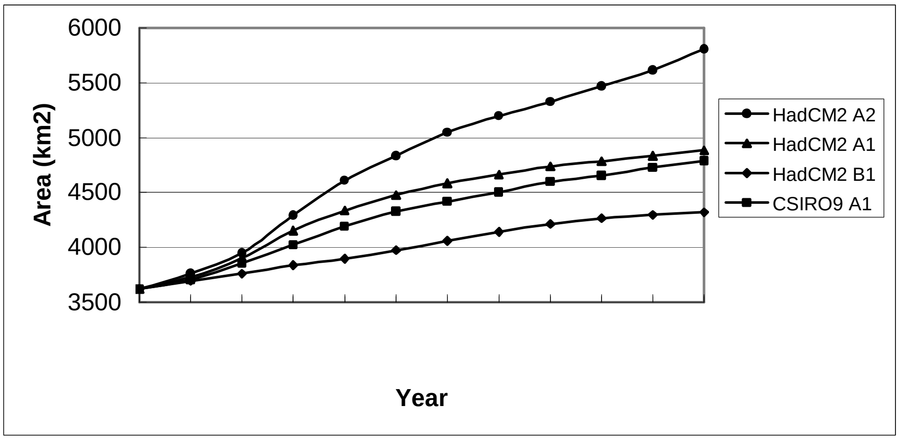

Figure 8.2: Changes in Canterbury land area with an average summer deficit of 300mm or more, for two GCM patterns and a range of emissions scenarios.

fairly obvious result, given that temperature was increased and rainfall decreased, relative to the 1997/98 drought anomaly. However, what this analysis does provide is an indication of how drought severity could change in future and where these changes are most likely to occur. Such information can then be combined with analyses of changes in crop suitability, as done for grain maize below. Changes in drought frequency were not examined (due to lack of time series data for the spatial analyses) but it is likely that this would increase based on an increase in average summer water deficit.

Changes in Maize Suitability

Maize is a highly temperature dependent crop that is presently marginal in Canterbury. It has a relatively long growing season and is water demanding. Under present conditions (1951-80 average, as represented by 1990) the average date of maturity in coastal/central Canterbury for an October sown, early maturing, cultivar is in the latter part of April (Figure 8.4, day 110). Based on information on autumn frost risk at the southern (cool) margin (Wilson and Salinger, 1994) a cut-off date of 30 April (day 120) was applied in the analysis, beyond which maize is considered unsuitable. Thus, inland and south Canterbury are not presently suitable for maize production.

A single, mid-case, scenario (HadCM2 GCM, SRES A1 mid GHG emissions scenario) of climate change was used to examine changes in maturity date, in coastal/central Canterbury, for the different sowing time and cultivar combinations identified earlier. As would be expected for a temperature dependent crop, the results show an earlier date of maturation as the climate becomes warmer (Figure 8.4). In this analysis the cut-off date for suitability (day 120) is unchanged, but it is likely that the risk of frost would occur progressively later, increasing the opportunities for maize. The important result is that maize becomes less limited by temperature over time and the range of options, in terms of cultivar choice and sowing time, increases.

The implications of this result, in the context of the preceding analyses, are that the demand for water, from increasing land-use opportunities, could increase. This increase would most likely be greatest in the warmer areas of Canterbury, in the central/coastal part of the region, where the 1997/98 drought showed the greatest deficit and where drought severity will possibly worsen in the future.

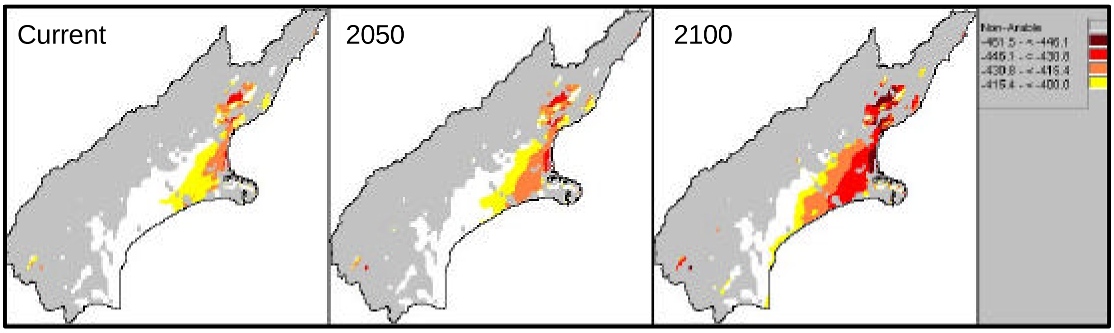

Figure 8.3: Future changes in drought severity in Canterbury, relative to the current situation (a simulation of the 1997/98 drought).

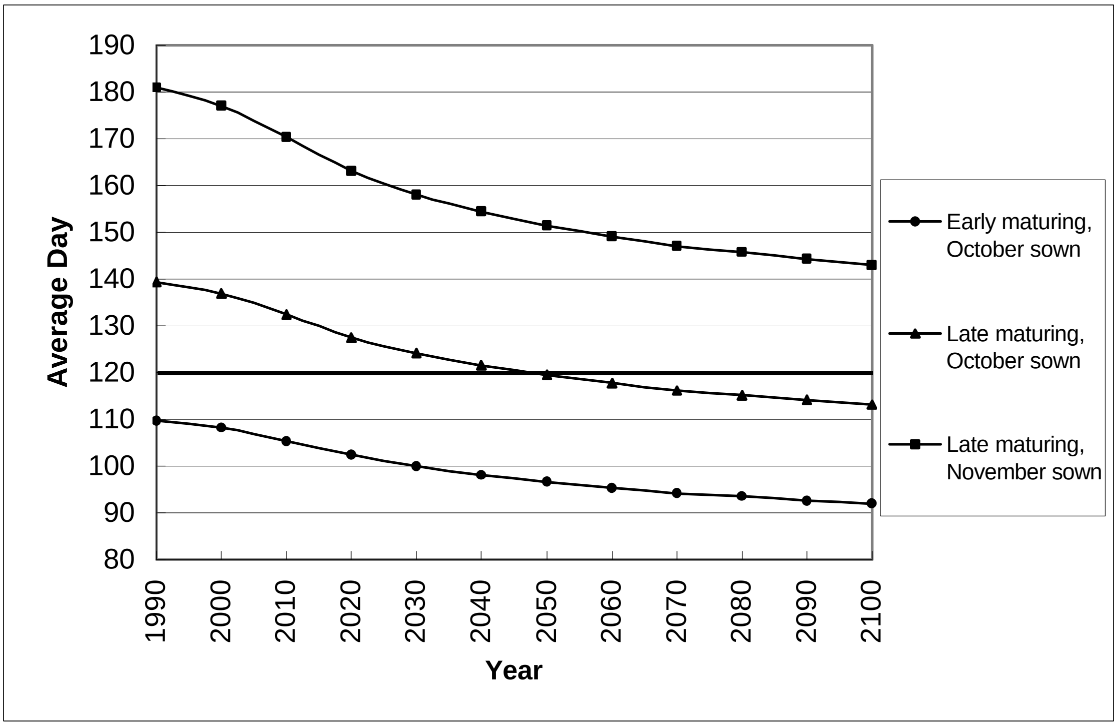

Figure 8.4: Changes in average date of maize maturity in coastal/central Canterbury, for different cultivars and sowing times.

Table 8.3: Scenarios of summer (DJF) temperature and precipitation change for Waikato, 2050 and 2100.

			SRES A2	**SRES A1**	**SRES B1**
HadCM2	D**T**	2050	1.0°C	0.6-0.8°C	0.3 - 0.36°C
		2100	2.0 – 2.5°C	1.0°C	0.5°C
	D**P**	2.0 to 5.0% per degree of temperature change			
CSIRO9	D**T**	2050	1.6°C	1.0°C	0.45°C
		2100	3.0 – 3.1°C	1.4°C	0.7°C
	D**P**	-1.7 to -0.5% per degree of temperature change			

Waikato Region

The climate change scenario results for Waikato, for the years 2050 and 2100 are summarised above (Table 8.3). In general the scenarios based on the CSIRO9 GCM pattern give warmer and drier conditions than those based on the HadCM2 GCM pattern. Based on the CSIRO9 results, the warming tends to be fairly uniform across the region, with a very slight north to south rainfall gradient. This pattern shows slightly drier summer conditions over most of the Waikato. The temperature changes from the HadCM2 pattern also show fairly uniform temperature changes, but with a small north (warmer) to south (cooler) gradient. This pattern shows wetter summer conditions over most of the Waikato, with greater increases in the south and west grading to smaller increases in the north-east.

Current Average Water Deficit and Drought Conditions

All arable land areas (LUC classes 1-4) in Waikato are in deficit, on average, in the summer months. The dairy farming land of the north and central Waikato experience the greatest summer deficit, from 200 to 300 mm, with the highest deficit areas (greater than 250 mm) to the northeast of Hamilton and in the Hauraki plains. The land area in the high deficit category is approximately 2400 km^2. A simulation of the 1997/98 drought indicates that the arable land area in Waikato experienced a summer deficit of at least 250 mm at this time. In the higher deficit areas northeast of Hamilton, the deficit was of the order of 400 mm, a significant increase on the average.

Changes in Average Summer Water Deficit

Changes in the average summer water deficit were evaluated as for Canterbury, with the exception that the 250 mm threshold was used for calculating changes in land area in deficit. Results show marked differences between the CSIRO9 and HadCM2 GCM patterns, with the former showing increases in land area in deficit and the latter showing decreases (Figure 8.5). For example, by 2050, the mid case (A1 mid) scenario for the CSIRO9 pattern shows a 1000 km^2 increase whereas the HadCM2 pattern shows a 500 km^2 decrease. The increases are centred from the high deficit area identified earlier, to the north and east of Hamilton, extending also to the immediate south (Figure 8.6). The differences between the GCM patterns in Waikato, as compared to the similar results in Canterbury, are due to the contrasting effects of relatively warmer, drier conditions (CSIRO9) and less warming with wetter conditions (HadCM2).

Changes in Drought Severity

For 2050, the results show an increase in area of the most drought prone land, in north-central Waikato, as well as an intensification of drought (Figure 8.7). Based on the slight differences between the GCM results at this time, this “average” drought would vary from slightly less severe than the 1997/98 drought to being slightly worse than presented here. There is a significant contrast in results for 2100 (Figure 8.7). Based on the HadCM2 pattern, the 1997/98 drought would be relatively less severe. The CSIRO9 pattern would lead to a significant increase in drought severity.

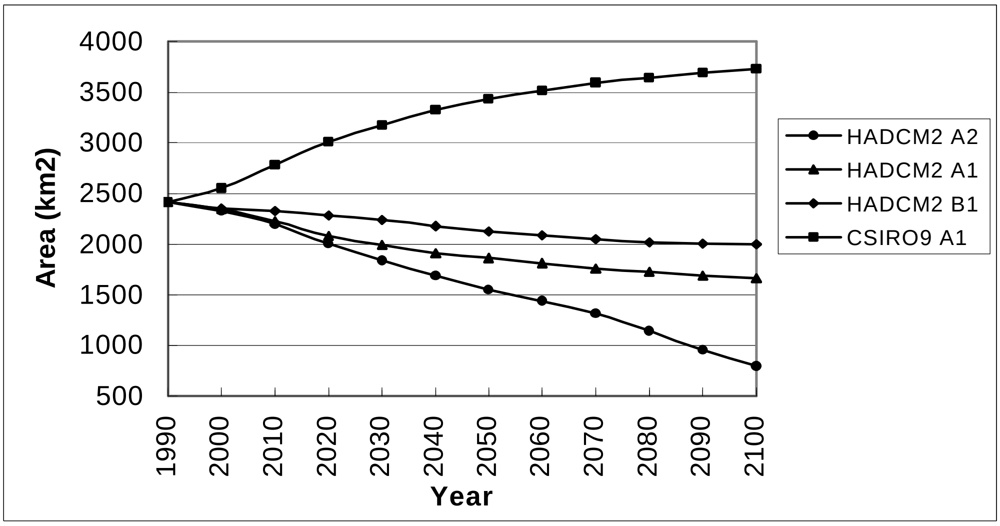

Figure 8.5: Changes in Waikato land area with an average summer deficit of 250 mm or more, for two GCM patterns and a range of emissions scenarios.

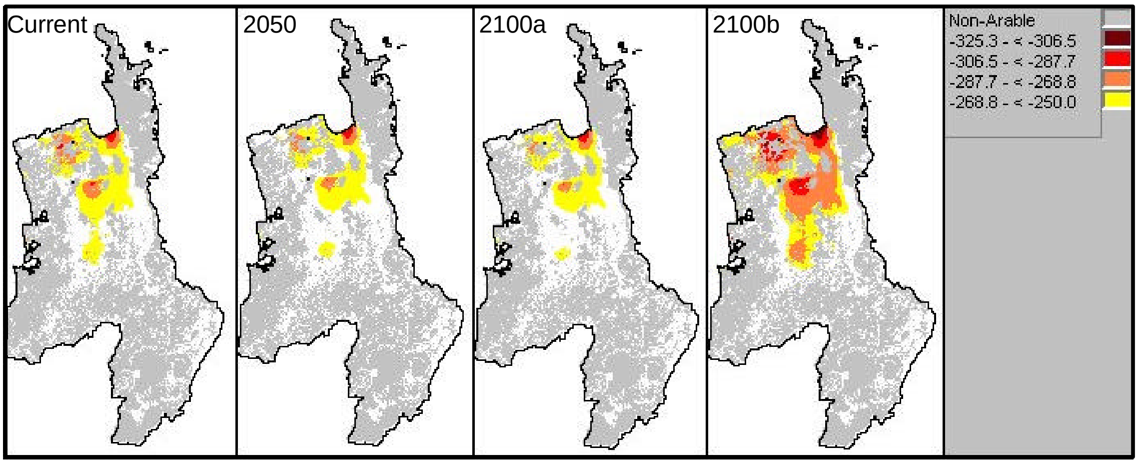

Figure 8.6: Spatial changes in average summer water deficit in Waikato for the HadCM2 GCM pattern (2050, 2100a) and the CSIRO9 GCM pattern (2100b), and the A1 emission scenario.

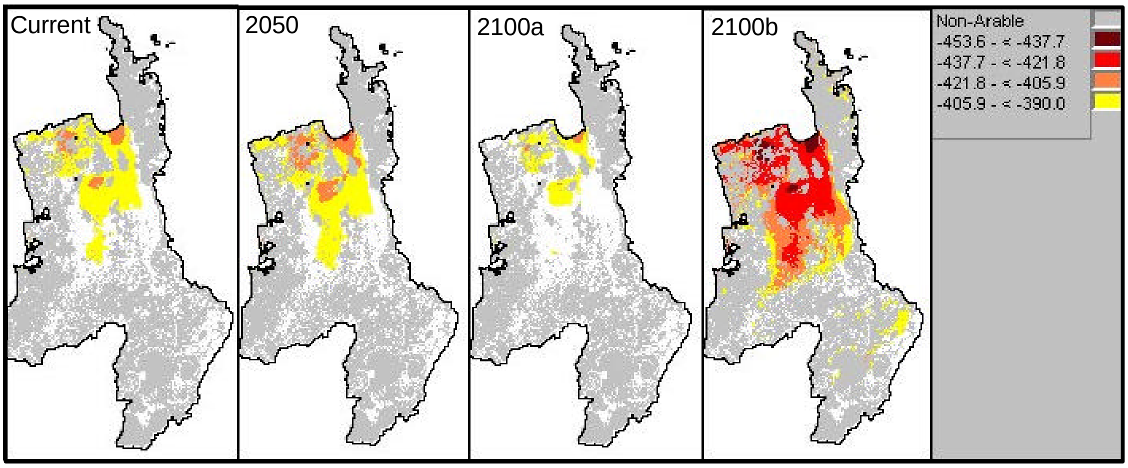

Figure 8.7: Future changes in drought severity in Waikato, relative to the current situation (a simulation of the 1997/98 drought), for an "average" scenario (2050) and for the HadCM2 and CSIRO9 GCM patterns (2100a, 2100b).

Summary

Based on the scenarios used in this study the following effects can be identified for Canterbury and Waikato regions.

Effects of Climate Change on Average Summer Water Deficit and Drought in Canterbury:

- The magnitude and areal extent of the average summer water deficit is likely to increase in the Canterbury plains over the next 50 to 100 years. By 2040, the increase in area where the deficit is 300 mm or greater will increase by 400 to 1000 km^2.

- Drought severity is likely to increase with climate change, based on analysis of the 1997/98 drought.

- Warmer temperatures will increase opportunities for temperature-dependent crops, such as maize, which are presently marginal in Canterbury. This could increase further the demand for water, which is already projected to increase in future with ongoing development in the region.

Effects of Climate Change on Average Summer Water Deficit and Drought in Waikato:

- Changes in the magnitude and areal extent of average summer water deficit vary in Waikato, due to differences between the HadCM2 and CSIRO9 GCM patterns. The relative increase in area in deficit (CSIRO9) is greater than the relative decrease (HadCM2).

- Drought severity, based on the 1997/98 drought, may tend towards minimal change or to worsen slightly by 2050, and either become less severe (HadCM2) or significantly more severe by 2100 (CSIRO9).

Links to Policy and Adaptation

Both Canterbury and Waikato regional councils have developed plans that consider possible adverse effects arising from natural hazards such as droughts and floods. In Canterbury it is expected that, with increasing development, the potential for adverse effects from natural hazards, such as drought, is likely to increase in future (Canterbury Regional Council, 1999).

A barrier to regional councils acting on the type of information presented here is the perception of a problem that is in the distant future, the effects of which are still uncertain. This is understood to imply that costs must be incurred now to adapt, for uncertain benefits in the future. There are two important things to consider:

1. Climate change is not just in the future. The best available evidence, and the consensus of international experts, indicates that it is already happening, although this trend is within the “noise” of natural climate variability (see Houghton *et al.*, 1996);
2. Adaptation to the effects of climate change should be viewed as a ***process*** that does not necessarily require high costs in the short-term. Depending on the specific issue in question there might be a range of adaptation measures, of varying cost, that require implementation over time and which should be integrated within the wider context of resource management.

Griffiths (1990) identified the need for a more flexible approach to meeting water resource problems that may arise from climate change. He identified three types of adjustment, which might occur in an incremental manner:

1. Progressive adjustment under current management regimes;
2. Changes in management criteria;
3. Revamping of the system, including major structural solutions.

In relation to drought, and the possibility of drought risk increasing in the future, a range of measures might be considered over time, which are consistent with the types of adjustment identified by Griffiths (1990). These could include:

Short-term (next 10-20 years) measures, such as reviewing policies and plans and identifying low-cost adjustments that could be made to existing drought mitigation measures, focussing particularly on farm management practices, that take into account the possible effects of climate change. In many cases, the encouragement of sustainable land management practices, such as planting of trees for improved catchment protection and water quality, will have flow-on benefits in terms of providing a greater buffer against climatic extremes such as drought, both in the short and longer term.

Medium-term (next 20-50 years) measures, such as developing new policies and plans which provide specific guidelines and regulations for addressing effects of climate change on drought, as well as other regional effects on land and water resources that may be increasingly apparent. For example, there could be a need for increased monitoring and regulation of ground-water use.

Long-term (next 50-100 years) measures are more difficult to specify, but could involve more stringent regulations and structural solutions. Importantly, if a process is established now, which explicitly considers effects of climate change in regional policies and plans, then mechanisms will be established for progressive adaptation to changing conditions in the future. Increasingly over time, such measures should be designed to address the longer-term sustainability of regional resources.

Key Uncertainties and Future Directions

The analysis presented here is far from comprehensive, both in terms of a detailed understanding of possible effects of climate change on drought and in terms of a broader understanding of the likely effects of climate change in different regions of New Zealand.

In terms of the case studies examined here, the following are required to improve understanding of drought effects:

1. an analysis of changes in drought risk, using time series data for selected sites and scenarios of changes in climate variability;
2. a water balance model that incorporates reliable soils data and is linked to crop or land use models, so that the relationship between drought and different land-use practices can be evaluated more fully;
3. coupling of the above information with scenarios of non-climatic change, such as population increases and changes in land use, and developing projections of future demand for water;
4. identifying changes in ground-water as a result of climate change, and the capacity to meet changing demand with irrigation;
5. extension of the capacity to examine regional effects of climate change to other regions in New Zealand.

To broaden the understanding of regional effects and to encourage proactive measures aimed at adaptation, a more integrated approach is required aimed at linking climate change to the broader context of resource management and which takes account of a range of inter-related issues, including: biosecurity, biodiversity, coastal hazards, as well as droughts and floods. To achieve this, there needs to be continued interaction with regional councils.

References

Canterbury Regional Council, (1999). *Looking ahead 1999-2008.* Canterbury Regional Council.

Griffiths, G.A. (1990). Water Resources. In: Ministry for the Environment. *Climatic Change: Impacts on New Zealand, Implications for the Environment, Economy, and Society.* Ministry for the Environment, Wellington.

Harman, J.J. (1999). *Drought hazard and risk within the Waikato region.* Unpublished MSc thesis, University of Waikato.

Horrell, G.A., Dicker, M.J.I., Pilbrow, R.D., and McFall, K.B. (1998). *1997/98 drought in the Canterbury region.* Technical Report U98(31), Environmental Management Group, Canterbury Regional Council.

Houghton, J.T., Meiro Filho, L.G., Callender, B.A., Harris, N., Kattenberg, A., and Maskell, K. (eds.). (1996). *Climate Change 1995: The Science of Climate Change.* Cambridge University Press, Cambridge, United Kingdom.

Kenny, G.J., Warrick, R.A., Mitchell, N., Mullan, A.B., and Salinger, M.J. (1995). CLIMPACTS: An integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography.* 22(4/5), 883-895.

Kenny, G.J., Harman, J.J., Warrick, R.A., Flux, T.L., and Ye, W. (2000a). *CLIMPACTS Description And Users Guide for a Regional Version of the CLIMPACTS system.* IGCI, University of Waikato.

Kenny, G.J., Warrick, R.A., Campbell, B.A., Sims, G.C., Camilleri, M.J., Jamieson, P.D., Mitchell, N.D., McPherson, H.G., and Salinger, M.J. (2000b). Investigating climate change impacts and thresholds: an application of the CLIMPACTS integrated assessment model for New Zealand agriculture. *Climatic Change.* 46(1/2), 91-113.

Ministry for the Environment, (1990). *Climatic Change: Impacts on New Zealand, Implications for the Environment, Economy, and Society.* Ministry for the Environment, Wellington.

Owens, I.F., Kirk, R.M., Bell, D.H., Cowan, H., Pettinga, J., and Todd, D. (1994). *Natural hazards in Canterbury.* Report 94(19), June 1994, Canterbury Regional Council.

Ryan, A.P. (1987). *The climate and weather of Canterbury.* N.Z. Met. Serv. Misc. Publ. 115 (17). New Zealand Meteorological Service, Wellington.

Warrick, R.A., Kenny, G.J., Sims, G.C., Ericksen, N.J., Ahmad, Q.K., and Mirza, M.Q. (1996). Integrated model systems for national assessments of the effects of climate change: Applications in New Zealand and Bangladesh. *Journal of Water, Air and Soil Pollution.* 92, 215-227.

Wilson, D.R., and Salinger, M.J. (1994). Climatic risk for sweet corn production in Canterbury, New Zealand. *New Zealand Journal of Crop and Horticultural Science.* 22, 57-64.

Annex 1:

Climate Data

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The CLIMPACTS system requires a large amount of climate data at both the monthly and daily timescales.

Monthly Base Climatology Data

Long-term monthly averages for temperature (maximum and minimum), rainfall and solar radiation (or sunshine hours) were used to develop spatial climates. The spatial climates used for national application (at a 0.05° lat/lon resolution) in the CLIMPACTS system were developed by Mitchell (1991), by analysing and fitting climate data sets using a smoothing spline method (ANUSPLIN) developed by Hutchinson (1989). In the regional version of CLIMPACTS, the spatial climates were developed by Leathwick and Stephens (1998), again using ANUSPLIN, and are provided at a 0.01° lat/lon resolution. For temperature and rainfall, the 1951-1980 period was chosen as the base period for the climatological averages. For the more limited and broken solar radiation/sunshine record, whatever data available were used.

Although CLIMPACTS presents future changes as “relative to 1990”, the year 1990 is only a nominal starting point. It is not sensible to use data for a single year as a base climatology (a 30-year period is the WMO standard). The period 1951-1980 was chosen in preference to 1961-1990 or some other period because (Kenny *et al.*, 1995):

- This is a relatively stable period in New Zealand climate history;
- It is the period of maximum climate station site coverage by the New Zealand Meteorological Service;
- Global temperatures have increased during the last two decades.

Furthermore, New Zealand went through an abrupt climate “shift” in the late 1970s (Salinger and Mullan, 1999). The base period 1951-1980 was almost entirely within one phase of the Interdecadal Pacific Oscillation, whereas a 1961-1990 climatology would be split across the most recent negative and positive IPO phases.

Daily Data – National and Regional

Daily time series of rainfall, maximum and minimum temperature, and solar radiation data were required for the weather generators and the extreme event analysis tool. Data for 15 sites nationally were produced. Sites were chosen to suit the impact model requirements, such as Te Puke for ‘Hayward’ kiwifruit analysis, and Winchmore for crop modelling, as well as for reliable long-term records. For the regional versions of CLIMPACTS, an extensive search of the NIWA climate database yielded reliable records for 20 sites in each of the Waikato and Canterbury regions, although here only rainfall and temperature were available at the resolution required. Since the data were required with no missing values, gaps in the records of ‘primary’ sites were replaced (with adjustment) from up to 4 ‘secondary’ sites where necessary (Porteous, 1997).

Daily data used are most often for the period 1972-95. A different period to the baseline monthly data was necessary because a suitable density of sites with daily data was not available prior to 1972. Lack of data (particularly solar radiation) at some sites, or inhomogeneities in the observations, meant that shorter periods were used in some cases. This introduces a slight internal inconsistency since there will be some warming between 1951-80 and (say) 1972-95. However, these changes will be small compared typical scenario changes by, say, 2050.

Table A1.1 lists the 15 sites contained in the national version of CLIMPACTS, and summarises some climatological characteristics. The period shown for each site is that period on which the weather generator is tuned to “current” climate.

Table A1.1: Weather statistics for national daily data files. For each site, the monthly averages over the period indicated are shown for: rainfall (mm), number of days with no rain (D_dry), maximum daily temperature (°C), number of days above 25°C (D>25C) and 30°C (D>30C), minimum temperature (°C), number of days below 0°C (D<0C).

Kerikeri 1972-1986

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	115.0	114.6	142.9	154.3	118.8	211.7	181.2	180.3	153.1	141.8	96.6	93.6
	D_dry:	20.0	16.5	15.2	13.4	12.6	9.7	7.8	9.7	9.7	13.4	15.1	17.3
TMax:	Mean:	23.7	24.3	23.1	20.6	18.1	16.2	15.3	15.5	16.5	17.9	19.8	21.8
	D>25C:	7.1	9.3	3.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.2
	D>30C:	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TMin:	Mean:	13.8	14.5	14.3	11.9	9.6	7.9	6.8	7.2	8.0	9.2	11.0	12.4
	D<0C:	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0

Ruakura 1972-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	88.9	65.6	88.0	91.9	100.8	118.9	126.6	115.8	95.1	94.7	91.1	94.3
	D_dry:	20.3	19.1	19.8	17.8	15.1	12.7	13.0	12.8	12.7	14.6	16.3	17.9
TMax:	Mean:	23.8	24.3	22.7	19.9	16.6	14.1	13.6	14.6	16.1	17.9	20.0	22.0
	D>25C:	9.9	10.8	4.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.7
	D>30C:	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tmin:	Mean:	12.6	12.9	11.6	9.1	6.6	4.6	3.9	5.0	6.6	8.3	10.0	11.6
	D<0C:	0.0	0.0	0.0	0.1	1.8	5.1	6.0	3.1	0.8	0.0	0.0	0.0

Te Puke 1973-1994

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	110.9	100.2	172.0	129.4	109.1	181.0	196.3	158.2	159.8	172.6	136.5	154.0
	D_dry:	20.7	18.7	18.8	18.3	18.5	15.8	15.6	14.8	14.4	16.3	17.0	18.6
TMax:	Mean:	23.8	23.7	22.3	19.8	16.8	14.4	14.0	14.8	16.4	18.2	20.0	22.0
	D>25C:	8.6	7.2	2.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.5	2.8
	D>30C:	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TMin:	Mean:	13.2	13.6	12.0	9.4	6.8	5.5	4.5	5.4	6.8	8.6	10.2	11.7
	D<0C:	0.0	0.0	0.0	0.0	0.4	1.5	2.9	0.8	0.2	0.0	0.0	0.0

Gisborne 1972-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	52.8	77.2	101.5	104.5	87.4	106.1	114.5	81.1	98.9	63.6	65.5	66.3
	D_dry:	21.5	17.3	18.3	16.6	17.7	13.8	14.9	15.6	14.8	17.6	18.6	20.1
TMax:	Mean:	25.1	24.4	22.7	20.0	17.3	14.7	14.4	14.9	16.7	18.9	21.4	23.5
	D>25C:	15.6	12.0	7.6	1.0	0.0	0.0	0.0	0.0	0.0	0.7	4.7	10.5
	D>30C:	2.8	1.8	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.0
TMin:	Mean:	13.9	13.9	12.3	9.8	7.0	5.2	5.0	5.4	6.7	8.5	10.6	12.6
	D<0C:	0.0	0.0	0.0	0.0	0.3	1.3	1.4	0.9	0.1	0.0	0.0	0.0

Havelock North 1972-1993

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	33.5	61.9	92.2	72.2	61.4	86.2	89.4	71.7	67.5	46.8	54.8	56.8
	D_dry:	23.3	20.1	20.7	20.7	20.3	17.0	18.2	17.2	17.4	19.9	20.9	21.0
TMax:	Mean:	24.4	23.8	22.2	19.5	16.8	14.3	13.8	14.5	16.5	18.9	20.7	22.7
	D>25C:	13.2	9.5	5.7	1.0	0.1	0.0	0.0	0.0	0.0	1.0	3.3	7.5
	D>30C:	1.5	0.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
TMin:	Mean:	12.5	12.2	10.8	7.6	4.2	2.7	2.3	3.3	5.2	7.4	9.2	11.2
	D<0C:	0.0	0.0	0.1	0.6	5.5	9.1	9.7	7.2	2.4	0.3	0.0	0.0

Table A1.1: (continued)

Whakatu (Napier) 1983-1994

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	34.6	55.0	67.9	52.9	64.9	57.3	95.0	51.6	61.6	51.2	55.2	37.1
	D_dry:	23.4	20.2	20.7	21.1	20.4	18.7	19.9	18.4	17.9	20.6	19.8	22.0
TMax:	Mean:	23.8	23.1	21.7	19.2	16.8	14.6	13.7	14.6	16.1	18.5	20.0	22.3
	D>25C:	10.6	6.5	4.1	0.8	0.1	0.0	0.0	0.0	0.0	0.7	1.9	6.6
	D>30C:	1.1	0.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
TMin:	Mean:	13.0	12.9	10.9	8.0	5.3	3.5	3.0	4.1	5.8	8.1	10.0	12.1
	D<0C:	0.0	0.0	0.0	0.3	1.5	5.9	7.6	4.4	1.6	0.0	0.0	0.0

Waingawa 1984-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	40.7	72.2	88.5	78.4	72.8	102.6	91.8	85.9	81.9	79.5	87.4	59.0
	D_dry:	19.7	17.3	16.1	17.3	15.6	12.0	11.8	12.5	13.3	15.3	16.2	18.5
TMax:	Mean:	24.1	23.7	21.3	18.6	15.5	13.1	12.4	13.3	15.1	17.6	19.4	21.9
	D>25C:	12.8	11.4	5.7	0.4	0.0	0.0	0.0	0.0	0.0	0.1	1.1	6.3
	D>30C:	1.1	0.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
TMin:	Mean:	11.2	11.1	9.7	7.1	4.5	3.4	2.8	3.6	5.0	6.7	8.0	10.3
	D<0C:	0.0	0.0	0.1	0.6	4.3	5.1	7.5	5.7	1.9	0.4	0.3	0.0

New Plymouth 1973-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	107.9	73.4	121.6	135.3	133.6	148.0	157.6	196.0	118.0	114.0	104.3	106.2
	D_dry:	18.8	18.0	18.1	16.0	14.0	12.4	12.2	12.0	12.2	13.9	15.3	17.3
TMax:	Mean:	21.5	22.1	20.8	18.5	15.8	13.9	13.2	13.7	14.8	16.1	17.9	19.8
	D>25C:	1.4	1.9	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
	D>30C:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TMin:	Mean:	13.5	13.6	12.5	10.5	8.4	6.6	5.8	6.5	7.9	9.2	10.6	12.4
	D<0C:	0.0	0.0	0.0	0.0	0.1	0.7	0.8	0.2	0.0	0.0	0.0	0.0

Ohakea 1954-1991

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	66.3	59.7	66.5	68.8	84.3	83.9	86.8	77.1	69.0	76.0	64.5	89.4
	D_dry:	20.9	19.4	20.1	18.1	16.3	15.3	15.6	15.4	15.6	15.9	17.2	18.5
TMax:	Mean:	22.4	22.8	21.5	18.5	15.4	13.1	12.3	13.4	15.0	16.7	18.7	20.7
	D>25C:	5.5	5.9	3.6	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.2	1.6
	D>30C:	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TMin:	Mean:	13.3	13.4	12.3	9.8	7.4	5.5	4.4	5.5	7.1	8.7	10.2	12.0
	D<0C:	0.0	0.0	0.0	0.0	0.2	1.0	1.7	0.5	0.2	0.0	0.0	0.0

Motueka 1972-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	78.3	84.8	107.8	116.6	109.5	129.3	151.2	167.3	118.1	126.5	106.6	104.0
	D_dry:	22.5	20.8	21.7	20.3	20.8	18.5	18.2	17.7	16.6	18.2	18.5	20.8
TMax:	Mean:	23.2	23.1	21.3	18.6	15.7	13.1	12.5	13.5	15.5	17.6	19.7	21.5
	D>25C:	7.0	5.2	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.5	2.8
	D>30C:	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TMin:	Mean:	11.7	11.5	10.0	7.2	4.1	1.8	1.2	2.6	4.8	6.8	8.8	10.8
	D<0C:	0.0	0.0	0.0	0.2	2.5	9.8	11.2	6.2	1.4	0.1	0.0	0.0

Table A1.1: (continued)

Appleby (Nelson) 1972-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	67.9	60.4	75.3	88.3	80.3	88.9	93.5	102.2	82.4	90.7	80.1	77.3
	D_dry:	22.8	21.3	21.7	20.6	20.8	19.4	19.7	18.5	17.0	18.9	18.1	20.3
TMax:	Mean:	22.3	22.4	20.8	18.3	15.4	13.0	12.4	13.3	15.1	16.8	18.7	20.5
	D>25C:	4.1	3.2	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8
	D>30C:	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TMin:	Mean:	12.7	12.7	11.3	8.5	5.4	3.1	2.4	3.7	5.8	7.8	9.6	11.6
	D<0C:	0.0	0.0	0.0	0.0	0.7	5.4	7.1	2.9	0.4	0.0	0.0	0.0

Blenheim 1972-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	45.7	43.6	52.2	57.4	58.3	58.8	69.5	70.3	54.1	57.9	48.2	55.2
	D_dry:	24.1	22.1	22.3	22.5	22.1	19.7	20.3	19.2	19.0	20.1	20.5	22.4
TMax:	Mean:	23.8	23.3	21.6	18.9	15.9	13.2	12.8	13.8	15.8	18.0	19.9	21.8
	D>25C:	12.1	9.6	5.1	0.5	0.0	0.0	0.0	0.0	0.0	0.6	1.8	6.3
	D>30C:	1.4	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
TMin:	Mean:	12.5	12.1	10.8	7.9	5.0	2.5	2.0	3.3	5.5	7.5	9.5	11.4
	D<0C:	0.0	0.0	0.0	0.2	2.0	8.1	9.8	4.9	1.4	0.3	0.0	0.0

Lincoln 1960-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	55.6	47.5	59.5	58.8	56.2	63.8	68.5	63.6	45.4	47.6	55.1	56.2
	D_dry:	21.5	19.5	20.7	19.3	18.4	16.6	17.3	18.6	19.5	20.1	19.7	20.0
TMax:	Mean:	22.4	21.9	20.0	17.4	13.9	11.5	10.8	12.0	14.0	16.7	18.3	20.2
	D>25C:	8.6	6.4	4.3	1.2	0.0	0.0	0.0	0.0	0.0	0.7	2.2	5.2
	D>30C:	2.0	2.1	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
TMin:	Mean:	11.2	11.0	9.8	6.7	3.9	1.8	1.6	2.3	4.0	6.2	7.7	10.0
	D<0C:	0.0	0.0	0.1	1.0	4.4	9.8	10.1	8.2	3.6	1.0	0.2	0.0

Winchmore 1972-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	52.9	53.8	65.0	62.3	60.3	61.5	62.3	73.2	59.6	66.0	54.2	65.2
	D_dry:	21.1	18.4	20.9	19.7	21.5	20.1	20.0	19.6	20.0	20.3	20.1	19.5
TMax:	Mean:	22.3	21.7	19.7	17.0	13.4	10.6	10.2	11.6	13.8	16.2	18.3	20.2
	D>25C:	8.9	6.7	3.7	0.6	0.0	0.0	0.0	0.0	0.0	0.3	1.8	4.5
	D>30C:	1.4	1.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
TMin:	Mean:	10.4	10.4	8.9	6.3	3.3	1.2	0.7	2.1	3.7	5.6	7.4	9.3
	D<0C:	0.0	0.0	0.1	0.7	4.8	11.8	13.4	8.5	3.1	0.9	0.2	0.0

Gore 1967-1995

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain:	Mean:	109.6	76.0	86.7	77.5	92.1	69.2	64.0	62.4	70.3	81.2	69.9	96.0
	D_dry:	13.4	14.4	13.8	13.6	11.2	12.4	13.7	14.8	13.0	13.1	13.4	13.9
TMax:	Mean:	18.9	18.8	17.3	14.8	11.5	8.9	8.7	10.7	12.6	14.3	16.1	17.9
	D>25C:	2.4	2.3	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4
	D>30C:	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TMin:	Mean:	9.3	8.8	7.9	5.8	3.5	1.4	0.9	2.1	3.7	5.3	6.7	8.5
	D<0C:	0.0	0.0	0.1	0.9	4.1	9.8	11.5	7.1	1.9	0.6	0.3	0.0

References

Hutchinson, M.F. (1989). A new objective method for spatial interpolation of meteorological variables from irregular networks applied to the estimation of monthly mean solar radiation, temperature, precipitation and windrun. *CSIRO Division of Water Resources Technical Memorandum.* 89/5, 95-104.

Kenny, G.J., Warrick, R.A., Mitchell, N., Mullan, A.B., and Salinger, M.J. (1995). CLIMPACTS: An integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography.* 22, 883-895.

Leathwick, J.R., and Stephens, R.T.T. (1998). *Climate surfaces for New Zealand.* Landcare Research Contract Report: LC9798/126.

Mitchell, N.D. (1991). The derivation of climate surfaces for New Zealand, and their application to the bioclimatic analysis of the distribution of kauri (Agathis australis). *Journal of the Royal Society of New Zealand.* 21, 13-24.

Porteous, A. (1997). *CLIMPACTS 1996/97: Daily climate data for the CLIMPACTS research programme.* NIWA Internal Report WLG97/19, May 1997.

Salinger, M.J., and Mullan, A.B. (1999). New Zealand climate: temperature and precipitation variations and their link with atmospheric circulation 1930-1994. *Int. J. Climatol.* 19, 1049-1071.

Annex 2:
Scenario Methodology – GCMs and Downscaling

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GCM Data

There are currently seven global climate model (GCM) patterns available for selection, identified as: Greenhouse 94 Rank 2 and Rank 4, DARLAM, CCC, CSIRO9, HadCM2 and Japan. The first three of these patterns come from equilibrium GCM simulations, where a comparison is made between a current climate control run and a doubled carbon dioxide run. A number of other equilibrium GCM patterns used by earlier versions of CLIMPACTS have now been removed from the CLIMPACTS database. The Greenhouse 94 patterns have been retained as the most recent widely publicised "official" scenarios of New Zealand climate change (Mullan, 1994; Whetton *et al.*, 1996). The DARLAM scenario has been retained because it is the only example to date of a New Zealand climate change scenario generated from a high resolution regional climate model nested within a GCM (Renwick *et al.*, 1998).

The other four GCM patterns are from more recent transient simulations. Two of these, CSIRO9 and HadCM2, are the focus of the CLIMPACTS National Assessment Report. This section provides some technical background on the source of the model data and the downscaling methodology. Figures A2.1 to A2.5 show the precipitation and mean temperature patterns, averaged over winter (April-September) and summer (October-March) half-years for the Greenhouse Rank2 and 4, DARLAM, CCC and Japan scenarios. Diagrams for the other two scenarios, CSIRO9 and HadCM2, are given in the main report (Figures 2.7 and 2.8 in Chapter 2). All changes are normalised by the global warming, as simulated by each model.

The two Greenhouse 94 scenarios are composites generated from five equilibrium GCM simulations, and were prepared for the 1994 Australian and New Zealand Greenhouse Conference (Whetton *et al.*, 1996). The GCMs used were: the CSIRO9-level model, the Australian Bureau of Meteorology Research Centre model, the Canadian Climate Centre model, the U.S. Geophysical Fluid Dynamics Laboratory high resolution model, and the United Kingdom Meteorological Office high resolution model. For all five models, the "$2xCO_2$ – Control" differences were separately downscaled (see section on downscaling) onto a high resolution grid over New Zealand, and the changes then ranked from lowest (Rank 5) to highest (Rank 1). At each gridpoint, the second lowest (Rank 4) and second highest (Rank 2) values were selected to form the composite scenario. This procedure, which duplicated what was done for Australia by CSIRO, thus shows the range of possibilities, where the extreme high and low values are treated as "outliers" and omitted from consideration. Thus, for example, the Rank 4 precipitation pattern shows the second most negative precipitation change - which may actually be positive if at least four of the five models show precipitation increases at the gridpoint in question.

The DARLAM scenario (named from CSIRO Division of Atmospheric Research Limited Area Model) comes from a double nesting of a limited area high resolution model into the CSIRO 9-level GCM (a later version from the one for Greenhouse 94, but still an equilibrium model). The model setup and control run is described in Renwick *et al.* (1998) and the New Zealand climate change results in Renwick *et al.* (1999). In this case, the downscaling is done dynamically instead of statistically, and the high resolution output from these runs was imported directly into the CLIMPACTS system.

The more recent transient climate model data have been downloaded from the IPCC website (http://www.dkrz.de/ipcc/ddc/) where climate simulation results for a number of coupled atmosphere-ocean general circulation models (AOGCMs) are archived. This so-called IPCC Data Distribution Centre (IPCC DDC) contains global monthly–average fields for at least seven AOGCMs for a selection of climate variables, and for various forcing emissions scenarios.

For the purposes of CLIMPACTS, the data downloaded pertain to the "1% greenhouse gas plus sulphate" emissions scenarios, where atmospheric concentration of sulphate in the GCM was specified with time, and the carbon dioxide concentration followed historical observations up to 1989, and was thereafter compounded at 1% annually. This arbitrary imposition of a 1% per annum growth in future greenhouse gas concentrations is fairly close to the IS92a scenario, one of six alternative emissions scenarios published in the 1992 Supplementary Report to the IPCC Assessment (Leggett *et al.*, 1992).

Four models on the IPCC DDC site provided simulations through to 2099 - CCC from the Canadian Centre for Climate Modelling and Analysis, Japan from the Japanese Centre for Climate Study Research, CSIRO9 from the Australian Commonwealth Scientific and Industrial Research Organisation, and HadCM2 from the U.K. Hadley Centre for Climate Prediction and Research. Table A2.1 lists these models, and some information about them. Other model characteristics can be found from the IPCC website and key references. For two of the AOGCMs, CCC and HadCM2, ensemble runs were available, but only the first ensemble member was used. (Ensemble simulation means that a number of runs were performed with identical forcing (changes in CO2, sulphate, etc), but with conditions initialised from different periods in the control run).

Table A2.1: Model characteristics of the four AOGCMs used.

Model	**Resolution**	**Resolution**	**# Land Pts**	**Reference**
	# GridPts	**Lon° x Lat°**	**N.Z.**	
CCC	96x48	3.75 x 3.71	1	Flato *et al.* (2000)
CSIRO9	64x56	5.625 x 3.19	2	Gordon and O'Farrell (1997)
HadCM2	96x73	3.75 x 2.5	3	Mitchell and Johns (1997)
Japan	64x32	5.625 x 5.54	0	Emori *et al.* (1999)

Downscaling

The statistical downscaling procedure applied to all the equilibrium GCM results was first described in detail in Mullan and Renwick (1990). The method involves defining a set of equations that describe how observed New Zealand climate variations relate to observed "large-scale" circulation and climate variables, and then applying these equations to the climate model output for a changed climate.

Monthly rainfall and mean temperature data for 32 New Zealand stations, for the 30-year period 1957-87, were first "summarised" in terms of principal component (PC) patterns – 6 for rainfall, and 5 for temperature. Then, for each PC pattern, a screening regression analysis was carried out, to relate the PC time series to a set of 35 predictors – 31 of these being for mean sea level pressure (MSLP), either grid-point anomalies or coefficients of 6 MSLP PC patterns over the region 30°-50°S by 150°E-170°W. The remaining four predictors were "island-averages" (a North Island and South Island) of the station rainfall and temperature anomalies. Only significant predictors were retained in the regression equations. These regression equations were then applied, separately for each month of the year and for control ($1xCO_2$) and doubled-CO_2 simulations, to the GCM data, viz: gridpoint MSLP, and area averages of precipitation and temperature over regions approximating the North and South Islands. The predicted PC coefficients of the difference ($2xCO_2$ – $1xCO_2$) were then transformed back to station changes, and interpolated over New Zealand.

Mullan and Renwick (1990) experimented with different sets of predictors before deciding on the above approach. The results appeared quite reasonable, although there is always a danger when extrapolating regression equations beyond the range of values upon which they were calculated. This applies particularly to temperature, since the doubled CO_2 temperature increases in the model were larger than any observed interannual temperature anomalies. Indeed, the downscaled rainfall scenarios have a tendency to look like precipitation anomalies one would associate with warm northerly situations.

The statistical downscaling of the transient model output followed a similar procedure in that regression equations derived from observations were then applied to model output data (Mullan *et al.*, 2000). Observed monthly rainfall and temperature data for 92 and 58 New Zealand stations, respectively, were used. Three large-scale meteorological fields were used: atmospheric mean sea level pressure, surface air temperature, and total precipitation. The observational data came from NCEP reanalyses; the model data were taken from the transient simulation and a long "control" integration with constant carbon dioxide. In the case of coupled ocean-atmosphere climate models, taking the difference between the transient and control runs minimises the effect of long-term trends that may occur due to the ocean temperatures not being in balance with the implied ocean heat fluxes.

In the downscaling approach, we assume the GCM simulates the correct change in precipitation and temperature away from New Zealand (the "background" or large-scale change). Close to the country, orography distorts the pattern. The regression equations specify how the deviation of precipitation or temperature from the longitudinal average (across 160°E-170°W), at the same latitude as the climate station, relates to indices of meridional and zonal flow (which in turn are derived from MSLP gradients, observed and model). This downscaling method is more robust than that of Mullan and Renwick (1990), because by using deviations from the average background changes, the future deviations remain within the observed range of interannual variability. The main effect on the resulting regression equations is from the changes in westerlies. An increasing southerly flow over the New Zealand region will, of course, tend to reduce temperatures (or at least minimise the global warming signal locally), but this effect will be present in the background latitudinal fields. Stronger westerlies increase precipitation in the west of the country, and reduce it in eastern areas; temperatures tend to increase more in eastern areas, although this is seasonally dependent. For example, in summer when New Zealand land temperatures are higher than upwind sea temperatures, increasing westerlies reduce the land-sea difference.

Further details can be found in Mullan *et al.* (2000). Mitchell *et al.* (1999) discuss general issues associated with generating scenarios from transient model output. In particular they describe how the model changes should be weighted with time, if a single value (a "change per degree global warming") is required, which is the situation with CLIMPACTS. If the transient simulation generates changes that are non-linear in time, these are effectively smoothed over or even eliminated. An example of this happening is with the CSIRO9 results. This model shows westerly winds increasing over southern New Zealand out to about 2050, and thereafter decreasing, so the average MSLP change over 1990-2100 shows little amplitude (and is the reason the CSIRO9 scenario, Figure 2.8 in Chapter 2, has little geographic structure to it).

Discussion of Scenario Patterns

Figures A2.1 to A2.5, and Figures 2.7 and 2.8 in Chapter 2 of the main report, show the scenario patterns of precipitation and mean temperature change per degree of global warming for the seven available scenario options. Changes are shown for winter (April to September) and summer (October to March) half-years separately. The sectoral impact models concentrate on just two of the scenarios – the CSIRO9 transient and HadCM2 transient – but the other model results are summarised here to illustrate the large uncertainty that exists in future climate change scenarios. Note that the contoured precipitation changes are mapped at either 2% (for most cases) or 5% (where strong rainfall gradients are indicated, as in winter for HadCM2 and Japan).

The precipitation scenarios in the transient models (CCC, CSIRO9, HadCM2 and Japan) all generally suggest an increase in gradient across the country – with the wet western regions getting wetter and the drier eastern regions getting drier. However, there is considerable difference between models in the magnitude of the changes, which in turn are related to model westerly wind changes. The equilibrium scenarios (Greenhouse 94 and particularly DARLAM) have greater precipitation increases in eastern parts of New Zealand.

The temperature scenarios all show New Zealand warming at a slower rate than the globe (i.e., values less than 1.0°C). The transient models generally have less warming locally than the equilibrium ones and, in some cases, have greater regional structure to the temperature changes. Scenarios for maximum and minimum temperature were also produced, but are not discussed here.

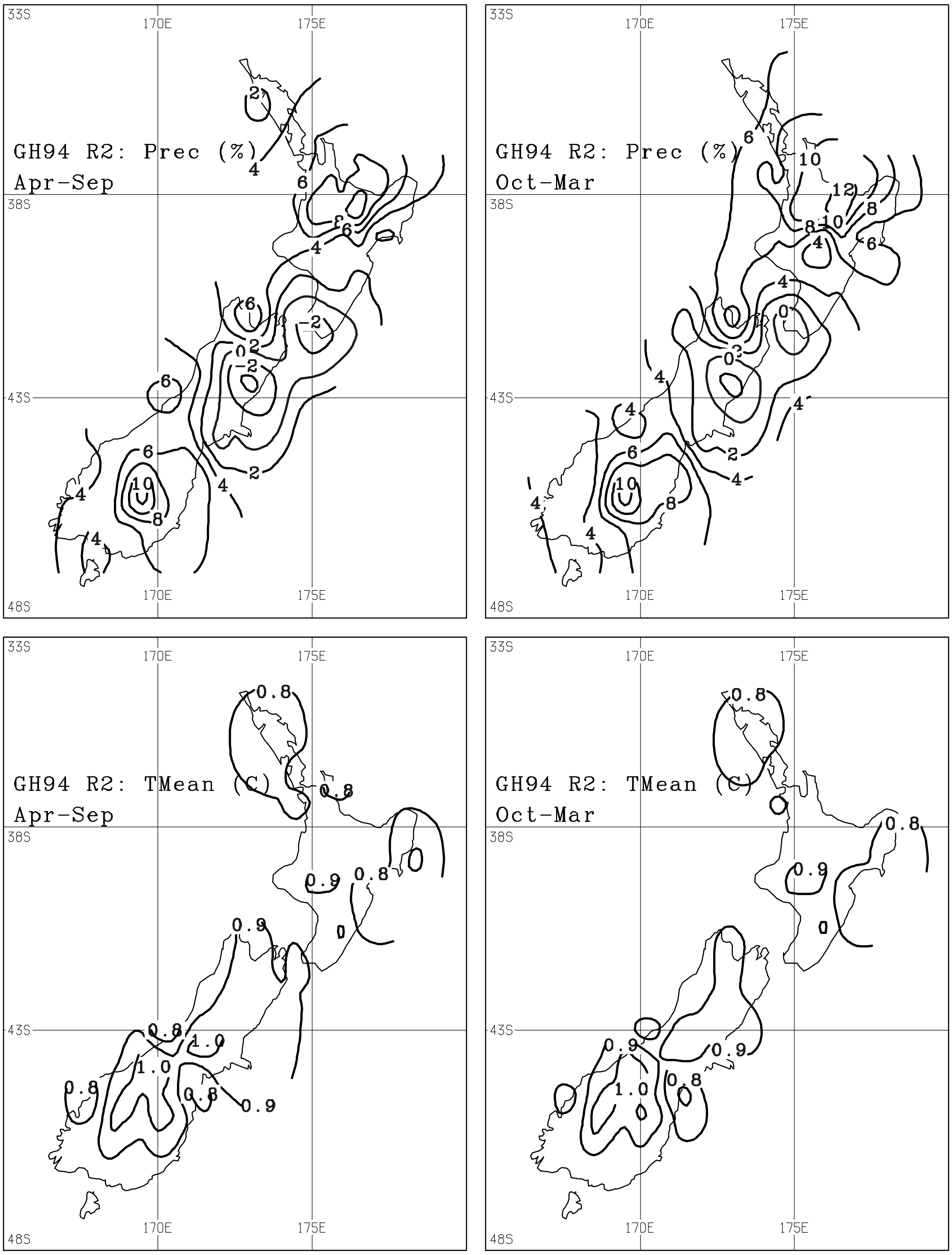

Figure A2.1: Greenhouse 94 Rank 2 changes per degree global warming, for precipitation (upper panels, contours in %) and mean temperature (lower panels, contours every 0.1°C): Winter (Apr-Sep), left-hand panels; Summer (Oct-Mar), right-hand panels.

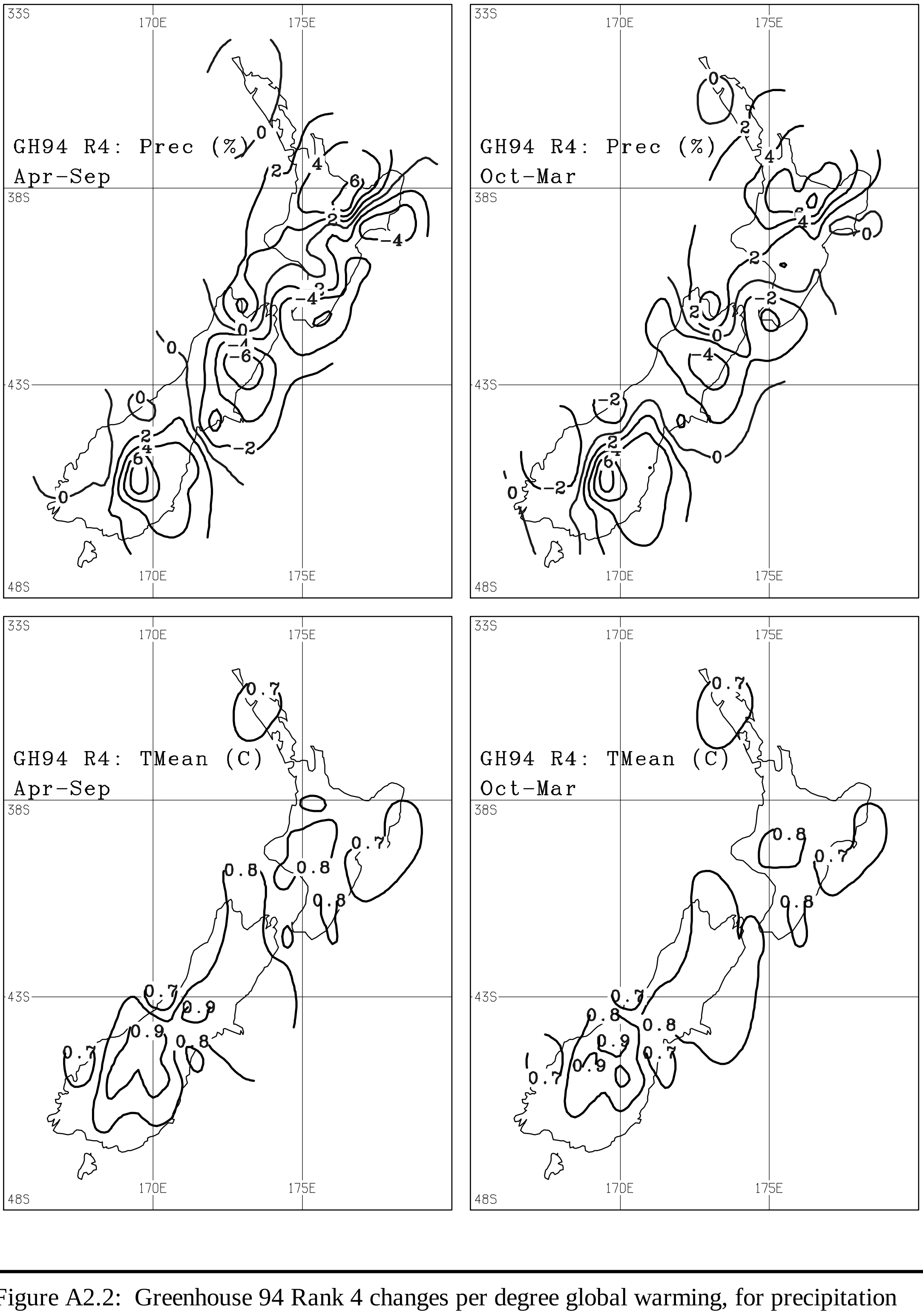

Figure A2.2: Greenhouse 94 Rank 4 changes per degree global warming, for precipitation (upper panels, contours in %) and mean temperature (lower panels, contours every 0.1oC): Winter (Apr-Sep), left-hand panels; Summer (Oct-Mar), right-hand panels.

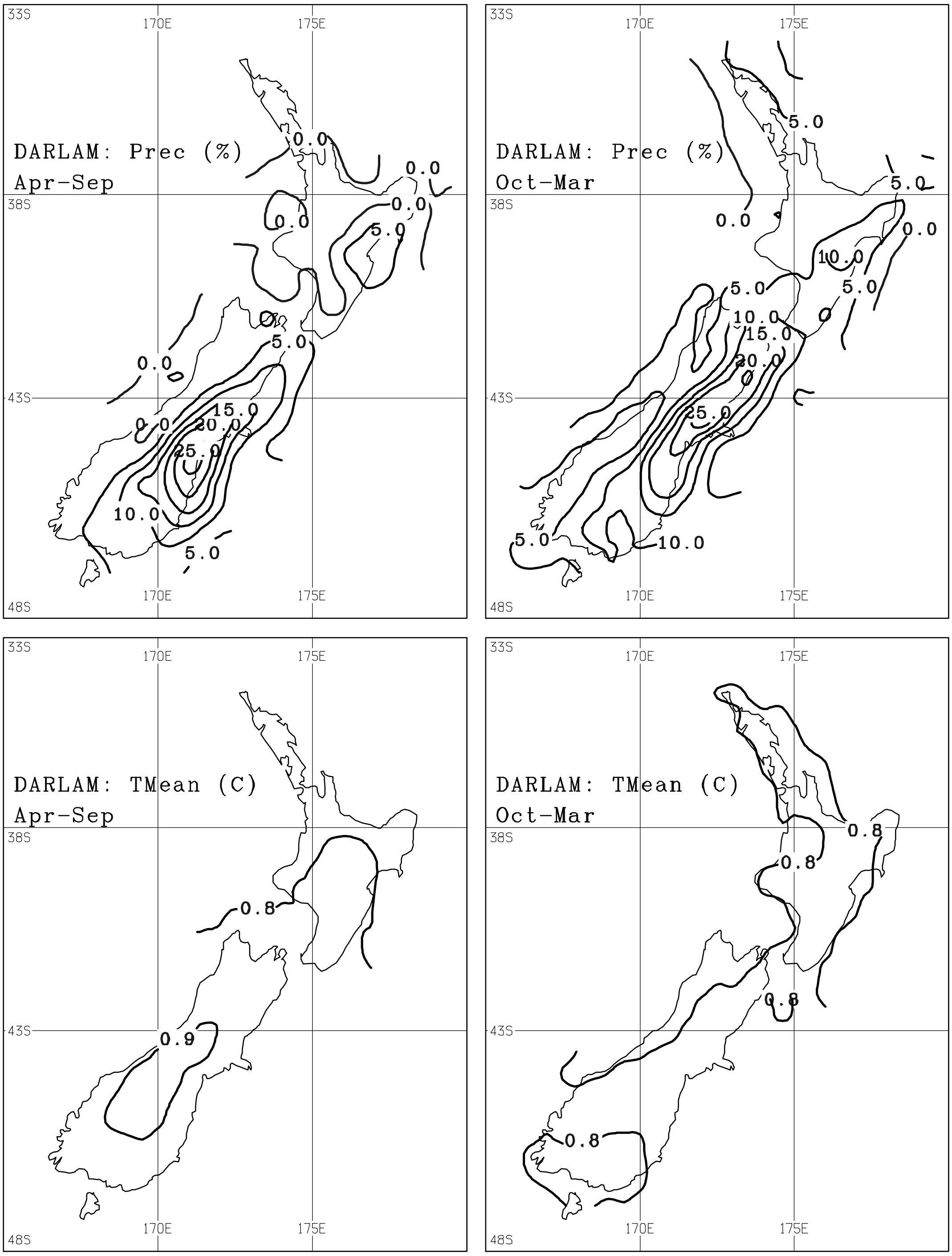

Figure A2.3: DARLAM changes per degree global warming, for precipitation (upper panels, contours in %) and mean temperature (lower panels, contours every 0.1°C): Winter (Apr-Sep), left-hand panels; Summer (Oct-Mar), right-hand panels.

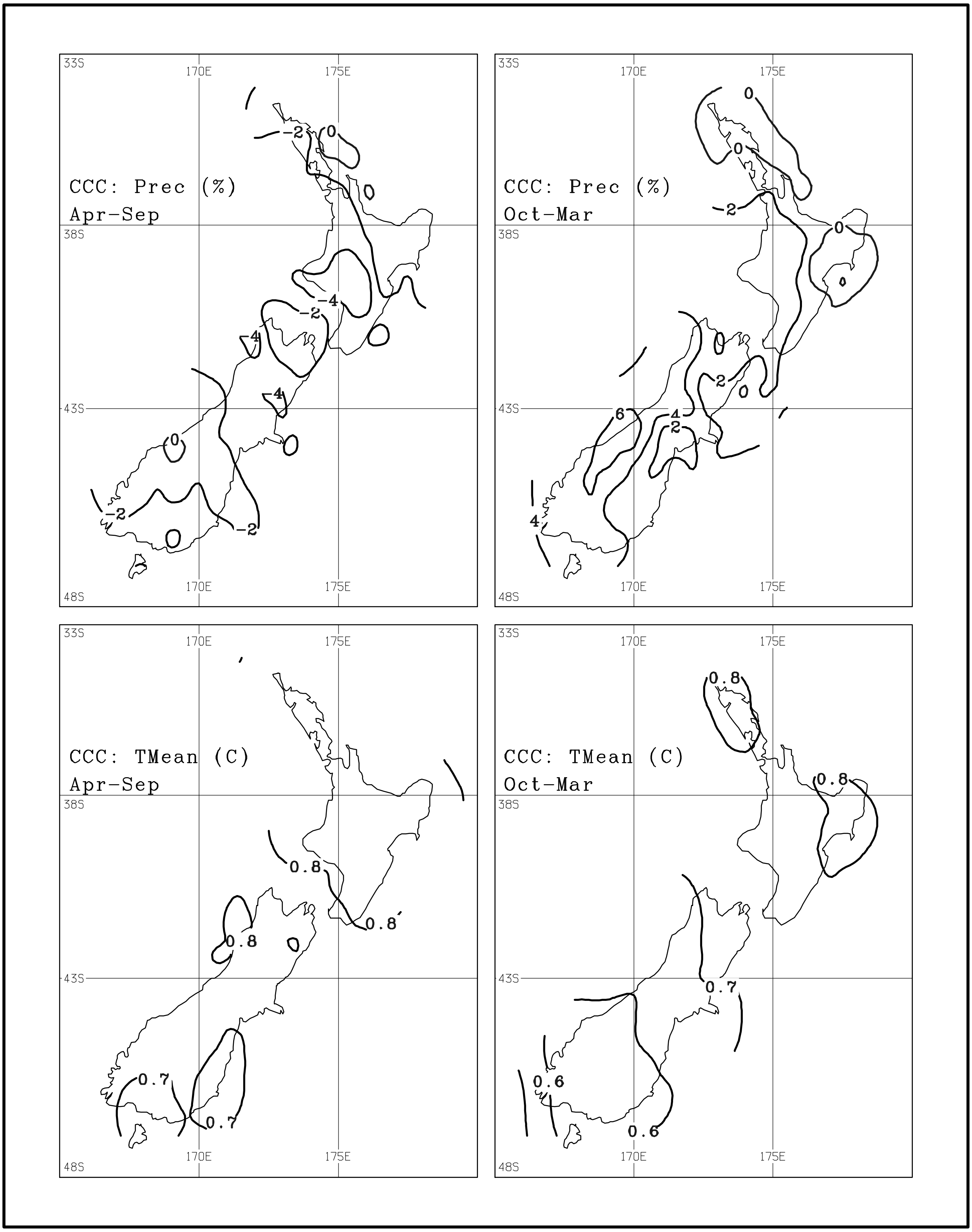

Figure A2.4: CCC model downscaled changes per degree global warming, for precipitation (upper panels, contours every 2%) and mean temperature (lower panels, contours every 0.1^{o}C): Winter (Apr-Sep), left-hand panels; Summer (Oct-Mar), right-hand panels.

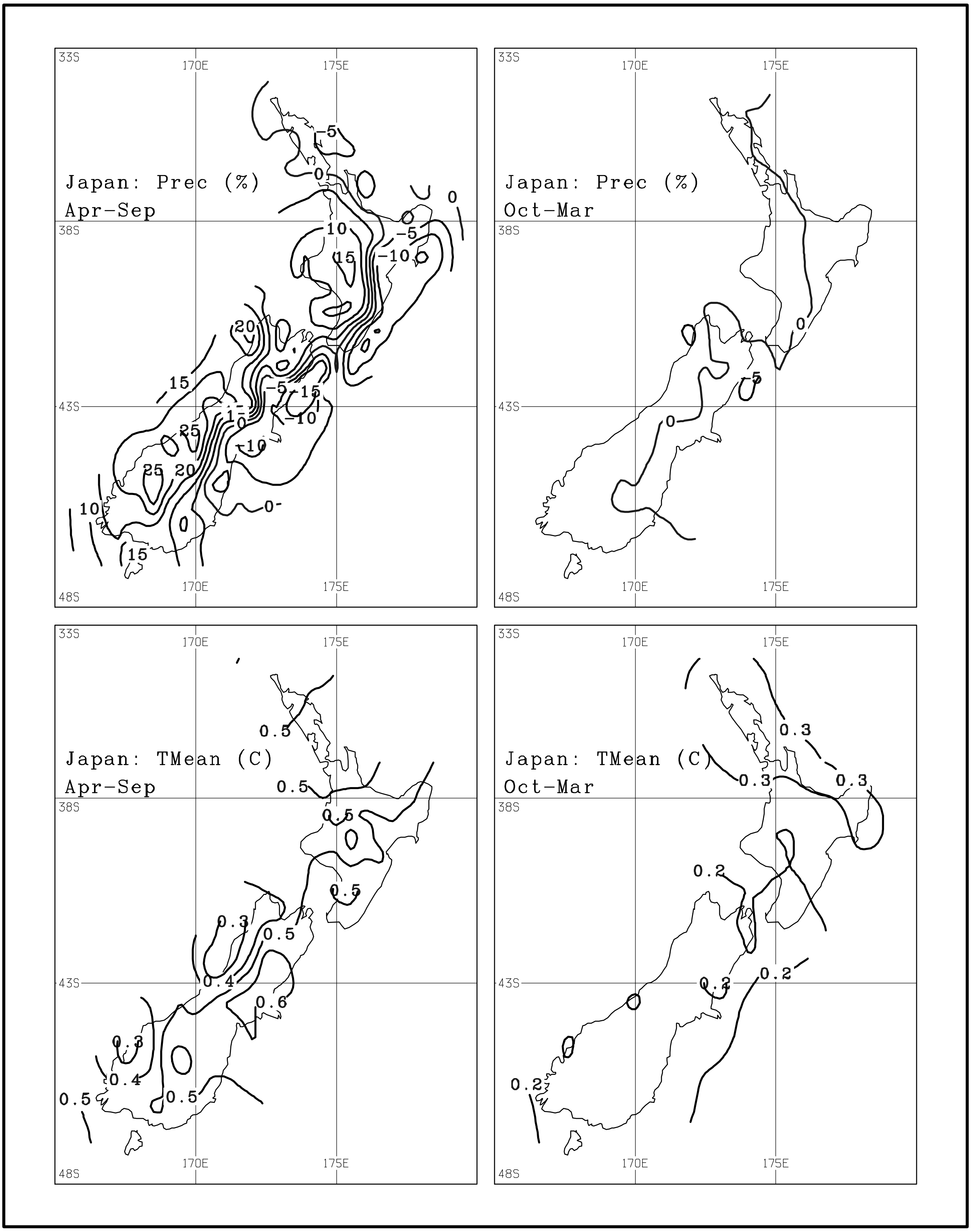

Figure A2.5: Japan model downscaled changes per degree global warming, for precipitation (upper panels, contours in %) and mean temperature (lower panels, contours every 0.1°C): Winter (Apr-Sep), left-hand panels; Summer (Oct-Mar), right-hand panels.

References

Emori, S., Nozawa, T., Abe-Ouchi. A., Numaguti, A., Kimoto, M., and Nakajima, T. (1999). Coupled ocean-atmosphere model experiments of future climate changes with an explicit representation of sulfate aerosol scattering. *J. Meteorol. Soc. Japan.* 77, 1299-1307.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C., and Weaver, A.J. (2000). The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate. *Climate Dynamics.* 16, 451-467.

Gordon, H. B., and O'Farrell, S.P. (1997). Transient climate change in the CSIRO coupled model with dynamic sea ice. *Mon. Wea. Rev.* 125, 875-907.

Leggett, J., Pepper, W.J., and Swart, R.J. (1992). Emissions scenarios for the IPCC: an update. In: J.T. Houghton, B.A. Callander, and S.K. Varney (Eds.). *Climate change 1992: the supplementary report to the IPCC scientific assessment.* Cambridge Univ. Press, Cambridge. 75-95.

Mitchell, J.F.B., Johns, T.C., Eagles, M., Ingram, W.J., and Davis, R.A. (1999). Towards the construction of climate change scenarios. *Climatic Change.* 41, 547-581.

Mullan, A.B. (1994). *Climate change scenarios for New Zealand: Statement for Greenhouse '94.* NIWA Climate Internal Report No. 94-004, August 1994. 9 pp.

Mullan, A.B., and Renwick, J.A. (1990). *Climate change in the New Zealand region inferred from general circulation models.* N.Z. Meteorological Service report, 1990. 142 pp.

Mullan, A.B., Wratt, D.S., and Renwick, J.A. (2000). *Transient model scenarios of climate change for New Zealand..* (in prep.).

Renwick, J.A., Katzfey, J.J., Nguyen, K.C., and McGregor, J.L. (1998). Regional model simulations of New Zealand climate. *J. Geophys. Res.* 103, 5973-5982.

Renwick, J.A., Katzfey, J.J., McGregor, J.L., and Nguyen, K.C. (1999). On regional model simulations of climate change over New Zealand. *Weather and Climate.* 19, 3-14.

Whetton, P., Mullan, A.B., and Pittock, A.B. (1996). Climate change scenarios for Australia and New Zealand. In: W.J. Bouma, G.I. Pearman, and M. Manning (Eds.). *Greenhouse '94: Coping with Climate Change.* CSIRO/DAR, Melbourne. 145-168.

Annex 3:
Weather Generators

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Structure of Weather Generators

Several weather generator algorithms have been developed for CLIMPACTS (Thompson and Mullan, 1995, 1997), based on techniques described in the literature (Richardson, 1981; Racsko *et al.*, 1991). These weather generators have been incorporated into the CLIMPACTS model framework, and are used by the various impacts models to generate daily time series of weather elements to assess crop responses.

The daily weather elements simulated by the CLIMPACTS weather generators are precipitation occurrence and amount, maximum temperature, minimum temperature and solar radiation. The choice of this set of weather variables is motivated by their common use in many crop response models (Wilks, 1992). One of the most widely used models is the Richardson (1981) model. In this weather generation model, daily precipitation occurrence is represented as a two-state first-order Markov process, with transition probabilities parameters p_{01} (probability a wet day follows a dry day) and p_{11} (the probability a wet day follows a wet day).

To provide a method for making prescribed adjustments to the baseline (or current) climate, it is convenient to express these probabilities in terms of two parameters:

$$d = p_{11} - p_{01}$$

which is the lag-1 autocorrelation for the precipitation occurrences (i.e., its persistence), and

$$\pi = p_{01}/(1 - d)$$

which is the long-term climatological probability of a wet day. Precipitation amounts on wet days are characterised by a gamma distribution, with parameters α (shape) and β (scale or precipitation intensity). Separate sets of the four precipitation parameters (p_{01}, p_{11}, α, β) are fitted to the local historical data for each calendar month or any other suitable period, and their seasonal cycle is represented from a Fourier series analysis using annual and semi-annual cycles. The product $\alpha\beta$ is equal to the average daily precipitation on wet days at the site.

The maximum temperature, minimum temperature and solar radiation are represented as a first-order multi-variate autoregressive model:

$$x(t) = [A]x(t-1) + [B]\,\varepsilon(t)$$

where the parameter matrices [A] and [B] reflect the serial and cross-correlation of the variables, the ε's are independent normal variates with a $N(0, \sigma_\varepsilon^2)$ distribution. The x's are normalised residuals (i.e. N(0,1) distribution) conditional on whether the day is wet or dry according to;

$$x_k = (X_k - \mu_{kj})/\sigma_{kj}; \qquad k = 1, 2, 3;\ j = 0, 1$$

where X_k is the actual daily value of the k^{th} weather variable. For each weather variable, separate means and variances (standard deviations) are used for dry (j=0) and wet (j=1) days. The seasonal variation in the model parameters is determined from a Fourier series analysis using daily climate data.

Simulation of Future Climate

The weather generator simulations access a file of pre-determined parameters for the site in question. These parameters are "fitted" initially to a sequence of observed daily data (i.e., current climate). A procedure whereby the weather generator parameters can be adjusted to represent future climate scenarios is described in Thompson and Mullan (1999). The detailed adjustment procedures are applicable only to the Richardson weather generator.

There are two basic ways in which scenario information on climate change might be provided to the CLIMPACTS system. By far the most common way is to have climate change information specified only for the monthly timescale: e.g., monthly average temperature increase for a particular year. Many different scenarios are available for selection by the user: e.g., an observational change scenario based on a "more El Niño-like future", a paleoclimate analogue, or a GCM-based scenario. There is insufficient information in the monthly changes to fully determine the new parameters that describe weather interactions on the daily timescale. Additional user-supplied constraints must be specified in order to calculate the weather generator parameters for a changed climate.

Scenario information might also be available directly at the daily timescale as, for example, output from a nested GCM (DARLAM) simulation (Salinger and Mullan, 1997). These model daily data could be used directly to tune the weather generator parameters for either present or future climates.

Thompson and Mullan (1999) provided a "recipe" to adjust the weather generator parameters for changes in monthly mean temperature and precipitation under future climates. The method followed Wilks (1992), who exploited the strong link between daily and monthly weather data, as provided by the statistical properties of the distributions of the averages and variances of the daily data. Daily parameters, describing the present-day (or baseline GCM output) climate at a location, are then adjusted in a manner that is consistent with the imposed changes in the climate from the output of GCM integrations. Any changes in variances can be entered manually as an option when the CLIMPACTS Richardson weather generator is run for a future climate.

Validation of the Richardson Weather Generator

Weather generators have been extensively validated in a number of overseas studies (Wallis and Griffiths, 1995; Johnson *et al.*, 1995). In the New Zealand context, Thompson and Mullan (1995) validated the Richardson weather generator ("WXGEN") at a number of sites. Thompson and Mullan (1997) compared the Richardson model with other weather generators supplied to the CLIMPACTS system. Statistical tests of simulated output were based on comparisons with historical data, taking into account the differences in sample size. Tests of monthly and annual means and variances of precipitation amount and frequency, temperature and radiation were performed using t and F tests respectively. Sequences of wet and dry spells and threshold exceedances of temperature were tested with a chi-square test. Significance levels were calculated for these three statistical tests, to see well how observed variations were being simulated.

An example for Lincoln, comparing 42 years of observations with 30 years of simulated daily data, is given in Table A3.1. Details of the intercomparisons will of course differ for other simulations (with a different starting "seed" for the random number generator) because of the stochastic nature of the model, but the results shown in this table are fairly typical. For the mean values (rainfall, rainday frequency, maximum and minimum temperature), the test statistic (tval, Fval) is given below each sub-table, along with significance levels. A small probability

(Pr_t, Pr_F) indicates a significant difference between the historical and simulated time series and hence, by implication, the simulation is poor. For runs of specific weather characteristics (dry days, wet days, days above 25°C, days below 0°C), the chi-square statistic and its associated probability is shown. Tables for other sites, and for varying length of simulation are shown in Thompson and Mullan (1995), although note that the chi-square statistic is not calculated correctly in that publication.

Table A3.1 shows that mean values are well simulated but that interannual variances are frequently underestimated. For example, for rainfall the t-value of the differences can be positive or negative but is significantly different from zero at the 5% level in only one month; on the other hand, the F-value of the ratios is always greater than one, and significantly so on 6 of 13 occasions. This bias is carried forward into the impacts models, and results in yield predictions, for example, being less variable from year to year than observational data or experience would indicate.

Simulated sequences of wet and dry days match the observed record well, whereas simulation of extreme temperature sequences is less successful. For high temperature days (maximum > 25°C), the table shows the weather generator has too many "singleton" days above the threshold and too few consecutive extreme days (chi-square statistic significant at 0.02), even though the average number of hot days overall is realistic. There is a similar bias for low temperature days (minimum < 0°C), although for Lincoln it is not significant (probability of 0.18).

Table A3.1: Evaluation of simulated time series using the weather generator WXGEN for Lincoln (1950-1991) for a simulation period of 30 years. Statistics are calculated on differences in the means (tval), ratios of the mean variances (Fval), and differences in sequences of "runs" (Chi). Low values of associated significance probabilities (Pr_t, Pr_F, Pr_X, respectively) indicate a poor match between simulation and observed. See text for further explanation, and Thompson and Mullan (1995) for additional tables.

Rainfall (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Observed													
Mean	58.2	52.7	64.8	63.0	64.8	60.4	70.5	62.2	41.0	52.5	57.2	59.8	707.3
Std	39.3	35.0	40.9	49.8	38.2	35.5	36.3	40.7	28.7	31.1	31.4	32.9	158.7
Simulated													
Mean	49.1	51.7	73.7	61.7	71.4	60.7	51.4	66.1	49.6	57.6	52.8	59.1	705.0
Std	23.5	30.0	52.8	30.6	25.3	18.7	17.6	29.2	20.6	30.3	29.1	27.1	110.5
tval	1.23	0.13	-0.80	0.14	-0.88	-0.04	2.96	-0.44	-1.41	-0.69	0.60	0.10	0.07
Pr_t	0.22	0.89	0.42	0.89	0.38	0.97	0.00	0.66	0.16	0.49	0.55	0.92	0.94
Fval	2.79	1.36	1.67	2.66	2.28	3.59	4.24	1.93	1.94	1.05	1.17	1.48	2.06
Pr_F	0.00	0.39	0.13	0.01	0.02	0.00	0.00	0.07	0.06	0.90	0.67	0.27	0.04

Rainday frequency

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Observed													
Mean	9.3	8.5	10.3	10.8	13.1	12.9	13.9	12.7	9.6	10.8	10.7	11.0	133.6
Std	3.1	3.1	3.6	4.6	3.4	3.9	3.3	4.4	3.9	3.3	3.3	3.2	16.7
Simulated													
Mean	9.2	8.4	9.5	10.1	13.3	13.2	12.4	12.7	10.9	10.5	10.1	11.0	131.3
Std	3.5	2.9	2.9	3.4	3.2	3.0	3.0	3.5	3.1	2.8	3.9	3.3	10.3
tval	0.21	0.14	1.06	0.76	-0.20	-0.32	1.92	-0.03	-1.50	0.39	0.66	-0.07	0.74
Pr_t	0.83	0.89	0.29	0.45	0.84	0.75	0.06	0.97	0.14	0.70	0.51	0.94	0.46
Fval	1.25	1.14	1.52	1.86	1.15	1.65	1.18	1.64	1.56	1.40	1.37	1.00	2.63
Pr_F	0.50	0.73	0.24	0.08	0.70	0.16	0.65	0.17	0.21	0.34	0.34	0.98	0.01

Runs of dry days

```
Observed (1950-1991: 15340 days)
    1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  20+
  689 472 347 297 184 164 110  79  57  45  27  19  23  14   5   6   3   4   4   2   7

Simulated (30 years: 10950 days)
    1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  20+
  530 336 254 219 147  85  91  62  42  19  30  16  14   6   8   7   5   2   1   0   3

 Chi     df    Pr_X
 32.33   26    0.18
```

Runs of wet days

```
Observed (1950-1991: 15340 days)
    1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  20+
 1158 647 343 191  87  65  32  18   5   4   3   1   2   1   0   0   0   0   0   0   0

Simulated (30 years: 10950 days)
    1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  20+
  899 458 252 135  50  30  34  12   3   2   0   0   0   0   1   0   0   0   0   0   0

  Chi     df    Pr_X
  18.44   14    0.19
```

Maximum temperature (C)

```
          Jan   Feb   Mar   Apr   May   Jun   Jul   Aug   Sep   Oct   Nov   Dec   Ann
Observed
  Mean   22.4  22.1  20.1  17.4  13.9  11.5  10.7  12.0  14.2  16.8  18.5  20.1199.7
  Std     1.6   1.4   1.2   1.2   1.2   1.0   0.8   1.2   1.8   1.5   1.7   1.3   6.9

Simulated
  Mean   21.5  22.1  20.2  17.2  13.7  11.3  10.8  12.1  14.2  16.5  18.3  20.7 198.6
  Std     1.3   1.0   1.0   1.2   1.0   0.8   0.8   0.9   0.8   1.1   1.4   1.0   3.4

  tval   2.47  0.17 -0.37  0.60  0.61  1.07 -0.45 -0.49 -0.01  0.94  0.70 -1.92  0.95
  Pr_t   0.02  0.86  0.72  0.55  0.54  0.29  0.65  0.62  0.99  0.35  0.49  0.06  0.35
  Fval   1.37  1.98  1.36  1.04  1.51  1.35  1.04  1.81  4.78  1.67  1.34  1.91  4.18
  Pr_F   0.38  0.06  0.39  0.89  0.25  0.40  0.93  0.10  0.00  0.15  0.42  0.07  0.00
```

Frequency temperature > 25C

```
         Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Ann
Observed
  Mean   8.5  7.3  4.2  1.3  0.1  0.0  0.0  0.0  0.0  0.8  2.4  4.7 29.3
  Std    3.4  2.9  2.4  1.7  0.3  0.0  0.0  0.2  0.0  1.6  2.1  2.6  7.6

Simulated
  Mean   7.5  6.8  4.9  0.8  0.0  0.0  0.0  0.0  0.1  0.8  2.0  5.0 27.9
  Std    3.3  2.4  2.3  1.0  0.2  0.0  0.0  0.0  0.3  1.1  1.8  2.5  5.0
```

Runs of temperatures > 25C

```
 Observed (1950-1991: 15340 days)
     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  20+
   474 196  58  30   6   2   2   2   0   0   0   0   0   0   0   0   0   0   0   0   0

Simulated (30 years: 10950 days)
     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  20+
   369 111  32  13  14   2   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0

  Chi     df    Pr_X
  18.70    8    0.02
```

Minimum temperature (C)

```
        Jan    Feb    Mar    Apr    May    Jun    Jul    Aug    Sep    Oct    Nov    Dec    Ann
 Observed
   Mean  11.0   11.0    9.7    6.6    3.8    1.6    1.3    2.0    3.8    6.1    7.6    9.8   74.3
   Std    1.4    1.0    1.3    1.3    1.2    1.1    1.0    1.2    1.1    1.0    1.1    1.3    6.9

 Simulated
   Mean  10.9   11.1    9.4    7.1    3.4    1.8    1.0    2.4    4.1    5.7    7.5    9.8   74.1
   Std    0.9    1.0    1.1    1.3    1.3    0.9    0.9    0.9    0.8    0.8    1.1    0.7    3.5

   tval  0.23  -0.57   0.92  -1.36   1.15  -0.73   1.35  -1.36  -1.31   1.74   0.41   0.18   0.10
   Pr_t  0.82   0.57   0.36   0.18   0.25   0.47   0.18   0.18   0.20   0.09   0.68   0.86   0.92
   Fval  2.30   1.01   1.29   1.07   1.25   1.44   1.41   1.89   1.95   1.48   1.09   3.10   3.95
   Pr_F  0.02   0.98   0.48   0.87   0.51   0.31   0.34   0.08   0.06   0.27   0.78   0.00   0.00
```

Frequency temperature < 0C

```
        Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Ann
 Observed
   Mean  0.0  0.0  0.1  1.1  4.9 10.2 10.9  9.2  4.2  1.2 0.4  0.1 42.3
   Std   0.2  0.0  0.4  1.3  2.8  4.0  4.3  3.8  2.7  1.6  0.8  0.3 11.8

 Simulated
   Mean  0.0  0.0  0.2  1.0  5.4  8.6 11.6  6.6  3.4  1.4  0.5  0.1 38.9
   Std   0.2  0.0  0.5  1.3  3.5  3.5  3.7  3.0  2.0  1.2  0.8  0.3  7.8
```

Runs of temperatures < 0C

```
 Observed (1950-1991: 15340 days)
     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  20+
   528 221 104  42  22  17   7   5   3   0   0   0   0   0   0   0   0   0   0   0   0

 Simulated (30 years: 10950 days)
     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  20+
   399 140  71  26  13   7   9   0   0   0   0   0   0   0   0   0   0   0   0   0   0

  Chi     df    Pr_X
  11.33    8    0.18
```

References

Johnson, G.L., Hanson, C.L., Hardegree, S.P., and Ballard, E.B. (1995). Stochastic weather simulation: Overview and analysis of two commonly used models. *J. Applied Meteorology.* 35, 1878-1896.

Kenny, G.J., Warrick, R.A., Mitchell, N., Mullan, A.B., and Salinger, M.J. (1995). CLIMPACTS: An integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography.* 22, 883-895.

Racsko, P., Szeidl, L., and Semenov, M.A. (1991). A serial approach to local stochastic weather models. *Ecological Modelling.* 57, 27-41.

Richardson, C.W. (1981). Stochastic simulation of daily precipitation, temperature and solar radiation. *Water Resources Research.* 17, 182-190.

Richardson. C.W., and Wright, D.A. (1984). *WGEN: A model for generating daily weather variables.* U.S. Department of Agriculture, Agricultural Research Publication, ARS-8. 83 pp.

Salinger, M.J., and Mullan, A.B. (1997). *CLIMPACTS 1996/97: Climate change and variability scenarios for temperature, rainfall and sunshine, based on observed changes and a nested GCM.* NIWA Report AK97083, July 1997.

Semenov, M.A., and Barrow, E.M. (1997). Use of a stochastic weather generator in the development of climate change scenarios. *Climate Change.* 32, 293-311.

Thompson, C.S. (1995). *CLIMPACTS 1995/96: Stochastic simulation of daily rainfalls with Markov chain models.* NIWA Report. 25 pp.

Thompson, C.S. (1997). *CLIMPACTS 1997/98: Statistical evaluation of simulated and historical time series of daily data.* NIWA Internal Report No. 10, November 1997.

Thompson, C.S., and Mullan, A.B. (1995). *CLIMPACTS 1995/96: Intercomparison of stochastic weather generators.* NIWA Internal Report. 35 pp.

Thompson, C.S., and Mullan, A.B. (1997). *CLIMPACTS 1997/98: Models for generating daily weather variables.* NIWA Internal Report No. 4, August 1997. 99 pp + floppy disk.

Thompson, C.S., and Mullan, A.B. (1999). *CLIMPACTS 1998/99: Applying the Richardson weather generator to climate change studies.* NIWA Internal Report No. 55, June 1999. 17 pp.

Wallis, T.W.R., and Griffiths, J.F. (1995). An assessment of the weather generator (WXGEN) used in the erosion/productivity impact calculator (EPIC). *Agriculture for Meteorology.* 73, 115-133.

Wilks, D.S. (1992). Adapting stochastic weather generation algorithms for climate change studies. *Climate Change.* 22, 67-84.

Annex 4:
Kiwifruit Models

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Time of Budbreak

We use the model of Hall and McPherson (1997a), in which a state variable *S*, set to zero on day D_0, is incremented each day according to the weather. Budbreak occurs on the day when $S>=1$. Each day, the state variable is incremented by

$$dS = (1 - w(S))\,c(T) + w(S)\,h(T)$$

where *c(T)* and *h(T)* are "chilling" and "warming" responses respectively, and *w(S)* is a weighting function which changes from 0 to 1 as *S* progresses from 0 to 1, given by

$$w(S) = \frac{(1+e^{-0.5k})}{(1+e^{-k(S-0.5)})}\frac{(1-e^{-kS})}{(1-e^{-k})}$$

The chilling function when the daily mean temperature is T °C is given by

$$c(T) = \begin{cases} c_1(T_{hi} - T)(T - T_{lo}), & T > T_1 \\ 0, & \text{otherwise} \end{cases},$$

and the warming function is simply the usual "degree-day" response

$$h(T) = \begin{cases} r(T_{hi} - T_{\text{base}}), & T > T_{\text{base}} \\ 0, & \text{otherwise} \end{cases}.$$

The original model was developed using half-hourly temperature data, but was reparameterised for this application to use maximum and minimum temperatures only. Parameter values used here are D_0=1 April, k=4, T_{hi}=18.2, T_{lo}=-250, C_1=0.00001187, r=0.0001829, T_0=2.45, and T_{base}=5.4

Time of Flowering

The time from budbreak to flowering is described by McPherson *et al.* (1992) as a linear response to temperature, with a state variable S_1 set to zero at budbreak and accumulating daily according to

$$dS_1 = -0.0124 + 0.00205T\,,$$

where T is the mean temperature for the day. Flowering occurs when *S* reaches 1. McPherson *et al.* (1992) point out that this relationship does not hold well when the winter had been particularly warm so budbreak is spread out over a long period, but a model taking winter temperatures into account has yet to be developed.

Time of Maturity

Hall and McPherson (1997b) found that late-season temperatures had a major effect on the time of commercial maturity (6.2 °brix) in 'Hayward' kiwifruit. The soluble solids level (SS) is assumed to start at 4.5 °brix a_0 days after flowering, then accumulate by

$$dSS = K(a - a_0)^p e^{-lT} dt$$

after time dt at temperature T, where a is the "age" of the fruit (time since flowering). Parameter values fitted were a_0=90 days, K=0.00126, l=0.185, and p=1.424. This model was developed using half-hourly temperatures, and in order to apply using daily maxima and minima we applied here an (unpublished) interpolation procedure in which the daily temperature distribution is described by a daylength-dependent quadratic between the minimum and maximum. The relative proportion of time y spent at proportion x of the way between the maximum and minimum is given by

$$y = y_0 + k(x - x_0)^2$$

where x_0 = 0.716-0.0134*Daylength, y_0 = 0.598, and k is chosen so the daily integral is 1. This method works well when maxima and minima are half-hourly averages, but has not been tested for robustness when using maxima and minima from standard meteorological sites.

The models outlined above enable us to predict the dates of budbreak, flowering, and maturity for 'Hayward' kiwifruit. However, these dates are not of themselves indicators of whether this crop will flourish in a particular climate. Of more importance are various quantitative measures of crop performance, which can be estimated by accumulation of appropriate weather variables between pairs of these dates. Two important indicators of crop performance are the number of "king" flowers per winter bud (KFWB), and the proportion of the fruit which is dry matter (i.e. not water) (DM%). While fruit size is also important, the relationship between fruit size and climate is complex (Hall *et al.*, 1996) and useful models have not been developed.

"Natural" Flowering

An approximately linear relationship exists between the number of flowers produced and the proportion of the development due to chilling in (1) above. If CHTOT is the total accumualted "chilling", i.e. the sum of daily increments

$$d\mathrm{CHTOT} = (1 - w(S))\,c(T)\,,$$

then the number of flowers per winter bud is given approximately by

$$\mathrm{KFWB} = \begin{cases} 0, & \mathrm{CHTOT} < 0.762 \\ -8.45 + 11.09 * \mathrm{CHTOT}, & \text{otherwise} \end{cases}.$$

Flowering Following HC Application

Based on data collected in a survey between 1996 and 1998, we estimate that for canes treated with HC the relationship should instead be approximately:

$$\mathrm{KFWB}_{\mathrm{HICANE}} = \begin{cases} 0, & \mathrm{CHTOT} < 0.693 \\ -6.30 + 9.09 * \mathrm{CHTOT}, & \text{otherwise} \end{cases}.$$

This means that $\mathrm{KFWB}_{\mathrm{HC}}$ will exceed the threshold of 1.0 when KFWB is less than 0.5, and when KFWB is about 1.0, $\mathrm{KFWB}_{\mathrm{HC}}$ is about 1.45.

Annex 5:
Pasture Yield Model

H. Clark and P.C.D. Newton
AgResearch Grasslands

Pasture yields in CLIMPACTS were estimated using a model based on the mechanistic physiological model of pasture growth developed at Hurley by Johnson and Thornley (1983, 1985). It was developed originally to explore the relationship between temperature, radiation and growth in vegetative swards amply supplied with moisture and nutrients. Modification to the model means that it now also takes into account the influence of (1) atmospheric CO_2 concentration on photosynthesis and assimilate partitioning, (2) reproductive development on sward processes and (3) variable moisture supply.

Reproductive development has been incorporated by assuming that the timing and duration of reproductive development are a function of temperature and photoperiod. Growth within the reproductive period is then enhanced by increasing the maximum light saturated rate of photosynthesis. A very simple approach has been taken towards incorporating the influence of soil moisture into the model. A soil water balance based on the Priestley Taylor method is calculated and at a critical soil water deficit the maximum rate of photosynthesis is reduced linearly. Elevated atmospheric CO_2 concentrations increase the maximum rate of photosynthesis and partition more carbon below ground, especially in dry conditions. Thus the partitioning of assimilates between above and below ground has been made a function of both CO_2 and soil moisture status.

Model Validation

Output obtained using daily meteorological records from Hawera, Invercargill and Winchmore has been compared to data obtained from cutting trials at these sites. At all sites fertility was assumed to be non-limiting. Quantitative data for soil moisture holding capacity was not available, although in broad terms it was known to be lower at Winchmore than at the other two sites. Values of 75mm for Winchmore and 100mm for Invercargill and Hawera were used when modelling dry matter yields. As can be seen from Figure A5.1, modelled and actual monthly yields were generally in good agreement, with r^2 values being 0.92, 0.97 and 0.96 for Hawera, Invercargill and Winchmore respectively. The largest differences between predicted and measured yields occurs in the late summer – autumn period and perhaps indicates that the simple water model used in the model is not adequate in all situations. The response of pasture yields to elevated CO_2 is an integral part of this assessment but it is an area where lack of experimental data constrains any testing of modelled outcomes.

Site Locations for the Pasture Growth Model

Data requirements of the model (temperature, solar radiation and rainfall) mean that a pre-requisite for any site was that it must have a reliable long term weather record that included either direct measurements of solar radiation or measurements of sunshine hours. This placed severe restrictions on the potential number of sites and only 13 sites met these requirements. The final choice of sites was therefore a compromise between obtaining a good geographical and climatic spread. The sites chosen were Gisborne, Gore, Kerikeri, New Plymouth and Winchmore.

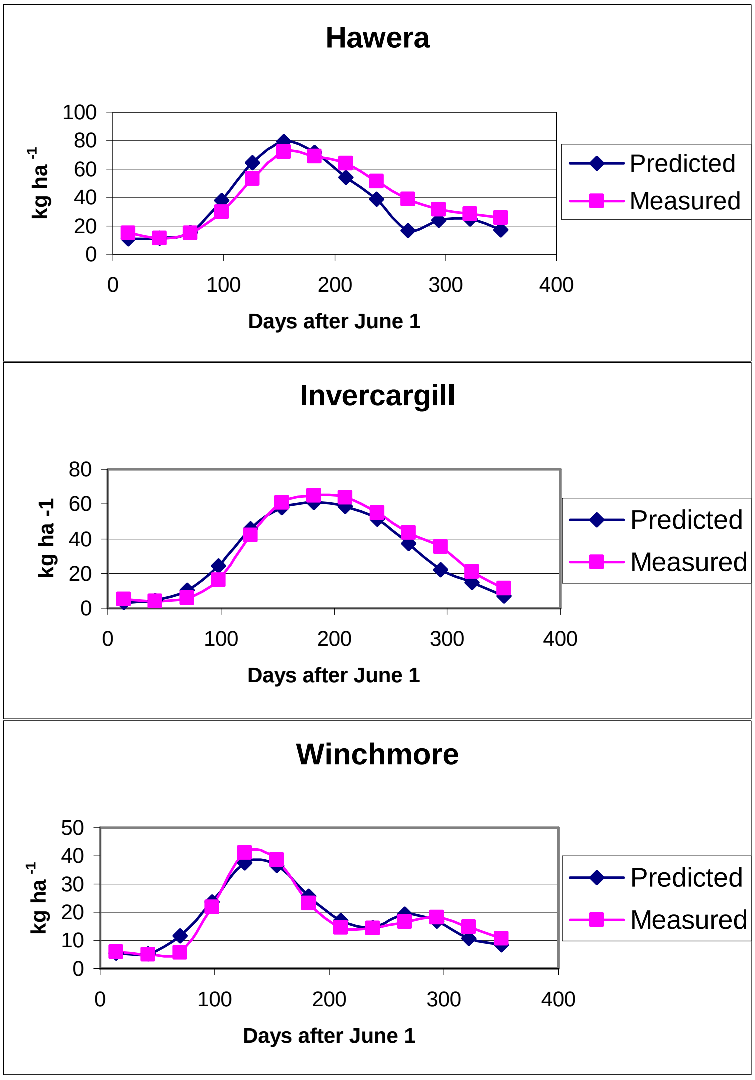

Figure A5.1: Modelled versus measured monthly dry matter yields at three sites.

Assumptions at all Locations

The parameter values used in the model runs are the same at the five locations with no attempts made to 'tune' the model to obtain a better fit to any existing data pasture yield data for the site. Model output is therefore confined to examining differences arising from the influence of climate, not differences due to soil factors. In broad terms the assumed site characteristics are best described as high fertility with medium soil water holding capacity.

Site Details

Table A5.1: Summary climatic data (1951-1980, NZ Met Service 1983) for the five sites used in the pasture yield analysis.

Location	**Annual Rainfall**	**Av. Max Temp**	**Av.MinTemp**
Gisborne	1058	19.2	8.8
Gore	1025	15.6	5.0
Kerikeri	1682	20.1	10.0
New Plymouth	1539	17.1	9.9
Winchmore	753	16.1	5.3

References

Johnson, I.R., and Thornley, J.H.M. (1983). Vegetative crop growth model incorporating leaf area expansion and senescence, and applied to grass. *Plant, Cell and Environment.* 6, 721-729.

Johnson, I.R., and Thornley, J.H.M. (1985). Dynamic model of the response of a vegetative grass crop to light, temperature and nitrogen. *Plant, Cell and Environment.* 8, 485-499.

This document has been produced as part of the CLIMPACTS Programme, which is funded by the New Zealand Foundation for Research, Science and Technology (FRST). For further copies of this publication, or copies of related publications, please contact:

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ISBN 0-473-07988-7