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FINE RESOLUTION ASSESSMENT OF ENHANCED GREENHOUSE CLIMATE CHANGE IN VICTORIA

Annual Report 1997-98

CLIMATE AVERAGES AND VARIABILITY BASED ON A TRANSIENT CO_2 SIMULATION

Research undertaken for the
Department of Natural Resources and Environment

by

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FOREWORD

Climate change could have significant impacts on important resources in Australia. Changes in rainfall and temperature patterns, and in the frequency of extreme events, could affect water resources, coastal environments, native flora and fauna, agriculture and forestry. It is therefore important that governments have access to the best possible information on likely future climate scenarios to help plan for, and adapt to, changed climatic conditions.

The Victorian Government is therefore supporting a program of research by the CSIRO Division of Atmospheric Research with the aim of developing regional climate change scenarios for Victoria. Work undertaken during 1995-96 and 1996-97 involved the development of scenarios for temperature and precipitation at a horizontal resolution of 60 km. These scenarios were presented for 'control' (1 x CO_2) and 'enhanced greenhouse' (2 x CO_2) conditions and for the years 2030 and 2070. Changes in climatic variability under enhanced greenhouse conditions were also analysed. This 1995-97 work was based on results obtained using CSIRO's limited area model (DARLAM) nested in a global climate model with a simplified ocean.

In 1997-98, an updated version of DARLAM has been nested in a new CSIRO global climate model coupled to a more realistic ocean model. A gradual increase in greenhouse gas concentrations has been used in a 140-year simulation of climate from 1961 to 2100. This report describes the resulting changes in temperature and rainfall averages, variability and extremes over Victoria.

This new simulation represents a major advance in climate change research, and the resulting scenarios are rather different from those produced in the previous two years. A range of possible changes in temperature and rainfall is presented to allow for major uncertainties in estimating the extent of global warming. Because of these uncertainties, the scenarios cannot be considered to be 'forecasts'; rather they describe a range of possible climate change outcomes, and provide a starting point for studies to assess the regional impacts of climate change.

Subsequent research will involve further analysis of the results from this simulation to examine the implications of climate change for water resources.

PETER SUTHERLAND
Executive Director
Catchment & Water Division

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Scientists from the Climate Modelling Program of CSIRO Atmospheric Research developed and provided data from the CSIRO coupled ocean-atmosphere climate model. In particular the experiment used for nesting DARLAM was conducted by Martin Dix.

Observed climate data were supplied by the Australian Bureau of Meteorology National Climate Centre. The gridded precipitation data set for September 1972 to August 1992 was supplied by the Queensland Department of Primary Industries.

This work is funded by the Victorian Department of Natural Resources and Environment and contributes to the CSIRO Climate Change Research Program.

GLOSSARY

1xCO_2	Describes a climate simulation of a global climate model under conditions of present-day (or sometimes pre-industrial) atmospheric concentration of carbon dioxide.
2xCO_2	Describes a climate simulation by a global climate model in which the atmospheric concentration of carbon dioxide is instantaneously doubled from the equivalent of a present-day (or sometimes pre-industrial) concentration, and the atmosphere has been allowed to come to equilibrium after responding to the increase in carbon dioxide.
coupled	Term used to describe global climate models which use a full ocean model ‘coupled’ to an atmospheric model (in contrast to a ‘slab ocean’)
DARLAM	Division of Atmospheric Research Limited Area Model
ENSO	El Niño – Southern Oscillation
El Niño	Dry phase of the El Niño – Southern Oscillation variability in Australia
GCM	Global Climate Model
IPCC	Intergovernmental Panel on Climate Change
limited-area model	Climate model run over a limited (i.e. non-global) geographical region or domain
slab ocean	Term used to describe global climate models which use a simplified ocean model in which there is no deep ocean (in contrast to a ‘coupled’)

EXECUTIVE SUMMARY

Background

Human activities will continue to increase greenhouse gas concentrations in the atmosphere over the next 50 to 100 years. A doubling of pre-industrial carbon dioxide levels during the second half of the 21st century is almost certain. Such changes to the composition of the atmosphere are predicted to lead to global warming, resulting in climate change and sea level rise. Regional changes will affect a range of sectors making adaptation necessary. In recognition of this, the Victorian Department of Natural Resources and Environment has funded CSIRO Atmospheric Research to develop climate change scenarios for Victoria to assist the Government and the community to plan for climate change. This report describes the results of research undertaken in the fourth year of an ongoing research project aimed at providing fine resolution climate change scenarios for Victoria.

The research project

The research is based upon climate simulations using two CSIRO climate models — a coarse resolution global model and a fine resolution regional model. The regional model (DARLAM – Division of Atmospheric Research limited area model) requires input data from the global climate model (GCM). DARLAM has been formulated to focus on south-eastern Australia, with a grid resolution of 60 km. This allows the development of detailed scenarios of climate change which are suitable for use in regional impact assessments.

The research reported in this report builds upon three previous years of modelling work with DARLAM at 125 km resolution (1994-95) and at 60 km resolution (1995-96, 1996-97). In the previous work, DARLAM was nested in a GCM with a simplified ocean, and short duration simulations were undertaken (ten to twenty years). Results from this work are reported in Whetton et al. (1997) and Whetton et al. (2000a,b). This year (1997-98), an updated version of DARLAM was nested in a new CSIRO GCM coupled to a more realistic ocean model. A realistic gradual increase in greenhouse gas concentrations was used in a 140-year simulation of climate from 1961-2100. Changes in temperature and rainfall averages, variability and extremes over Victoria are described in this report.

The results

The experiment performed this year represents a major step forwards in regional climate change research and is the longest duration experiment of its type in the world. Improvements in the CSIRO GCM and DARLAM, and the extended duration of the run, have led to scenarios which are rather different from those produced in the first two years. A *range* of possible changes in temperature and rainfall is given to cover the range of quantifiable uncertainty in two factors: (i) future greenhouse gas emissions and (ii) the sensitivity of simulated warming to a doubling of carbon dioxide concentration.

By 2050, the DARLAM simulation for Victoria indicates the following:

Temperature

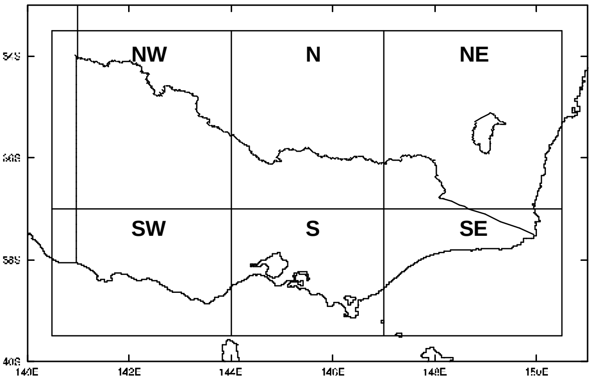
- a warming of 0.5 to 2.2°C.

Rainfall

- north of the Divide, wetter conditions in summer, drier conditions in winter and spring;
- south of the Divide, drier in spring and little change in the other seasons;
- northern and northwest regions (statistically significant)
  4-14% wetter in summer
  4-14% drier in spring;
- southwest, southern and southeast regions (statistically significant)
  2-8% drier in spring;
- otherwise negligible change in average rainfall.

Extreme events

- number of hot summer days over 35 °C
  10 to 120% more;
- number of frosty winter days below 0 °C
  10 to 60% fewer;
- number of extremely wet summers
  doubles in the northwest and northern regions;
- number of winter droughts
  doubles in the northern region;
- number of spring droughts
  doubles in all regions except the southeast;
- extreme daily rainfall intensity and frequency
  increases substantially in many regions, particularly in summer and autumn.



Map 1: Six Victorian regions used

In summary, Victoria becomes 0.5 to 2.2°C warmer by 2050, with more hot summer days and fewer frosty winter days. In the north, rainfall increases in summer and decreases in winter and spring. In the south, rainfall decreases in spring with little change in the other seasons. The number of spring droughts doubles throughout the state except in the southeast, and the number of wet summers doubles in the north. Extreme daily rainfall events become more intense and more frequent in many regions.

Uncertainty

Although the science of regional climate modelling is rapidly developing, many uncertainties still remain. We have included quantifiable uncertainty in the Victorian scenarios where possible. However, other sources of uncertainty remain. For example, changes in sulfate aerosol pollution (which would occur mainly in the northern hemisphere) may affect climate in Australia. This pollution has not yet been included in the CSIRO modelling studies for Victoria although (based on preliminary modelling results) the impact is not expected to be large.

The current results represent a plausible future scenario, rather than a firm prediction. We have less confidence in the rainfall scenarios than the temperature scenarios for a few reasons, such as:

- Climate (particularly rainfall) in the Australian region is likely to be very sensitive to the oceanic response to enhanced greenhouse conditions, and ocean modelling is less well developed than atmospheric modelling.

- Our confidence in the simulation of El Niño – Southern Oscillation behaviour and its impact on Australian climate is not yet high.
- Natural climatic variability at the yearly-to-decadal time scale may partially (or wholly) mask enhanced greenhouse changes in climate for some decades, both in the model and in the real world. This variability introduces significant uncertainty into the projection of regional climate change, particularly for rainfall.
- Drier conditions (especially in winter) appear to be more strongly evident in a number of other GCMs than in the CSIRO GCM. This suggests that if DARLAM was nested in other GCMs we may obtain drier enhanced greenhouse climates than reported here, thus placing the current DARLAM results towards the wetter end of conceivable results.

Implications of climate change and future research

Climate change over Victoria has the potential to significantly affect many aspects of the natural and managed environment such as biodiversity, agriculture, water resources, health, coastal activities, forestry, fire danger, built infrastructure, transport and communication. A recent IPCC assessment of regional impacts of climate change in Australia (Basher and Pittock, 1998) indicates high vulnerability for ecosystems, hydrology, and some coastal zones. Moderate vulnerability applies to human settlements and health, and net impacts are unclear for forestry and fisheries. In the next 30-50 years, some agricultural enterprises like wheat may be able to adapt and possibly even expand production, but vineyard and orchard enterprises may find adaptation to inadequate chilling more difficult. In the longer term, agricultural vulnerability increases.

Future research directions should include application of DARLAM scenarios in impact studies which assess potential risks, benefits, and adaptation strategies. This could be undertaken for the following areas: water resources, coastal activities, fire danger, ecosystems, forestry, health, snow cover and agriculture. Further analysis of the output of the current DARLAM run and other GCM results would also be desirable, with a particular focus on soil moisture change and climatic variability associated with the El Niño – Southern Oscillation.

CONTENTS

Page

LIST OF FIGURES

Page

LIST OF FIGURES (cont.)

LIST OF TABLES

1. BACKGROUND

Introduction

Water vapour, carbon dioxide and other greenhouse gases including methane and nitrous oxide trap heat in the atmosphere. They keep the Earth's surface warm. Without these gases, the average surface temperature would fall from today's global average of 15ºC to about minus 18ºC. Life as we know it would not exist. This trapping of heat by the atmosphere is a natural phenomenon, which has happened on Earth for millions of years.

The difference today is that our activities are adding significant quantities of greenhouse gases to the atmosphere. Measurements in Australia and around the world clearly show a rise in greenhouse gas concentrations in the atmosphere since the Industrial Revolution (Houghton et al., 1996). During the last century, global average surface temperatures have increased by about half a degree Celsius, and sea level has risen by 10 to 25 cm largely due to thermal expansion of the oceans and melting of glaciers.

Human activities will continue to increase greenhouse gas concentrations in the atmosphere over at least the 21st century (Houghton et al., 1996). This is despite industrial nations agreeing to emission reduction targets in the Kyoto Protocol negotiations. A doubling of pre-industrial carbon dioxide levels during the 21st century is almost certain. Since greenhouse gases keep the planet warm, an increase in these gases is likely to lead to global warming and regional climate change. This will have a range of impacts, and adaptation will be essential.

Detailed regional climate change information is needed to investigate potential impacts and adaptation strategies. Accordingly, the Victorian Department of Natural Resources and Environment (NRE) funded CSIRO Atmospheric Research to develop fine resolution climate change scenarios for Victoria to assist the Government and the community plan for climate change.

Global climate modelling

The global climate system is very complex. Quantifying the effect of increasing greenhouse gases is not straightforward. The main tool used by scientists to project climate change is the global climate model (GCM). This is a computer model representing, in a simplified manner, the atmosphere, oceans, biosphere and sea-ice. By solving mathematical equations based upon the laws of physics, a GCM simulates the behaviour of the climate system.

About thirty GCMs are operating worldwide. The Intergovernmental Panel on Climate Change (IPCC) has used results from these models in an assessment of likely future climate change and its impacts with input from almost 2500 scientists. The IPCC has concluded that global temperatures may increase by 0.6 to 2.1 ºC by the year 2050 and 0.8 to 4.5ºC by 2100, assuming sulfate aerosol emissions remain at 1990 levels (Box 1).

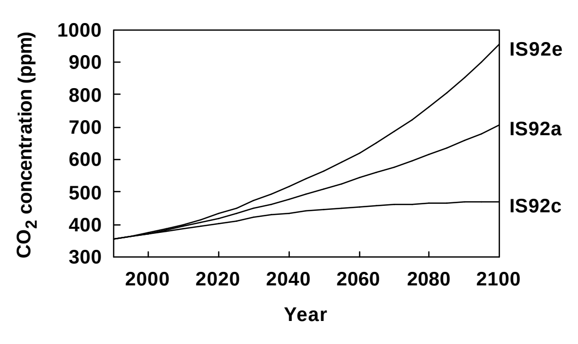
Regional deviations from global average changes can be substantial. In general, climate models simulate greater warming over land and near the poles with less warming over the oceans and the tropics. Different climate models give different rates of change and regional patterns, and this needs to be taken into account when projecting regional climate change.

Box 1: The IPCC international assessment

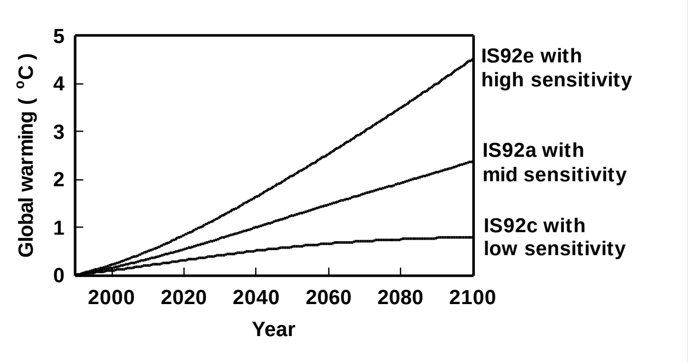
In July 1996, the IPCC Second Assessment Report (Houghton et al., 1996) was endorsed by governments represented at the Second Conference of Parties to the UN Framework Convention on Climate Change, including Australian government ministers. The ministerial statement declared the report to be "the most comprehensive and authoritative assessment of the science of climate change, its impacts and response options now available". In its Summary for Policymakers, the IPCC identified six key findings:

- Greenhouse gas concentrations have continued to rise;
- Anthropogenic aerosols (microscopic airborne particles) tend to produce a cooling effect;
- Climate has changed over the past century;
- The balance of evidence suggests a discernible human influence on global climate;
- Climate is expected to continue to change in the future;
- There are still many uncertainties.

The IPCC identifies a range of plausible greenhouse gas projections (Plot 1). For each of these projections, climate models simulate a global warming which depends the sensitivity of the model. Climate sensitivity is defined as the equilibrium global warming simulated for a doubling of carbon dioxide concentration. The IPCC estimates a sensitivity ranging from 1.5 to 4.5°C, with a mid-range value of 2.5°C. When the IPCC applies these sensitivities to greenhouse gas projections, the global warming is 0.6-2.1°C by 2050 and 0.8-4.5°C by the year 2100 (Plot 2). This assumes that sulfate aerosol emissions, which have a cooling effect, remain at 1990 levels. If aerosol emissions increase in proportion to CO_2 emissions, the warming is 0.5-1.3°C by 2050 and 0.9-3.5°C by 2100. An increase in global average rainfall, evaporation and sea-level should accompany global warming.



Plot 1: IPCC range of carbon dioxide (CO_2) concentration scenarios in parts per million (ppm). IS92c is the lowest scenario, IS92e is the highest, and IS92a is a central estimate. Projections for other greenhouse gases, like methane and nitrous oxide, exist but are not shown.



Plot 2: IPCC global warming scenarios for 1990-2100. Warming values are relative to 1990 and assume constant 1990 sulfate aerosol emissions. The lowest line is IS92c gas concentrations with low climate sensitivity, the top line is IS92e concentrations with high climate sensitivity, and the middle line is IS92a concentrations with mid-range climate sensitivity.

Modelling climate change over Victoria

GCMs do not have fine enough horizontal resolution to simulate climate and climate change over sub-continental regions such as Victoria. In global climate models, the Earth's surface is split into a grid of horizontal boxes separated by lines similar to latitudes and longitudes. Limits to computer power prevent the horizontal size of a grid box in the CSIRO GCM being smaller than about 600 km × 350 km.

CSIRO has a regional climate model, designed to run at fine resolution over small areas. It is known as DARLAM (Division of Atmospheric Research Limited Area Model). Driven by input data from the CSIRO GCM, DARLAM has been formulated to focus on south-eastern Australia, with a grid resolution of 60 km. This allows development of detailed scenarios of climate change which are suitable for regional impact assessments.

DARLAM is able to reproduce observed seasonal average patterns of temperature and rainfall over Victoria much better than a GCM. Figure 1 shows an example of DARLAM's superiority over the GCM in simulating regional rainfall. The good performance of DARLAM increases our confidence in the reliability of the enhanced greenhouse simulations for both average conditions and variability.

Previous studies

NRE funded high resolution (60 km) modelling for Victoria in 1995-96 (Whetton et al., 2000a) and 1996-97 (Whetton et al., 2000b). In 1995-96, the CSIRO GCM with a simple ocean 50 metres deep was used to drive DARLAM for ten years with present levels of carbon dioxide ($1xCO_2$) and ten years with double present levels ($2xCO_2$). Differences between the two simulations gave patterns of climate change which, making some assumptions, could be scaled for any year between 2000 and 2100. Climate change scenarios for average precipitation, maximum temperature and minimum temperature for the years 2030 and 2070 were presented for specific regions of Victoria in the 1995-96 annual report. By 2030, temperatures were increased by 0.4 to 1.3°C and precipitation mainly decreased except in southern Victoria in some seasons.

In 1996-97, improvements were made to DARLAM and the simulation period was extended from ten to twenty years to enhance the reliability of the simulated patterns of climate change. In addition, DARLAM-simulated climatic variability under current and enhanced greenhouse conditions was analysed. This had not been analysed previously for Victoria. Results were presented in the 1996-97 annual report (Whetton et al., 2000b). Simulated changes in average precipitation and temperature were broadly similar to those presented in the 1995-96 report, but summer precipitation decreased by a smaller amount and autumn decreases were more extensive. The intensity and frequency of heavy daily precipitation increased, implying a potential increase in floods. However, the general reduction in seasonal precipitation led to an increase in the frequency of extremely dry winters in northern Victoria. Hot summer days occurred more often and cold winter days declined.

Summer rainfall

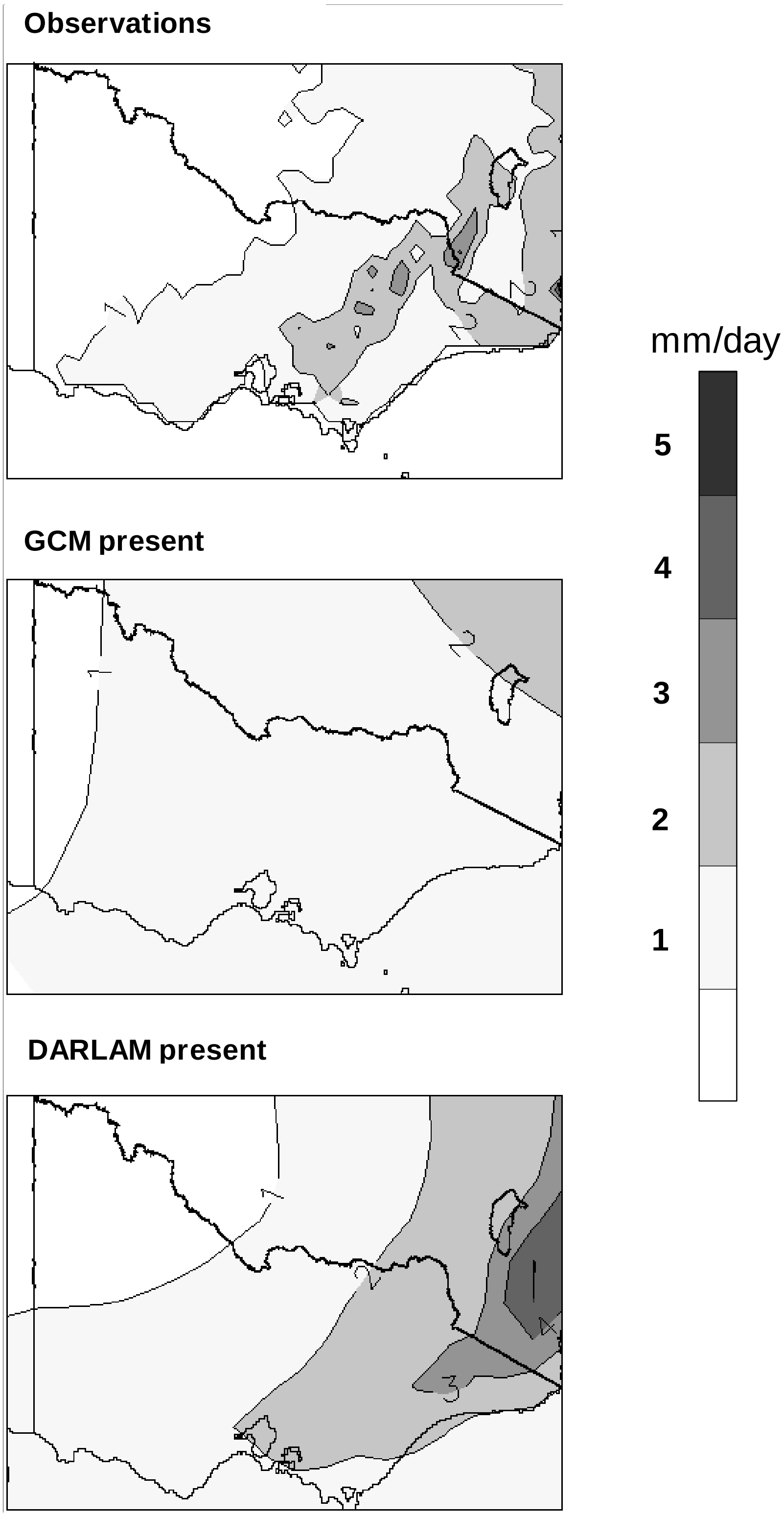


Figure 1: Summer rainfall rate (mm/day) as observed (1972-91), as simulated by the CSIRO GCM (1961-2000), and as simulated by DARLAM (1961-2000). DARLAM's fine resolution is able to capture regional features much better than the coarse resolution GCM.

Objectives of this study

As foreshadowed in the recommendations for further research in the 1996-97 report, the main objective of the research project in 1997-98 was to nest DARLAM at 60 km resolution in the CSIRO coupled ocean-atmosphere global climate model for present and enhanced greenhouse conditions. Nesting in the coupled model was necessary to bring high resolution regional modelling up-to-date with developments in global climate modelling. It also had been agreed that at least twenty years of current climate and of enhanced greenhouse climate would be simulated. However, to further enhance the reliability of the results, a total of 140 years of simulated climate data have been produced for this report. Details of this simulation experiment are set out at the beginning of Section 2.

As in previous years, the model results for temperature and precipitation are to be analysed for changes in the mean, variability and frequency of extremes. These results form the main body of this report (Section 3). This includes updated climate change scenarios for Victoria for change in average precipitation and maximum and minimum temperature that take into account quantifiable sources of uncertainty in estimating the rate of future global warming. Regional scenarios are given for 2050 (although scenarios for other years can be readily constructed) along with sample time series showing the evolution of changes from 1990-2100. Section 3 also examines possible changes in the frequency of years of extreme conditions (e.g. drought years or unusually wet years) over the coming decades. A discussion of these findings appears in Section 4, and future research recommendations are outlined in Section 5.

2. METHODOLOGY

The DARLAM experiment

The DARLAM simulation uses 140 years of input data from 1961 to 2100 provided by the CSIRO coupled ocean-atmosphere GCM. Over this period, greenhouse gas levels are increased gradually, following observations up to 1990 then extrapolated according to the IPCC IS92a scenario from 1991 to 2100 (Box 1). This scenario represents a mid-range scenario amongst those prepared by the IPCC. This experiment represents a major step forwards in regional climate change research and is the first of its type in the world. The first 40 years represent ‘present’ conditions from 1961-2000, while the following 100 years represent ‘enhanced greenhouse’ conditions. Relative to the experiments performed in 1995-96 and 1996-97, the advantages of this simulation are fourfold:

1. Input from a state-of-the science coupled ocean-atmosphere GCM which has more realistic ocean circulation and shows some aspects of El Niño - Southern Oscillation (ENSO) variability;
2. A physically plausible increase in greenhouse gases according to IPCC estimates;
3. Output from an improved version of DARLAM; and
4. 100 years of enhanced greenhouse data allowing time-varying scenarios to be developed.

Results from this experiment represent the culmination of many person-years of work to provide both a global climate model and a regional climate model which are state-of-the-science internationally. Analysis of data from this DARLAM simulation forms the basis of this report (although analysis of GCM results are also included as necessary).

The experiment involves DARLAM at a horizontal resolution of 60 km doubly-nested in the CSIRO GCM from 1961-2100. Double nesting requires two experiments. DARLAM is first nested in the GCM using a horizontal resolution of 125 km over Australasia and the south Pacific. This provides fine resolution boundary conditions for a second nesting over south-eastern Australia at 60 km resolution.

Analysis methods

The DARLAM simulation provides data for daily precipitation and maximum and minimum temperature for 140 years over an array of 135 land-points covering Victoria. Maps are used to convey spatial information extracted from these data and time series plots are used to convey temporal aspects. To keep the report concise, figures are shown for selected regions and seasons, and more comprehensive results are summarised in tables.

To assess the model’s ability to simulate the present climate, averages are computed for each season and climate variable from 1961-2000. Corresponding averages are also calculated using available observed data sets. Maps of the observed and simulated present climate are then compared.

To assess the enhanced greenhouse response of the model, spatial patterns of simulated change in temperature and rainfall are presented. Mapped results can be constructed in one of two ways:

- By simply taking the percent difference between the 2031-2070 average and the 1961-2000 average at each grid point; or
- By calculating the response of DARLAM at each grid point in terms of local temperature change (or percent rainfall change) per degree of global warming (PDGW) using data from the full 1961-2100 period. This is done by linearly regressing the local seasonal mean temperatures (or rainfalls) against global average temperatures (smoothed with an 11-year running mean as shown for the CSIRO GCM in Box 2) and taking the slope of the relationship at each grid point as the estimated response. This method assumes that the local rainfall or temperature signal (as opposed to noise) should evolve over time like that of smoothed global temperature (which contains very little noise.) Change centred on 2050 may then be calculated by multiplying the resultant PDGW map by the global warming that applies in the DARLAM simulation at that date (1.7°C).

The second method has the advantage of using all the simulation data with the result that the signal is less likely to be obscured by natural climatic variability at the decadal scale. The associated correlation coefficient for the relationship may also be tested for statistical significance to determine whether the response is large relative to background variability and thus unlikely to be due to chance. Maps of simulated change presented in this report will be constructed using this second method, unless otherwise indicated.

To assess changes in variability, some other statistical quantities are calculated. Standard deviation is used to measure scatter of the data. For temperature, the standard deviation of daily data is computed for the observed data, simulated present (1961-2000) conditions, and simulated enhanced greenhouse conditions centred on 2050 (2031-2070). The standard deviation of the precipitation data is also calculated, but in this case the data were first averaged seasonally (as the standard deviation cannot be appropriately applied to daily rainfall data). Thus the standard deviations measure daily (and implicitly, year-to-year) variability for temperature, and year-to-year variability for rainfall. In the case of rainfall we also examine the standard deviation divided by the average — a quantity known as the ‘coefficient of variation’. This gives a measure of the magnitude of variability relative to average conditions.

The data sets are also analysed for the occurrence of extremes. For temperature, maps of the frequency of days above and below selected thresholds are computed for current (1961-2000) ands future (2031-2070) conditions. Daily rainfall extremes are analysed using a different approach. The daily rainfall totals are ranked from highest to lowest and changes in the magnitude of the wettest events considered. Changes in the frequency of extreme seasonal conditions (wet or dry summers, cold or warm winters, etc.) are investigated by considering time series of seasonal average conditions and (for rainfall) the frequency of seasons below a dry threshold and above a wet threshold.

Observed data sets

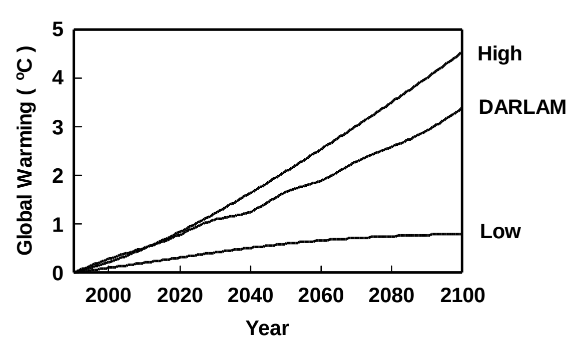
The observed daily temperature data set used here is based on records from Bureau of Meteorology stations using all available years of record. It has been interpolated to a regular grid of half-a-degree (about 50 km) resolution using the elevation-dependent interpolation program of Hutchinson and Bischoff (1983). A station-based precipitation record for 1910-1995 was used for constructing regional averaged time series of precipitation. A gridded precipitation data set for September 1972 to August 1992 was prepared by the Queensland Department of Primary Industries (also using the interpolation method of Hutchinson and Bischoff, 1983). The resolution of this data set was one-tenth of a degree (about 10 km).

Allowing for uncertainties

While the increase in greenhouse gas levels used in the simulation is based on the IPCC IS92a scenario, which is the mid-range scenario, the CSIRO GCM model used in the simulation (and which provides inputs to DARLAM) has a relatively high sensitivity to greenhouse forcing. As a consequence, the resulting rate of global warming simulated by this model is towards the high end of the range of warming scenarios estimated by IPCC. It is relevant to consider how the DARLAM results may differ for alternative global warming scenarios. This may be done by scaling DARLAM results as described in Box 2. Summary scenarios for the year 2050 which include the IPCC range of uncertainty are presented for six Victorian regions in Section 3. Other uncertainties which are less readily quantified are noted in the Discussion (Section 4).

Box 2: Including uncertainty in DARLAM climate change scenarios

Using the relationship between the global warming applicable to the DARLAM results and the full range of IPCC global warming shown below, DARLAM results can be scaled to give low and high scenarios of climate change. For example, by the year 2050, DARLAM global average warming is 1.7 °C while the IPCC range is 0.6 to 2.1°C.



A low scenario of temperature or rainfall change in Victoria for 2050 can be derived by multiplying the DARLAM change by 0.35 (i.e. 0.6/1.7), and a high scenario can be created by multiplying the DARLAM change by 1.24 (i.e. 2.1/1.7). The difference between the low and high scenarios is a measure of the range of uncertainty. This covers the range of quantifiable uncertainty in two factors: (i) future greenhouse gas emissions and (ii) the sensitivity of simulated warming to a doubling of carbon dioxide concentration.

3. DARLAM RESULTS

Daily maximum temperature

Average conditions

Figure 2 shows maps of average daily maximum temperature over Victoria in summer and winter as observed (1972-1991), as simulated for present (1961-2000) conditions, the simulated change per degree of global warming and the change by 2050. The simulations of present climate are very similar to those presented in the 1996-97 report in which the broad features of the observed patterns were well simulated. There is still a bias in the current simulation of about +3°C in the north of the state in summer. By 2050 there are increases of 1.5-2.0°C across the State relative to the current climate simulation. In winter the warming is largest in the north of the state, whereas in summer the greatest warming is in a band running west-east across the middle of the State. This pattern of change is similar to that presented in last year's report.

Variability

The DARLAM simulation of the daily standard deviation of maximum temperature for 1961-2000 generally compares well with observations. As the simulation is mostly rather similar to the current climate simulation presented in the 1996-97 report, comprehensive results are not shown here. The most substantial difference in this year's simulation is the improvement in the realism of the summer pattern (results shown in Figure 3). The tendency for day-to-day variability in maximum temperature in this season to be highest in southern Victoria is very well represented in the current simulation.

Under enhanced greenhouse conditions (2031-2070), changes in the standard deviation of summer maximum temperature are mostly less than 0.2°C. Such changes are negligible when considered relative to the background standard deviation (2.0-5.0°C, depending on region and season) and to the simulated warming.

Occurrence of daily extremes

In this investigation a threshold summer maximum temperature of 35°C was considered. This threshold was considered representative of hot weather across most of the state. The observed frequency of days of this temperature or higher varies from near zero days per summer in high altitude areas to around 25 days per summer in the far north-west (Figure 4). The distribution is quite well simulated in DARLAM, although there are 10 days too many throughout much of the north of the state and up to 20 days too many in the far north-west. This bias reflects the warm bias in average summer maximum temperatures.

The change by 2050 is assessed by comparing average frequencies for the 1961-2000 and 2031-2070 periods. There are increases of in excess of ten days north of Divide and of around five days south of the Divide.

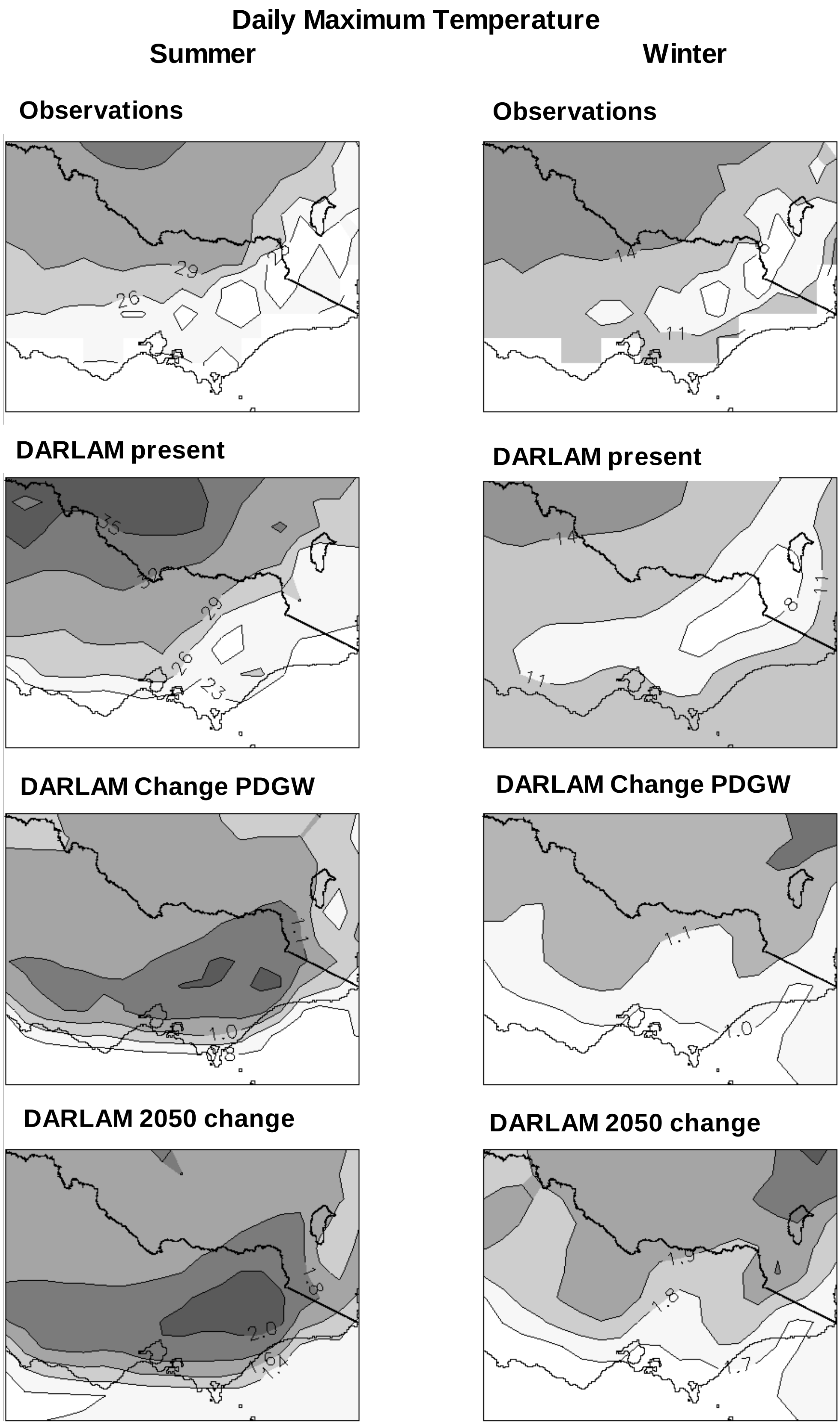
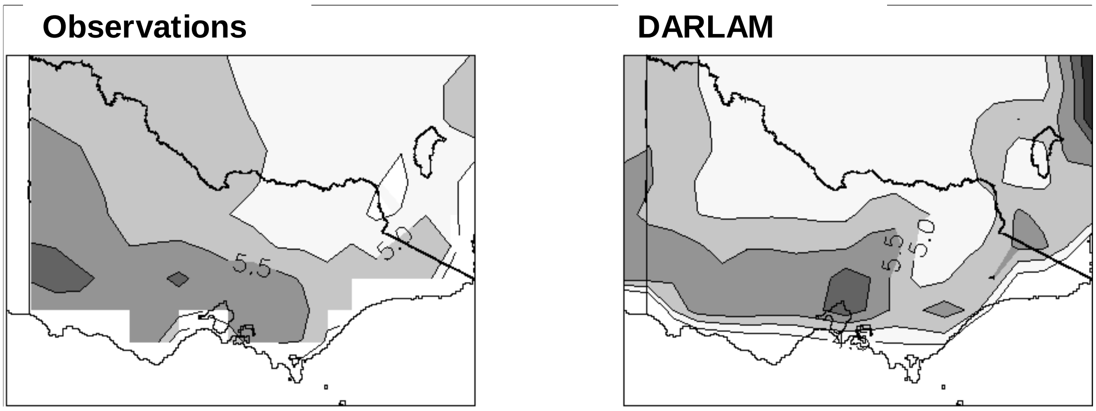


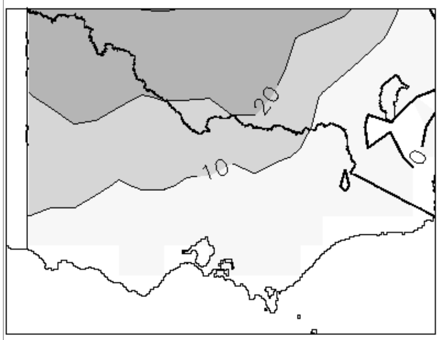
Figure 2: Average daily maximum temperature (^{o}C) for summer and winter as observed, as simulated for present conditions (1961-90), the simulated change per degree of global warming (PDGW), and the change by 2050 relative to present.



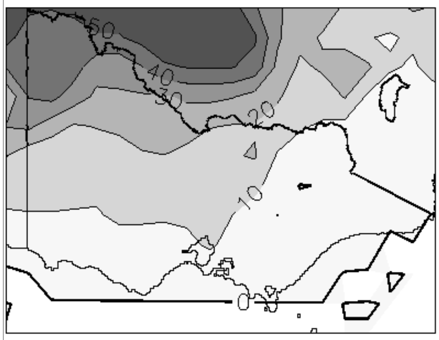
Observations **DARLAM**

Figure 3: Observed and model-simulated standard deviation of daily maximum temperature (°C) in summer.

Observations



DARLAM present



DARLAM 2050 change

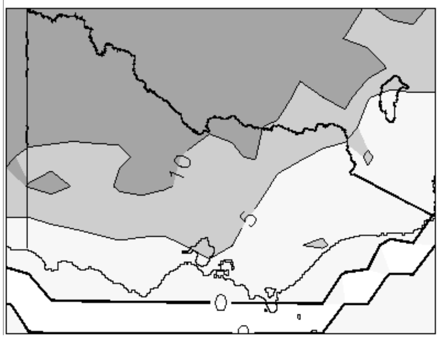


Figure 4: Average number of days of maximum temperature above 35°C in summer as observed, as simulated for present conditions (1961-2000), and simulated change for forty years centred on 2050 (2031-2070).

Time series of the seasonal frequency of days with maximum temperature over 35°C were also investigated using results averaged for each of six regions (Figure 5). Over the course of the run, the frequency of summer days over 35 ^{o}C increases by around 40% in the northern and northwest regions and roughly doubles in the other regions. Figure 6 shows results for the northwest region (which are also representative of the northern region) and the southwest region (representative of the results for the remaining regions).

Such increases in the frequency of hot days may lead to

- greater heat-stress in humans, livestock, ecosystems, agriculture and building materials;
- increased bushfire potential;
- higher energy demand for air-conditioning; and
- increased demands on water-supply systems.

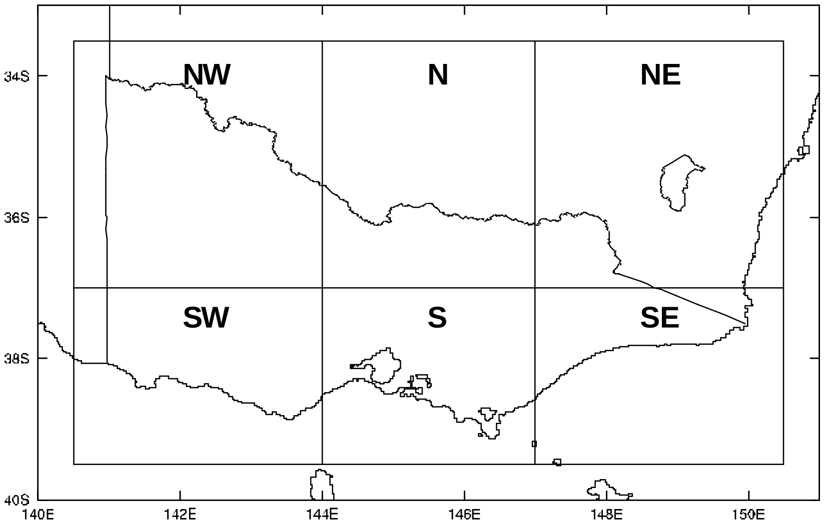


Figure 5: Division of Victoria into six regions used for presenting various regionally averaged results. The regions are 'northwest' (NW), 'northern' (N), 'northeast' (NE), 'southeast' (SE), 'southern' (S) and 'southwest' (SW).

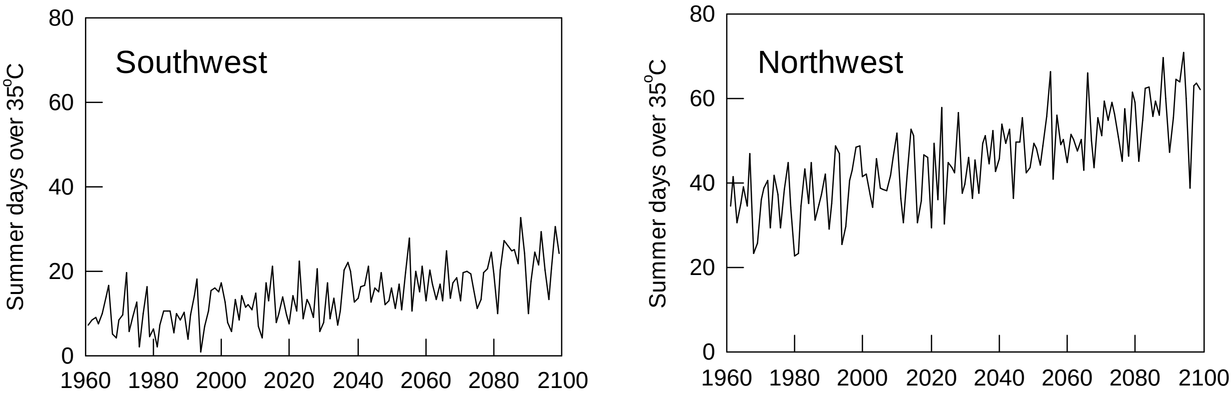


Figure 6: Simulated number of summer days over 35^{o}C in the southwest and northwest regions.

Occurrence of extreme seasonal conditions

How do changes in average temperature affect the frequency of extremely warm or cool seasons? Time series of average maximum temperature were considered and Figure 7 shows results for the southern region. In all regions, the change in average temperature is clearly discernible relative to simulated year-to-year variability. The detectability of the trend is most marked in winter when year-to-year variability is small. In the example shown, eight of the first 40 summers have a mean maximum of less than 25°C, whereas after 2030 there are no such summers. In the example, the warmest winter between 1961 and 2000 is exceeded in temperature by all but one of the last forty winters of the simulation (2061-2100).

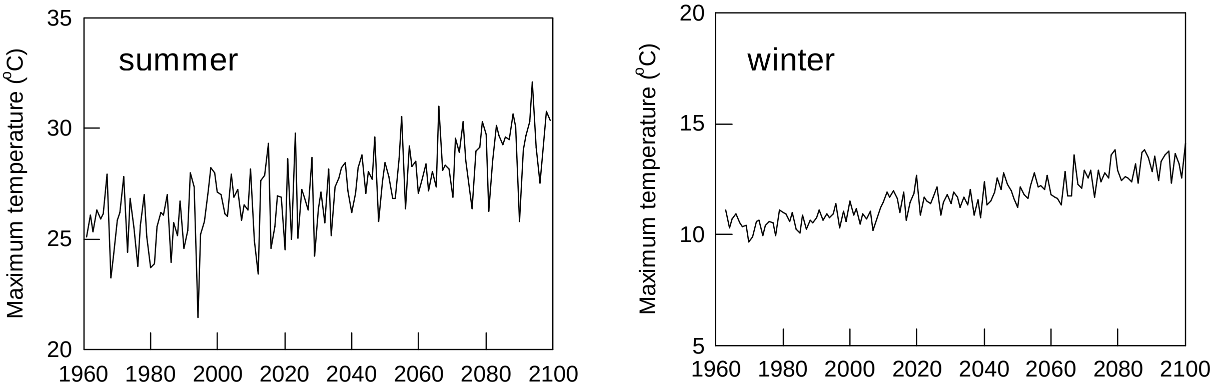


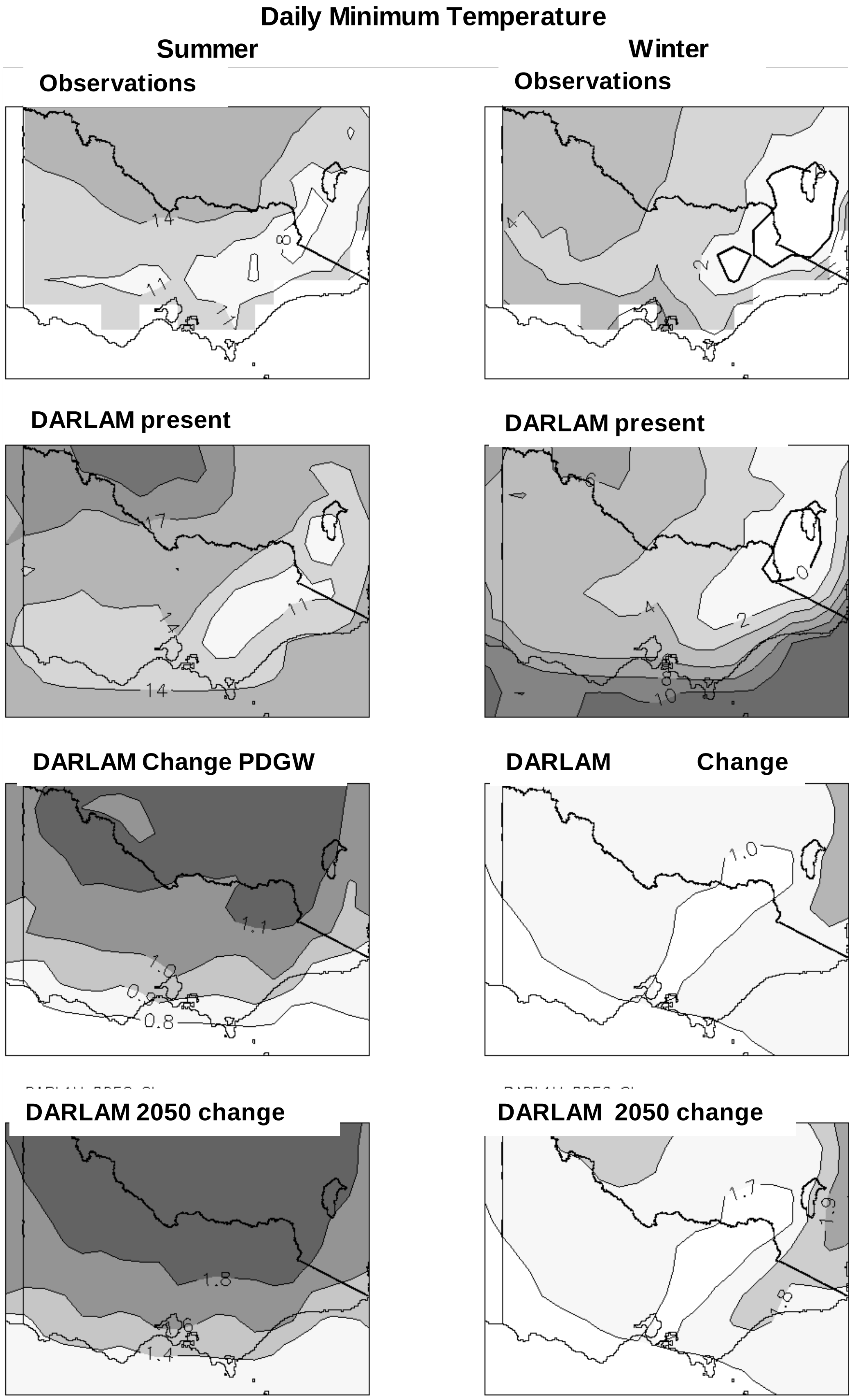
Figure 7: DARLAM average maximum temperature (°C) in the southern region in summer and winter.

Daily minimum temperature

Average conditions

Figure 8 shows maps of average summer and winter daily minimum temperature over Victoria as observed (1972-91), as simulated for present (1961-2000) conditions, the change per degree of global warming (PDGW), and the change simulated by about 2050. The current climate simulated minimum temperatures are around 1-3°C higher than in the simulation presented in the 1996-97 report. In most cases this has led to improved correspondence with observations, although the summer minimum temperatures in north-western Victoria are now up to 3°C too warm.

By 2050, minimum temperatures increase by 1.4 to 1.8°C with least warming in coastal areas in summer and winter and in mountain areas in winter. Overall there is a tendency for minimum temperature to rise slightly less than maximum temperature, leading to a reduction in the diurnal temperature range.


Daily Minimum Temperature

Summer

Winter

Observations

Observations

DARLAM present

DARLAM present

DARLAM Change PDGW

DARLAM Change

DARLAM 2050 change

DARLAM 2050 change

Figure 8: Average daily minimum temperature (^{o}C) for summer and winter as observed, as simulated for present conditions (1961-2000), the simulated change per degree of global warming (PDGW), and the scaled change for 2050 relative to present.

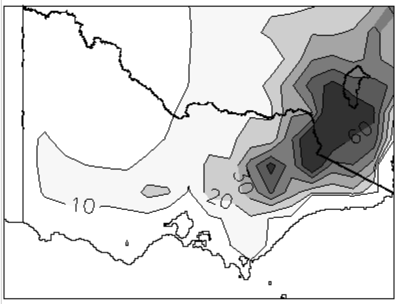
Variability

The simulated pattern of the standard deviation of minimum temperature (not shown) corresponds well with observations. The results are similar to those presented in the 1996-97 report, although they are slightly improved due to a general reduction of around 0.5°C in the magnitude of the simulated standard deviation. In both seasons, the standard deviation of minimum temperature shows changes in the range of -0.1 to +0.1°C. These changes are negligible relative to the background standard deviation and the simulated increase in the mean.

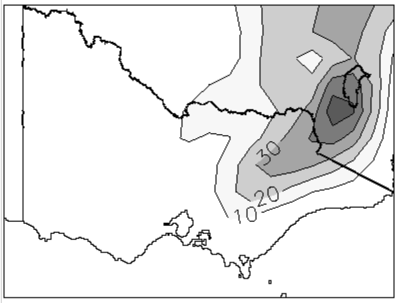
Occurrence of daily extremes

To investigate how changes in the average and standard deviation may affect extreme minimum temperatures, the number of winter days below 0°C was computed (Figure 9). In broad terms the observed pattern is well simulated, with the greatest frequency of frosty days being in the northeast of the state. The frequency is around ten days less than that seen the simulation presented in the 1996-97 report. In most regions this represents an improvement in the simulation, although the frequency in the northeast of the state is now around ten days too low.

Observations



DARLAM present



DARLAM 2050 change PDGW

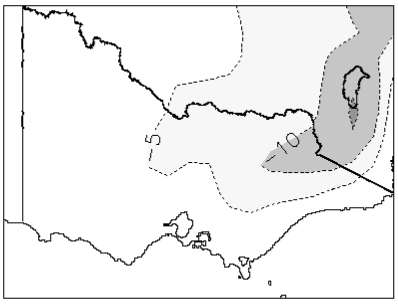


Figure 9: Average number of winter days below 0°C as observed, as simulated for present conditions (1961-2000), and simulated change for forty years centred on 2050 (2031-2070).

By 2050, there are 5 to 10 fewer frosty days per winter, on average, in the northeast and up to five days fewer elsewhere. This represents reductions of up to 50%. Figure 10 shows how the decline in frosty days becomes evident over time. In the southern region, 11 of the first 40 winters (1961-2000) have at least 10 frosty days, but there are only three such winters in the period 2000-2100. In the northeast, 33 of the first 40 winters have at least 20 frosty days, but only one of the last 40 winters (2060-2100). Results for the southeast and northern regions are similar to those in the southern region. Results for the southwest and northwest regions are similar to the southern region, but begin at a lower base level, and consequently give many frost-free years after 2060. It should be noted, however, that the decline in the number of frosty days is not continuous; due to the effects of natural variability the trend reverses for periods up to a decade.

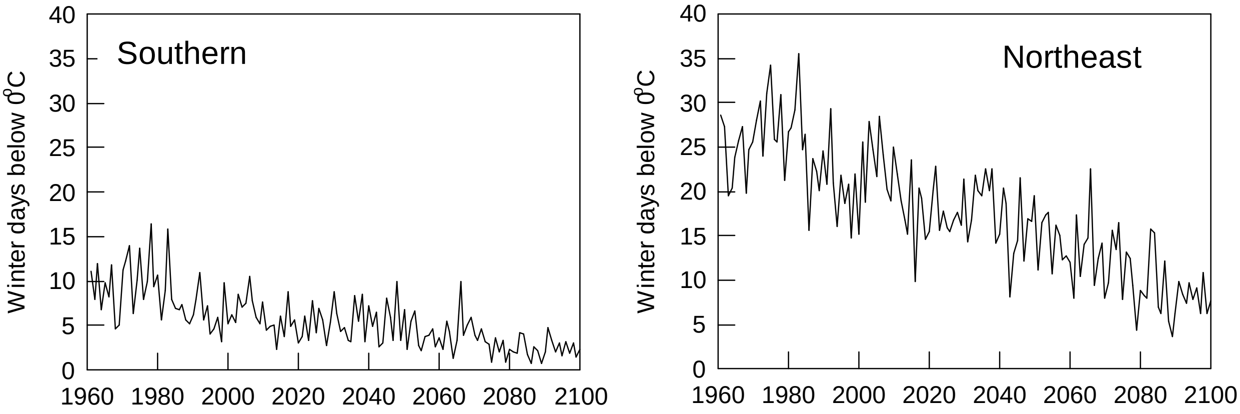


Figure 10: Simulated number of winter days below 0°C in the southern and northeast regions.

Occurrence of extreme seasonal conditions

Changes in the occurrence of unusually cool or warm winter average minimum temperature were investigated by considering time series for the six regions. Results for the southern region are shown in Figure 11. Again, in this and other regions the trend is very marked relative to the interannual variations. For the example in the figure, the warmest winter minimum temperature from 1961 to 2000 is exceeded by all but one winter from the year 2060 onward.

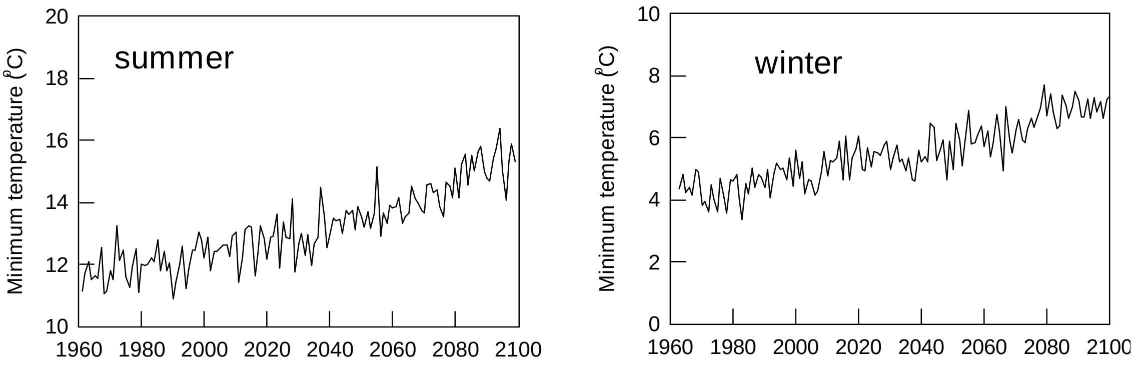


Figure 11: DARLAM-simulated average winter minimum temperature (°C) in the southern region in summer and winter.

Such decreases in the frequency of frosty days may lead to

- altered crop-sowing dates to suit a longer frost-free season;
- reduced frequency and intensity of frost damage to frost-sensitive crops, and reduced cost of frost protection measures;
- increased viability of frost-sensitive crops;
- reduced quality and quantity of horticultural crops due to inadequate accumulated winter chilling for normal bud-burst;
- reduced dormancy for pests and diseases;
- reduced proportion of precipitation that falls as snow, and implications for alpine ecosystems, recreation and resorts; and
- reduced energy demand for winter heating.

Rainfall

Average conditions

Figure 12 shows maps of average seasonal rainfall over Victoria as observed, as simulated for present conditions (1961-2000), the change per degree of global warming and the change by 2050. Since there is considerable seasonal variation in the results, the transition seasons of autumn and spring are presented in addition to summer and winter.

The main features of the observed pattern of rainfall over the state are the tendencies for rain to be greater near the coast and over the mountains of the north-east, and (in all areas but the southeast) to be greater in winter and spring than in summer and autumn. These features are reasonably well represented in the current DARLAM simulation. The simulation is also substantially improved over that presented in the 1996-97 report, with the main improvement being the much lower summer rainfall in the east in the current simulation. Consequently, the unrealistic summer domination of the annual cycle of rainfall seen in previous simulations has been removed from all areas except the far east of the state.

Under enhanced greenhouse conditions in northern Victoria there are rainfall decreases in winter and spring, rainfall increases in summer and little change in autumn. Except in autumn, the changes are statistically significant in at least some areas of the north (and the whole north in spring). By 2050 the significant changes approach 10% in magnitude in some areas. Southern Victoria also shows widespread statistically significant decreases in spring, although in magnitude they are smaller than those in the north (5% by 2050). In the other seasons changes in the south are small and mostly statistically insignificant, although a tendency for summer decreases and winter increases may be noted.

Year-to year variability and occurrence of extreme seasonal conditions

Year-to-year variability in seasonal precipitation in DARLAM was analysed using a number of methods. It was considered by comparing observed, simulated 1961-2000 and simulated 2031-2070 maps of the standard deviation and the coefficient of variation (not shown), and by comparing observed and model-simulated time series of regional rainfall (e.g. Figure 13). The latter method provides less spatial detail but is more appropriate because the averaging area is consistent for observations and model results.

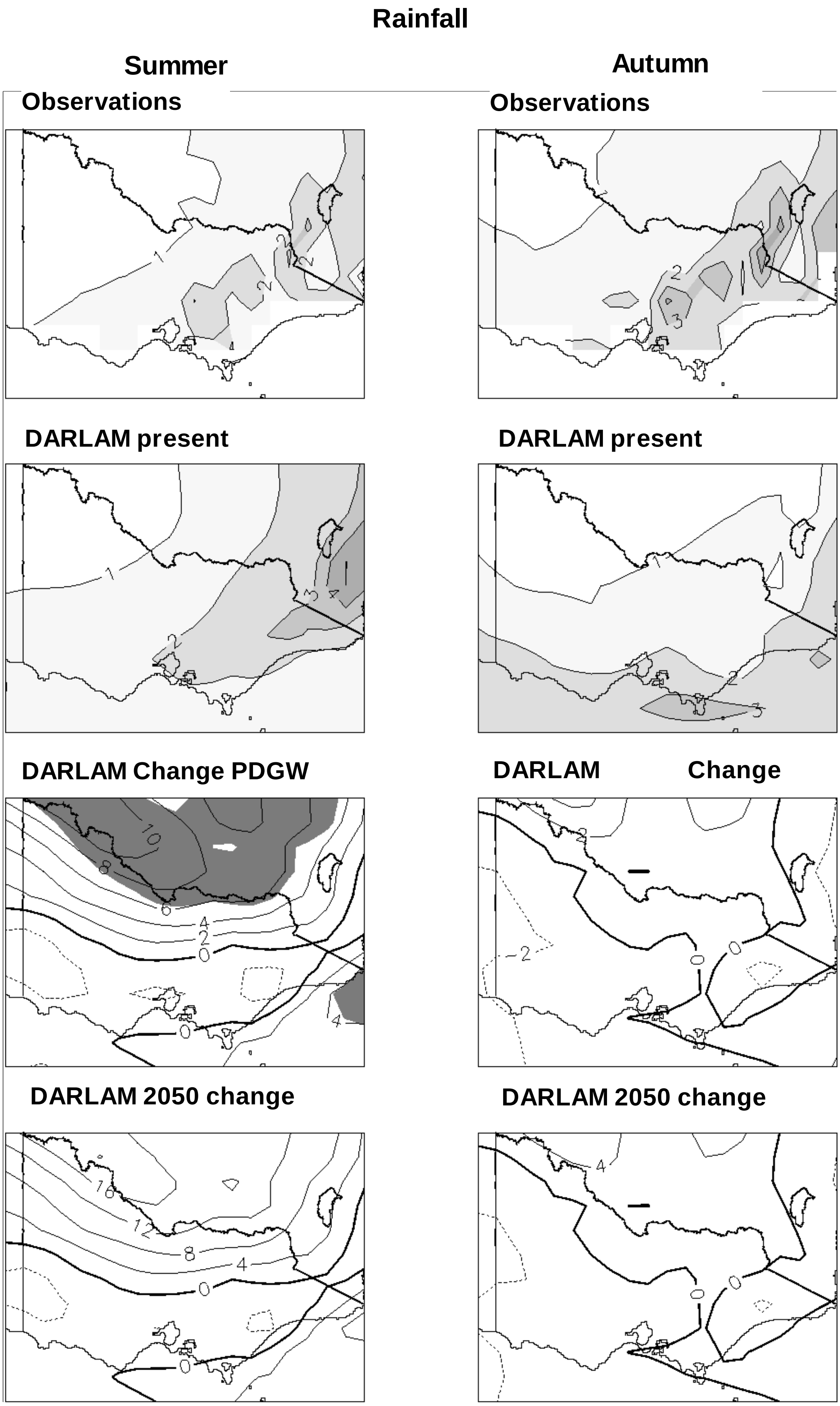


Figure 12: Average rainfall for summer, autumn, winter and spring: observed, simulated present (mm/day), change (%) per degree of global warming (PDGW) and simulated change (%) by 2050. Shading in the PDGW maps indicates areas of change significant at the 95% confidence level. Dashed contours are negative (reduced rainfall).

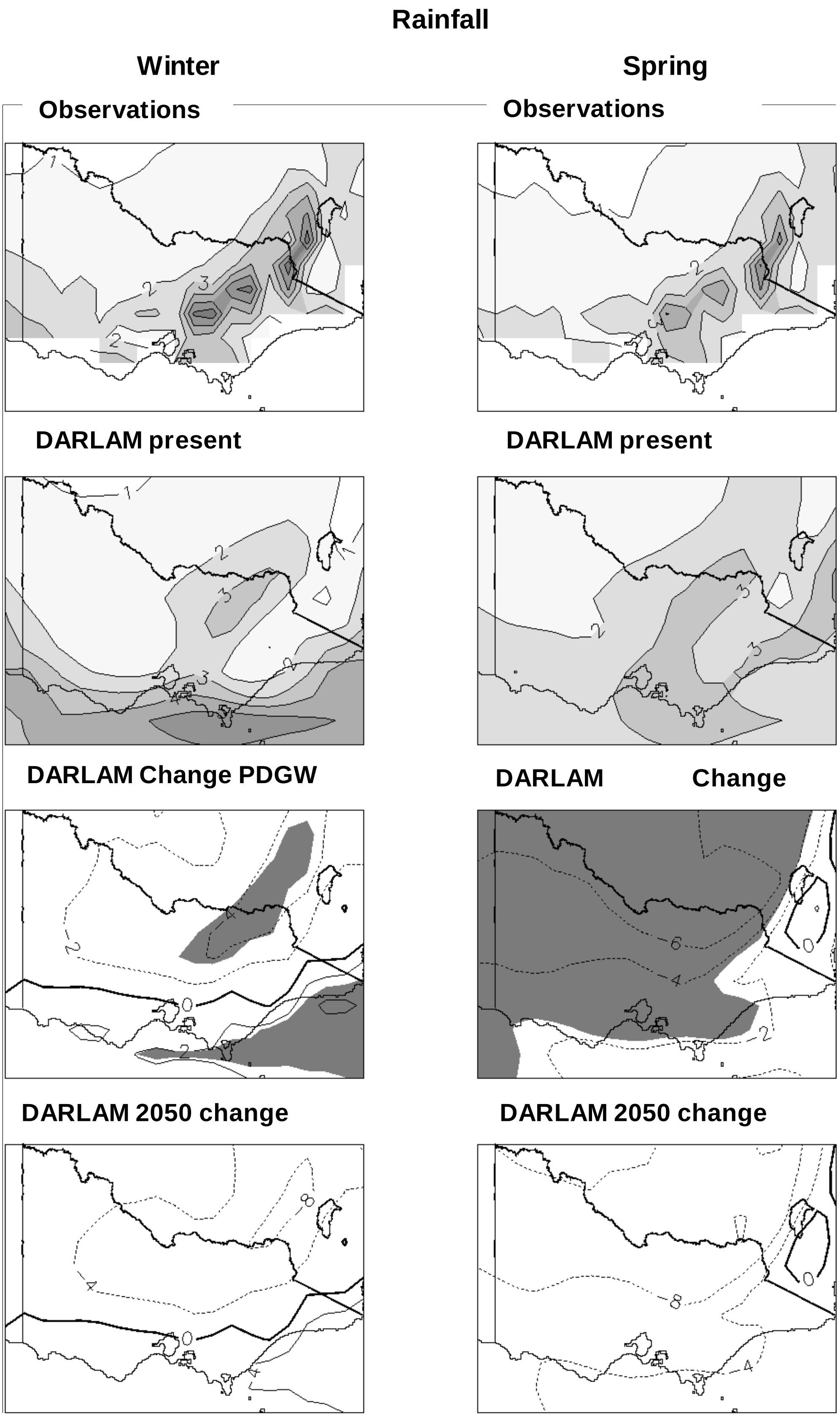


Figure 12 (cont.): Average rainfall for summer, autumn, winter and spring: observed, simulated present (mm/day), change (%) per degree of global warming (PDGW) and simulated change (%) by 2050. Shading in the PDGW maps indicates areas of change significant at the 95% confidence level. Dashed contours are negative (reduced rainfall).

In general, the simulation of year-to-year variability is rather similar to that presented in the 1996-97 report. The spatial pattern of variability (such as the tendency for variability to be greater inland) is well simulated in both summer and winter, and the magnitude of variability is well simulated in summer. However, there is a tendency for the magnitude of simulated rainfall variability to be too low in winter. The contrast between summer and winter performance may be seen in the observed and model time series for the northern region presented in Figure 13.

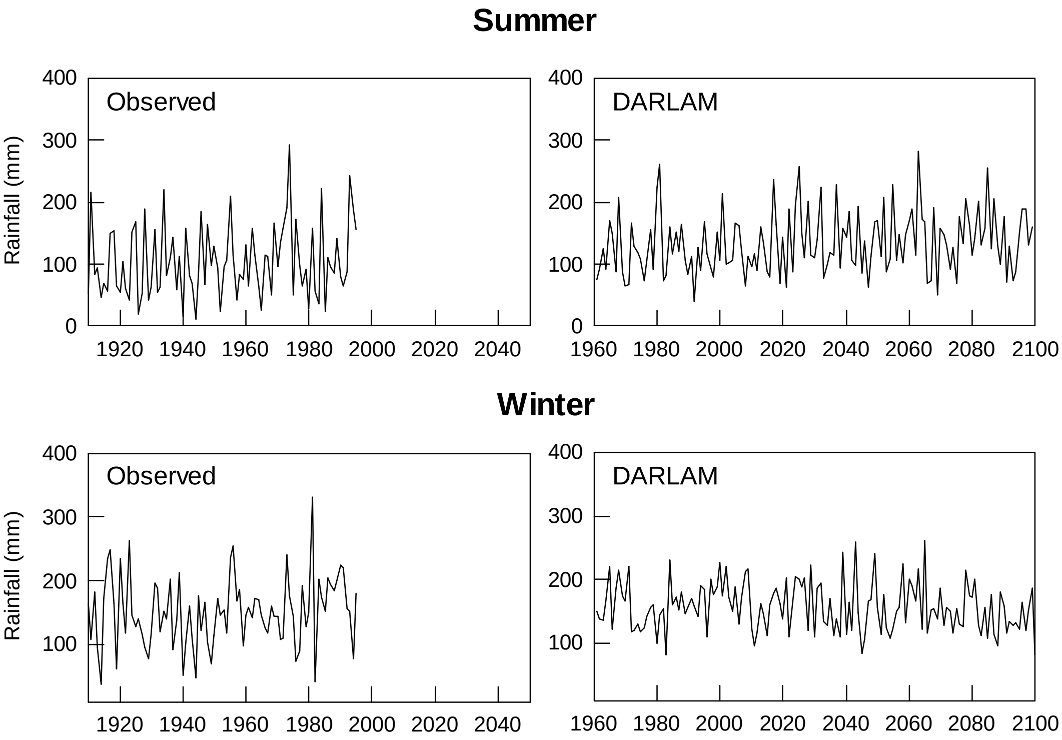
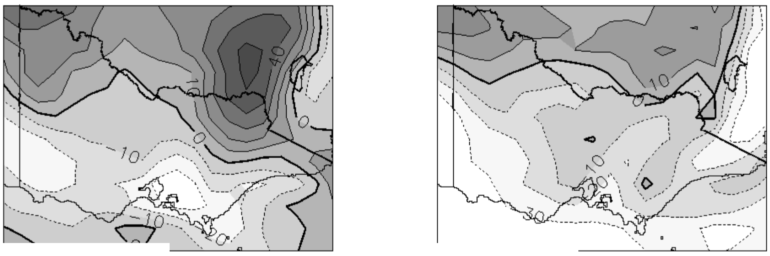


Figure 13: Observed and simulated rainfall (mm) averaged over the northern region in summer and winter.

The simulated change in standard deviation between the period 1961-2000 and 2031-2070 is shown in Figure 14. The pattern of change is complex with areas of both increase and decrease which vary substantially over the seasons. These changes are as large as 30% in some cases. This means that the changes in variability have the potential to have an impact on the frequency of occurrence of wet and dry years which may be as significant as that due to simulated changes in mean conditions. Although these changes may represent a systematic response of the model to enhanced greenhouse conditions, the reasons for these changes are not clear at present and will need to be addressed in further research. To do this, analysis of changes in the frequency and intensity of particular synoptic circulation systems may be required.

Changes in the frequency of unusually wet and dry seasons were calculated for each of the six regions. Figure 15 show detailed results for the northern region as an example. There is around a tripling of the frequency of wet summers by the end of the simulation and a corresponding slight decline in dry summers. Dry winters increase in frequency (a doubling by late in the simulation), but there is little decline the frequency of wet winters. Dry springs increase markedly (a tripling by late in the simulation) and there is a corresponding decrease in the frequency of wet springs.

Winter **Spring**



Summer **Autumn**

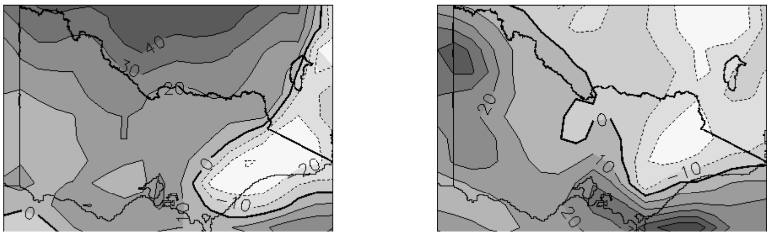


Figure 14: Seasonal changes in rainfall standard deviation (%) between the periods 2031-2070 and 1961-2000.

Most of these changes in frequency can be related to changes in mean rainfall, but the effect of changes in variability may also be seen. For example, while in winter and spring the frequency of dry years increases as mean rainfall decreases, the frequency of wet years is maintained in winter (when variability increases), but not in spring (when variability decreases). A better illustration of importance of changes in variability is provided by the results for the southeast region in winter (Figure 16), where we see a clear reduction in the frequency of both wet and dry years as a consequence of reduced variability.

Reviewing the results for all regions, the notable results are a doubling by 2050 in the frequency of wet seasons in the northern and northwest regions in summer; and a doubling by 2050 in the frequency of extremely dry seasons in northern region in winter and in all regions but the southeast in spring. Other changes are much less marked.

Occurrence of daily extremes

In this section we consider the occurrence of rainfall extremes at the daily time scale. Daily extremes are important for flood potential in small catchments. Previous studies based on daily data from various climate models have indicated marked increases in the magnitude and frequency of extreme daily rainfall events under enhanced greenhouse conditions for the Australian region (Whetton et al., 1993, Fowler and Hennessy, 1995; Whetton et al., 2000b).

Extreme daily rainfall totals were analysed for each of the DARLAM grid boxes over Victoria. Figure 17 shows the annual results averaged over all Victorian grid points for various return periods (average period between events of a given magnitude or higher). Under present conditions (1961-2000), the simulated 1-in-20 year daily rainfall total is 62 mm and the 1-in-10 year event is 52 mm. The present 1-in 20-year event increases in intensity by 13% for the 40 years centred on 2050; alternatively, the present 20-year event becomes a 13 year event by 2050.

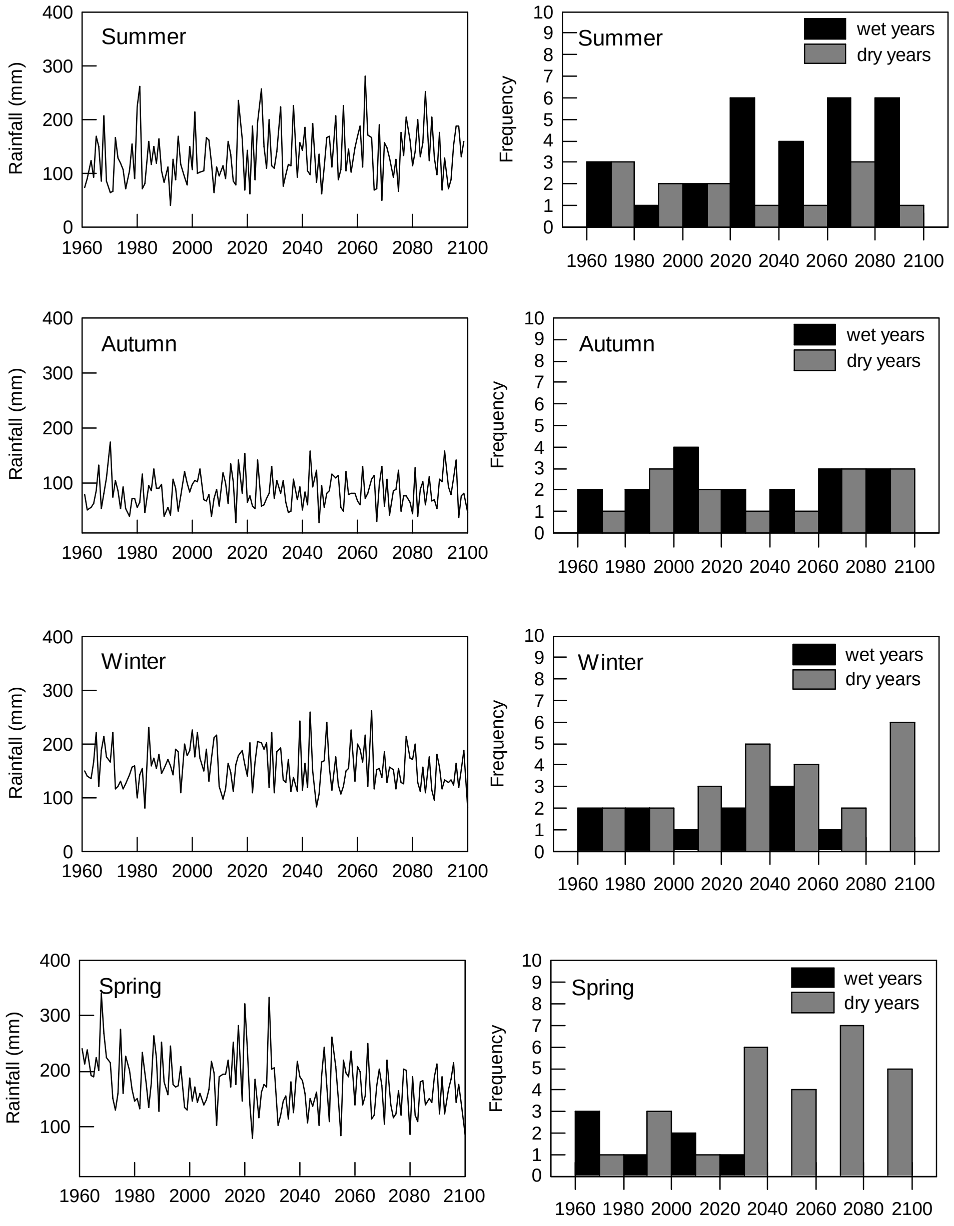


Figure 15: Simulated seasonal rainfall in the northern region (mm/day, left panels) and number of extremely dry or wet seasons in each 20-year period (right panels). Dry years have seasonal rainfall totals below the 4th driest year during 1961-2000 while wet years have seasonal rainfall totals above the 4th wettest year from 1961-2000.

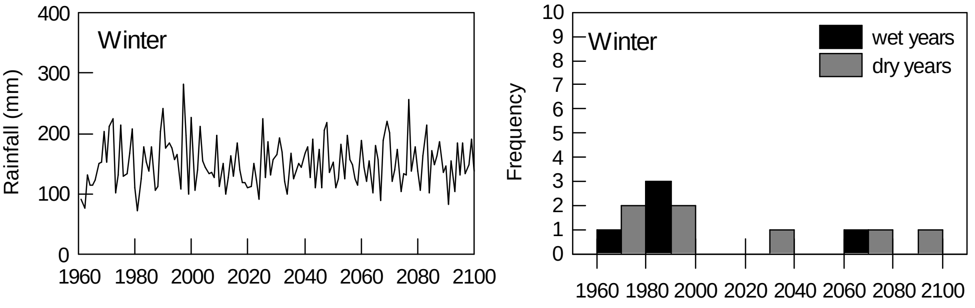


Figure 16: Simulated winter rainfall in the southeast region (mm/day, left panels) and number of extremely dry or wet seasons in each 20-year period (right panels). Dry years have seasonal rainfall totals below the 4th driest year during 1961-2000 while wet years have seasonal rainfall totals above the 4th wettest year from 1961-2000.

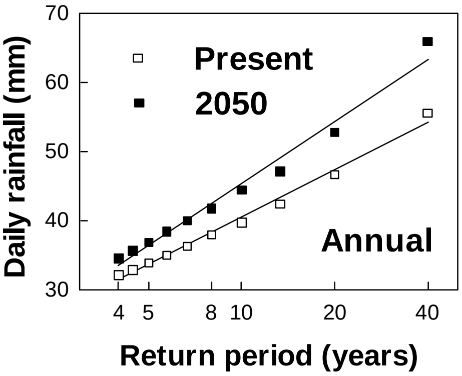


Figure 17: Heavy daily rainfall return periods averaged over Victoria for all seasons. Open squares are for the present (1961-2000) and solid squares are for 40 years centred on 2050.

The intensity of the annual 1-in-20 year event increases by 2050 in all regions except the southeast, with magnitude of the change varying from 7% in the northeast to 50% in the northwest (Figure 18). The 20% decrease in the southeast, partly reflects the decrease in year-to-year variability in that district (see Figure 14).

When the regional analysis is broken down by season it is found that the tendency for more intense rainfall is stronger in summer and autumn and weaker in winter and spring. Seasonal results for the northern region are shown in Figure 19 in which a strong summer and autumn response may be seen. This figure also shows that extreme rainfall can become more intense and more frequent even when average rainfall decreases.

Finally, the increase in the frequency of heavy rainfall events in summer in the northern region is presented in a different way to highlight the evolution of this tendency over the course of the run (Figure 20). The decadal total number of rain events exceeding 40 mm/day in summer for a typical 60 km × 60 km DARLAM grid box in the region is calculated.

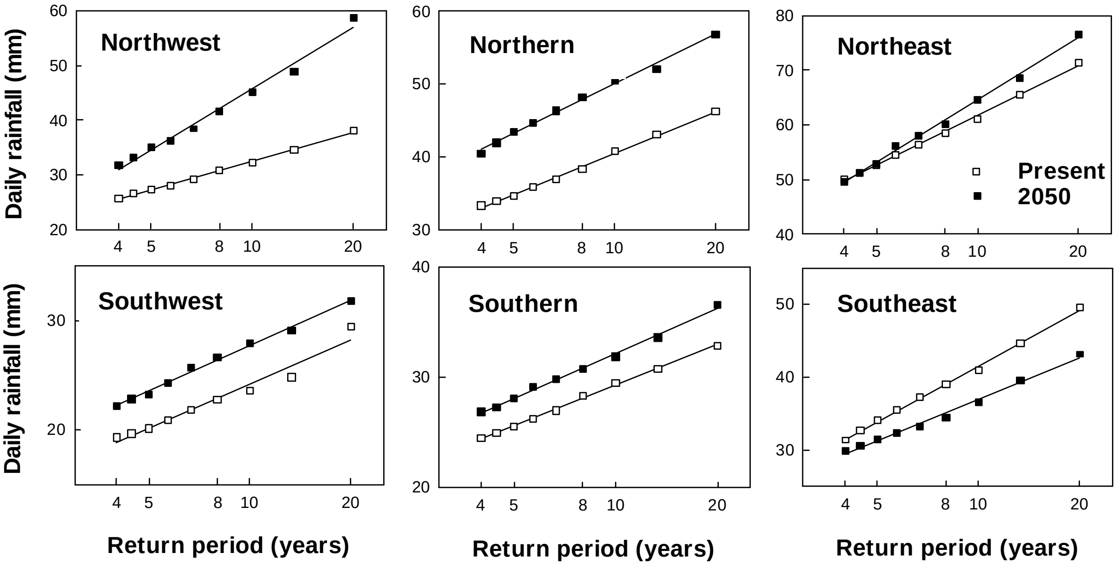


Figure 18: Heavy daily rainfall return periods for all seasons averaged over six Victorian regions. Open squares are for the present (1961-2000) and solid squares are for 40-years centred on 2050.

It should be noted that the region-to-region variations in the results for changes in rainfall return period will be significantly affected by natural variability in the model. It is therefore unclear as to the extent to which the regional variations in Figure 18 should be viewed as part of the systematic response of the model. However the fact that increases in the intensity of the 1-in-20 year event can be as large as 50% in some regions (as they are in the northwest in this simulation) is a notable result. A fuller interpretation of these regional results would require more research.

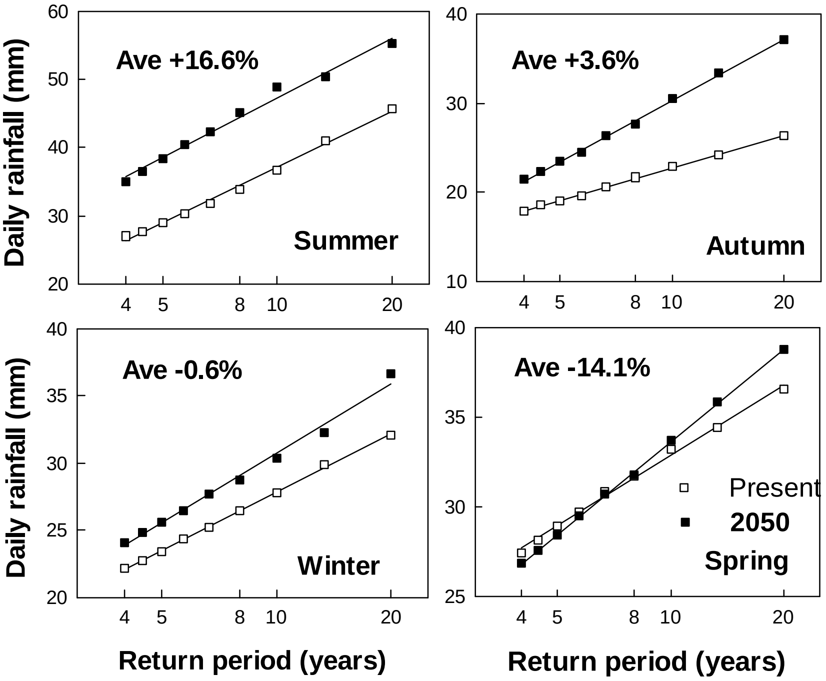


Figure 19: Heavy daily rainfall return periods averaged over the northern region for each season. Open squares are for the present (1961-2000) and solid squares are for 40-years centred on 2050. Changes in average seasonal rainfall (Ave) are also shown.

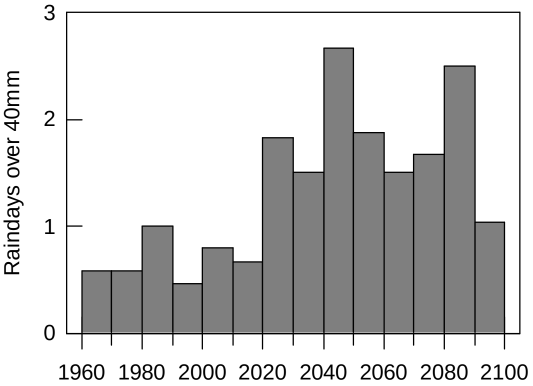


Figure 20: Number of summer rain events over 40mm/day each decade for a DARLAM gridbox in the northern region.

Summary of temperature and rainfall changes

Table 1 gives a summary of the simulated changes by 2050 in the temperature characteristics of the six Victorian regions used here. The table is based on the changes simulated by DARLAM as described in this Section, but also allows for uncertainty in the rate of future global warming by applying the scaling methods described in Box 2. It is for this reason primarily that ranges of change are given rather than a single figure (although the ranges of warming partly encompass seasonal variations).

The warming over Victoria by 2050 ranges from 0.5 to 2.2°C with least warming in southern areas. A reduction in the diurnal temperature range of around 0.1°C occurs in southern Victoria. The number of summer days over 35°C increases by 10 to 50% in the north-central and north-west and by 20-100% elsewhere. Winter days below 0°C decline in frequency by 10 to 60%. Such large changes in extreme events would have important implications for agriculture, ecosystems, health, rural pests and disease, and built infrastructure.

The corresponding results for changes in mean rainfall are shown in Table 2. Allowance has also been made for uncertainty in the average rainfall changes. Unlike temperature, changes in rainfall can be small compared to natural variability and so we have included in the table only those changes which are statistically significant or larger than 5% in magnitude under high case assumptions. Summer rainfall increases in the northern and northwest regions and spring rainfall decreases in all districts are the most notable changes.

DARLAM also simulates a doubling by 2050 in the frequency of wet seasons in the northern and northwest regions in summer; and around a doubling by 2050 in the frequency of extremely dry seasons in northern region in winter and in all regions but the south east in spring. The frequency and intensity of heavy daily rainfall increases in all regions but the southeast. The increase in the magnitude of the 1-in-20 year event is as large as 50% in some regions.

Table 1: Summary of change in average maximum temperature, average minimum temperature, number of summer days over 35°C and number of winter days below 0°C in six Victorian regions by the year 2050. Scaling for the range of IPCC uncertainty is included.

	Northwest	Northern	Northeast
Maximum temperature	↑ 0.6 to 2.2°C	↑ 0.6 to 2.2°C	↑ 0.5 to 2.2°C
Minimum temperature	↑ 0.6 to 2.1°C	↑ 0.6 to 2.2°C	↑ 0.6 to 2.2°C
Summer days over 35°C	↑ 10 to 40%	↑ 15 to 50%	↑ 20 to 80%
Winter days below 0°C	↓ 20 to 60%	↓ 15 to 60%	↓ 10 to 40%

	Southwest	Southern	Southeast
Maximum temperature	↑ 0.6 to 2.1°C	↑ 0.6 to 2.1°C	↑ 0.6 to 2.1°C
Minimum temperature	↑ 0.5 to 1.9°C	↑ 0.6 to 2.0°C	↑ 0.6 to 2.0°C
Summer days over 35°C	↑ 20 to 80%	↑ 30 to 100%	↑ 40 to 120%
Winter days below 0°C	↓ 15 to 60%	↓ 15 to 50%	↓ 15 to 50%

Table 2: Summary of changes in average seasonal rainfall by the year 2050. The range of IPCC uncertainty is included. * indicates changes significant at the 95% confidence level.

	Northwest	Northern	Northeast
Summer rainfall	↑ 4 to 13%	↑ 4 to 14% *	↑ 2 to 5%
Autumn rainfall	no change	no change	no change
Winter rainfall	no change	↓ 2 to 6%	↓ 2 to 5%
Spring rainfall	↓ 4 to 13%	↓ 4 to 13% *	↓ 2 to 7% *

	Southwest	Southern	Southeast
Summer rainfall	no change	no change	no change
Autumn rainfall	no change	no change	no change
Winter rainfall	no change	no change	no change
Spring rainfall	↓ 2 to 7% *	↓ 2 to 8% *	↓ 2 to 5% *

4. DISCUSSION

Simulated climatic averages

The DARLAM simulation reproduces the seasonal patterns of maximum and minimum temperature over Victoria reasonably well, although summer temperatures are up to three degrees too high. The model also represents the main features of the observed pattern of average seasonal rainfall over Victoria. Overall, the temperature and rainfall simulations are better than those presented in the 1996-97 report.

Simulated changes in temperature under enhanced conditions are consistent with those presented for 2030 and 2070 in the 1996-97 report. However, simulated rainfall changes differ significantly from those presented in previous reports. In particular, the increased summer rainfall in northern Victoria, and the widespread rainfall decreases in spring, contrast with the results of previous simulations. On the other hand, the pattern of winter rainfall change (increases in the south, decreases in the north) is similar to previous results, although weaker in the current simulation. The change in the enhanced greenhouse simulation of the host model (as a result of using the coupled atmosphere-ocean version of the GCM) is clearly a factor leading to these differences. However, there are also some differences which appear to have arisen due to independent behaviour within DARLAM. These are discussed further in the ‘Uncertainties’ discussion below.

Simulated variability and extremes

The spatial and seasonal variation of the standard deviation of daily maximum and minimum temperature is generally well captured by DARLAM. The frequency of very hot days in summer is overestimated due to a warm bias in average summer temperatures, but the number of frosty winter days is well simulated. Compared to the 1996-97 simulation, DARLAM is better able to simulate observed year-to-year rainfall variability, largely due to substantial improvements in the simulation of average rainfall. However, DARLAM still has a tendency to underestimate rainfall variability in winter.

Under enhanced greenhouse conditions, DARLAM simulates little change in temperature variability. Large increases are simulated in the frequency of summer days with maximum temperature greater than 35°C as well as rapid decreases in the frequency of winter days with minimum temperature less than 0°C. Decreases are simulated in the frequency of cool seasons, particularly in winter. Given the negligible simulated changes in variability, these changes in the frequency of extremes stem mainly from the simulated change in the average.

Simulated changes in year-to-year variability in rainfall are comparable in magnitude to changes in the mean and thus both contribute to the simulated changes in the frequency of wet and dry years. These changes can be substantial. For example, there is a doubling by 2050 in the frequency of wet seasons in the northern and northwest regions in summer; and around a doubling by 2050 in the frequency of extremely dry seasons in all regions but the southeast in spring.

Extreme daily rainfall events have the potential to inflict substantial costs through urban and rural inundation, erosion, loss of crops and livestock, disruption to services, damage to infrastructure, and sometimes loss of human life. Increases in intensity of up to 50% for the 1-in-20 year event by 2050 are indicated in some smaller regions. Some increases in intensity are present even where average rainfall decreases. Qualitatively, this result is consistent with results from earlier studies using GCMs and is likely to be quite robust. The increases in extreme daily rainfall and the increases in extremely wet summers, autumns and winters in some regions suggest that one of the most important impacts may be an increase in flood frequency and magnitude.

Uncertainties

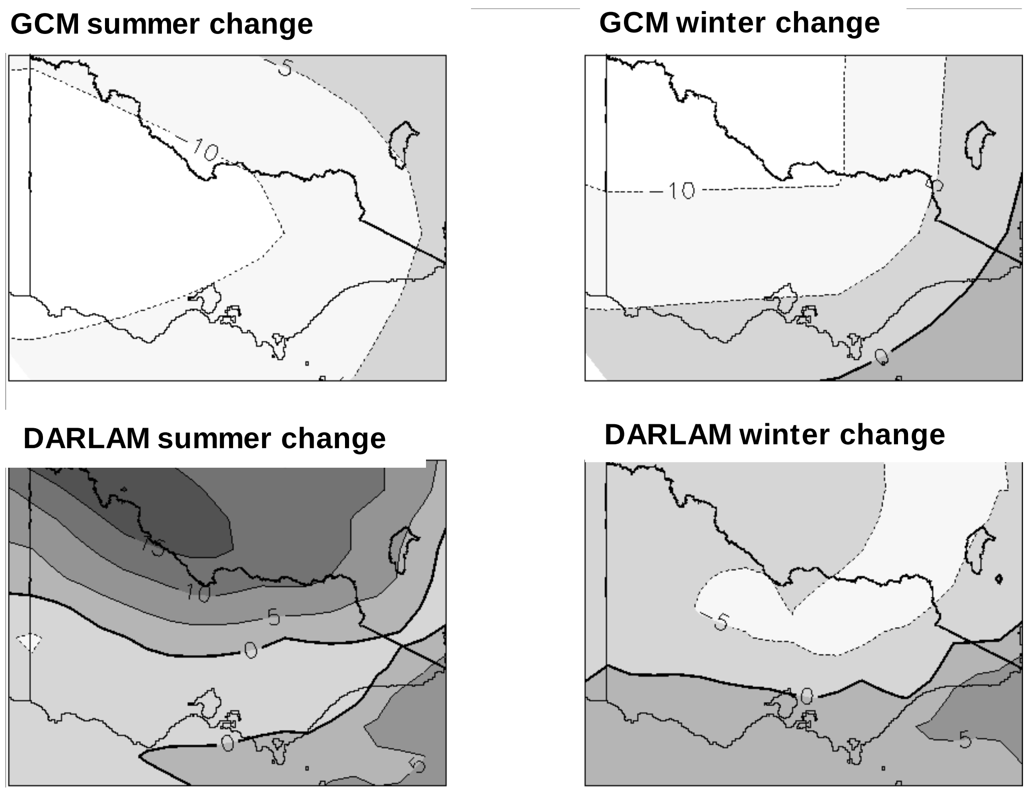
Comparison of the DARLAM and CSIRO GCM results

When the DARLAM results for simulated rainfall change are compared to those in the host GCM, important differences are apparent. Some differences in detail can be related to the improved representation of topography in DARLAM and are not surprising. However, more significantly, DARLAM has a generally wetter enhanced greenhouse climate than the host GCM. Areas showing strong rainfall decreases in the GCM show weaker rainfall decreases in DARLAM, and areas showing small rainfall decreases in the GCM often reverse to small rainfall increases in DARLAM. For example, Figure 21 shows rainfall change in summer and winter in the GCM and DARLAM. A tendency for rainfall decreases to be weaker in DARLAM has been apparent in previous DARLAM simulations for Victoria (see Whetton et al., 2000b), although it is more striking in the current simulation. The cause of this somewhat independent behaviour of DARLAM needs to be understood and assessed so that an overall assessment of the reliability of the DARLAM results may be made.

The difference in the results may be related to differences in the representation of the land surface between DARLAM and the GCM. As well as having coarser resolution, the GCM uses ranges of soil and vegetation types that are much more limited than those used by DARLAM. In the GCM Australian soil is classified as either sand or sandy clay loam, whereas six different types are used in DARLAM based on the system of Zobler (1988). Similarly, in the GCM, Australian vegetation is classified into six globally-derived types, whereas DARLAM uses a locally-derived classification of 31 types (D. Graetz, pers. comm.).

The effect of using these more detailed and more accurate land surface classifications in DARLAM has been to reclassify much of Australia into soil-types, and to a lesser extent vegetation-types, that are better at retaining moisture (E. Kowalczyk, pers. comm.). For example, in DARLAM there is less sand and more of other types of soil. It is thus not surprising to find that soil moisture in DARLAM is better conserved than in the GCM, and has less sensitivity to changes in climate.

Figure 22 compares the mean annual cycle in soil moisture over south-eastern Australia in the two models and under present and enhanced greenhouse conditions. In general, soil moisture is lower in summer and under enhanced greenhouse conditions, reflecting increases in evaporative demand with increased temperature. More significantly, the magnitude of the annual cycle and the decreases under enhanced greenhouse conditions are much larger in percentage terms in the GCM than they are in DARLAM (the results are not strictly comparable in absolute terms). The greater responsiveness of the GCM soil moisture is also noticeable when the magnitude of interannual variability is compared (results not shown).


GCM summer change

GCM winter change

DARLAM summer change

DARLAM winter change

Figure 21: Simulated percent rainfall change per degree of global warming (PDGW) over the period 1961-2100 in the CSIRO coupled GCM and in DARLAM for summer and winter.

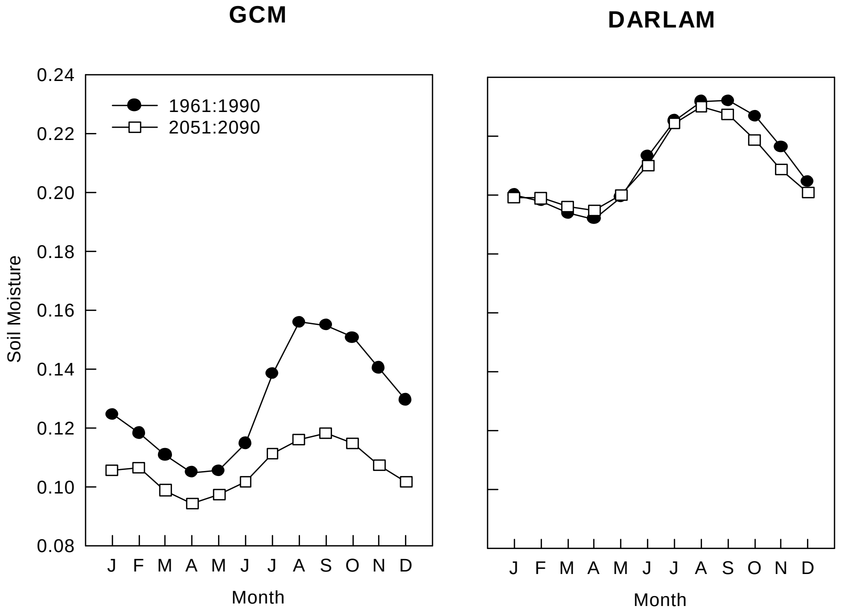


Figure 22: Annual cycle of simulated soil moisture (volume of water per volume of soil) in southeastern Australia in the CSIRO GCM and DARLAM under current and enhanced greenhouse conditions.

Unfortunately, it is very difficult to validate soil moisture simulations against observations, as the relevant observations are extremely limited and usually not in a form that allows a valid comparison. However, in principle, the DARLAM results should be preferred because of the more realistic representation of the land surface in DARLAM.

The greater sensitivity of soil moisture to climate in the GCM may be relevant to simulated rainfall change through its impact on evaporation. Modelling studies in the international literature (e.g. Mintz, 1984; Wetherald and Manabe, 1995) including an Australian study (Simmonds and Lynch, 1992) demonstrate that decreased continental soil moisture can lead to decreased precipitation due to reduced evaporation (or vice versa). So in the case at hand, the marked decreases in soil moisture which occur in the GCM, but not in DARLAM, may be contributing to simulated rainfall decreases.

However, the importance of this mechanism cannot be confirmed without undertaking some further long simulations of a diagnostic nature. As there are also substantial differences between the simulated rainfall changes of DARLAM and the GCM over some ocean areas, at best the soil moisture mechanism would explain only part of the differences. To date we have not been able to identify any other processes that are leading to the difference in the results. This area needs further research.

Remaining Uncertainties

The ranges of future climate change for Victoria presented here are best viewed as a set of plausible scenarios of future regional climate change rather than as predictions. Despite the rapid improvement in modelling tools in recent years, regional climate change projection is still affected by various uncertainties. We have attempted to allow for uncertainties associated with projecting future greenhouse gas emissions, and with estimating the sensitivity of the global climate system, but others remain which are less easily quantified and are particularly relevant to estimating future regional rainfall change. Some current concerns include:

- Whether current climate models adequately simulate enhanced greenhouse changes in the El Niño-Southern Oscillation (a major cause of year-to-year rainfall variability over northern Victoria). Although coupled atmosphere-ocean GCMs (including the CSIRO GCM) are able to reproduce El Niño-like behaviour, there are significant deficiencies in its simulation which may affect the reliability of the enhanced greenhouse simulated changes.
- Whether the pattern of warming at the ocean surface is adequately simulated in GCMs. Climate (particularly rainfall) in the Australian region is likely to be very sensitive to the oceanic response to enhanced greenhouse conditions (through changes in sea surface temperature patterns). The use this year of a coupled atmosphere-ocean GCM is an important step in the right direction in this area, but ocean modelling remains less well developed than atmospheric modelling and it is possible that modelling improvements will lead to significantly different results.
- Whether climate processes at the land surface are adequately simulated. As discussed in the previous section, there is evidence that enhanced greenhouse rainfall results are quite sensitive to the representation of soil and vegetation over the continent.
- That natural climatic variability at the yearly to decadal time scale may partially (or wholly) mask enhanced greenhouse changes in climate for some decades into the future both in the

model and in the real world. This variability introduces significant uncertainty into the projection of regional climate change, particularly for precipitation. This uncertainty can be estimated using single and multiple simulations of many decades of climate and the present 140-year run is a big step forward.

- Whether changes in sulfate aerosol pollution (which would occur mainly in the northern hemisphere) would affect Australian climate. This has not been included in the CSIRO simulations for Victoria as yet, although based on GCM results from some other modelling centres, and a very recent CSIRO GCM study, the impact is not expected to be large.

In all of these areas, different climate models will vary in their behaviour and components. This will lead to differences in simulated regional climate change (particularly rainfall change).

As noted earlier, the current simulation of rainfall change differs in some significant ways from that provided by previous DARLAM simulation. This change partially reflects differences between the enhanced greenhouse simulations of the coupled ocean-atmosphere GCM used this year and the slab-ocean GCM used in the 1996-97 report, and may be seen as a consequence of model improvements. However, in part the differences are due to decadal climatic variability in the different simulations.

A tendency for rainfall decrease (in winter particularly) appears to be more strongly evident in a number of other coupled GCMs than in the CSIRO GCM (see Figure 16 in Hennessy et al. 1997). This suggests that were DARLAM to be nested in other coupled models we may obtain drier enhanced greenhouse climates than we have seen here, thus placing the current DARLAM results towards the wetter end of the range of results conceivably obtainable from current models. However, such inferences may be misleading given the tendency seen here for rainfall change in DARLAM to evolve somewhat independently of rainfall in the host GCM.

In summary, although the current high resolution scenarios are the best available at present, further revisions to scenario information may be expected in the future as new simulations are undertaken using improved models. Although in time development of the science may allow uncertainties to be significantly narrowed, it is inevitable that climate change information will continue to contain significant uncertainty. This means that it may be best to consider climate change and its impacts in a risk assessment framework in which the probability of various future climates are estimated and the risk of exceeding key sectoral thresholds is assessed. This approach is currently under development in CSIRO (see ‘Further Research’ below).

5. IMPLICATIONS AND FURTHER RESEARCH

Climate change over Victoria has potential to significantly affect many aspects of the natural and managed environment, such as:

- water resources, including floods, water supply security, irrigation allocations and demand;
- coastal activities, particularly in support of coastal management strategies;
- fire danger;
- ecosystem vulnerability;
- forest productivity and tree-farming to take advantage of carbon trading;
- health, including infectious diseases, air pollution and extreme temperature-related deaths;
- agriculture and horticulture, including carbon dioxide enhancement of plant growth, crop irrigation, land degradation, pests and disease; and
- built infrastructure including flood damage, ports, transport and communications.

In a Special Report for the IPCC (Basher and Pittock, 1998), an assessment of regional impacts of climate change in Australia indicates high vulnerability for ecosystems, hydrology, and some coastal zones. Moderate vulnerability applies to human settlements and health, and net impacts are unclear for forestry and fisheries. In the next 30-50 years, some agricultural enterprises like wheat may be able to adapt and possibly even expand production, but vineyard and orchard enterprises may find adaptation to inadequate chilling more difficult. In the longer term, agricultural vulnerability increases.

Some of these impact areas, particularly hydrology, have been the subject of research over the years for the Victorian context and the two previous reports (Whetton et al., 2000a,b) summarised a range of relevant studies. There is a need to update this impact work taking into account the latest DARLAM results, but also allowing for methodological developments which will enhance the practical relevance of impact research. Use of CSIRO’s OzClim desktop computer software allows generation of climate change scenarios based on a choice of climate models, including DARLAM. The effect of different greenhouse gas emission scenarios can be explored. Impact models can be directly incorporated in OzClim so that time-varying scenarios of impacts based on a range of assumptions can be produced. Impact studies would also be enhanced by use of CSIRO’s risk assessment methodology (which is discussed in detail in the following section).

It would also be desirable to undertake further analysis of the current DARLAM simulation with a focus on output which is highly relevant to many of the impact areas listed above but which has been neglected to date. In particular, hydrological variables such as soil moisture and evaporation deserve attention, at least to identify broad tendencies across the state. (Site-specific assessment of soil moisture change will remain better addressed in off-line modelling studies.)

Current climate models, including the host GCM for the latest DARLAM simulation, are able to reproduce rudimentary El Niño behaviour. Given this, and given the importance of El Niño-Southern Oscillation to climatic variability over Victoria, it would be desirable to undertake an assessment of the implications of current modelling results (including those of DARLAM) for changes in ENSO-related climatic variability over the State.

CSIRO is developing a new Mark 3 version of its coupled ocean-atmosphere GCM, with better representation of physical processes and finer global resolution. It is anticipated that this GCM will better simulate ENSO and associated rainfall variability over Australia.

Risk Assessment

Risk assessment is an activity that aims to maximise benefit and minimise loss in the face of uncertainty by assessing the likelihood of possible future outcomes and by using this information to change behaviour accordingly. There are three major stages within this process: identification, assessment, and treatment. The risk of climate change has been identified at the international level (Houghton et al., 1996; Watson et al., 1996), at the national level (Basher and Pittock, 1998) and at the regional scale in Victoria as described in the previous Section and Whetton et al. (2000a,b).

A framework for risk assessment and treatment (in the form of adaptations) is currently being developed by CSIRO's Climate Impact Group. This methodology assesses the impacts of climate variability and change within a statistical framework, and diagnoses adaptation options. It is a "bottom-up" methodology that allows for the fact that climate, biophysical systems and many socio-economic systems are best characterised on a regional basis.

When specifically applied to the impacts of climate change, the framework has three major features:

1. Independent uncertainties such as those contained within climate scenarios, when combined, create a non-uniform probability distribution that is highest near the centre of the resultant range and lowest at the extremes. This allows the probability of a particular scenario to be estimated (eg. Figure 23).
2. *Impact thresholds* are constructed in the early stages of an impact assessment rather than a range of impacts being the final outcome of a linear assessment. The sensitivity of these thresholds to climate can then be assessed with reference to climate change scenarios (eg. Figure 24). Impact thresholds are location dependent, activity dependent and value dependent, requiring socio-economic factors to be addressed early within the life of a truly integrated project. This step requires the involvement of stakeholders to construct *user-determined thresholds.*
3. The probability of exceeding critical impact thresholds is assessed within the limits of uncertainty contained within the climate scenarios. Adaptation options to reduce the risk of these critical impacts being reached are then surveyed .

A specific example demonstrating the application of the methodology has been developed for irrigation demand by perennial pasture in northern Victoria and is described in Jones (1999, 2000) and Pittock and Jones (2000). This example incorporates the above three features in the following ways:

- Probabilistic scenarios for temperature and rainfall change in northern Victoria based on CSIRO (1996) are developed.
- User activities are incorporated into a soil moisture model where irrigation occurs when soil moisture reaches wilting point for a given pasture species. This model reproduces irrigation water use to within 5% of the seasonal total.
- Thresholds are constructed to represent the recently instituted annual farm irrigation cap based on a maximum of 200% of water right (all water purchases above this cap must take

place on the open market at a much higher cost), and on a projected level of operation where this cap is exceeded too frequently for the irrigation enterprise to remain viable.
- The probabilities of exceeding these thresholds are calculated at 10 year intervals from 1990 to 2100.
- The concept of windows of adaptation is introduced, where the degree of adaptation required to avoid a critical threshold can be estimated.

The overall methodology is shown in Figure 25. This is a highly iterative method, whereas earlier impact assessments have usually been linear, progressing from climate modelling, to scenario development, sensitivity analysis, assessment and adaptation as seen on the right side of the flowchart. In risk assessment, stakeholders are integrated into the process, allowing a more detailed and realistic representation of a particular activity. The process is also carried out in a very different manner to earlier assessments, in that a suitable framework is developed as early as possible in the process, rather than modules being built sequentially from the physical through to the socio-economic sphere. This allows the weakest points in the framework to be identified earlier in a project allowing it to proceed in a more strategic manner. One of the major advantages of the framework is the way it manages uncertainty, which has been one of the major obstacles to implementing the results of the earlier, more linear assessments (Jones, 1999, 2000; Pittock and Jones, 2000)

The risk assessment framework has also been applied within the following research projects:
- A three year project into water resources in the northeast NSW Murray-Darling Basin under the auspices of the Rural Industries Research and Development Corporation involving the Climate Impact Group, NSW Department of Land and Water Conservation, and Hassall and Associates.
- A short-term project assessing the risk of climate change to transport infrastructure, with the Climate Impact Group, PPK Environment and Infrastructure, and Queensland Transport.
- A short-term project assessing the risk of climate change in the South Pacific, allowing for the effects of the Kyoto Protocol.

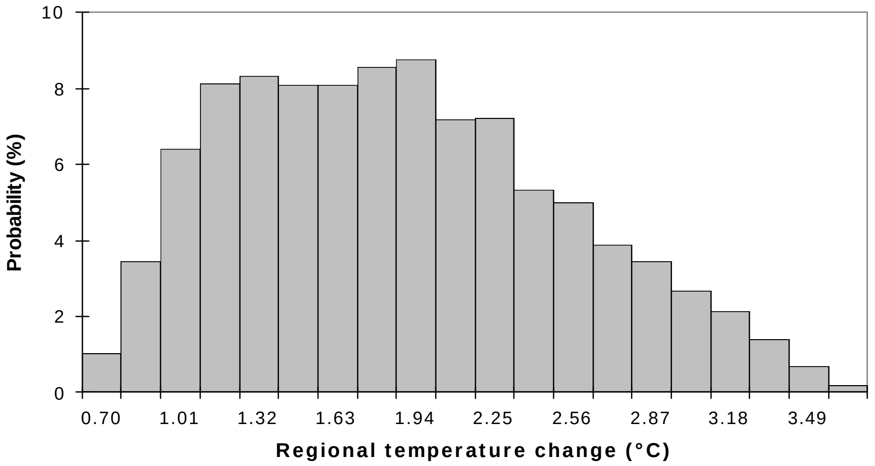


Figure 23: Probability distribution of a regional scenario for temperature change in 2070 for inland Australia (CSIRO, 1996), showing the probability of occurrence for 5% increments within the total range of 0.7–3.8°C, based on Monte Carlo sampling. The component ranges of 0.7–2.1°C (global warming, assuming increasing sulfate aerosols) and 1.0–1.8°C (local warming per degree global warming from a range of GCMs), are assumed to be independent, being randomly sampled 5,000 times and multiplied to obtain the distribution shown. Uniform probability would assume a 5% outcome for each frequency class across the range.

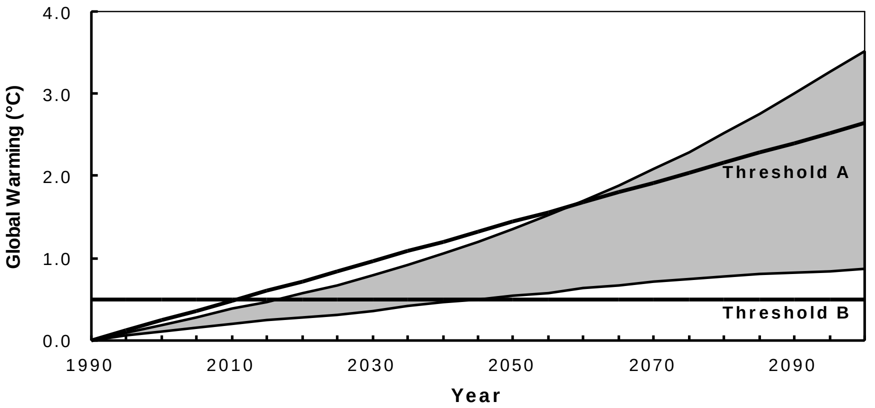


Figure 24: Depiction of two thresholds relative to the IPCC global warming scenarios (assuming increased sulfate aerosols). Threshold A is a transient threshold that allows for a level of autonomous or planned adaptation. It may be related to the adjustment of a species to climate change, or to a level of crop breeding adaptations to temperature increase. Threshold B is absolute and marks a level above which a specific impact occurs, e.g. a temperature above which breeding can no longer occur.

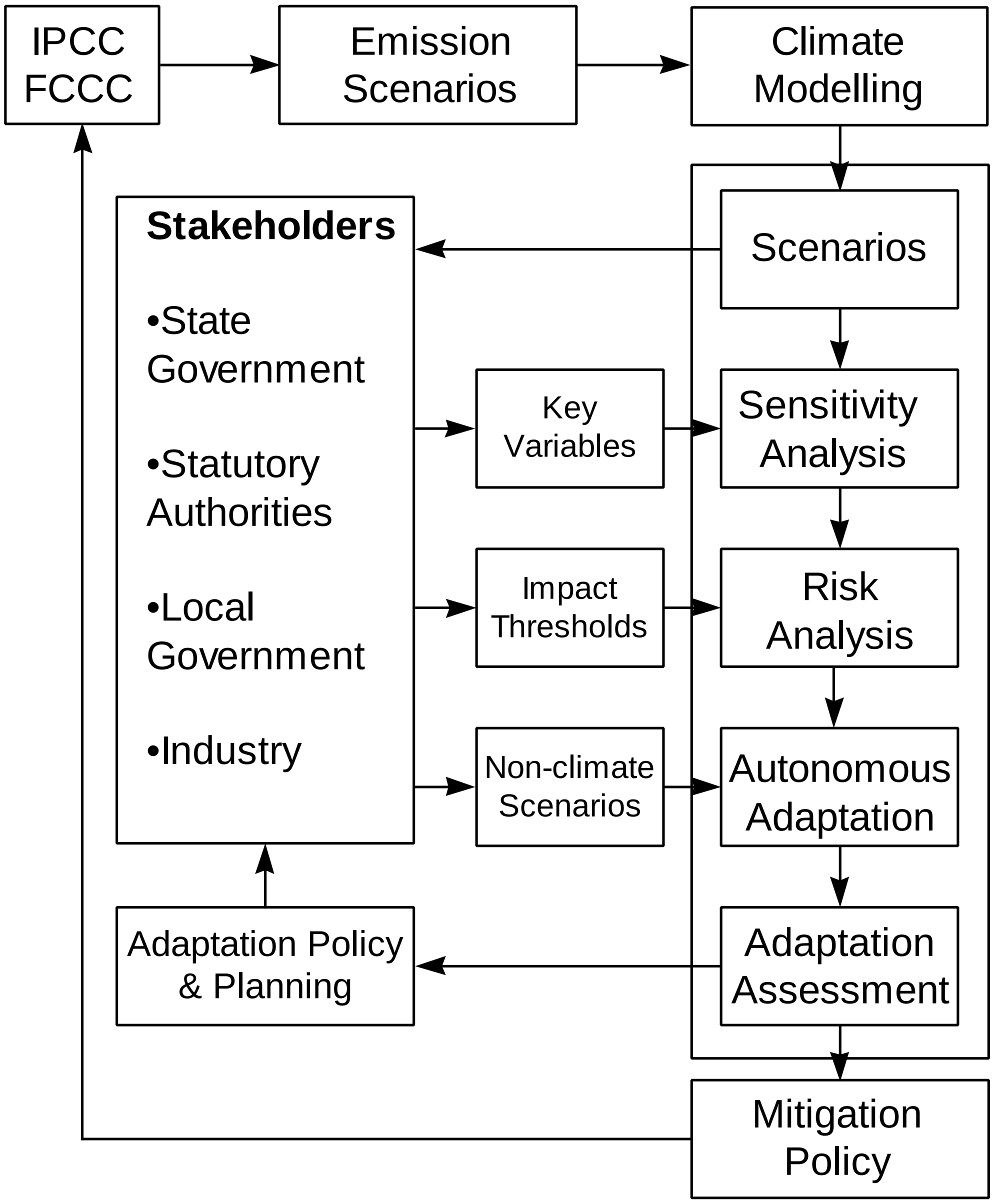


Figure 25: Flow chart for climate risk assessment methodology developed by the CSIRO Climate Impact Group.

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