Fine Resolution Climate Change Scenarios for New South Wales

Annual Report
1997-98

Research undertaken for the
New South Wales Environment Protection Authority

by

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Important Disclaimer

This report relates to climate change scenarios based on computer modelling. Models involve simplifications of the real physical processes that are not fully understood. Accordingly, no responsibility will be accepted by CSIRO or the NSW EPA for the accuracy of forecasts or predictions inferred from this report or for any person's interpretations, deductions, conclusions or actions in reliance on this report.

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Minister's foreword

NSW is faced with the prospect of long-term changes to its climate brought about by the steadily rising concentrations of greenhouse gases in the Earth's atmosphere. Changing climate could have significant implications for NSW's environment, affecting health, biodiversity, agriculture, water resources, rainfall and many other factors in our way of life and the economy. To gain an assessment of the impacts of climate change on NSW, the EPA commissioned CSIRO Division of Atmospheric Research in 1989 to carry out a 5-year study using global climate models. A Major Findings Report on the study was published in 1995.

In 1995, the EPA commissioned the CSIRO to carry out a 3-year research study titled "Fine Resolution Climate Change Scenarios for NSW". This detailed study on climate change in regional NSW was made possible by the CSIRO's capacity to further develop the science of climate modelling at the regional level by imbedding a regional model in a global model. The accompanying report is the third and final annual report to be published. The findings of the whole of the three-year study have been published in a separate Summary Report.

CSIRO has produced scenarios of changes in temperature, rainfall and frequency of extreme events that may appear in NSW by around 2050 due to elevated concentrations of greenhouse gases. Although regional climate modelling is a rapidly developing science, there is still considerable uncertainty as to how global greenhouse concentrations will change over the next century, combined with scientific uncertainty on how temperature will respond. Furthermore, uncertainties in rainfall variability due to the El Niño phenomenon and the effect of oceans may lead to different results to those suggested in the report. In summary, the current results represent plausible future scenarios, rather than firm predictions.

The research carried out in the third year of the study represents an advance in the science of climate modelling. It has produced the most reliable scenarios to date for six regions covering NSW, being based on a gradual increase in greenhouse gas concentrations and a more representative ocean model. Two localities, Newcastle and Bathurst, were also investigated.

I would like to draw attention to some of the important points made in the report. Firstly, due to the effects of climate change, rain may fall in different seasonal patterns and with higher intensity, especially in inland NSW. Secondly, the study suggests that there is a likelihood of increased frequency and magnitude of some extreme events such as floods. Thirdly, more heatwaves and fewer frosts are anticipated. Finally, the use of more realistic soil types and vegetation types in the regional model suggests that soil moisture may not be reduced as much as global models have indicated.

I trust this report and its companion reports will be used to assist governments and the community to better plan for the impacts of climate change on NSW.

Pam Allan

PAM ALLAN MP
Minister for the Environment

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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 next 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 New South Wales Environment Protection Authority (NSW EPA) has funded CSIRO Atmospheric Research to develop climate change scenarios for NSW to assist the Government and the community to plan for climate change.

The research project

This report describes research undertaken in the third and final year of a project entitled “Fine resolution climate change scenarios for New South Wales”. 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) requires input data from the global climate model (GCM), which has a relatively coarse grid size of 600 km × 350 km. 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.

In the first year, DARLAM simulated ten years of climate for present levels of carbon dioxide and a step-change to ten years of double present levels. Changes in average temperature and rainfall patterns over NSW were presented in the 1995-96 annual report. In the second year, the simulations were extended to twenty years to enhance the reliability of the patterns of average climate change and to enable analysis of variability, as described in the 1996-97 annual report. In the third year, 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 NSW are described in this report.

The results

The experiment performed in the final year represents a major step forwards in regional climate change research and is the first 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. We consider results from the final year the most reliable. 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 NSW indicates the following:

Temperature

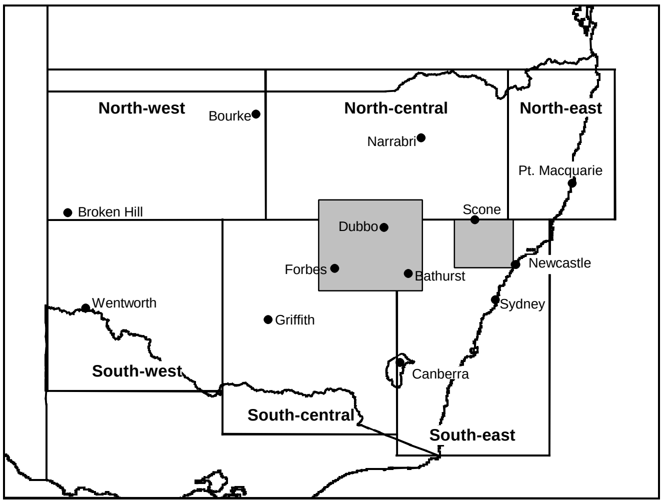
- a warming of 0.5 to 2.7°C.

Rainfall

- wetter conditions in summer and autumn, drier conditions in winter and spring.
- south-central and south-west (statistically significant)
  3-14% drier in spring,
  4-19% wetter in summer.
- north-central and north-west (not statistically significant)
  at least 10% wetter (for the high scenario) in summer and autumn.
- otherwise negligible change in average rainfall.

Extreme events

- number of hot summer days over 35°C
  increases by 10 to 50%.
- number of frosty winter days below 0°C
  decreases by 20 to 100%.
- number of extremely wet summers
  triples in the south-west.
- number of extremely wet autumns
  doubles in the north-central and
  south-central regions, and
  triples in the north-west.
- number of extremely wet winters
  doubles in the north-west.
- number of spring droughts
  doubles in all regions except the south-east.
- extreme daily rainfall intensity and frequency
  increases in many regions, particularly in summer and autumn.



Map 1: Six NSW regions. Bathurst and Newcastle areas are shaded.

Temporal changes in extreme temperature and rainfall events have been examined more closely in the Newcastle and Bathurst regions. Sample time series of seasonal temperature and rainfall were constructed for each region by combining observed variability with DARLAM scenarios for 1990-2100. For the low scenarios, trends are almost imperceptible with little change in extreme events. For the high scenarios, some interesting trends emerge.

For example, near Newcastle, the observed average winter minimum of about 9°C becomes an extremely rare event, exceeded in all but one winter after 2020. The number of winters with at least four days below 5°C drops by 80% between the periods 1997-2036 and 2037-2076, and the number of summers with at least 10 days over 30°C is more than doubled. Near Bathurst, winters with at least five days with minima below minus 5°C decline markedly - from six in the first 40 years to just one in the last 36 years. The present 1-in-20 year daily rainfall event increases by about 15% from 50mm to 57mm; alternatively the 50 mm daily total becomes a 1-in-10 year event, or twice as common.

In summary, NSW becomes 0.5 to 2.7°C warmer by 2050, with more hot summer days and fewer frosty winter days. Rainfall increases in summer and autumn and decreases in winter and spring. The number of spring droughts doubles throughout NSW except in the south-east region, and the number of wet summers, autumns and winters doubles in some areas. 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 NSW 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 NSW 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

Climate change over NSW 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 Intergovernmental Panel on Climate Change (IPCC) 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. Agriculture may be able to adapt and possibly expand production in the short term, but vulnerability increases in the long term when warming reaches higher levels.

While few impact studies have focussed specifically on NSW, those that have suggest significant consequences. For example, a preliminary study of the Macquarie River Basin, using a scenario for 2030 from the 1996-97 report, indicated that the local economy would decline by 12 to 35%, and annual runoff to the Burrendong Dam would fall by 10 to 30%.

Fire frequency in NSW increases under greenhouse warming scenarios. Heat-related deaths in Sydney increase for a 2030 scenario of climate change and population growth. A scenario for 2030 indicates an 18-66% reduction in the area of south-east Australian snow cover, stressing ecosystems and perhaps requiring some adaptations by the ski industry. Fewer frosts would benefit many agricultural activities, although less winter chilling would reduce stone-fruit and apple productivity. An increase in extreme rainfall would exacerbate soil erosion and flood damage, increasing insurance claims and the need for government assistance.

Future research

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. Simulated changes in east coast low pressure systems, tropical cyclones and the El Niño – Southern Oscillation should also be investigated since these factors have a strong influence on rainfall variability in parts of NSW.

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. 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 next century. 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 next 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 New South Wales Environment Protection Authority (NSW EPA) funded a three-year research program from 1995-96 to 1997-98 for CSIRO Atmospheric Research to develop climate change scenarios for NSW to assist the Government and the community plan for climate change. The results of this research are summarised here.

Global climate modelling

The global climate system is very complex. Quantifying the effect of increasing greenhouse gases is not straight-forward. The main tool used by scientists to project climate change is the global climate model (GCM). This is a computer model representing 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 IPCC has used results from these models in an assessment with input from almost 2500 scientists. The IPCC has concluded that global temperatures may increase by 0.6 to 2.1ºC by the year 2050 and 0.8 to 4.5ºC by 2100, assuming sulfate aerosol emissions remain at 1990 levels (Box 1).

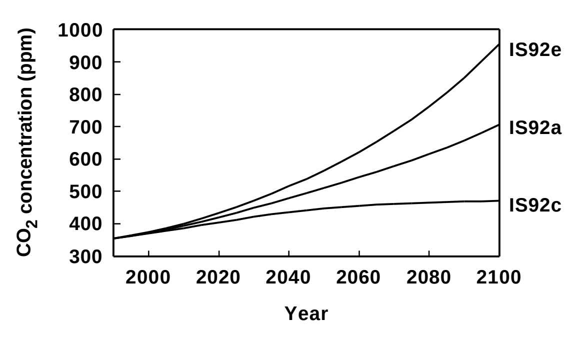
Regional deviations from global average changes can be substantial. In general, climate models simulate greater warming over land and near the poles with less warming over the oceans and the tropics. Different climate models give different rates of change and regional patterns, and this needs to be taken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

Box 1: The IPCC international assessment

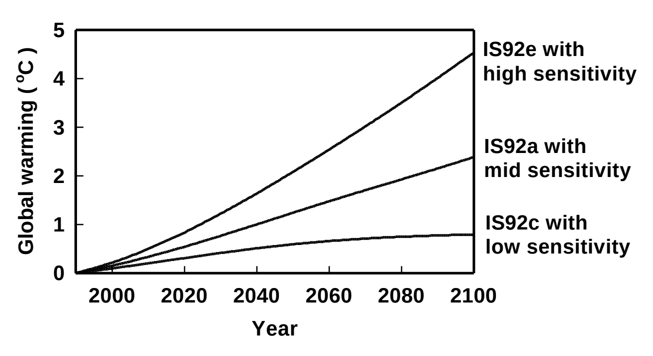
In July 1996, the IPCC Second Assessment Report (Houghton et al., 1996) was endorsed by governments represented at the Second Conference of Parties to the UN Framework Convention on Climate Change, including Australian government ministers. The ministerial statement declared the report to be “the most 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 NSW

Global climate models do not have fine enough horizontal resolution to simulate climate and climate change over sub-continental regions such as NSW. 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.

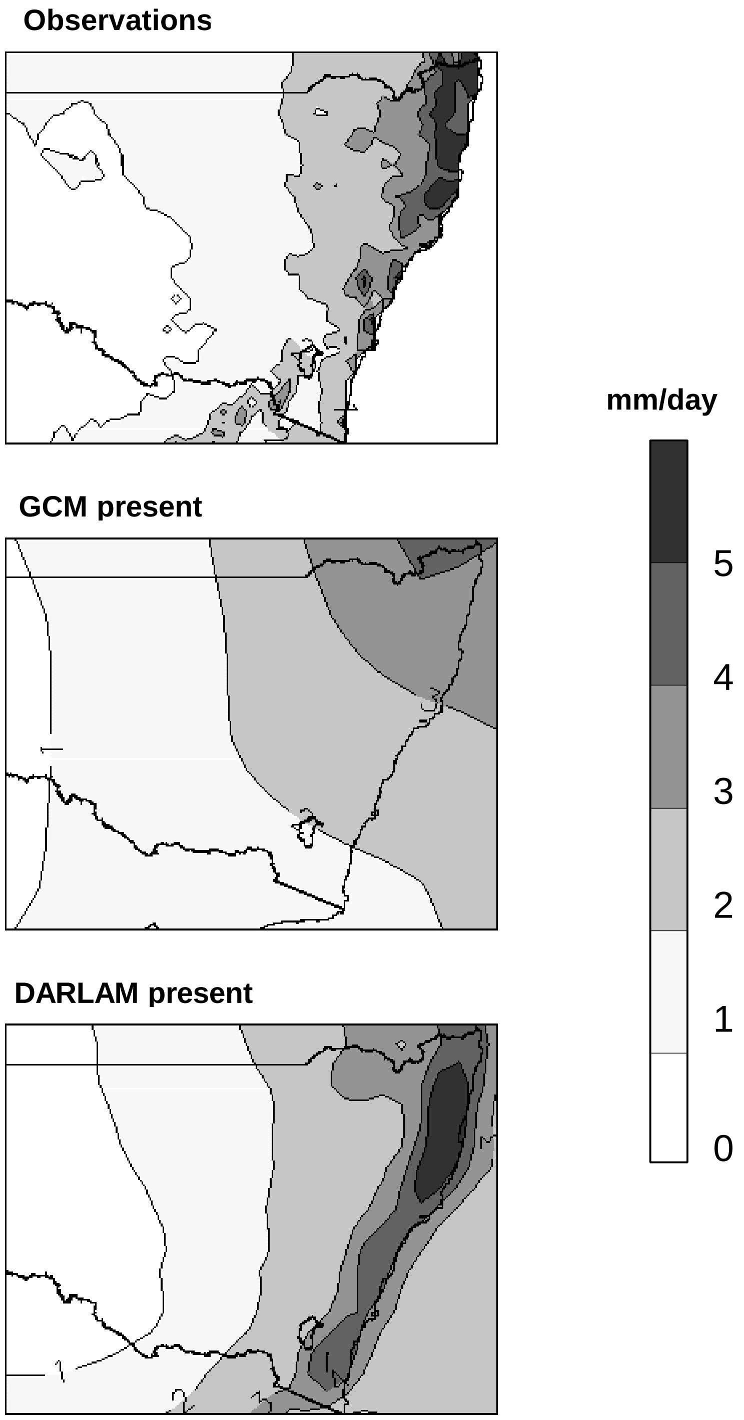
DARLAM is able to reproduce observed seasonal average patterns of temperature and rainfall over NSW much better than a GCM. Figure 1 shows an example of DARLAM's superiority over the GCM in simulating regional rainfall. The performance of DARLAM increases our confidence in the reliability of the enhanced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

Results from the first and second years of the project

In 1995-96, the CSIRO GCM with a simple ocean 50 metres deep was used to drive DARLAM for ten years of present levels of carbon dioxide ($1xCO_2$) and ten years of double present levels ($2xCO_2$). Differences between the two simulations gave patterns of climate change which 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 NSW in the 1995-96 annual report (Hennessy et al., 1997). By 2030, temperatures increased by 0.4 to 1.6°C and precipitation decreased in all seasons except spring.

In 1996-97, 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 NSW, or for elsewhere in Australia. Changes in variability are potentially important in climate change impact assessment. Results were presented in the 1996-97 annual report (Whetton et al., 1997). 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 spring precipitation decreased over most of NSW. Even though climate variability did not change significantly, changes in average conditions caused marked changes in the frequency of extremes. 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 parts of inland NSW. Hot summer days occurred more often and cold winter days declined.

Summer rainfall



Observations

GCM present

DARLAM present

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 for the final year of the project

There are five milestones for research in 1997-98 which are numbered 2.7 to 2.11 in the Research agreement between CSIRO and NSW EPA. Milestones 2.7 to 2.9 were modified as a result of consultation with the NSW EPA during 1997. The milestones, and how they are addressed in this report, may be summarised as follows:

Milestone 2.7 required DARLAM to be nested 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 and this was an essential step in the improvement of climate change information available for NSW. The milestone required that at least twenty years of current climate and of enhanced greenhouse climate be simulated. However, to enhance the reliability of the results, a total of 140 years of simulated climate data have been produced for this report. Details of this experiment are set out at the beginning of Chapter 2.

Milestone 2.8 and 2.9 dealt with changes in extreme temperature and rainfall, including the requirement that two focus regions be considered: Newcastle and Bathurst. These results are included in Chapter 3 of this report. This includes updated climate change scenarios for NSW for change in average precipitation and 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 times can be readily constructed) along with sample time series showing the evolution of changes from 1990-2100. Chapter 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 Chapter 4.

Milestone 2.10 is production of this annual report and a short summary report which briefly covers results from all three years of the contract. The summary report (Hennessy et al., 1998) is available from the NSW EPA.

Milestone 2.11 requires CSIRO to provide briefings to the EPA and other relevant bodies in NSW. The following briefings have been provided:

- On April 2 1998 in Sydney, CSIRO provided briefings to representatives from the NSW Cabinet Office, Treasury, Office of the Minister for the Environment, Department of Land and Water Conservation (DLWC), Public Works and Services, Health, Urban Affairs and Planning, EPA, National Parks and Wildlife Service (NPWS), Road Traffic Authority, and Sustainable Energy Development Authority (SEDA).
- On May 6-7 1998 in Sydney, CSIRO gave briefings to the Parliamentary Secretary for the Environment, Mr Pat Rogan (MP), the ALP Caucus Committee for the Environment, senior policy advisors and departmental CEO’s. More detailed discussions were held with representatives from the EPA, DLWC, NPWS and State Forests.
- CSIRO also gave a presentation at a local/state government climate change meeting in Narrandera on 11 June 1998. About 25 local government participants attended, as well as Mr Pat Rogan (MP), and representatives from the Office of the Minister for the Environment, the Cabinet Office, SEDA, Environs Australia, Australian Local Government Association, and Newcastle City Council.

These interactions have been very beneficial, providing a useful exchange of views which has assisted CSIRO formulate its research strategy and prepare this report.

2. Methodology

The DARLAM experiment

The latest 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 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 El Niño - Southern Oscillation (ENSO) variability;
2. a physically plausible increase in greenhouse gases according to IPCC recommendations;
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 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.

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 235 land-points covering NSW. Maps are used to convey spatial information and time series plots are used to convey temporal aspects. To keep the report concise, diagrams are shown for selected regions and seasons, and more comprehensive results are summarised in tables.

To assess the model’s ability to simulate 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 are 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.

Temporal aspects of climate change are shown using time series for six sub-regions in NSW, and for focus regions near Newcastle and Bathurst.

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 observations, simulated present (1961-2000) conditions, and simulated enhanced greenhouse conditions (2031-2070). Standard deviation of the precipitation data is also calculated, but in this case the data are averaged seasonally first (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 the year 2050. 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.

Observed data sets

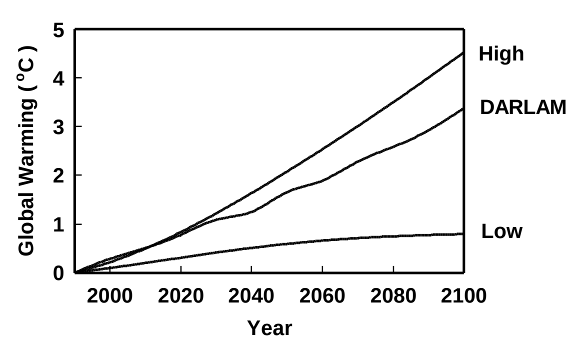
The observed daily temperature data set used here is based on records from Bureau of Meteorology stations using all available years of record. It has been interpolated to a regular grid of half-a-degree (about 50 km) resolution using the elevation-dependent interpolation program of Hutchinson and Bischoff (1983). Daily temperature data for Bathurst (1921-96) and Jerry’s Plains near Newcastle (1957-96) were used in the extreme temperature analysis for those focus regions. A station-based precipitation record for 1910-1995 was used for constructing regional averaged time series of precipitation. Daily rainfall time series for Bathurst and Clarence (near Newcastle) were used for the focus regions. A gridded rainfall 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

The DARLAM results are based on a GCM simulation that has a rate of global warming towards the high end of the range of 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 making adjustments to DARLAM results (Box 2). Summary scenarios for the year 2050 which include the IPCC range of uncertainty are presented for six NSW regions. Other uncertainties which are less readily quantified are noted in the Discussion (Chapter 4).

Box 2: Including uncertainty in DARLAM 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 NSW for 2050 can be derived by multiplying the DARLAM change by 0.35 (i.e. 0.6/1.7), and a high scenario is 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 New South Wales in summer and winter as observed, as simulated for present (1961-2000) conditions, the simulated change per degree of global warming (PDGW) and the change by 2050.

The summer and winter simulations of present climate shown in the 1996-97 report are very similar to the latest simulations. The broad features of the observed patterns are well simulated, although the summer temperatures are still too high west of the highlands. Autumn and spring patterns (not shown) also compare well with observations.

By 2050 there are increases of 1.4 to 2.6°C relative to the present climate simulation, with a tendency for coastal areas to warm less than inland areas, and for summer/autumn to warm less than winter/spring.

Variability

In summer, observed daily standard deviations (not shown) are 3.5 to 5.0°C across the State, with a tendency for values to decrease northwards and towards the coast. The general magnitude of deviations is well simulated by DARLAM but the pattern is not well captured, with excessive variability in the east and north, and inadequate variability in the west. Observed standard deviations in winter are 2.5 to 3.5°C with smallest deviations in the south and east. DARLAM reproduces this pattern well but the magnitudes are about 0.5°C too low.

Under enhanced greenhouse conditions (2031-2070), the standard deviation of summer maximum temperature increases by 0.1 to 0.2°C in the south with little change elsewhere. The standard deviation of winter maximum temperature increases by 0.1 to 0.2°C across the State. These changes are negligible when considered relative to the background standard deviation and to the average warming.

Occurrence of daily extremes

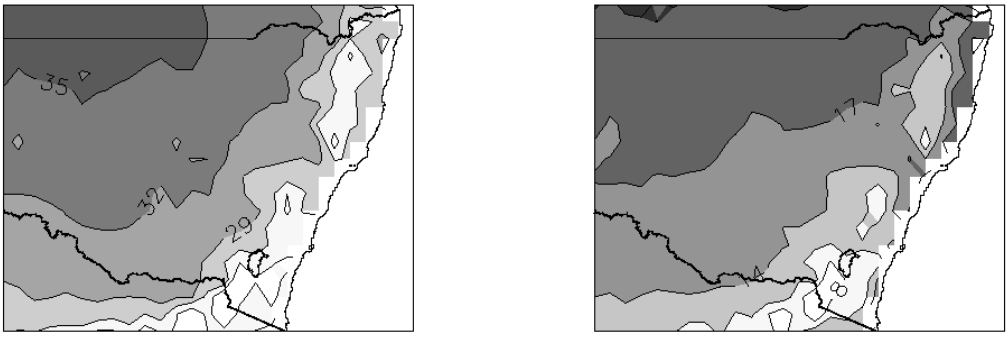
To investigate how these simulated changes in the average and standard deviation may affect extreme maximum temperatures, the number of summer maximum days over 35°C was computed. The observed number ranges from zero days per summer in high altitude and coastal areas to around 50 days per summer in the far north-west (Figure 3). The distribution is quite well simulated in DARLAM, although there are 10 to 20 days too many in the west, reflecting the warm bias in average summer maximum temperatures.

The change by 2050 is assessed by comparing average frequencies for the periods 1961-2000 and 2031-2070. There are increases of up to five days east of the Divide, and of 5 to 15 days elsewhere, except in the central-north where the limit of 90 summer days is reached.

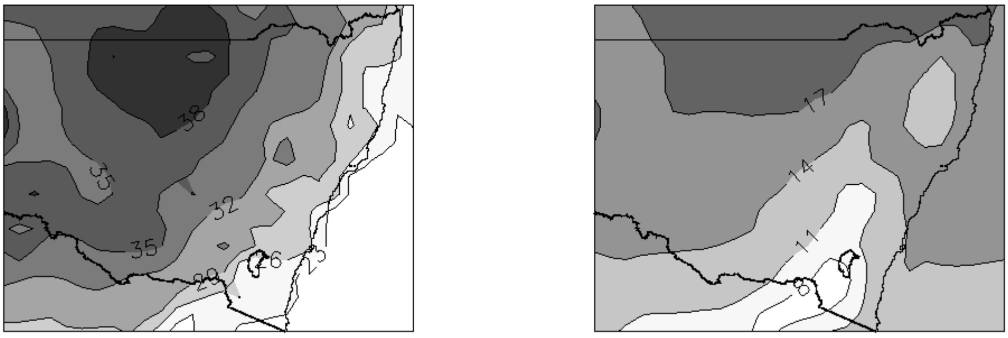
Daily Maximum Temperature

Summer **Winter**

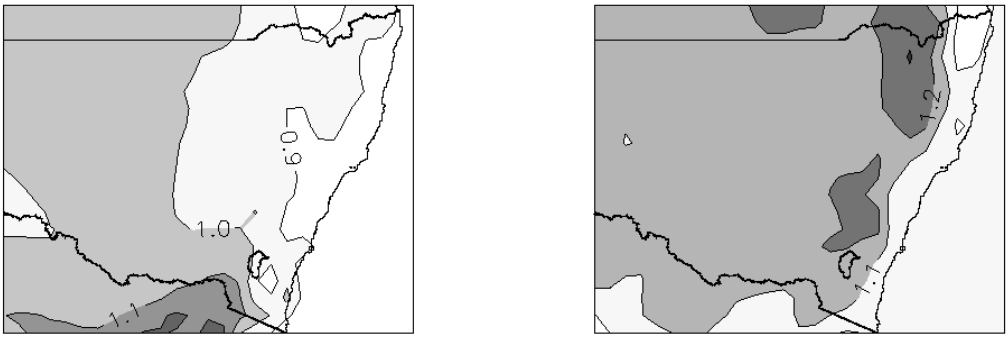
Observations **Observations**



DARLAM present **DARLAM present**



DARLAM change PDGW **DARLAM change PDGW**



DARLAM 2050 change **DARLAM 2050 change**

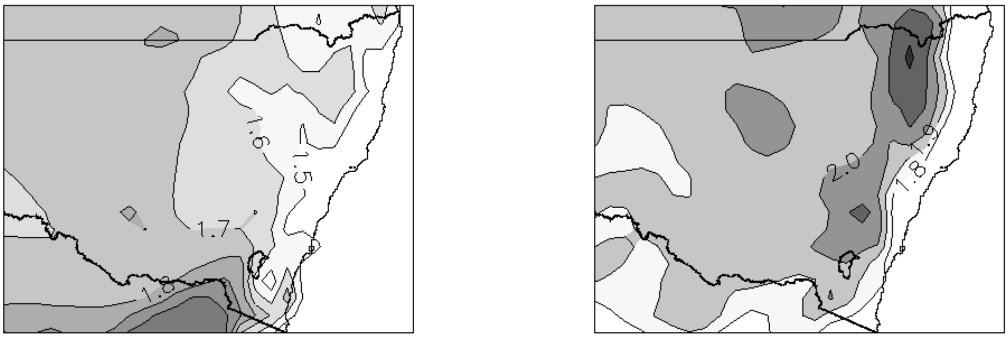
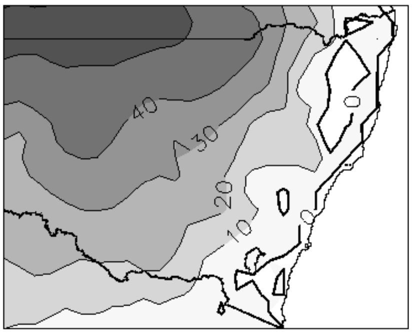


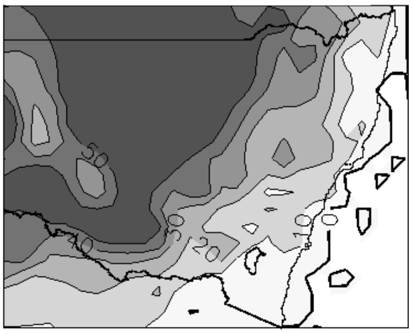
Figure 2: Average daily maximum temperature (°C) for summer and winter as observed, as simulated for present conditions (1961-90), the simulated change per degree of global warming (PDGW), and the change by 2050 relative to present.

Number of hot summer days

Observations



DARLAM present



DARLAM 2050 change

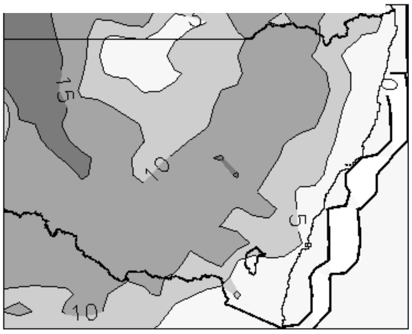


Figure 3: Average number of days of maximum temperature above 35°C in summer as observed, as simulated for present conditions (1961-2000), and simulated change for 2031-2070.

To present temporal aspects of climate change, the simulated daily maximum temperatures are shown as time series for the same six regions used in the 1995-96 and 1996-97 reports (Figure 4). Regional results are produced by averaging data at all grid boxes in a given region. Sample time series (Figure 5) show that the number of summer days over 35°C increases by 20% in the north-west between present (1961-2000) and 40 years centred on 2050, and by 40% in the south-east. Increases of 15%, 35%, 30% and 35% occur in the north-central, north-east, south-west and south-central regions, respectively.

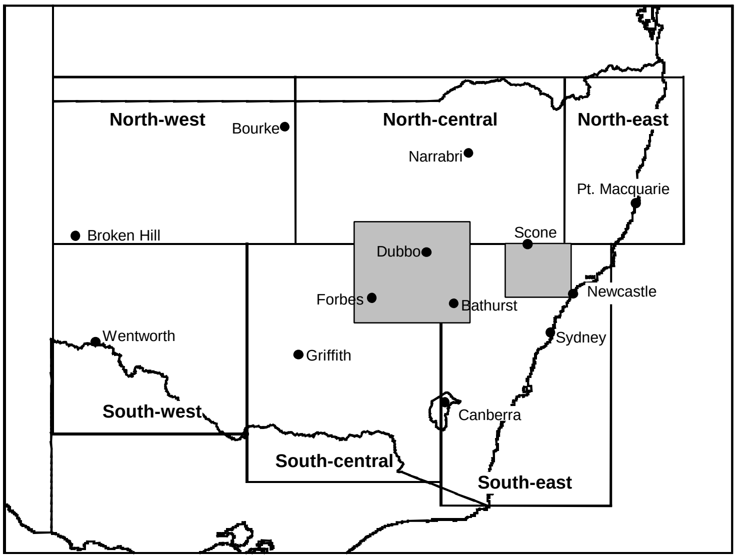


Figure 4: Division of NSW into six regions used for presenting various regionally averaged results. The regions are 'north-west', 'north-central', 'north-east', 'south-east', 'south-central' and 'south-west'.

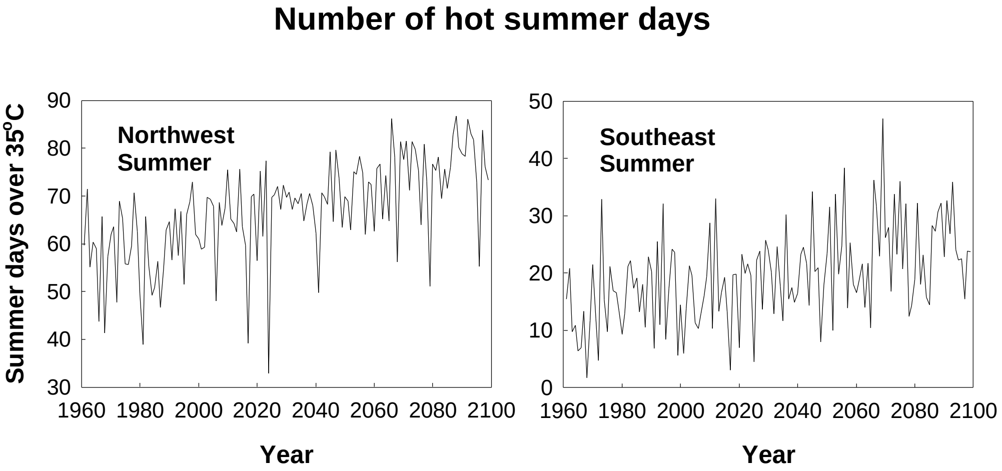


Figure 5: DARLAM number of summer days over 35°C in north-west and south-east NSW.

Such changes may lead to

- greater heat-stress in humans, livestock, ecosystems, agriculture and building materials,
- increased bushfire potential, and
- higher energy demand for air-conditioning.

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 for the north-west in summer and south-east in winter are shown in Figure 6. The changes in average temperature are significant relative to simulated year-to-year variability, particularly in winter near the coast where variability is low. In the south-east, eight of the first 40 winters average at least 14°C, increasing to 20 of the next 40 years and 39 of the last 40 years. In the north-west, the number of summers averaging at least 38°C increases from seven in the first 40 years to 23 in the next 40 years, and 33 in the last 40 years.

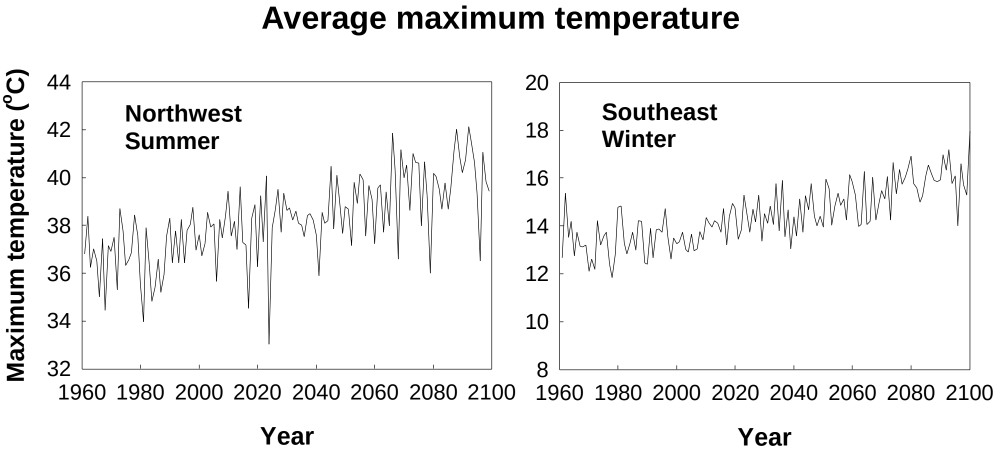


Figure 6: DARLAM average maximum temperature in north-west NSW in summer and south-east NSW in winter.

Daily minimum temperature

Average conditions

Figure 7 shows maps of average summer and winter daily minimum temperature over New South Wales as observed, as simulated for present (1961-2000) conditions, the change per degree of global warming (PDGW), and the change simulated by about 2050. The simulation of present summer conditions is about 3°C too warm and a little poorer than that presented in the 1996-97 report. The winter simulation is good and generally better than the 1996-97 simulation, but about 2°C too warm in the north-west. Autumn and spring minimum temperatures (not shown) are generally well simulated.

By 2050, minimum temperatures increase by 1.5 to 2.2°C relative to the present climate simulation, with least warming in coastal areas and in spring/summer. In summer and autumn, minimum temperatures increase more than maximum temperatures, giving a reduction in the diurnal temperature range (DTR: difference between daily maximum and minimum temperature). There is little change in the DTR in winter and an increase in spring. These changes are consistent with rainfall changes described below, i.e. reduced DTR where rainfall increases and increased DTR where rainfall decreases. However, the DTR changes are in contrast to the results presented in the 1996-97 report, reflecting different rainfall tendencies.

Variability

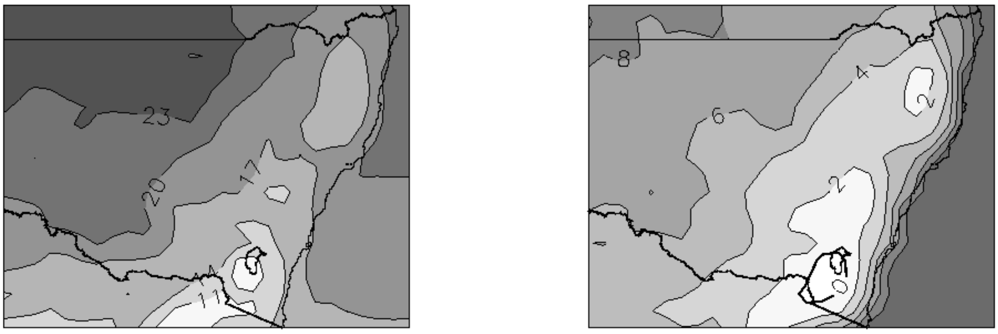
In summer the observed pattern of standard deviation of minimum temperature (not shown) is similar to that of maximum temperature (greater inland and in the south), but the overall magnitude of standard deviation is smaller (2.5–4°C). This pattern is well simulated by DARLAM, but the magnitude is about 0.5°C too low west of the Divide. In winter the observed standard deviation of minimum temperature increases from 3.0°C in the south-west to 4.0°C in the north-east, with values below 3.0°C along the coast. DARLAM simulates the winter standard deviation very well.

Daily Minimum Temperature

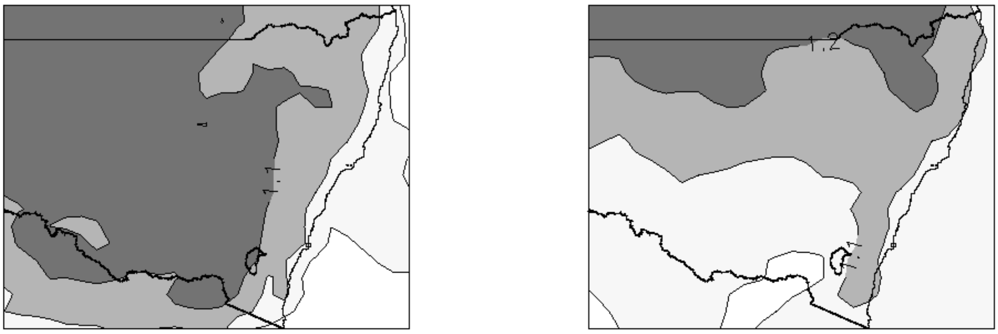
Summer **Winter**

Observations **Observations**

DARLAM present **DARLAM present**



DARLAM change PDGW **DARLAM change PDGW**



DARLAM 2050 change **DARLAM 2050 change**

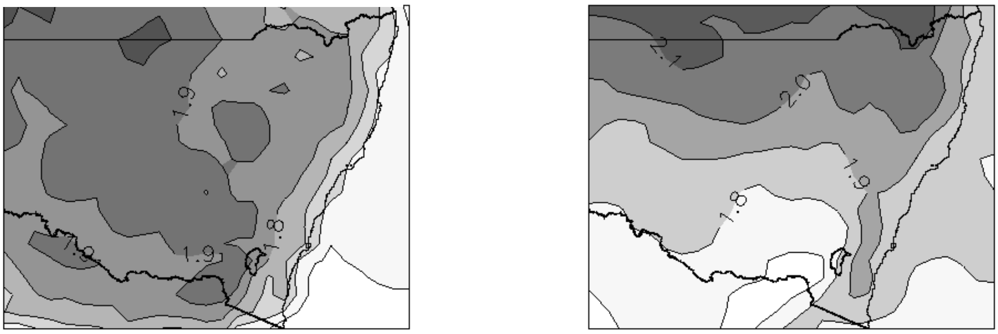


Figure 7: Average daily minimum temperature (°C) for summer and winter as observed, as simulated for present conditions (1961-2000), the simulated change per degree of global warming (PDGW), and the scaled change for 2050 relative to present.

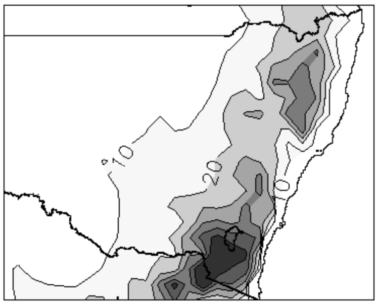
In both seasons, standard deviation of minimum temperature shows little change, although increases of 0.1 to 0.2°C occur in the south-east and south-west in summer. These changes are negligible relative to the background standard deviation and the simulated increase in the average.

Occurrence of daily extremes

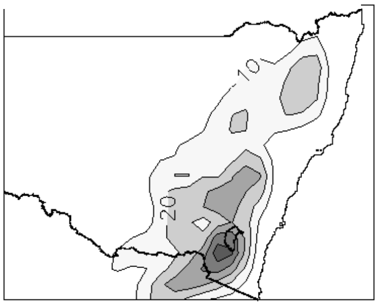
To investigate how changes in the average and standard deviation may affect extreme minimum temperatures, the number of winter days below 0°C was computed (Figure 8). In broad terms the observed pattern is well simulated, with the greatest frequency of frosty days being along the Great Divide (around 20-40 per winter in the model and the observations). The frequency is slightly lower than observed on the inland slopes of the north-east of the State, but this could be expected given that simulated average minimum temperatures were a little too high.

Number of frosty winter days

Observations



DARLAM present



DARLAM 2050 change

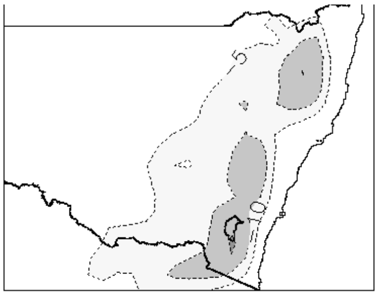


Figure 8: Average number of winter days below 0°C as observed, as simulated for present conditions (1961-2000), and simulated change for 2031-2070.

By 2050, there are 5 to 10 fewer frosty days per winter, on average, over the western plains and 10 to 15 fewer over the north-east and south-east mountains. These reductions are equivalent to about 50% fewer frosty days. Figure 9 shows that the decline in frosty days is rapid. In the south-central region, 11 of the first 40 winters (1961-2000) have at least 20 frosty days, but there are no such winters after the year 2000. Similarly, in the south-east, 12 of the first 40 winters have at least 15 frosty days, but there is only one such winter in the next 40 years, and no winters thereafter.

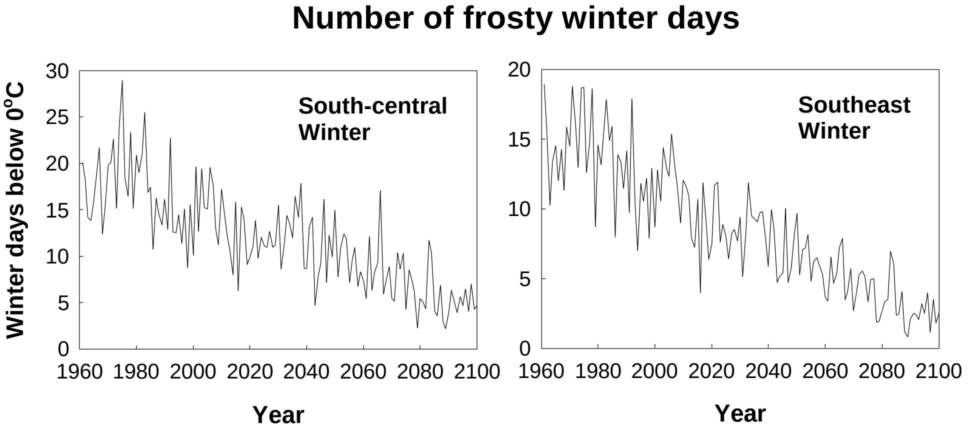


Figure 9: DARLAM number of winter days below 0°C in south-central and south-east NSW.

Occurrence of extreme seasonal conditions

The occurrence of extremely cool or warm winter average minimum temperature was investigated. Sample time series are shown in Figure 10. The increase in the frequency of winters with high minimum temperatures appears more marked than for maximum summer temperature because winter minimum temperatures are less variable. In the south-east, the warmest winter minimum temperature from 1961 to 2000 is exceeded by all but two winters from the year 2040 onward.

Such changes 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,

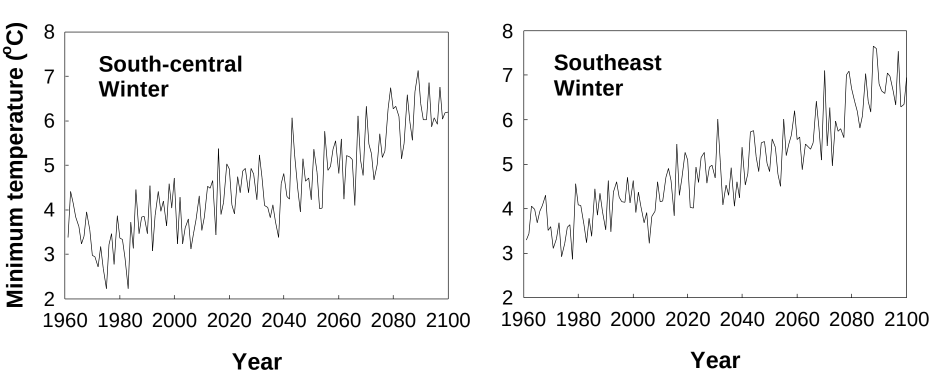


Figure 10: DARLAM average winter minimum temperature in south-central and south-east NSW.

- 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 11 shows maps of average seasonal rainfall over New South Wales as observed, as simulated for present conditions (1961-2000), the change per degree of global warming (PDGW) and the change by 2050 relative to simulated present conditions. 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 simulation of the present climate is generally better than that presented in the 1996-97 report due to improvements in the pattern of rainfall in the east, particularly in spring and summer. However, the overestimation of rainfall in spring is still present, winter rainfall is still too low in the south-east, and autumn rainfall is too low in the west.

The maps of rainfall change show statistically significant increases west of the highlands in the south and in the north near Narrabri in summer, and statistically significant decreases in southern and south-western regions in spring. By 2050, the south-central and south-west regions become 10% drier in spring and 10-15% wetter in summer. Increases of 8% occur in the north-central and north-west regions in summer and 9-14% in autumn. Rainfall changes are negligible elsewhere.

Year-to-year variability and occurrence of extreme seasonal conditions

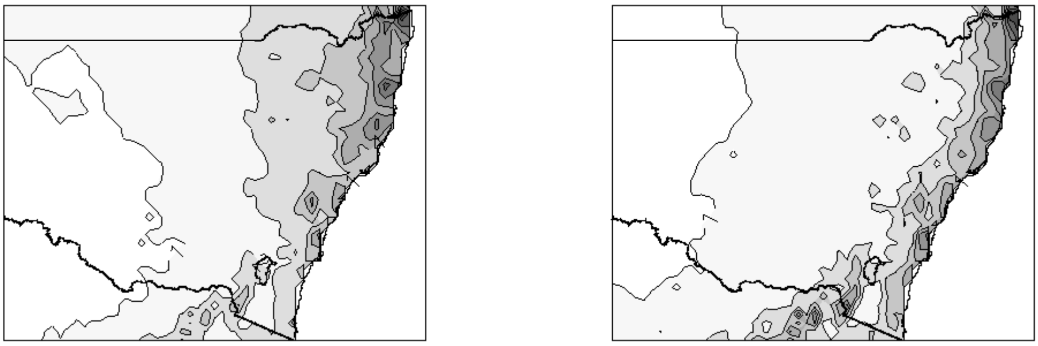
Year-to-year variability in seasonal precipitation in DARLAM was analysed using a number of methods. Variability was considered by comparing observed, simulated 1961-2000 and simulated 2031-2070 maps of the standard deviation and the coefficient of variation (not shown), and by comparing observed and model-simulated time series of regional rainfall (e.g. Figure 12).

In general, year-to-year variability is realistically simulated by DARLAM, although there is a tendency for the most extreme years in the observations to have no equivalent in the simulated time series. Figure 12 illustrates these features for summer in north-central NSW.

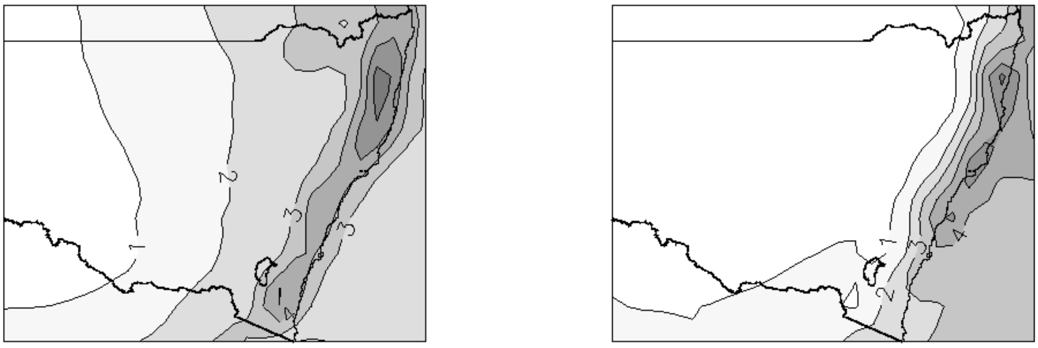
Under enhanced greenhouse conditions, variability tends to increase in inland areas and decrease along the coast. This pattern in most strongly evident in autumn, when decreases and increases in standard deviation by 2050 are as large as 40% in some regions. A tendency for increased variability in summer rainfall in south-west NSW may seen in the time series presented in Figure 13. The reasons for these changes are not clear at present and need further research to be addressed. However, it is notable that the changes are large enough to have an impact on the frequency of occurrence of wet and dry years which is at least as significant as that due to simulated changes in mean conditions.

Summer rainfall

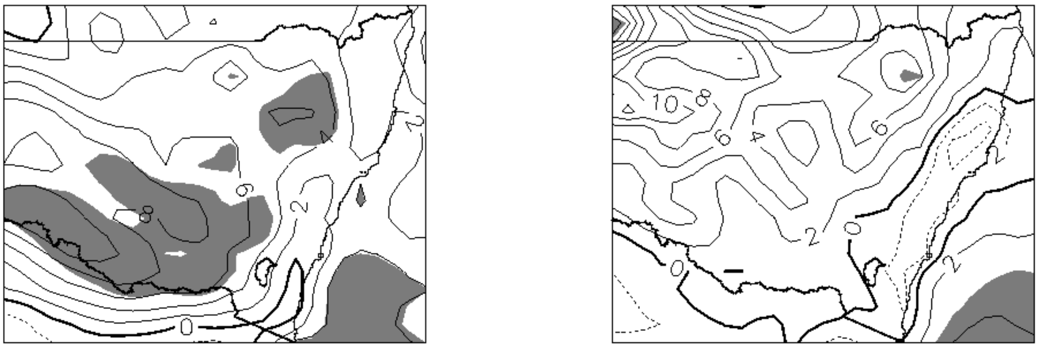
Autumn rainfall


Observations

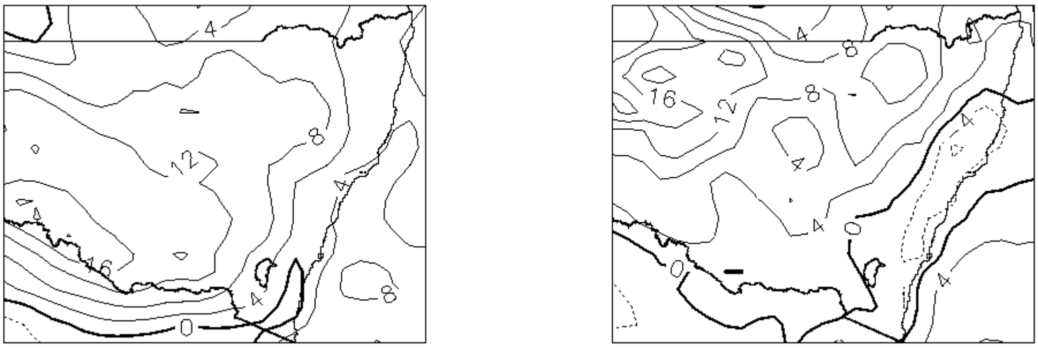
Observations


DARLAM present

DARLAM present


DARLAM change PDGW

DARLAM change PDGW

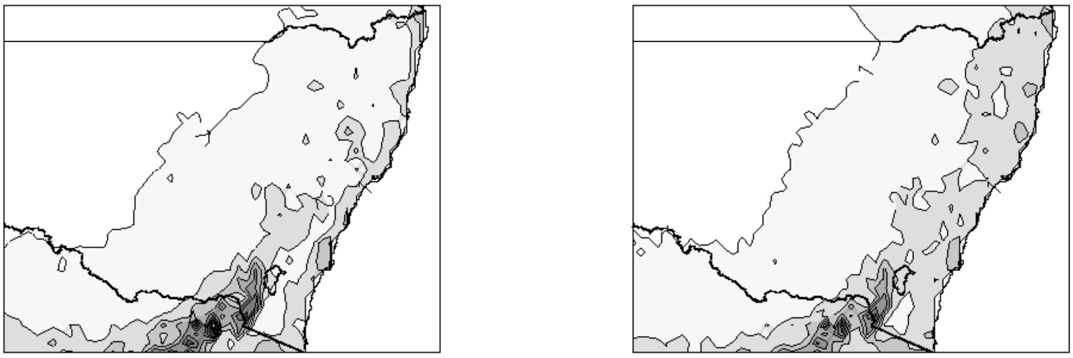

DARLAM 2050 change

DARLAM 2050 change

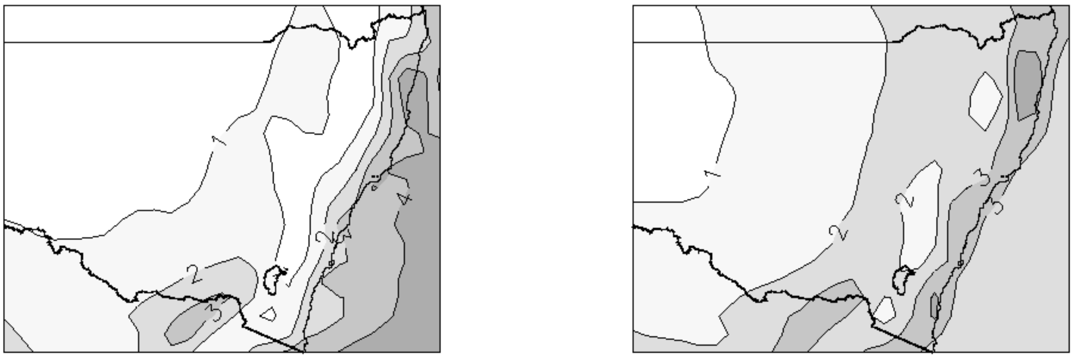
Figure 11, Part A: Average rainfall for summer and autumn: observed, simulated present (mm/day), change (%) per degree of global warming (PDGW) and simulated change (%) by 2050. Shading in the PDGW maps indicates areas of change significant at the 95% confidence level. Dashed contours are negative (reduced rainfall).

Winter rainfall **Spring rainfall**

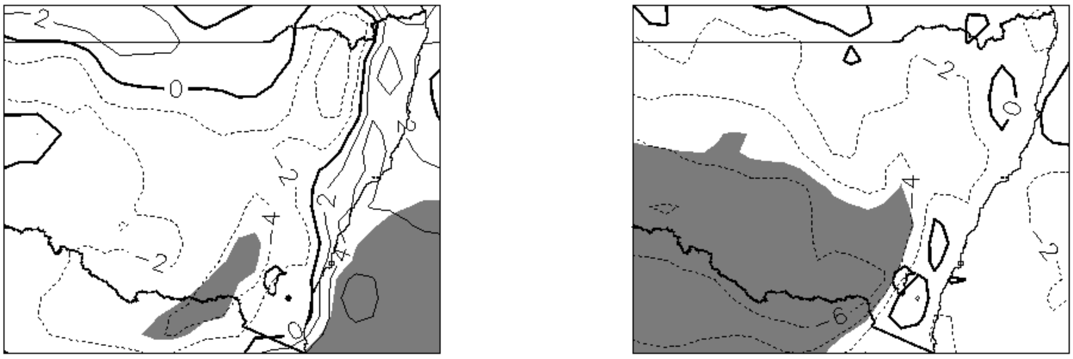
Observations **Observations**



DARLAM present **DARLAM present**



DARLAM change PDGW **DARLAM change PDGW**



DARLAM 2050 change **DARLAM 2050 change**

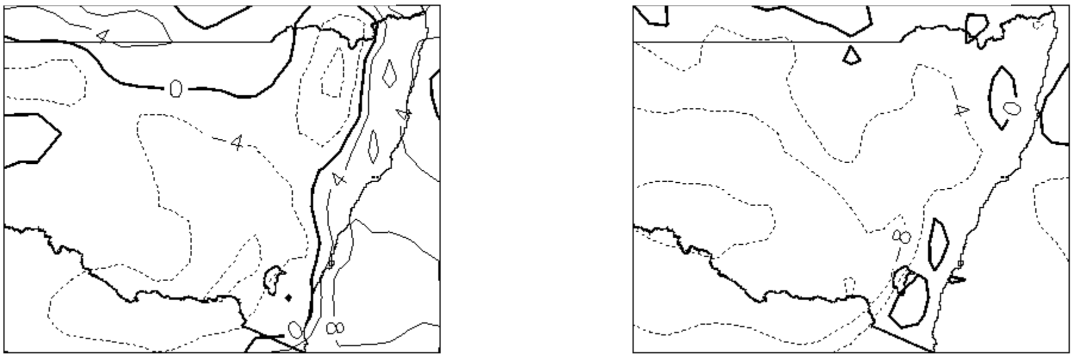


Figure 11, Part B: As for Part A, but for winter and spring.

Figures 13 and 14 provide an example of how the frequency of unusually wet or dry seasons may change. The south-west region is an area in which simulated spring rainfall decreases and summer rainfall increases (Figure 13). There are also moderate increases in variability in summer but little change in spring. The number of extremely wet summers per 20-years from 1961-2000 more than doubles after 2020, as does the number of extremely dry springs (Figure 14).

By about 2050, at least a doubling of the present frequency of extremely dry springs occurs in all regions except the south-east. The present frequency of extremely wet seasons is at least doubled by 2050 in the following seasons/regions: summer in the south-west, autumn in the north-west, south-central and north-central, and winter in the north-west. This could lead to an increased frequency of floods in large inland catchments.

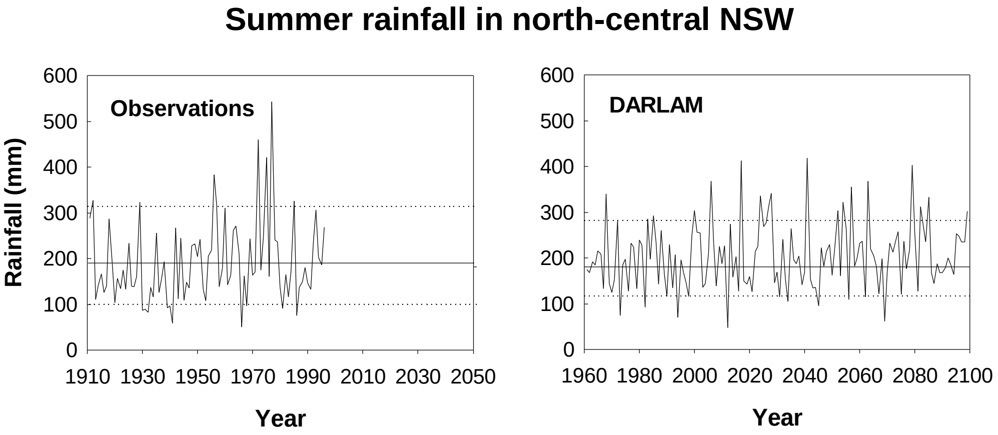


Figure 12: Observed and simulated summer rainfall averaged over the north-central region. Dashed lines indicate the 10th and 90th percentiles, while the solid line is the average (based on 1910-1995 for observations and 1961-2000 for DARLAM).

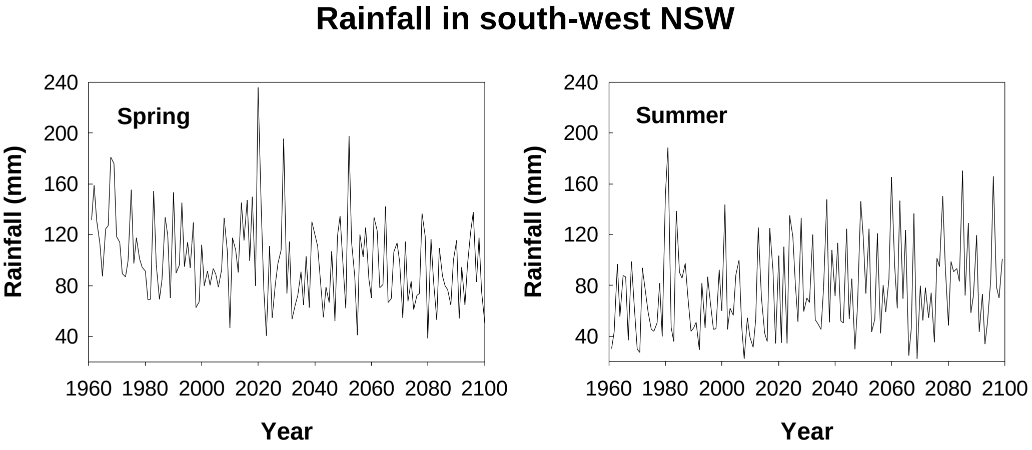


Figure 13: DARLAM spring and summer total rainfall in south-west NSW.

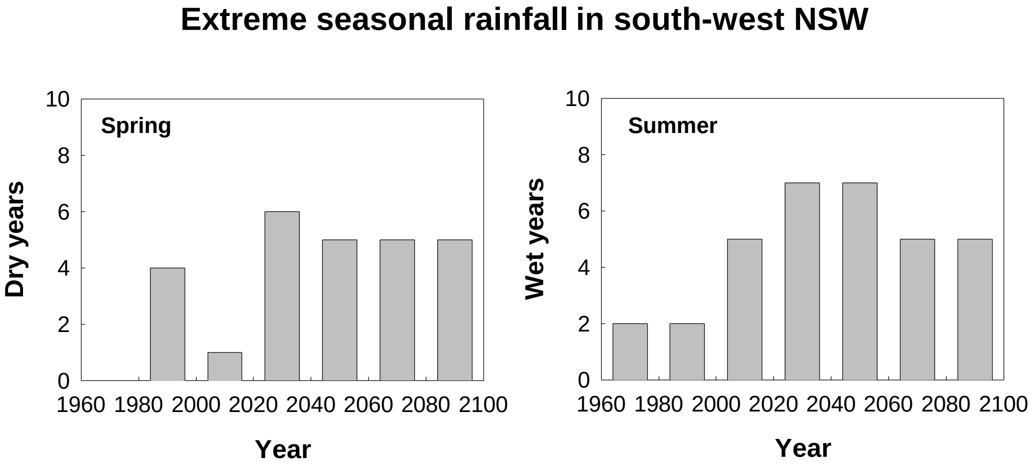


Figure 14: Simulated number of extremely dry springs or wet summers each 20-years in south-west NSW. Dry years have rainfall below the 4th driest year from 1961-2000 while wet years have rainfall above the 4th wettest year from 1961-2000.

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; Hennessy *et al*., 1997b).

Extreme daily rainfall totals were analysed for each of the DARLAM grid boxes over NSW. Figure 15 shows the annual results averaged over all NSW 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.

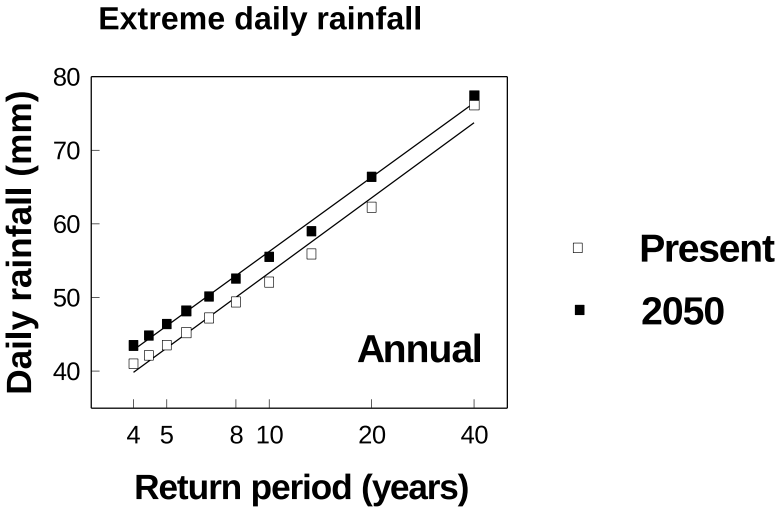


Figure 15: Heavy daily rainfall return periods averaged over NSW for all seasons. Open squares are for the present (1961-2000) and solid squares are for 40-years centred on 2050.

The present 1-in 20-year event increases in intensity by 7% for the 40 years centred on 2050; alternatively, the present 20-year event becomes a 15 year event by 2050. Increases of 5-50% in the intensity of the 1-in-20 year event occur by 2050 in all seasons in the south-west, south-central and north-central regions. In other the regions, such increases are restricted to certain seasons: autumn and winter in the north-west, winter and spring in the north-east, and autumn and spring in the south-east. As found in previous studies, extreme rainfall can become more intense and more frequent even when average rainfall decreases. The south-west region is a good example (Figure 16). By way of exception, decreases in extreme summer daily rainfall occur in the north-west, north-east and south-east (see Newcastle section).

Figure 17 shows the decadal total number of rain events exceeding 40 mm/day in summer for a typical 60 km × 60 km DARLAM grid box in south-central NSW. An increase in such events is clearly evident with the 1961-2000 total being almost doubled in 2001-2040 and almost tripled in 2061-2100.

Results are not summarised quantitatively for each region because we are not confident that the regional variations are systematic. They may be primarily due to the effect of natural variability in the model. More research would be required to address this issue.

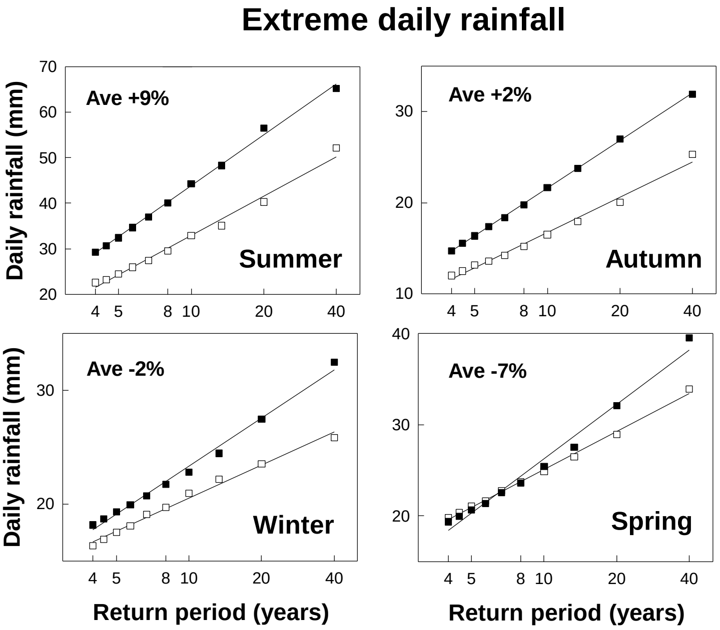


Figure 16: Heavy daily rainfall return periods averaged oversouth-west NSW for each season. Open squares are for the present (1961-2000) and solid squares are for 40-years centred on 2050. Changes in average seasonal rainfall (Ave) are also shown.

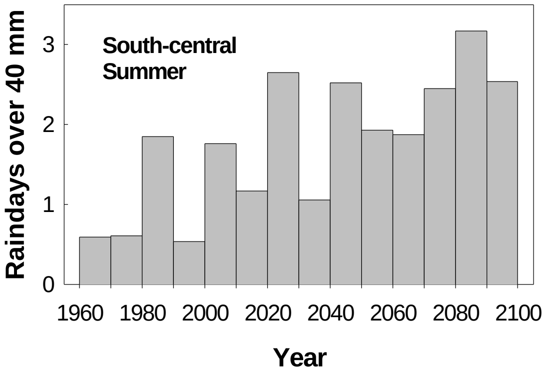


Figure 17: Number of summer rain events over 40mm/day each decade for a typical DARLAM grid box in south-central NSW.

Summary of temperature and rainfall changes

The DARLAM results presented above can be scaled to allow for quantifiable uncertainty (see Box 2). This has been undertaken for changes in average maximum and minimum temperature, summer days over 35°C and winter days below 0°C (Table 1).

While there is variation in temperature changes between seasons, it is generally small within each region, so the annual range of variation is presented in place of a seasonal breakdown. The warming over NSW by 2050 ranges from 0.5 to 2.7°C with least warming near the coast. A reduction in the diurnal temperature range occurs in summer and autumn, with little change in winter and an increase in spring. The number of hot summer days over 35°C increases by 10 to 50% and frosty winter days below 0°C decline by 20 to 100%. Such large changes in extreme events would have important implications for agriculture, ecosystems, health, rural pests and disease, and built infrastructure.

Allowance has also been made for uncertainty in the average rainfall changes. Statistical significance has been computed for each region and season since rainfall has high temporal and spatial variability (Table 2). By 2050, rainfall changes are statistically significant in the south-central and south-west regions which become 3-14% drier in spring and 4-19% wetter in summer. Non-significant increases of at least 10% for the high scenario occur in summer and autumn in the north-central and north-west regions. Average rainfall changes are negligible elsewhere. The number of extremely wet summers, autumns and winters doubles in some regions, and spring droughts double in all regions except the north-east. The frequency and intensity of heavy daily rainfall increases in most regions, but quantification of uncertainty (while technically possible) is considered inappropriate due to high year-to-year variability.

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 NSW regions by the year 2050. Scaling for the range of IPCC uncertainty is included.

	North-west	North-central	North-east
Maximum temperature	↑ 0.6 to 2.4°C	↑ 0.6 to 2.7°C	↑ 0.5 to 2.3°C
Minimum temperature	↑ 0.6 to 2.5°C	↑ 0.6 to 2.5°C	↑ 0.6 to 2.5°C
Summer days over 35°C	↑ 7 to 25%	↑ 6 to 20%	↑ 12 to 45%
Winter days below 0°C	↓ 30 to 100%	↓ 20 to 75%	↓ 20 to 75%

	South-west	South-central	South-east
Maximum temperature	↑ 0.6 to 2.4°C	↑ 0.6 to 2.5°C	↑ 0.6 to 2.3°C
Minimum temperature	↑ 0.6 to 2.4°C	↑ 0.6 to 2.4°C	↑ 0.6 to 2.3°C
Summer days over 35°C	↑ 10 to 35%	↑ 12 to 45%	↑ 14 to 50%
Winter days below 0°C	↓ 30 to 100%	↓ 14 to 50%	↓ 18 to 60%

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.

	North-west	North-central	North-east
Summer rainfall	↑ 3 to 9%	↑ 3 to 10%	no change
Autumn rainfall	↑ 5 to 17%	↑ 3 to 11%	no change
Winter rainfall	no change	no change	no change
Spring rainfall	↓ 2 to 7%	no change	no change

	South-west	South-central	South-east
Summer rainfall	↑ 5 to 19% *	↑ 4 to 12% *	no change
Autumn rainfall	no change	no change	no change
Winter rainfall	no change	↓ 2 to 7%	no change
Spring rainfall	↓ 4 to 14% *	↓ 3 to 12% *	no change

Scenarios for Newcastle and Bathurst

In accordance with Milestone 2.9, temporal changes in extreme temperature and rainfall events have been examined more closely for the Newcastle and Bathurst regions. Except where otherwise indicated, the data used in this investigation were generated by imposing 1990-2100 trends in local climate as simulated by DARLAM on observed temperature and rainfall time series for stations in these regions. In areas of strong topographic variation, DARLAM does not have fine enough horizontal resolution to directly simulate, without any bias, the climate of individual towns. The method employed here allows for this deficiency. However, it has the disadvantage of representing the effect on extreme events of simulated changes in mean climate only, and not that due to simulated changes in variability.

For temperature, we used the 1957–1996 observed temperature record at Jerry's Plains (100 km up the Hunter Valley from Newcastle) and the 1921–1996 record at Bathurst. These stations have records relatively free of inhomogeneities (B. Trewin, pers comm.). Rainfall data for Clarence from 1910-1995 (30 km north of Newcastle) and Bathurst from 1910-1995 are considered to have high quality (Lavery et al., 1997). Simulations of future conditions are based on results at four DARLAM grid boxes over the region covering the Newcastle-Hunter Valley-Muswellbrook region, and sixteen grid boxes over the Bathurst-Forbes-Dubbo region (see Figure 4).

<u>Newcastle</u>

Figure 18 shows the results for maximum summer temperature and minimum winter temperature near Newcastle. Warming trends are evident in the observations. These trends were removed from the data before DARLAM scenarios of future warming were applied. The scenario time series are constructed by combining the observed year-to-year variations (de-

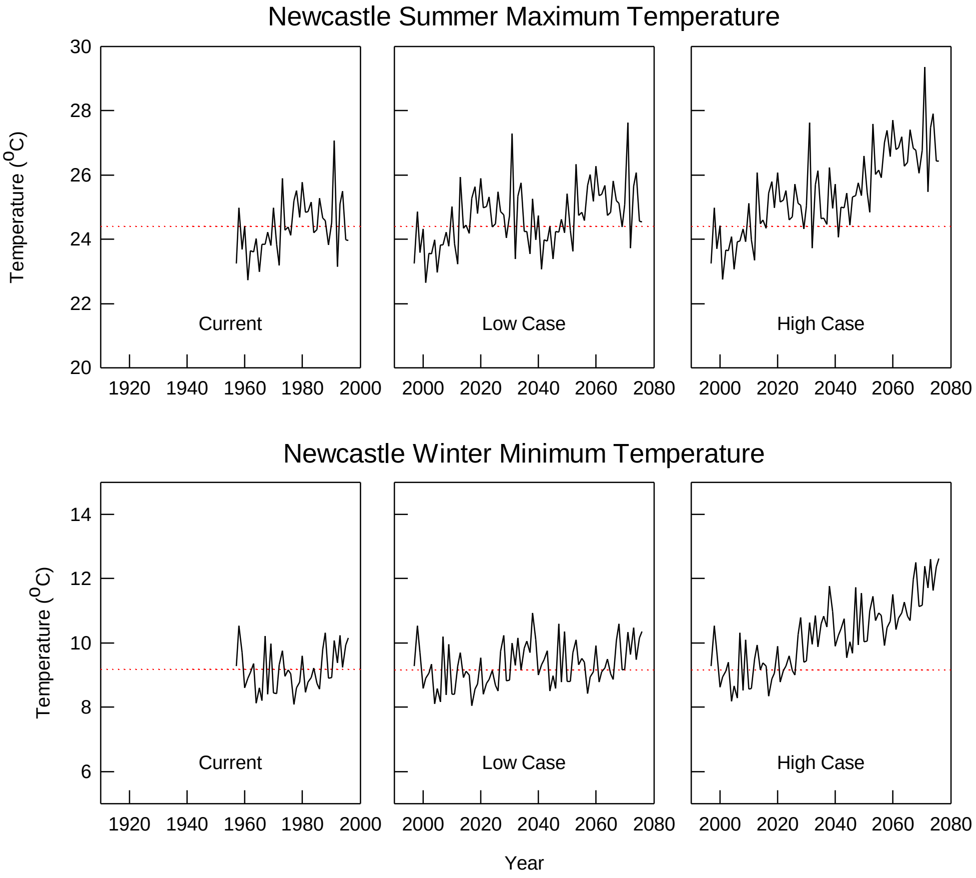
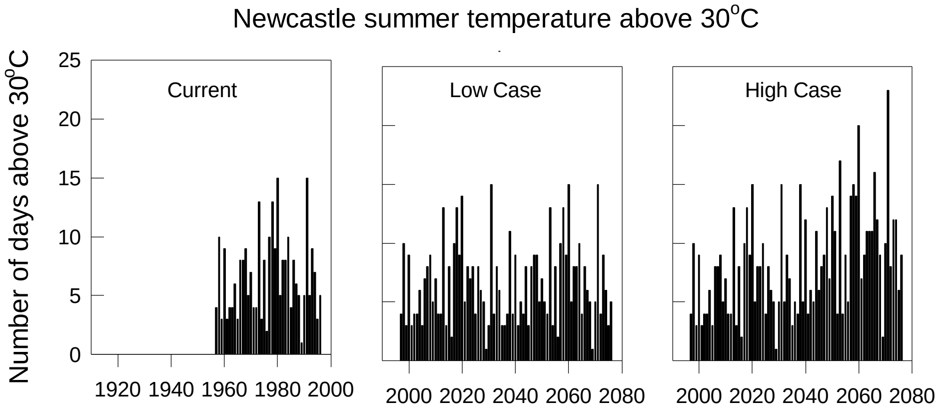


Figure 18: Time series of average summer maximum temperature (upper panels) and winter minimum temperatures (lower panels) at Newcastle (Jerry's Plains) as observed from 1957-1996, and according to two future scenarios for 1997-2076. The scenarios combine the observed (de-trended) variability with local warming trends for 1997-2100 derived from DARLAM but rescaled for low and high cases (see Box 2).

trended and repeated to extend their duration) with local warming trends for 1997-2100 derived from DARLAM but scaled for low and high cases (see Box 2).

For the high warming scenario, the increase in average temperature is obvious relative to interannual variability. For example, four summers average at least 26°C in the first 40 years (1997-2036), increasing to 20 in the last 40 years (2037-2076). The observed average winter minimum of about 9°C becomes an extremely rare event, exceeded in all but one winter after 2020. For the low warming scenarios, trends are almost imperceptible and there is little change in extreme seasons.

This type of analysis has been repeated for the number of summer days over 30°C and winter days below 5°C (Figure 19). Hot days have increased and cold days have decreased in the past 40 years. For the low scenario, there is little change in the frequency of summer days with maximum temperature greater than 30°C. However, the number of winters with at least 4 days below 5°C drops from 17 in the first 40 years (1997-2036) to nine in the last 40 years (2037-2076). For the high scenario, 20 summers from 2037-2076 have at least 10 days over 30°C compared to only seven from 1997-2036, and there is a 80% reduction in the number of winters with at least four days below 5°C.



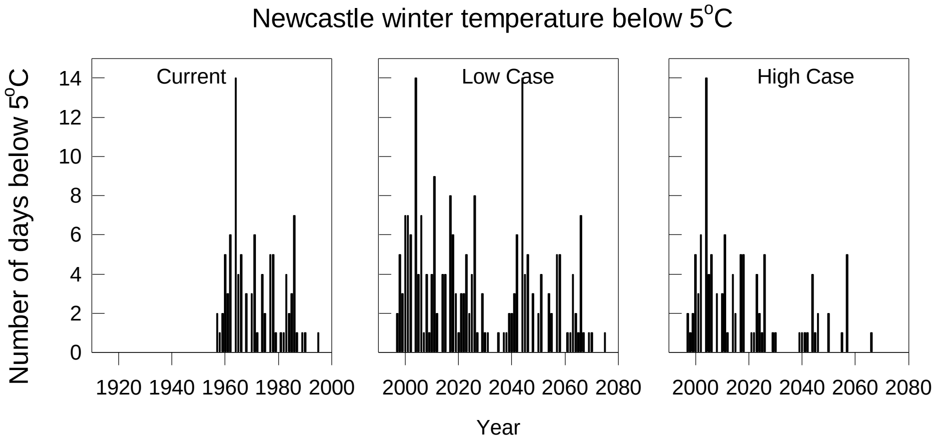


Figure 19: Time series of number of summer days exceeding 30°C (upper panels) and the number of winter days below 5°C (lower panels) as observed from 1957-1996, and according to two future scenarios for 1997-2076.

Similar analysis was undertaken for rainfall (Figure 20). The rainfall change scenarios for the Newcastle region are small in all seasons (about 3% wetter per degree of global warming in summer and winter, and even smaller decreases in autumn and spring, see Figure 11). Since year-to-year variability is high, changes in the frequency of extreme seasonal totals are imperceptible in the future scenarios. However, it should be noted that changes in year-to-year variability as simulated by DARLAM may have a significant impact on the frequency of extreme events. This has not been included in the present analysis.

Extreme daily rainfall return periods were analysed for the Newcastle region using direct model output. The changes were mostly negligible. Figure 21 shows the annual results for present (1961-2000) and 2050 conditions (2031-2070). There is some increase in the magnitude of the 1-in-20 and 1-in-40 year events, but little change in the shorter return period events. It must be noted that when analysis of this type is applied to small regions (as is done here), the results will be rather sensitive to the effect of natural climatic variability. Substantial further analysis would be required to determine whether the difference between the Newcastle results and the statewide trend (Figure 15) is systematic.

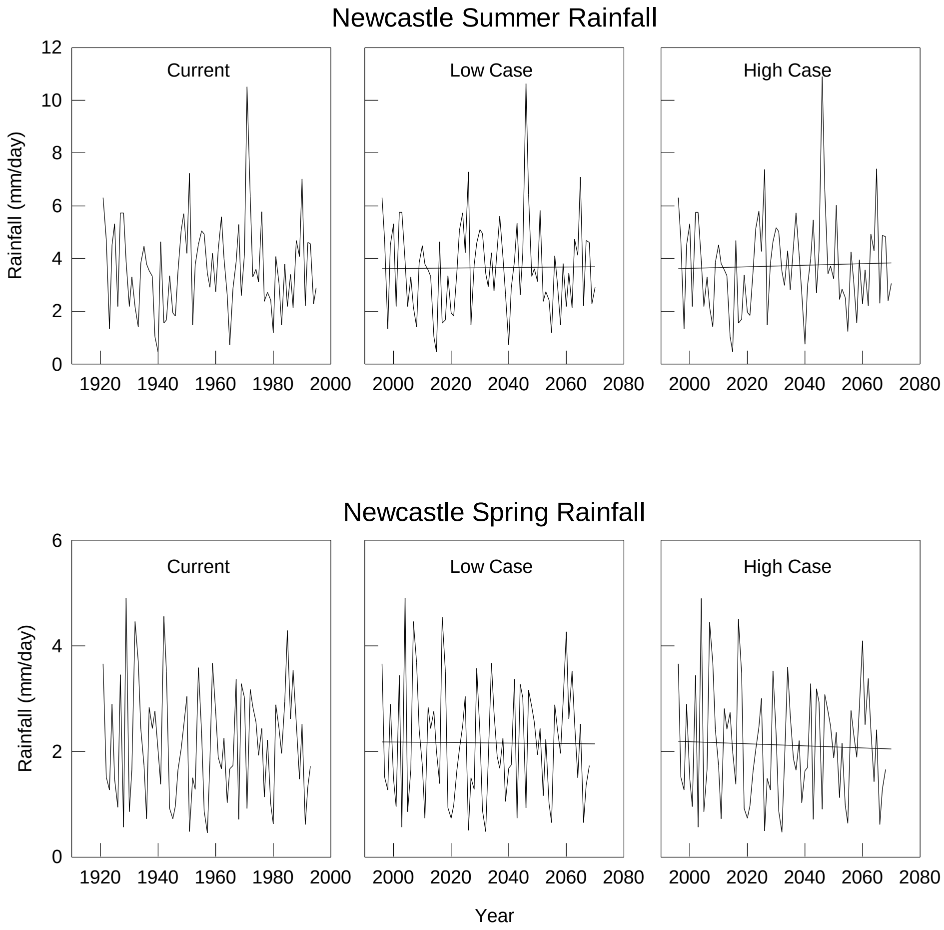


Figure 20: Time series of average summer and spring rainfall at Newcastle (Clarence) as observed from 1921-1996, and according to two future scenarios for 1997-2070. The scenarios combine the observed (de-trended) variability with enhanced greenhouse trends for 1997-2100 derived from DARLAM but rescaled for low and high cases (see Box 2). Linear trend lines are shown for the scenario time series.

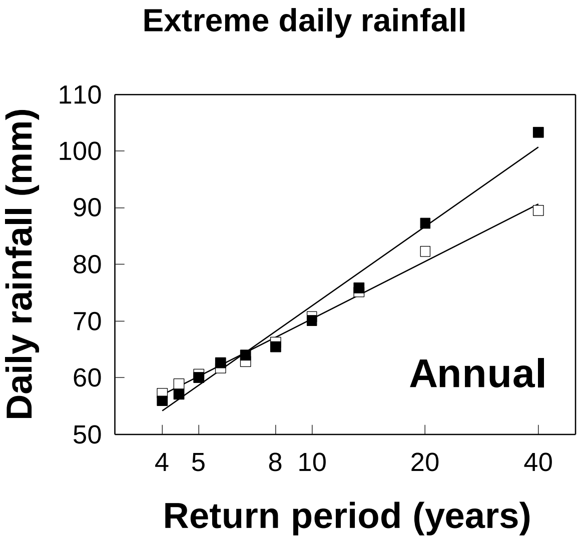
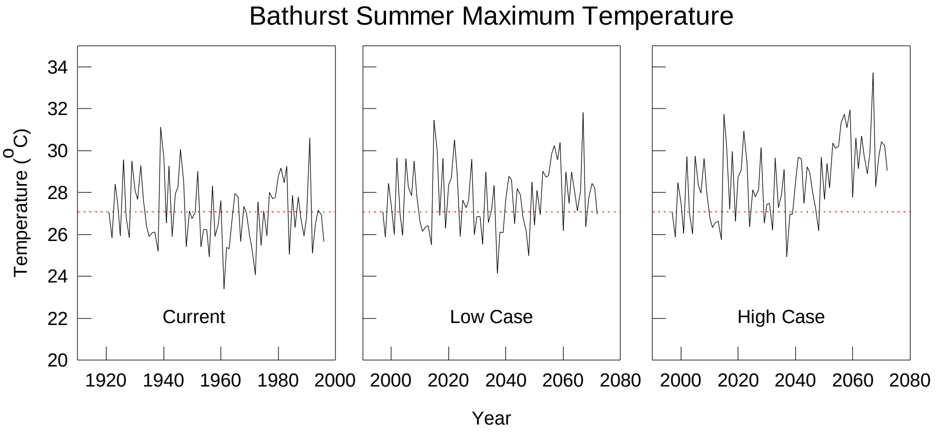


Figure 21: Simulated daily rainfall events with various return periods for present (1961-2000 open squares) and 40 years centred on 2050 (solid squares) near Newcastle.

Bathurst

The Bathurst temperature results are shown in Figure 22. A slight cooling trend is evident in observations of summer maximum temperature with no trend in winter minima. These trends were removed before applying DARLAM warming scenarios. In the high scenarios, trends are quite noticeable. For example, five summers average at least 30°C in the first 40 years (1997-2036), increasing to 12 in the last 36 years (2037-2072). The observed average winter minimum of about 1°C becomes an extremely rare event, exceeded in all but two winters after 2020. The increase in winter minima is particularly obvious since variability is much lower than that for summer maxima. For the low warming scenarios, there is little change in extreme events, and trends would be very hard to detect against background variability.



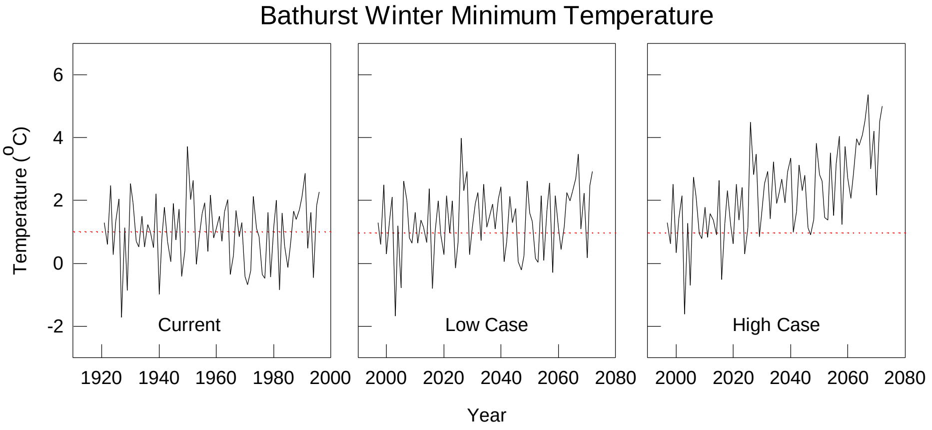


Figure 22: Time series of average summer maximum temperature (upper panels) and winter minimum temperatures (lower panels) at Bathurst as observed from 1921-1996, and according to two future scenarios for 1997-2072. The scenarios combine the observed (de-trended) variability with local warming trends for 1997-2072 derived from DARLAM butrescaled for low and high cases (see Box 2).

Figure 23 shows results for the change in summer days over 35°C and winter days below minus 5°C. The observations show that both hot days and cold days have decreased in the last 75 years. For the low scenario, trends are not clearly discernible. For the high scenario, there are 11 summers in the first 40 years (1997-2036) with at least 10 days over 35°C compared to 16 in the remaining 36 years (2037-2072). The frequency of winters with at least five days less than minus 5°C declines from six in the first 40 years to just one in the last 36 years.

Similar analysis was undertaken for summer and spring rainfall in Bathurst (Figure 24). The rainfall change scenarios for this region are small in each season except summer (about 3% wetter per degree of global warming (PDGW) in autumn, 3% drier PDGW in winter and spring and 6% wetter PDGW in summer, see Figure 11). The summer scenario is equivalent to 2-12% wetter by 2050. The effect of the enhanced greenhouse trend is not very noticeable against the background variability, and conclusions about trends in the frequency of extreme years cannot be readily drawn. However, it should be noted that changes in year-to-year variability as simulated by DARLAM may have a significant impact on the frequency of extreme events. This has not been included in the present analysis.

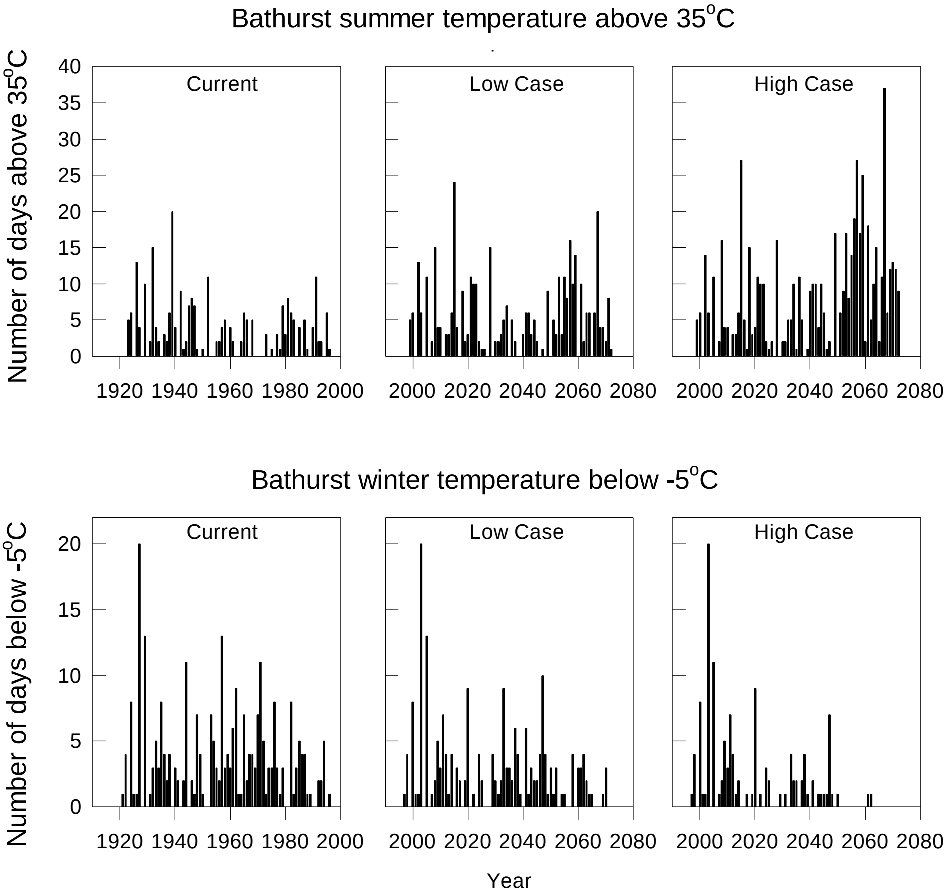


Figure 23: Time series of number of summer days exceeding 35°C (upper panels) and the number of winter days below minus 5°C (lower panels) as observed from 1921-1996, and according to two future scenarios for 1997-2072.

Figure 25 shows the annual extreme daily rainfall return periods for present (1961-2000) and 2050 conditions (2031-2070). There is a substantial increase in magnitude of daily rainfall across all the return periods shown. For example, the magnitude of the 1-in-20 year event increases by about 15%; or its frequency increases to 1-in-10 years. This behaviour is evident in all seasons except spring, and the annual results are dominated by summer, the season of heaviest rainfall. Figure 26 shows that despite decadal variability in the total number of summer days having at least 40 mm of rain, the increasing trend is sustained over the next century. These results demonstrate the potential for heavy rainfall events to substantially increase in frequency and intensity at inland NSW sites such as Bathurst.

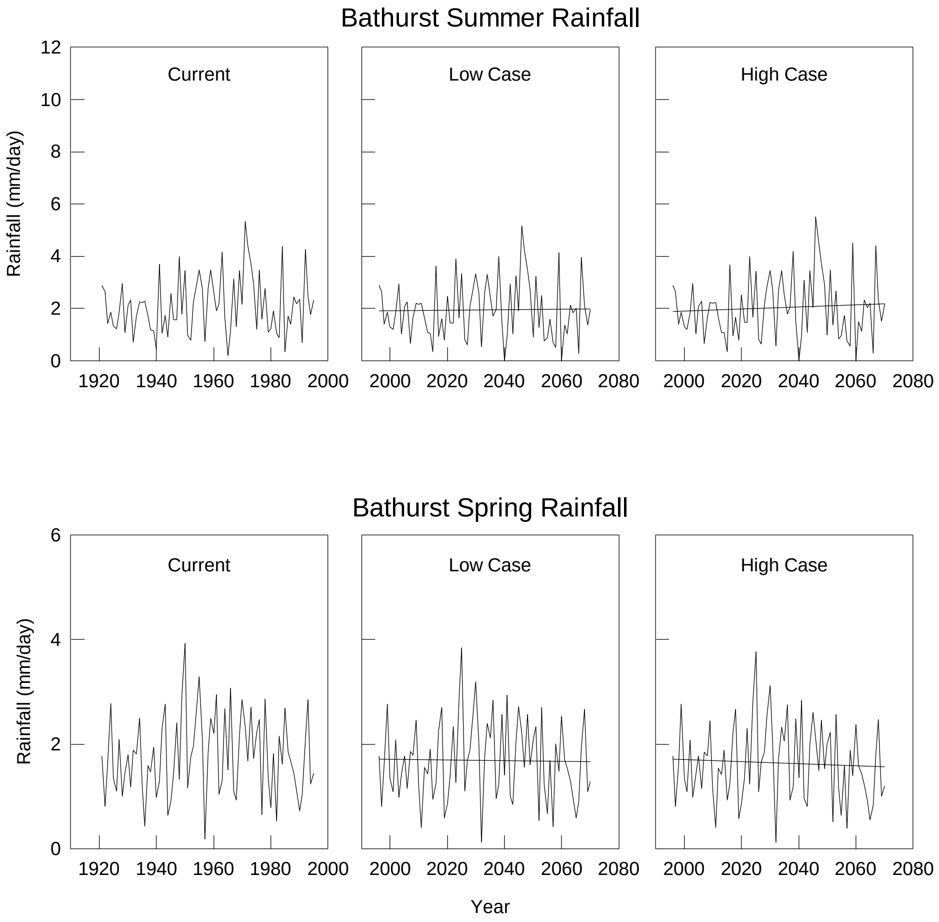


Figure 24: Time series of average summer and spring rainfall at Bathurst as observed from 1921-1996, and according to two future scenarios for 1997-2070. The scenarios combine the observed (de-trended) variability with enhanced greenhouse trends for 1997-2100 derived from DARLAM but scaled for low and high cases (see Box 2). Linear trend lines are shown for the scenario time series.

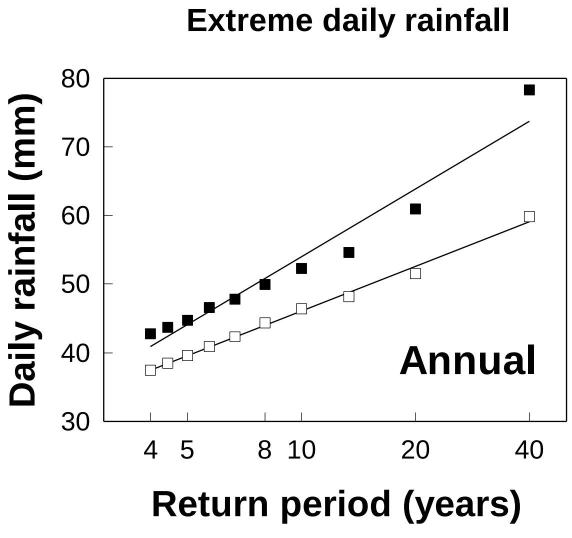


Figure 25: Simulated daily rainfall events with various return periods for present (1961-2000 open squares) and 40 years centred on 2050 (solid squares) near Bathurst. Annual rather than seasonal data have been used. Increases in intensity occur in all seasons except spring.

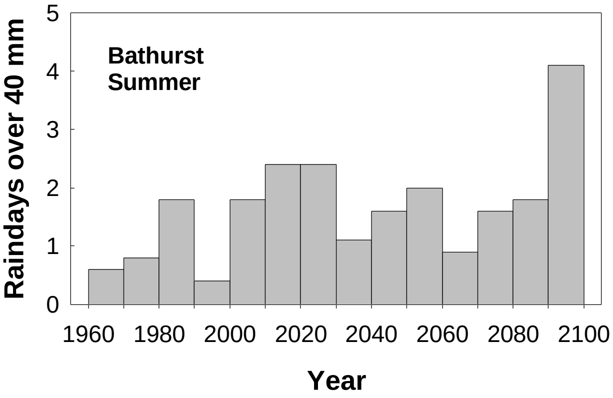


Fig 26: DARLAM decadal total summer rainfall events with at least 40 mm/day for a typical grid box near Bathurst.

These examples for the Newcastle and Bathurst regions have been included for illustrative purposes only. More realistic scenarios of how climate may evolve over the next century at local NSW sites would need to take into account additional factors. The analysis based on modified observations uses only one scenario for year-to-year variations in climate due to natural variability – the sequence from the historical record. There is in fact a multitude of alternative future sequences, all of which would be consistent with historical variability. The analysis should be expanded to include model-simulated changes in variability, which, for rainfall, are potentially significant. These issues could be explored using the observed record and more sophisticated statistical approaches.

4. Discussion

Simulated climatic averages

The DARLAM simulation reproduces the seasonal patterns of maximum and minimum temperature over NSW reasonably well, although summer temperatures are a little too high. The model can also represent many features of the observed patterns of average seasonal rainfall over NSW. However, the spring rainfall simulation is a little too wet. Overall, the temperature and rainfall simulations are better than that shown in the 1996-97 report.

Simulated changes in temperature under enhanced conditions are similar to those presented in the 1996-97 report, except that the previous tendency for increased diurnal temperature range in all seasons is now confined to spring with decreases in summer and autumn. This is a consequence of different rainfall change tendencies simulated by DARLAM. Rainfall decreases were simulated for all seasons in the previous report, but now primarily occur in winter and spring. Increases occur in summer and autumn. The statistical significance of the latest results is high in south-central and south-west NSW in spring and summer.

Simulated variability and extremes

DARLAM performs well in its simulation of temperature and rainfall variability in the NSW region. The spatial and seasonal variation of the standard deviation of daily maximum and minimum temperature is generally well captured by the model. 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 does not appear to simulate some of the extremely wet years that have occurred in the observations.

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. Clear decreases are simulated in the frequency of cool seasons, particularly in winter. Given the small simulated changes in variability, these changes in the frequency of extremes stem mainly from the simulated change in the average. Since temperature variability is very low for maximum temperature in winter, this may be a good variable to use when searching for indications of climate change (at reliable non-urban sites).

Simulated changes in the average, and year-to-year variability, of seasonal rainfall can affect the frequency of wet and dry years. For example, in the south-west region, where average summer rainfall increases almost 20% by 2050, extremely wet summers occur four times more often. In the same region, spring rainfall decreases by almost 15% and extremely dry springs occur three times more frequently.

Extreme daily rainfall events have the potential to inflict substantial costs through urban and rural inundation, erosion, loss to crops and livestock, disruption to services, damage to infrastructure, and sometimes loss of human life. When averaged over the whole of NSW, changes in extreme rainfall are small. However, increases in intensity of 5-50% for the 1-in-20 year event by 2050 can occur in smaller regions, 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 with 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 27 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 NSW (see Hennessy et al., 1997a), 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 28 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).

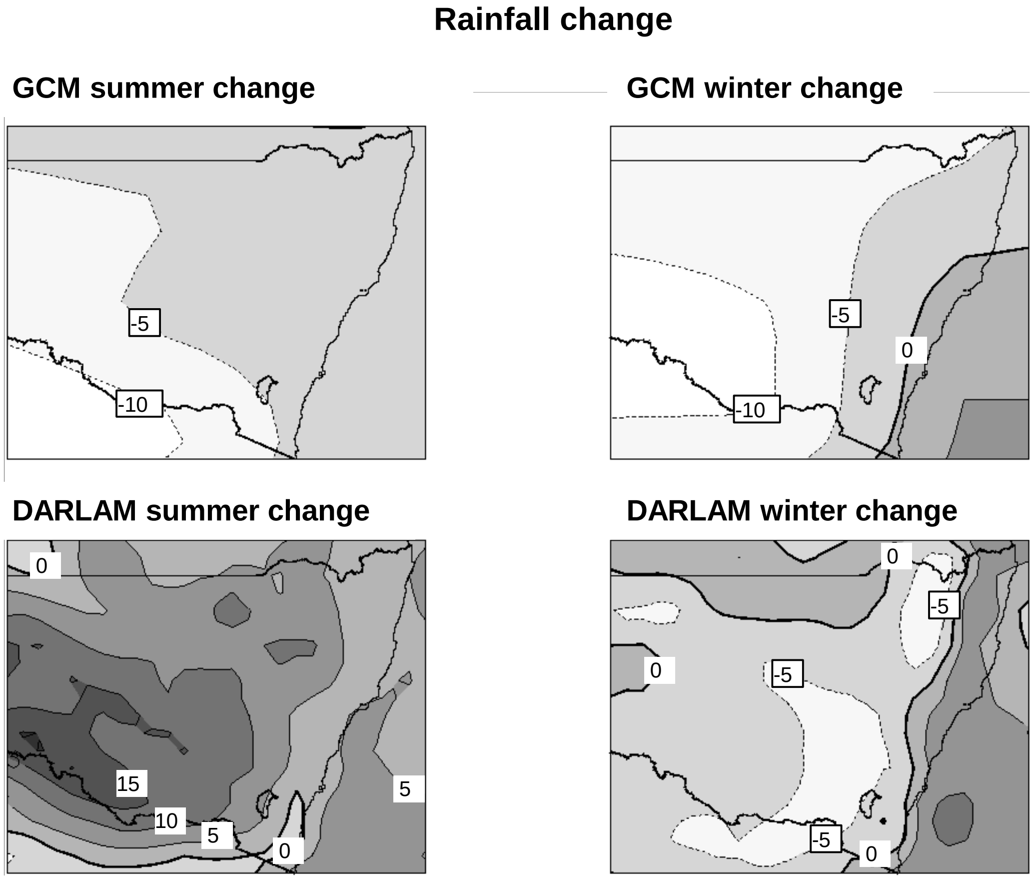


Figure 27: Simulated percent rainfall change per degree of global warming (PDGW) over the period 1961-2100 in the CSIRO coupled GCM and in DARLAM for summer and winter. Negative contour labels are shown in boxes.

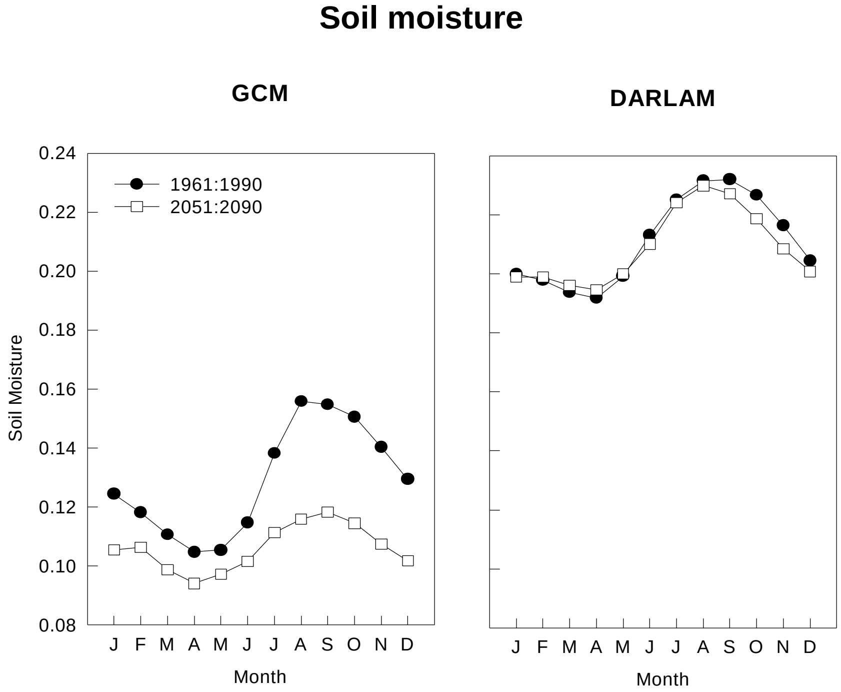


Figure 28: Annual cycle of simulated soil moisture (volume of water per volume of soil) in the CSIRO GCM and DARLAM under current and enhanced greenhouse conditions.

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. Consistent with this mechanism, the difference in rainfall change between DARLAM and the GCM is generally greatest in inland areas (where rain-bearing systems are likely to have a long path over land). Coastal rainfall, being dominated more by oceanic processes, is less affected by soil moisture—rainfall feedbacks.

However, the importance of this mechanism cannot be confirmed without undertaking some further long simulations of a diagnostic nature. It is possible that the differences in simulated rainfall change are due to some other cause and that the differences in soil moisture simply reflect those in rainfall. We considered some other possible causes, and in particular compared atmospheric circulation and sea-surface temperature patterns between DARLAM and the GCM, but were unable to identify differences that could otherwise explain the results we see here.

In summary, it is our assessment that the most likely explanation of the enhanced greenhouse climate in DARLAM being wetter than that in the GCM is that DARLAM has significantly weakened a strong tendency present in the GCM for reduced soil moisture and evaporation under enhanced greenhouse conditions. It also appears likely that this difference may be attributed to increased realism in the representation of soil and vegetation in DARLAM, and, if so, the DARLAM rainfall results should be preferred to those of the GCM. However, further modelling studies would be required to confirm this assessment.

Remaining uncertainties

The ranges of future climate change for NSW 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 NSW). 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 rainfall. 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 NSW 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).

In the DARLAM results shown here, moderate rainfall increases predominate over NSW except in winter and spring, whereas decreases featured in all seasons in the 1996-97 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 last year, 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., 1997a). 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 we expect 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 ‘Recommendations for further research’ below).

5. Climate change impacts for NSW

Any comprehensive assessment of the potential impacts of the DARLAM scenario for NSW is beyond the scope of the current research agreement. However, the issue was partially addressed in the 1995-96 and 1996-97 reports by including a brief survey of the results of a number of impact studies that have been conducted for south-eastern Australia. These studies indicated the potential for reduced wheat quality, much reduced frequency of years suitable for growing pome-fruit and stone-fruit, increased heat-related deaths, significant impacts on average and extreme runoff, and reductions in natural snow cover.

It was noted that various adaptation strategies could alleviate some impacts. The current update to the scenario has not changed the relevance of these impact studies. However, the current study has highlighted the possibility of there being an increase in the frequency of wet summers, autumns and winters in some regions, and more dry springs in most regions.

There may also be increases in the frequency and magnitude of high rainfall events, particularly in inland NSW. This could have important implications for agriculture, water and land management, flood control and emergency services, particularly in the light of NSW flood events in mid 1998.

During the past year some new impact assessment studies have been completed that have added significantly to knowledge of how climate change may affect NSW. We summarise the results of these here.

McInnes et al. (1998) have assessed the impact of climate change on coastal New South Wales. Using climate change output from the 1996-97 DARLAM simulation, a shift to fewer north-easterly winds and more south-easterly winds is found in winter, with a reduction in winds from all directions in autumn. On-shore sea-breezes become up to 10% stronger for a doubling of present carbon dioxide levels. East coast low pressure systems, associated with extreme winds and rainfall, become less frequent. Tropical cyclones may occur further south with the result that more systems may affect northern coastal NSW and more may redevelop into severe extratropical lows further south. Mean sea-level may rise 3-16 cm by 2020 and 10-60 cm by 2070. Local sea-level anomalies, or storm surges, of up to 50 cm under present conditions are often associated with east coast lows. Storm surge height may be increased due to an increase in east coast low intensity associated with higher ocean surface temperatures The need to re-assess these results using output from the 1997-98 DARLAM simulation is emphasised.

The Australian Greenhouse Office (1998) has published an extract of the Australasian chapter of an IPCC Special Report on regional climate change impacts (Watson et al., 1998). This is a comprehensive assessment of climate change impacts and vulnerability over a range of sectors including agriculture, water resources, forestry, coastal zones, fisheries, human settlements, ecosystems and health. The report draws on results from the 1995-96 annual report (Hennessy et al., 1997a) and the DARLAM-based Maquarie Basin study by Hassall and Associates (in press).

6. Recommendations for further research

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 El Niño and associated rainfall variability over Australia. By mid-1999, this new GCM will be ready for climate change simulations, and by mid-2000 it should be possible to produce new fine resolution scenarios for NSW using DARLAM.

In the meantime, the DARLAM-based scenarios presented here are the most detailed and realistic scenarios available for use in assessments of climate change impacts in NSW. There is scope for addressing a number of issues, such as

- water resources, including floods, water supply security, irrigation allocations and demand,
- coastal activities, particularly in support of coastal management strategies,
- fire danger in eastern NSW,
- 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,
- built infrastructure including flood damage, ports, transport and communications.

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. This allows expression of climate change and impact scenarios in terms of probability, using critical risk thresholds or performance criteria specified by regional experts, managers, policy-makers or stakeholders.

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 already been identified at the regional scale in NSW in projects described in the previous section.

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 29).

2. *Impact thresholds* are constructed in the early stages of an impact assessment. They are location dependent, activity dependent and value dependent, allowing socio-economic factors to be addressed. The sensitivity of these thresholds to climate can then be assessed with reference to climate change scenarios (eg. Figure 30). The involvement of stakeholders in the construction of *user-determined thresholds* both informs stakeholders about climate change, and involves them in the assessment of adaptation options.
3. The probability of exceeding critical impact thresholds is assessed within the limits of uncertainty contained within the climate scenarios. Adaptation options are then surveyed to reduce the risk of these critical impacts being reached.

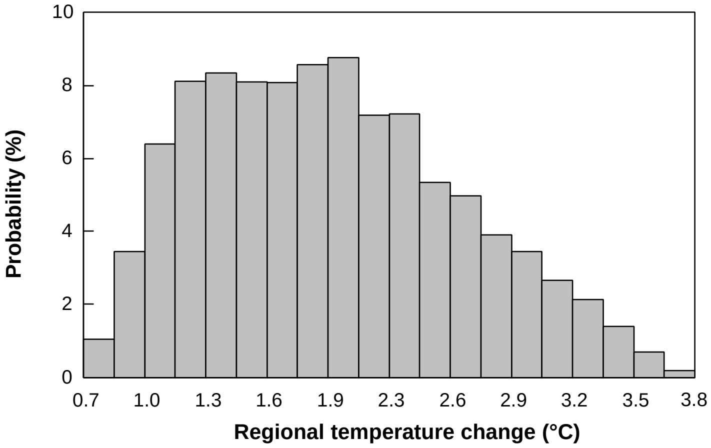


Figure 29: Probability distribution of a regional scenario for temperature change in 2070 for inland Australia (CSIRO, 1996), showing the probability of occurrence for 5% increments within the total range of 0.7–3.8°C, based on Monte Carlo sampling. The component ranges of 0.7–2.1°C (global warming, 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 bin across the range.

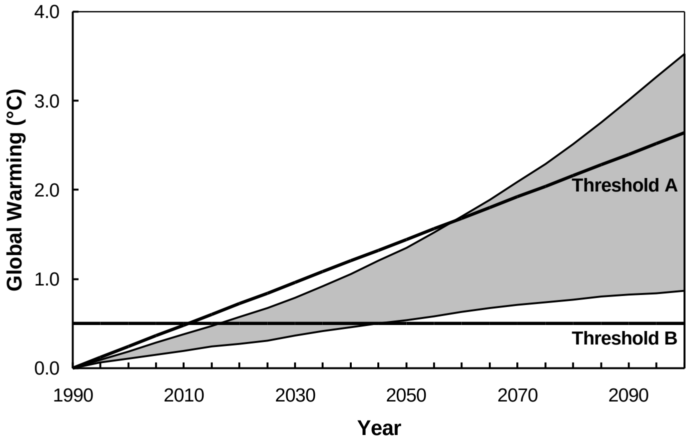


Figure 30: Depiction of two thresholds relative to the IPCC global warming scenarios (assuming increased sulfate aerosols). Threshold A is a transient threshold that allows for a level of autonomous or planned adaptation. It may be related to the adjustment of a species to climate change, or to a level of crop breeding adaptations to temperature increase. Threshold B is absolute and marks a level above which a specific impact occurs, eg. a temperature above which breeding can no longer occur.

The overall methodology is shown in Figure 31. It is still under development, and has been incorporated into the following research projects:

- A three year project into water resources in the north-east 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.

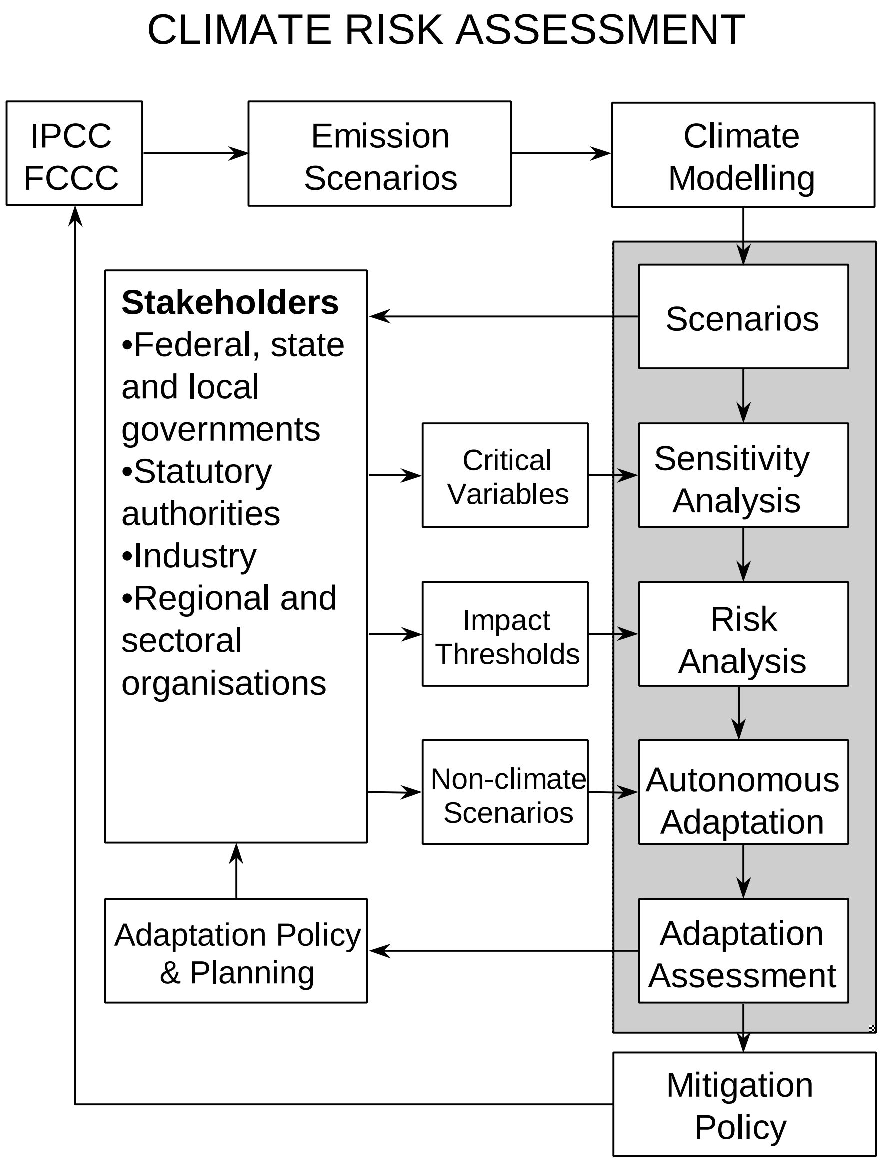


Figure 31: Flow chart for climate risk assessment methodology currently being constructed by the CSIRO Climate Impact Group.

East coast lows, tropical cyclones and ENSO

To date, three climatic factors that influence NSW have received little attention, yet may be strongly affected by climate change. These are east coast lows, tropical cyclones and ENSO.

East coast lows are intense low pressure systems which bring heavy rainfall, strong winds and oceanic storm surges to eastern NSW and south-eastern Victoria. Any change in the intensity or frequency of these systems would have a major impact. A study of east coast lows under enhanced greenhouse conditions was performed in 1991 (Whetton et al., 1992) using a superseded CSIRO GCM. A new study using output from the DARLAM simulation described in this report (driven by CSIRO's coupled GCM) would provide more reliable information.

Tropical cyclones can influence north-eastern NSW coastal regions, and climate change has the potential to alter cyclone paths intensity and frequency. CSIRO Atmospheric Research has developed a method of determining cyclone behaviour in DARLAM, and this could be used to assess possible future changes in cyclone activity near NSW. Early indications are that cyclones may travel further south in the Tasman Sea.

El Niño phases of the El Niño – Southern Oscillation (ENSO) are clearly linked to droughts in NSW and La Niña phases of ENSO are linked to floods. An assessment of GCM-simulated ENSO activity under present and future climate conditions would provide valuable insight into a major driver of rainfall variability over NSW.

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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. This work is a product of the CSIRO Climate Change Research Program, funded partly by Environment Australia and the National Greenhouse Advisory Committee.

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. Barrie Pittock provided valuable comments on the manuscript.

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