Climate Change in New South Wales

Part 2: Projected changes in climate extremes

Consultancy report for the New South Wales Greenhouse Office

by

K. Hennessy, K. McInnes, D. Abbs, R. Jones, J. Bathols, R. Suppiah,
J. Ricketts, T. Rafter, D. Collins* and D. Jones*

Climate Impact Group, CSIRO Atmospheric Research
* National Climate Centre, Australian Government Bureau of Meteorology

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EXECUTIVE SUMMARY

This report presents results from the second part of a project undertaken for the New South Wales (NSW) Greenhouse Office to assess future changes in NSW climate. Results focus on regionally-specific changes in droughts, extreme temperatures, heavy rainfall, strong winds, extreme weather systems and storm tides. This complements the first part of the project (Hennessy *et al.*, 2004) which focussed on past climate variability and projected changes in average climate. Conclusions from the first part are summarised in Appendix A.

To estimate future climate change, scientists have developed greenhouse gas and aerosol emission scenarios. These are not predictions of what will actually happen. They allow analysis of "what if?" questions based on various assumptions about human behaviour, economic growth and technological change (Appendix B). This report uses scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). Some IPCC scenarios assume "business as usual" without explicit policies to limit greenhouse gas emissions, although some scenarios include other environmental policies that indirectly affect greenhouse gases. These are described in the Special Report on Emission Scenarios (SRES). Other IPCC scenarios include actions to reduce CO_2 emissions and stabilise CO_2 concentrations at some level above the current value of 375 ppm. These would postpone or avoid some of the more serious damages associated with higher rates of warming. In this project, most projections are based on the SRES scenarios rather than the CO_2 stabilisation scenarios.

Climate models, driven by these emission scenarios, provide estimates of how climate may change in future. Results from 12 climate simulations have been used in this project (Appendix A).

Extreme daily temperatures

The annual frequencies of six types of extreme temperature events were considered at 12 NSW sites: days below 0°C, three consecutive days below 0°C (cold spells), days above 35°C, three consecutive days above 35°C (hot spells), days above 40°C and three consecutive days above 40°C (extremely hot spells).

Days below 0°C: Under the low warming scenario for 2030, some sites show no change while others exhibit decreases of about 10-20%. The high scenario for 2030 gives decreases of 50-100%. In 2070, the low scenario leads to decreases of 30-50% at most sites, while the high scenario gives decreases of 85-100%. At cold sites such as Bathurst and Canberra, the low scenario for 2030 has little effect on the number of 3-day cold spells, while the high scenario for 2030 reduces cold spells by about 50%. By 2070, the low scenario at these sites gives a 20% reduction in cold spells, while the high scenario makes cold spells extremely rare.

Table S1: Average number of days per year below 0°C at 12 NSW sites for present conditions (1964-2003), 40 years centred on 2030 and 40 years centred on 2070. A cold spell was defined as three consecutive days below 0°C. Ranges refer to high and low warming scenarios. * At Deniliquin, present conditions refer to 1963-2002.

Site	Days Below 0°C			Spells Below 0°C		
	Present	2030	2070	Present	2030	2070
Wilcannia	4	1-4	0-2	0	0-0	0-0
Cobar	2	0-2	0-1	0	0-0	0-0
Walgett	13	4-11	0-8	1	0-1	0-1
Gunnedah	3	1-3	0-2	0	0-0	0-0
Yamba	0	0-0	0-0	0	0-0	0-0
Bathurst	59	32-53	4-46	11	5-10	0-8
Sydney	0	0-0	0-0	0	0-0	0-0
Moruya	0	0-0	0-0	0	0-0	0-0
Canberra	62	39-60	9-52	12	7-12	1-10
Wagga	26	10-23	0-17	4	1-3	0-2
Wyalong	9	2-7	0-5	1	0-1	0-0
Deniliquin*	10	2-8	0-5	1	0-1	0-0

Days above 35°C: By 2030, the average number of days above 35°C at most sites increases 5-20% for the low warming scenario and 50-100% for the high scenario (Table 2.3). By 2070, the frequency increases 20-60% at most sites for the low scenario and 100-600% (2 to 7 times) for the high scenario. Deniliquin, Cobar, Walgett and Wilcannia currently average at least four 3-day hot spells over 35°C per year. At these sites, the low scenario for 2030 has little effect on the number of hot spells, while the high scenario for 2030 increases hot spells by 50-80%. By 2070, the low scenario at these sites gives a 20-40% increase in hot spells, while the high scenario gives a 180-360% (almost 3 to 5 times) increase.

Table S2: Average number of days per year above 35°C at 12 NSW sites for present conditions (1964-2003), 40 years centred on 2030 and 40 years centred on 2070. A hot spell was defined as three consecutive days above 35°C. * At Deniliquin, present conditions refer to 1963-2002.

Site	Days Exceeding 35°C			Spells Above 35°C		
	Present	2030	2070	Present	2030	2070
Wilcannia	59	62-83	70-136	13	14-20	16-37
Cobar	41	44-65	51-128	9	10-15	11-35
Walgett	56	61-87	71-153	12	14-21	17-44
Gunnedah	19	22-40	29-103	3	4-8	6-26
Yamba	1	1-2	1-7	0	0-0	0-0
Bathurst	4	4-11	6-43	0	1-2	1-9
Sydney	3	4-6	4-18	0	0-0	0-1
Moruya	2	2-3	2-6	0	0-0	0-0
Canberra	5	6-13	8-42	1	1-2	1-9
Wagga	20	21-34	25-78	3	4-7	4-20
Wyalong	26	27-42	32-93	5	5-9	6-23
Deniliquin*	24	25-37	28-75	4	4-7	4-17

Days above 40°C: Cobar, Walgett and Wilcannia currently average at least 6 days over 40°C per year. By 2030, the average number of days above 40°C at these sites increases 15-25% for the low warming scenario and doubles or triples for the high scenario. By 2070, the frequency increases 30-90% at these sites for the low scenario and increases 6 to 10 times for the high scenario. The high scenario for 2070 gives Sydney an annual average of 4 days over 40°C and Canberra an average of 10. If a very hot spell is defined as three consecutive days above 40°C, then Cobar, Walgett and Wilcannia currently average 1-2 very hot spells per year. At these sites, the 2030 low scenario has a small effect, while the 2030 high scenario gives 2-5 very hot spells. By 2070, the low scenario has a small effect, while the high scenario gives 13-20 very hot spells.

Table S3: Average number of days per year above 40°C at 12 NSW sites for present conditions (1964-2003) and 40 years centred on 2030 and 2070. A very hot spell was defined as three consecutive days above 40°C. * At Deniliquin, present conditions refer to 1963-2002.

Site	Days Exceeding 40°C			Spells Above 40°C		
	Present	2030	2070	Present	2030	2070
Wilcannia	15	17-29	20-74	2	3-5	3-17
Cobar	6	7-15	9-56	1	1-3	1-13
Walgett	9	10-23	16-83	1	2-4	3-20
Gunnedah	1	1-3	2-26	0	0-0	0-5
Yamba	0	0-0	0-1	0	0-0	0-0
Bathurst	0	0-0	0-8	0	0-0	0-1
Sydney	0	0-1	0-4	0	0-0	0-0
Moruya	0	0-1	0-2	0	0-0	0-0
Canberra	0	0-1	0-10	0	0-0	0-1
Wagga	2	2-6	3-27	0	0-1	0-5
Wyalong	3	4-9	5-35	0	0-1	0-7
Deniliquin*	4	4-8	5-27	0	0-1	0-4

Drought

Climate change projections for NSW indicate that increases and decreases in drought frequency are possible, but there is a tendency toward increases, especially in winter and spring. By the year 2030, the frequency is increased by about 70% for the worst case scenario (decreased rainfall) and decreased by 35% for the best case scenario (increased rainfall) (Figure S1). The range of uncertainty is much larger by 2070 when drought frequency could increase by more than 200% or decrease by up to 70%.

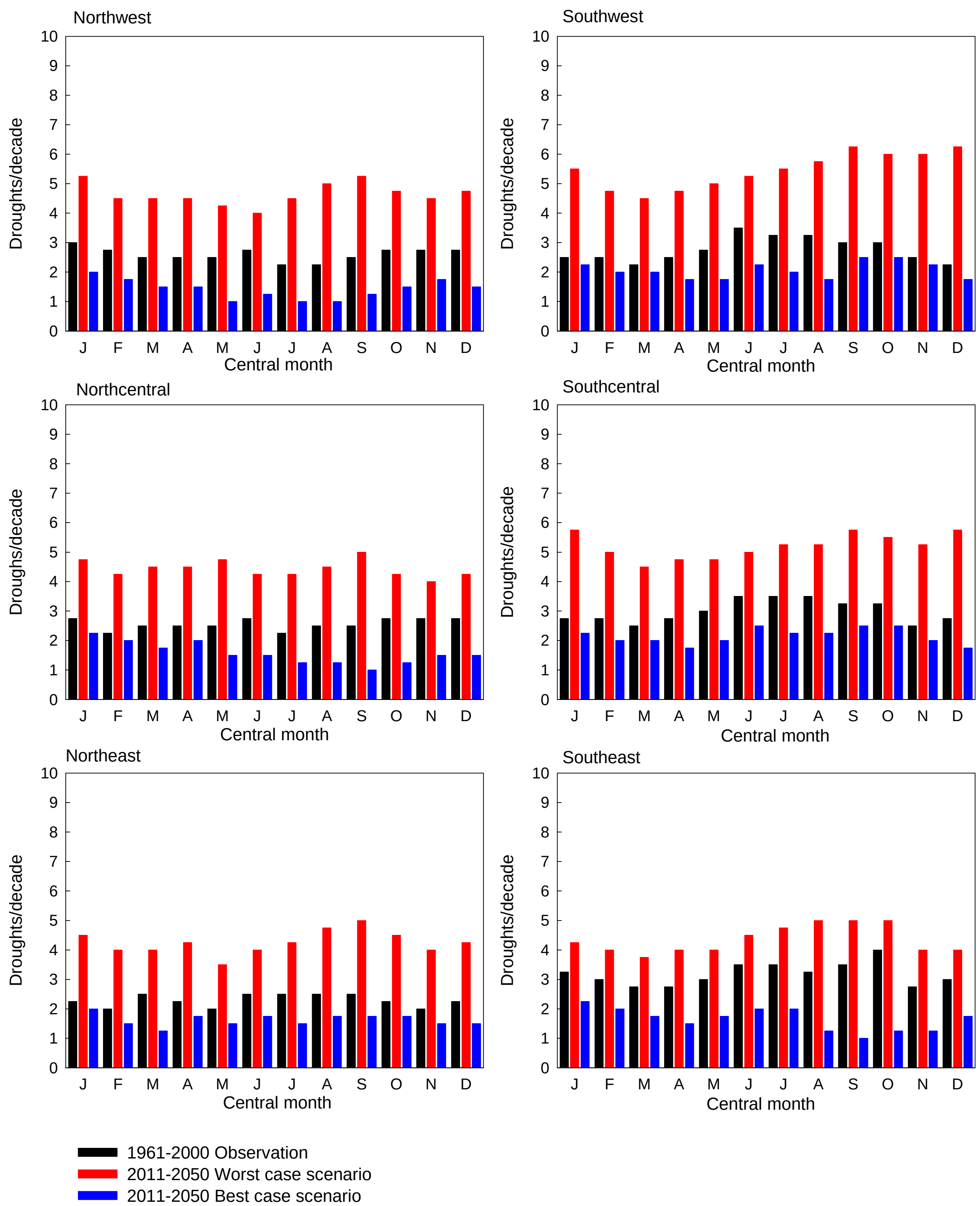

Figure S1. Observed (1961-2000) and projected (40 years centred on 2030) drought frequencies per decade for low and high rainfall change scenarios in the six regions in New South Wales shown in Figure 1.1. A nominated month refers to the central month in a three-month period, e.g. May refers to April-June.

Extreme rainfall

While much of NSW shows a tendency towards drier seasonal-average conditions under enhanced greenhouse conditions, it does not necessarily follow that extreme daily rainfall events will become less frequent or severe. Previous studies have indicated marked increases in the intensity and frequency of extreme daily rainfall events under enhanced greenhouse conditions for the Australian region.

Using daily rainfall data for NSW from four climate models, projected changes in the characteristics of the 1-in-40 year, 1-in-20 year, 1-in-10 year and 1-in-5 year events were calculated for annual and seasonal extremes for both 1-day and 3-day rainfall totals for the years 2030 and 2070.

The direction of the change in extreme rainfall for each of the four models was examined to help quantify the likelihood of an increase or decrease in each region (Figure S2). The highest likelihood of an increase in annual rainfall extremes occurs in central and south-east NSW. A small region of likely increase also occurs in the north-east. These regions coincide with increases in the intensity of extreme rainfall. In contrast, the projected increase in intensity of annual extreme rainfall for the south-west of the state is less likely to occur. A similar pattern occurs in summer. Increases in the intensity of autumn and winter extreme rainfall are most likely to occur west of the Great Dividing Range in the north-central, north-west and south-central regions. The majority of models show a decrease in rainfall extremes along the coast in autumn and winter. Most models project an increase in the intensity of extreme rainfall in spring and summer on the north-east coast and decreases in winter in the southeast. The central regions of NSW are most likely to experience increased rainfall extremes, especially in autumn and winter. By 2070, the agreement between models is much stronger regarding the direction of changes in extreme rainfall intensity.

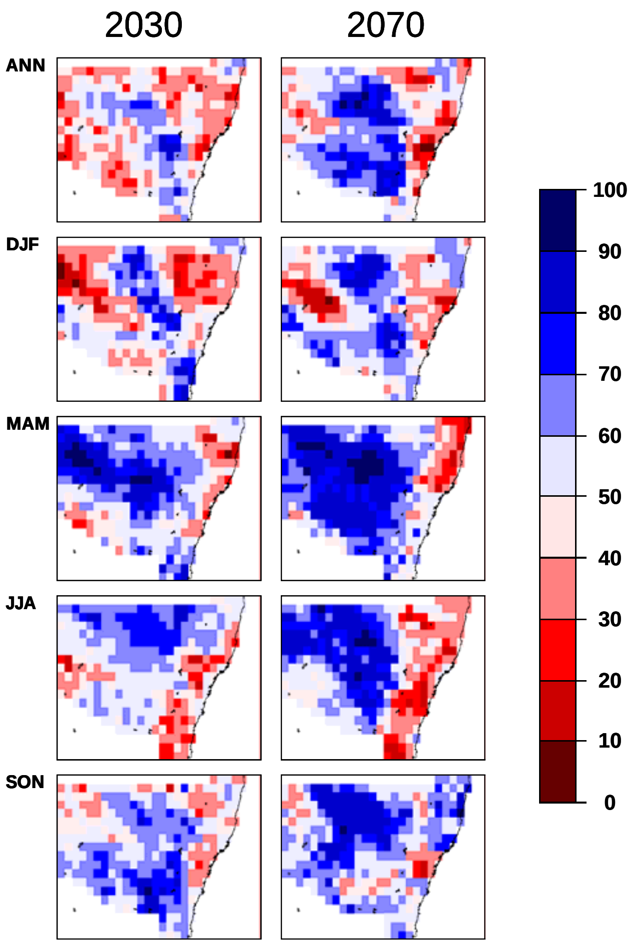

Figure S2. The likelihood (%) of an increase in 1-day extreme rainfall for 2030 and 2070 relative to the current climate. Red regions denote regions of where most models simulate a decrease in rainfall extremes and blue regions those where most models project an increase in extremes. ANN = annual, DJF = summer, MAM = autumn, JJA = winter, SON = spring.

Extreme winds

Mean wind-speed projections show a tendency for increases across much of the state in summer, with decreases in the north-east. In autumn, there is a tendency toward weaker winds in the south and east, and stronger winds in the north-west. The tendency in winter is toward increases in the far north-west and south and decreases elsewhere. A tendency for stronger winds is evident in spring, with greatest increases across central NSW.

Projected changes in extreme monthly winds (strongest 5%) showed similar patterns to the mean wind changes in summer and autumn, except that the magnitude of the increases and decreases tended to be larger (Figure S3). In winter, changes in extreme winds differed from changes in mean winds in that most of the state and the ocean in the south showed a tendency for increasing extreme winds with only the north-east indicating decreasing winds. In spring, extreme winds tended to increase, in agreement with the mean wind speed changes, except in a small area on the southern half of the coast where there was a tendency towards decreasing extreme winds.

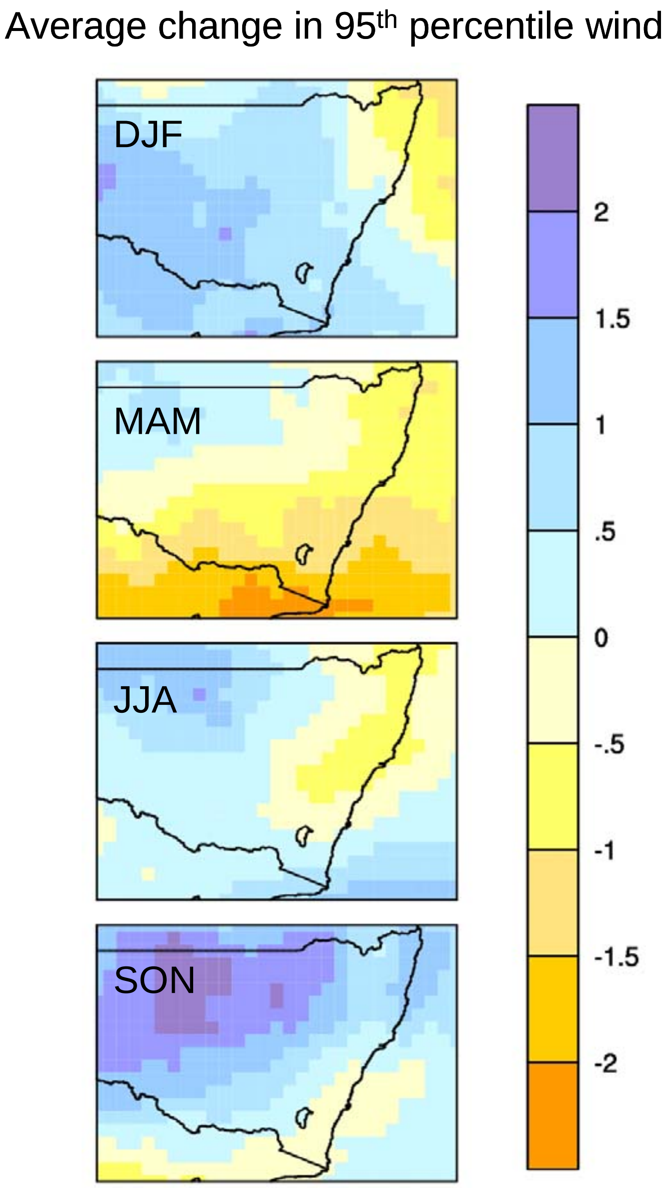

Figure S3: The change in extreme monthly wind speed derived by averaging the 12 models results. Units are % change per °C of global warming. DJF = summer, MAM = autumn, JJA = winter, SON = spring.

Extreme weather patterns

Assessment of CSIRO's Mark3 and CC50 models revealed that the Mark3 model does not adequately reproduce the key weather patterns that are responsible for extreme winds. It was postulated that a cool bias in sea-surface temperatures off the east coast of Australia in that model may have contributed to this result. CC50 on the other hand represented the main weather patterns much more realistically, particularly in the winter half-year. Therefore, this model was used to examine how the patterns may change under enhanced greenhouse conditions.

During the summer half-year, the frequency of Tasman lows that contribute to extreme wind days decreased from 19% at present to only 9% by the year 2070. The frequency of Tasman highs also decreased from 13% at present to 9% by 2070. The number of cold fronts increased slightly by 2070 and the number of unclassified systems increased by 2%. In the winter half-year, Tasman Lows contributing to extreme winds increased in frequency from 26% at present to 31% by 2070. Frontal systems also increased from 25% of extreme wind days at present to 29% by 2070.

Storm tides

The storm systems most conducive to elevated sea levels, through both storm surge and high waves along the NSW coast, are slow-moving low-pressure systems such as cut-off lows or lows of tropical origin that travel south along the NSW coast.

Cut-off lows contributing to the top one percent of wind speeds showed small increases in frequency in both summer and winter halves of the year. While the cause of the increase cannot be determined precisely in the present study, the spatial distribution of wind speed change in the model indicates that these systems may exacerbate extreme winds and sea levels along the southern half of the NSW coast.

The changes in frequencies of other weather patterns suggest a shift in wave climate with waves from the southeast becoming more prevalent and waves from the northeast and east becoming less prevalent. In summer this change comes about from a reduction in Tasman highs coupled with an increase in intense frontal systems. In winter, there is a smaller reduction in Tasman highs but larger increases in the numbers of intense winter fronts and Tasman lows. Based on the spatial pattern of change of extreme wind in the future, the increase in waves originating from the south would be expected to have greater impact on the southern half of NSW.

Risk assessment approaches

Risk is a combination of two factors:

- The probability that an adverse event will occur;
- The consequences of that adverse event.

The probability of an adverse event can be expressed as the likelihood of a given climate hazard. The consequences of that adverse event are measured in social terms and can be characterised as vulnerability. A hazard is *an event with the potential to cause harm*. Examples of climate hazards are tropical cyclones, droughts, floods, hailstorms or conditions leading to an outbreak of disease-causing organisms (plant, animal or human). Vulnerability is measured by indicators such as monetary cost, human mortality, production costs, ecosystem damage or any other metric that is considered important. Climate risk assessment involves identification of the relevant climatic hazards, how often they will occur and what the resulting consequences may be. Although the details of a risk assessment will be specific to a particular project, there are two major pathways for assessing climate risk. One is the natural hazards-based approach that tests the effect of climate on society; the other is the vulnerability-based approach that begins with damages, then diagnoses the climatic conditions that contribute to particular levels of damage. These methods are complementary.

Various risk assessment concepts are described, such as the coping range, critical thresholds, adaptation capacity, planning horizons, uncertainty and vulnerability. A case study is described for water resources in NSW.

Research priorities

The following recommendations were made by the IPCC to improve model reliability:

- Understand better the mechanisms and factors leading to changes in radiative forcing.
- Understand and characterise the important unresolved processes and feedbacks, both physical and biogeochemical, in the climate system.
- Address more completely patterns of long-term climate variability including the occurrence of extreme events such as El Niño-Southern Oscillation (ENSO).
- Improve methods to quantify uncertainties of climate projections and scenarios, including development and exploration of long-term ensemble simulations using complex models.
- Improve the integrated hierarchy of global and regional climate models with a focus on the simulation of climate variability, regional climate changes, and extreme events.

The development of projections of climate extremes under enhanced greenhouse conditions is less advanced than the development of projections of changes to average climate conditions and further work is needed in this area. Some priority research topics for assessing NSW climate extremes are:

- A more rigorous assessment of potential changes in extreme daily temperatures should include the effect of small changes in diurnal temperature range and daily temperature variability.
- Future research should aim to develop methods that minimise the impact of inter-decadal variability in projections of changes to extreme rainfall due to global warming. The development of a means of estimating likely change in extreme rainfall for a given change in average rainfall and global temperature is required. This would enable the preparation of ranges of change in extreme rainfall similar to those provided for average rainfall.
- An analysis of changes in extreme weather patterns in a larger sample of climate model simulations is needed to improve the robustness of projections.
- The robustness of the model results for severe winds needs to be determined by analysing the results of additional models.
- The effects of changes in wind and storm events and rising sea levels on coastal inundation through changes in storm surges could be undertaken using statistical methods that relate changes in broadscale atmospheric circulation to the risk of storm occurrence. Such studies would enable the relative impacts of storm frequency changes and mean sea level rise to be assessed for specific coastal locations.

In addition, new climate projections may be required to service the specific needs of priority impact research areas. This will involve the development of methods to characterise climate risk based on the modes of climate variability and extremes affecting coping ranges of key activities.

The best source of information on climate change impacts for Australia is “Climate change: an Australian guide to the science and impacts”, published by the Australian Greenhouse Office in 2003. The guide contains substantial material on potential impacts in NSW. Extracting and synthesizing the NSW material in a separate report would be a valuable exercise, highlighting the major vulnerabilities, opportunities, gaps in knowledge and priorities for further research on impacts and adaptation. Key uncertainties include the effect of climate change on the incidence of bush fires, flood frequency, water quality and biodiversity.

Table of Contents

1. Introduction

Substantial increases in greenhouse gas concentrations and global temperatures have occurred in the 20th century. The Intergovernmental Panel on Climate Change (IPCC, 2001) concluded that most of the warming observed over the last 50 years is attributable to human activities. Further global warming, sea-level rise and other changes in climate are likely during the 21st century. In order to assess potential impacts for New South Wales (NSW) and plan adaptation strategies, it is prudent to identify how the NSW climate has changed over the past century and how it may be affected by projected climate change.

In 2004, the NSW Greenhouse Office engaged CSIRO and the Bureau of Meteorology to undertake a two-part study of past and projected climate variability in NSW. The first part involved:

- An assessment of changes in temperature and rainfall in NSW over the past 50-100 years;
- A test of how well climate models perform over NSW, and selection of the most reliable models for climate change projections;
- Projections of mean temperature, rainfall, potential evaporation and moisture balance.

A summary of results from the first part can be found in Appendix A and full details are available in the report by Hennessy *et al*. (2004). The second part, detailed in the present report, covers:

- Projected changes in climate variability and extremes for 2030 and 2070
    a. extreme daily temperature;
    b. extreme daily rainfall;
    c. drought indicators;
    d. extreme mean sea-level pressure and winds;
    e. the frequency, intensity and movement of mid-latitude circulation systems associated with extreme weather (e.g. cold fronts and east coast lows);
    f. storm tides due to sea level rise and extreme weather (qualitative assessment).
- Summary of risk assessment approaches
  An assessment of current and future climate risks, including basic concepts of risk (impact x likelihood), vulnerability, the coping range and dealing with uncertainty.
- Recommendations for future research
  Gaps in knowledge and priorities for future research are identified.

Projections for extreme daily temperatures are discussed in chapter 2 for 12 sites selected by the NSW Greenhouse Office. Projections for drought, extreme daily rainfall and extreme daily wind are discussed in chapters 3 to 5 for six regions defined by the NSW Greenhouse Office (Figure 1.1).

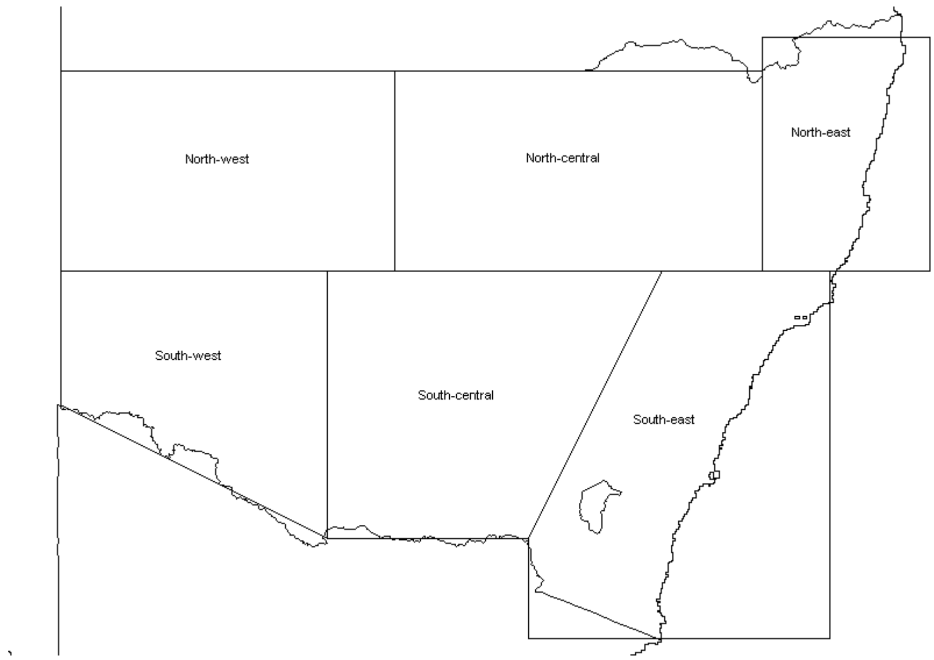

Figure 1.1: Six NSW regions used in the analysis of drought, extreme rainfall and extreme wind.

2. Extreme daily temperatures

2.1 Method

Small changes in average temperature can be associated with large changes in extreme daily temperatures. From 1950 to 2003, the NSW annual mean temperature rose 0.17°C/decade. The annual mean maximum temperature rose 0.15°C/decade and the annual mean minimum temperature rose 0.19°C/decade (Hennessy *et al*., 2004). There has been an associated increase in hot days (35°C or more) of 0.10 days per year, an increase in hot nights (20°C or more) of 0.26 nights per year, a decrease in cold days (15°C or less) of 0.22 days per year and a decrease in cold nights (5°C or less) of 0.29 nights per year.

In February 2004, NSW and other eastern States experienced a record-breaking hot spell over 40°C at a number of locations (BoM, 2004a). At Wilcannia, for example, 16 days in a row over 40°C occurred from 6-21 February 2004. On 13 October 2004, Sydney's maximum temperature of 38.2°C was the hottest October day in the city since records began back in 1858 (BoM, 2004b). Although in isolation, such events cannot be attributed to changing climate, it is reasonable to expect that such events will occur more frequently or earlier or later in the season than has tended to occur historically.

Although changes in temperature extremes can be analysed directly from climate model simulations, a potential disadvantage of this approach is that a model's present climate simulation can contain biases in the frequency of extremes and this lowers confidence in the reliability of the enhanced climate simulation. The alternative and preferred approach for analysing extreme temperatures is to apply the range of projected change in average temperature to observed daily temperature records, then analyse the modified record for changes in extreme events above or below specific thresholds. A disadvantage of this approach is the assumption that the mean warming occurs with no change in daily temperature variability. However, results from climate models analysed over the Australian region by CSIRO do not give clear and consistent changes in variability, so the assumption of no change in variability is reasonable.

Maximum and minimum temperatures may not change at the same rate as average temperature. Indeed, NSW minimum temperatures have increased at a slightly faster rate than maximum temperatures since 1950. Figure 2.2 shows the projected change in maximum and minimum temperatures in the 21st century, expressed as a ratio of average temperature averaged across the seven climate models for which maximum and minimum temperatures were available. Consistent with a decrease in rainfall, maximum temperatures rise slightly faster than average temperatures whereas minimum temperatures rise at a slightly slower rate. However, both maximum and minimum temperatures increase within 10% of the average temperature increase, suggesting that scaling daily temperatures with the average range of warming is reasonable.

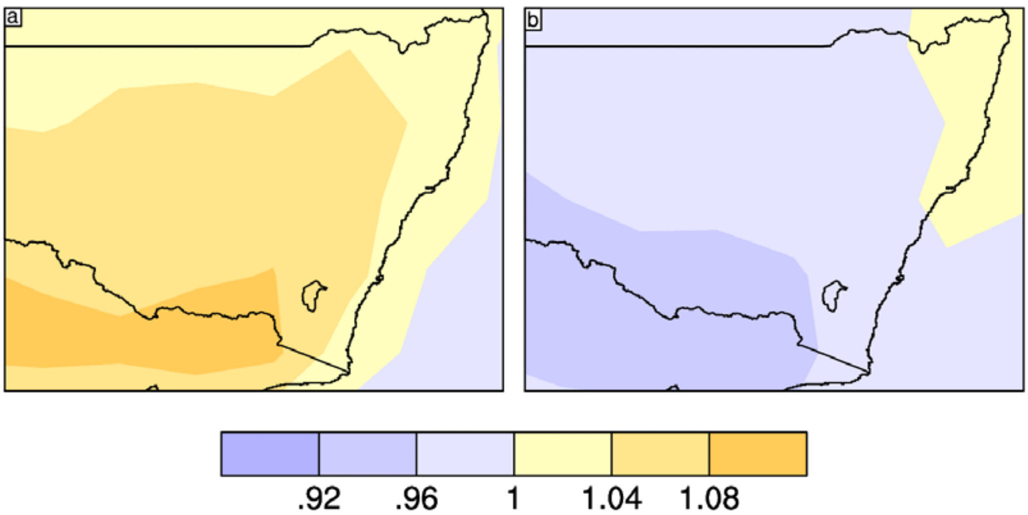

Figure 2.2. The projected ratio of change in (a) maximum to mean temperature and (b) minimum temperature to mean temperature averaged across seven models for which monthly maxima and minima data were available.

2.2 Projections for 2030 and 2070

Projected changes in extreme daily temperatures were calculated for 12 sites selected by the NSW Greenhouse Office, for which high quality observed daily data were available from the Bureau of Meteorology for the last 40 years (1964-2003). Projected average warming values applied to the observed data are shown in Table 2.1. The ranges of change reflect uncertainty in SRES emission scenarios, climate sensitivity and regional patterns of climate change (Appendix B).

Table 2.1: Average warming ranges (°C), relative to 1990, applied to observed daily temperature data at 12 NSW sites for the years 2030 and 2070. The ranges are derived from SRES values in Figure A2 of Appendix A.

Site	Summer 2030	Summer 2070	Autumn 2030	Autumn 2070	Winter 2030	Winter 2070	Spring 2030	Spring 2070
Moruya	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8
Wilcannia	0.3-2.1	0.9-6.4	0.4-1.8	1.1-5.6	0.2-1.8	0.7-5.6	0.3-2.1	0.9-6.4
Cobar	0.3-2.1	0.9-6.4	0.4-1.8	1.1-5.6	0.2-1.8	0.7-5.6	0.4-2.3	1.1-7.2
Walgett	0.4-2.3	1.1-7.2	0.4-1.8	1.1-5.6	0.2-1.8	0.7-5.6	0.4-2.3	1.1-7.2
Gunnedah	0.4-1.8	1.1-5.6	0.2-1.8	0.7-5.6	0.2-1.6	0.7-4.8	0.3-2.1	0.9-6.4
Yamba	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8	0.2-1.8	0.7-5.6
Bathurst	0.3-2.1	0.9-6.4	0.2-1.8	0.7-5.6	0.2-1.6	0.7-4.8	0.3-2.1	0.9-6.4
Sydney	0.2-1.8	0.7-5.6	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8	0.2-1.8	0.7-5.6
Canberra	0.3-2.1	0.9-6.4	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8	0.3-2.1	0.9-6.4
Wagga	0.3-2.1	0.9-6.4	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8	0.4-1.8	1.1-5.6
Wyalong	0.3-2.1	0.9-6.4	0.2-1.8	0.7-5.6	0.2-1.6	0.7-4.8	0.3-2.1	0.9-6.4
Deniliquin	0.2-1.8	0.7-5.6	0.2-1.6	0.7-4.8	0.2-1.6	0.7-4.8	0.4-1.8	1.1-5.6

The annual frequencies of six types of extreme temperature events were considered: days below 0°C, three consecutive days below 0°C, days above 35°C, three consecutive days above 35°C, days above 40°C and three consecutive days above 40°C.

Table 2.2 shows the present and projected average number of days per year in which the temperature drops below zero. Under the low warming scenario for 2030, some sites show no change while others exhibit decreases of about 10-20%. The high scenario for 2030 gives decreases of 50-100%. In 2070, the low scenario leads to decreases of 30-50% at most sites, while the high scenario gives decreases of 85-100%. Figure 2.3 shows the variability of the annual number of sub-zero days at Canberra and Bathurst from 1964-2003, and for the same data modified to represent 40 years centred on 2030 and 2070. The variability declines under warmer conditions.

A cold spell was defined as three consecutive days below 0°C (note that five consecutive days was counted as a single cold spell while six days as counted as two cold spells). At cold sites such as Bathurst and Canberra, the low scenario for 2030 has little effect on the number of cold spells, while the high scenario for 2030 reduces cold spells by about 50%. By 2070, the low scenario at these sites gives a 20% reduction in cold spells, while the high scenario makes cold spells extremely rare.

These changes would reduce energy demand for heating and reduce cold stress for humans and animals. For agriculture, a reduction in sub-zero days would benefit many frost-sensitive crops, but the decline in accumulated winter chilling would reduce the productivity of crops with high vernalisation requirements such as stone-fruits, pome-fruits and cool-climate grapes. The risk of some agricultural weeds, pests and diseases may rise with warmer winter temperatures.

Table 2.2: The average number of days per year below 0°C at 12 NSW sites for present conditions (1964-2003), 40 years centred on 2030 and 40 years centred on 2070. A cold spell was defined as three consecutive days below 0°C. Ranges refer to high and low warming scenarios. * At Deniliquin, present conditions refer to 1963-2002.

Site	Days Below 0°C			Spells Below 0°C		
	Present	2030	2070	Present	2030	2070
Wilcannia	4	1-4	0-2	0	0-0	0-0
Cobar	2	0-2	0-1	0	0-0	0-0
Walgett	13	4-11	0-8	1	0-1	0-1
Gunnedah	3	1-3	0-2	0	0-0	0-0
Yamba	0	0-0	0-0	0	0-0	0-0
Bathurst	59	32-53	4-46	11	5-10	0-8
Sydney	0	0-0	0-0	0	0-0	0-0
Moruya	0	0-0	0-0	0	0-0	0-0
Canberra	62	39-60	9-52	12	7-12	1-10
Wagga	26	10-23	0-17	4	1-3	0-2
Wyalong	9	2-7	0-5	1	0-1	0-0
Deniliquin*	10	2-8	0-5	1	0-1	0-0

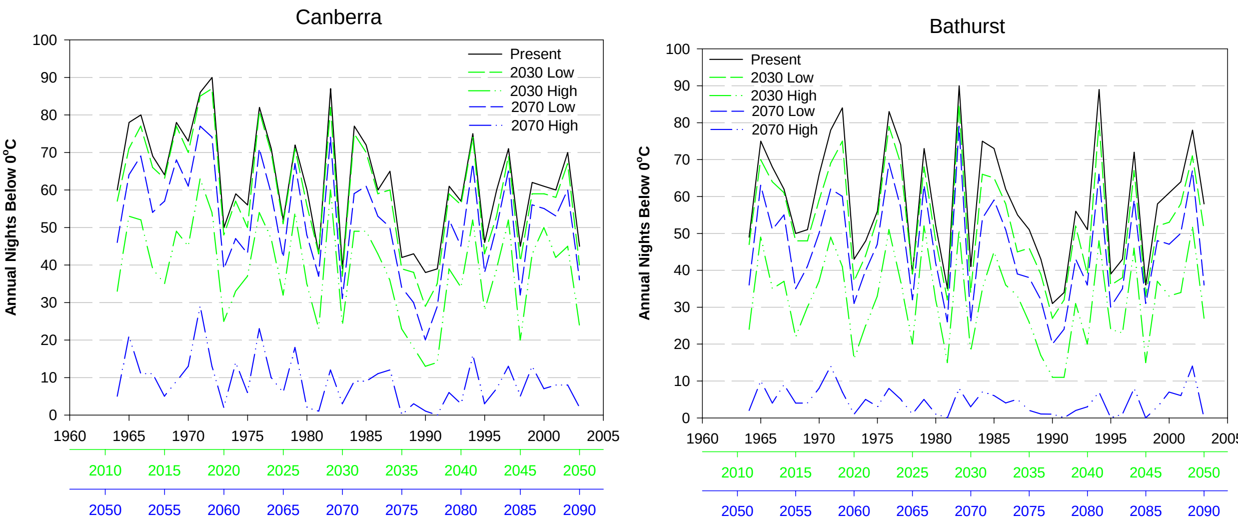

Figure 2.3. Annual number of days below 0°C at Canberra and Bathurst for present conditions (1964-2003), 40 years centred on 2030 and 40 years centred on 2070.

By 2030, the average number of days above 35°C at most sites increases 5-20% for the low warming scenario and 50-100% for the high scenario (Table 2.3). By 2070, the frequency increases 20-60% at most sites for the low scenario and 100-600% (2 to 7 times) for the high scenario. Figure 2.4 shows the variability of the annual number of 35°C days at Canberra and Sydney from 1964-2003, and for the same data modified to represent 40 years centred on 2030 and 2070. The variability increases under warmer conditions. A hot spell was defined as three consecutive days above 35°C (note that five consecutive days was counted as a single hot spell while six days as counted as two hot spells). Deniliquin, Cobar, Walgett and Wilcannia currently average at least 4 of these hot spells per year. At these sites, the low scenario for 2030 has little effect on the number of hot spells, while the high scenario for 2030 increases hot spells by 50-80%. By 2070, the low scenario at these sites gives a 20-40% increase in hot spells, while the high scenario gives a 180-360% (almost 3 to 5 times) increase.

Table 2.3: The average number of days per year above 35°C at 12 NSW sites for present conditions (1964-2003), 40 years centred on 2030 and 40 years centred on 2070. A hot spell was defined as three consecutive days above 35°C. * At Deniliquin, present conditions refer to 1963-2002.

Site	Days Exceeding 35°C			Spells Above 35°C		
	Present	2030	2070	Present	2030	2070
Wilcannia	59	62-83	70-136	13	14-20	16-37
Cobar	41	44-65	51-128	9	10-15	11-35
Walgett	56	61-87	71-153	12	14-21	17-44
Gunnedah	19	22-40	29-103	3	4-8	6-26
Yamba	1	1-2	1-7	0	0-0	0-0
Bathurst	4	4-11	6-43	0	1-2	1-9
Sydney	3	4-6	4-18	0	0-0	0-1
Moruya	2	2-3	2-6	0	0-0	0-0
Canberra	5	6-13	8-42	1	1-2	1-9
Wagga	20	21-34	25-78	3	4-7	4-20
Wyalong	26	27-42	32-93	5	5-9	6-23
Deniliquin*	24	25-37	28-75	4	4-7	4-17

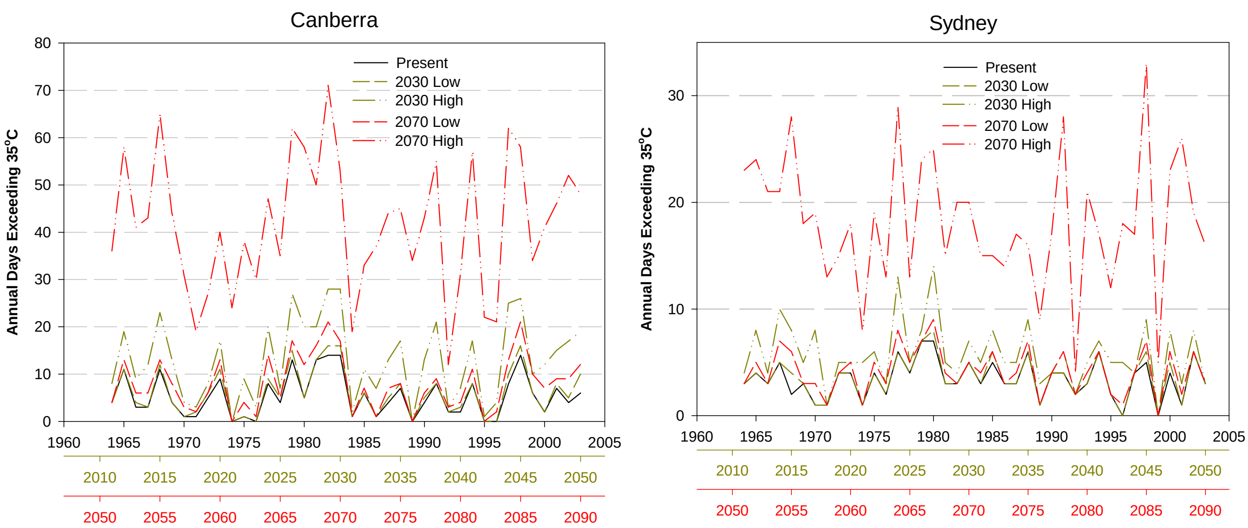

Figure 2.4. Annual number of days above 35°C at Canberra and Sydney for present conditions (1964-2003), 40 years centred on 2030 and 40 years centred on 2070.

Table 2.4 shows similar results for temperatures over 40°C. Cobar, Walgett and Wilcannia currently average at least 6 days over 40°C per year. By 2030, the average number of days above 40°C at these sites increases 15-25% for the low warming scenario and doubles or triples for the high scenario. By 2070, the frequency increases 30-90% at these sites for the low scenario and increases 6 to 10 times for the high scenario. The high scenario for 2070 gives Sydney an annual average of 4 days over 40°C and Canberra an average of 10. If a hot spell is defined as three consecutive days above 40°C, then Cobar, Walgett and Wilcannia currently average 1-2 of these hot spells per year. At these sites, the low scenario for 2030 has a small effect on the number of hot spells, while the high scenario for 2030 gives 2-5 hot spells on average. By 2070, the low scenario at these sites has a small effect, while the high scenario gives 13-20 hot spells on average.

Increases in hot days and hot spells can increase bushfire risk, human mortality and energy demand for air-conditioning. Heat stress to animals and crops is likely to increase. Transport infrastructure is also likely to be affected with greater frequency of buckling of railway lines and melting of road tar.

Table 2.4: The average number of days per year above 40°C at 12 NSW sites for present conditions (1964-2003), 40 years centred on 2030 and 40 years centred on 2070. A hot spell was defined as three consecutive days above 40°C. * At Deniliquin, present conditions refer to 1963-2002.

Site	Days Exceeding 40°C			Spells Above 40°C		
	Present	2030	2070	Present	2030	2070
Wilcannia	15	17-29	20-74	2	3-5	3-17
Cobar	6	7-15	9-56	1	1-3	1-13
Walgett	9	10-23	16-83	1	2-4	3-20
Gunnedah	1	1-3	2-26	0	0-0	0-5
Yamba	0	0-0	0-1	0	0-0	0-0
Bathurst	0	0-0	0-8	0	0-0	0-1
Sydney	0	0-1	0-4	0	0-0	0-0
Moruya	0	0-1	0-2	0	0-0	0-0
Canberra	0	0-1	0-10	0	0-0	0-1
Wagga	2	2-6	3-27	0	0-1	0-5
Wyalong	3	4-9	5-35	0	0-1	0-7
Deniliquin*	4	4-8	5-27	0	0-1	0-4

3. Drought

The definition of drought is based on the criteria for serious rainfall deficiency used by the Bureau of Meteorology. Drought is classified by examining 3-month periods to see whether they lie below the first decile (lowest 10% on record). Once a 3-month period has been classified as a drought, it remains in the drought category until the rainfall deficiency is removed. Rainfall deficiency is considered removed if (1) the rainfall of the past month is above the third decile (lowest 30% on record) for the three-month period commencing that month, or (2) rainfall for the past three months is above the seventh decile (highest 30% on record). The overall period of drought could be any number of consecutive months. There are two features of this drought definition which should be noted:

- Whether any individual month or season is classified as under drought depends on the rain received in the preceding months as well as during the month itself. For example, moderately dry conditions may be sufficient to continue an existing drought but not to initiate a new drought.
- Since the drought definition is decile-based, the observed drought sequences can be directly compared with simulated sequences, even though the spatial and temporal patterns of the climate model simulations do not capture all aspects of the variability.

To investigate changes in future drought frequency, the observed monthly rainfall data from 1961 to 2000 were modified using seasonal rainfall projections for six regions of New South Wales (see Figure 1.1) for 40 years centred 2030 and 2070 (Table 3.1). The worst-case scenario is a decrease in rainfall in all cases, while the best–case scenario is an increase in rainfall in most cases. As the first step, three-month total rainfall was taken as the sum of January to March; next, February to April, and so on. The last value for a given year was the sum of December of the present year and January and February of the following year. In the following results, a nominated month refers to the central month in a three-month period, e.g. May refers to April-June.

Table 3.1: NSW regional rainfall change (%) scenarios for 2030 and 2070, relative to 1990. These SRES scenarios are derived from Figure A3 in Appendix A.

Region	Season	2030	2070
North-west	Summer	±14	±40
	Autumn	-7 to +14	-20 to +40
	Winter	-14 to +7	-40 to +20
	Spring	-20 to 0	-60 to 0
North-central	Summer	-14 to +7	-40 to +20
	Autumn	-14 to +7	-40 to +20
	Winter	-14 to +7	-40 to +20
	Spring	-20 to +7	-60 to +20
North-east	Summer	-7 to +14	-20 to +40
	Autumn	±7	±20
	Winter	-14 to +7	-40 to +20
	Spring	-20 to +7	-60 to +20
South-west	Summer	±14	±40
	Autumn	±14	±40
	Winter	-14 to 0	-40 to 0
	Spring	-20 to 0	-60 to 0
South-central	Summer	±14	±40
	Autumn	±7	±20
	Winter	-14 to 0	-40 to 0
	Spring	-20 to 0	-60 to 0
South-east	Summer	±14	±40
	Autumn	±7	±20
	Winter	-14 to +7	-40 to +20
	Spring	-14 to 0	-40 to 0

Figure 3.1 shows observed and projected monthly frequencies of drought for 2030 for worst and best case scenarios. The average frequency during 1961-2000 is about three months per decade. Southern NSW regions tend to have more droughts in winter and spring while northern regions tend to have a uniform spread of droughts throughout the year. The projections indicate that increases and decreases in drought frequency are possible, but there is a tendency toward increases, especially in winter and spring. The frequency is increased by about 70% for the worst case (decreased rainfall) scenario and decreased by 35% for the best case (increased rainfall) scenario by 2030. The range of uncertainty is much larger by 2070 (Figure 3.2) when drought frequency could increase by more than 200% or decrease by up to 70%.

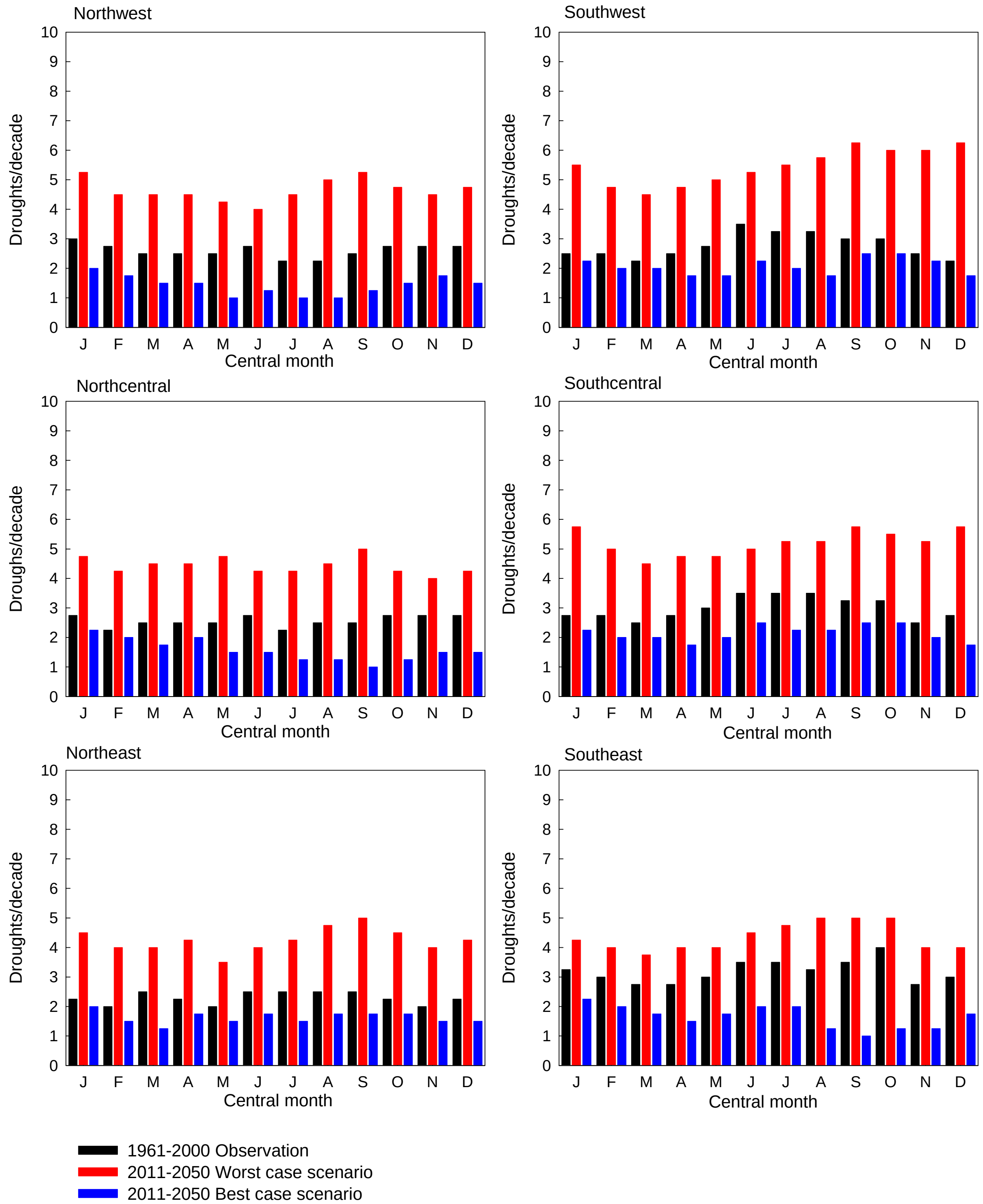

Figure 3.1. Observed (1961-2000) and projected (40 years centred on 2030) drought frequencies per decade for low and high rainfall change scenarios in the six regions in New South Wales shown in Figure 1.1. A nominated month refers to the central month in a three-month period, e.g. May refers to April-June.

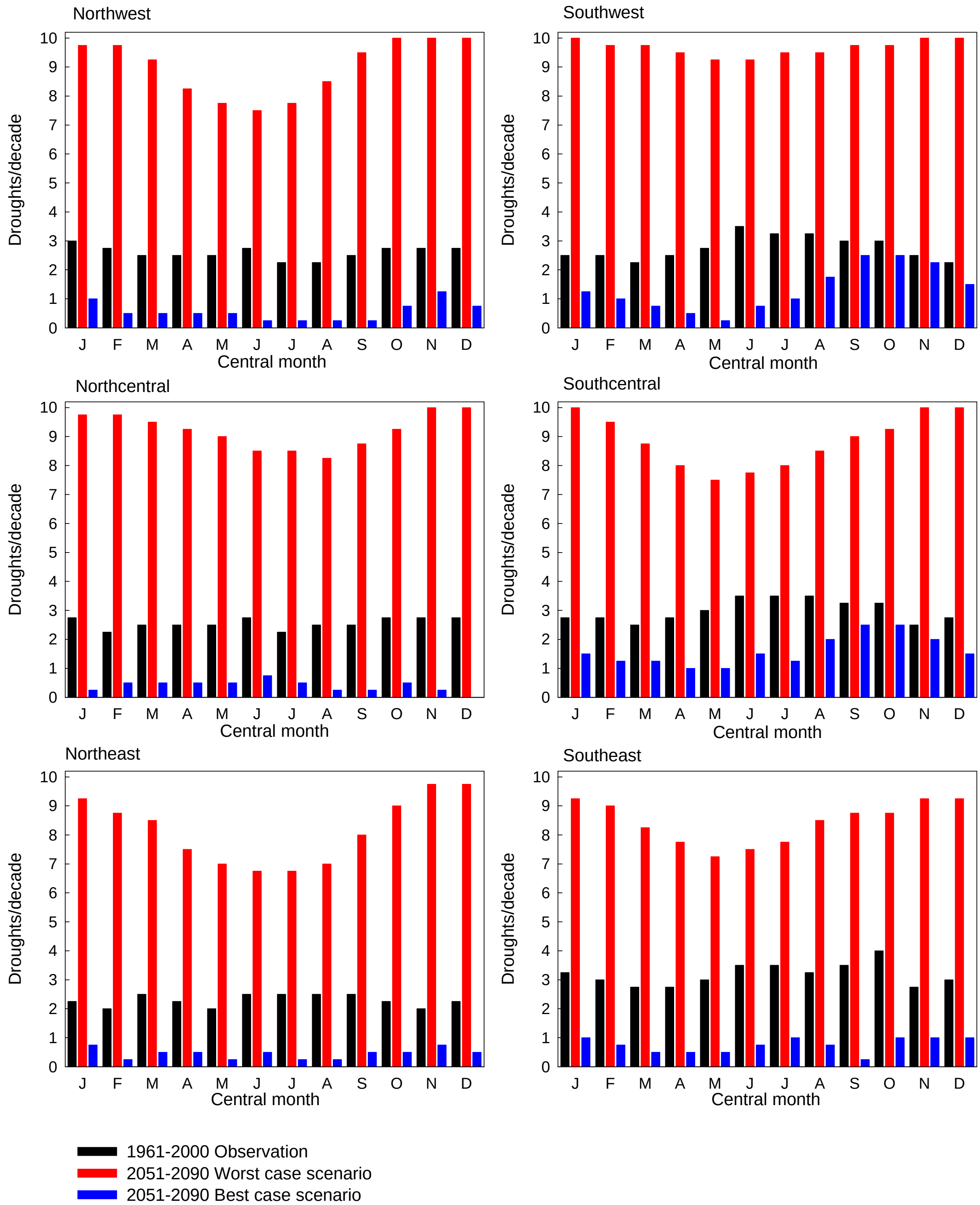

Figure 3.2. Observed (1961-2000) and projected (40 years centred on 2070) drought frequencies per decade for low and high rainfall change scenarios in the six regions in New South Wales shown in Figure 1.1. A nominated month refers to the central month in a three-month period, e.g. May refers to April-June.

4. Extreme rainfall

While much of NSW shows a tendency towards drier seasonal-average conditions under enhanced greenhouse conditions, it does not necessarily follow that extreme daily rainfall events will become less frequent or severe. Previous studies based on daily rainfall data from various climate models have indicated marked increases in the intensity 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.*, 1998; Whetton *et al.*, 2002; McInnes *et al.*, 2002; Walsh *et al.*, 2002).

4.1 Climate models used in this analysis

This analysis requires outputs of daily rainfall and thus uses a subset of the models used in Part 1 of this study (Hennessy *et al.*, 2004. Each model has met the performance criteria described in that report. The models used in this analysis are described in Table 4.1.

Table 4.1: Climate model simulations used in this analysis.

Research centre	Model	Emission scenarios post-1990 (historical forcing prior to 1990)	Years	Horizontal grid size (km)	Temporal resolution available
CSIRO, Australia	CSIRO Mark2.1	IS92a,	1881-2100	~400	daily
CSIRO, Australia	CSIRO DAR125	RCM in Mark2 with IS92a	1961-2100	125	daily
CSIRO, Australia	CSIRO CC50	Linked to Mark2 with SRES A2	1961-2100	50 over Aus	daily
CSIRO, Australia	CSIRO Mark3	SRES A2	1961-2100	~200	daily

4.2 Method

The daily rainfall outputs from each of the four models have been interpolated to a common grid with about 50-km resolution. One-day and three-day rainfall totals have been calculated for each grid point. The following analysis is based on two 40-year periods centred on 2030 and 2070. All projected changes are relative to the present climate, a 40-year period centred on 1980 1961-2000.

The horizontal grid sizes used by the models range from approximately 400 km to 50 km and so the magnitude of the rainfall extremes from each model will vary significantly. To overcome the difficulties associated with comparing model outputs of varying magnitudes, the derived rainfall time series for each model/season/region are normalized (divided) by the 1-in-40-year value for the present climate for that model/season/region in 2030 or 2070. The 1-in-40 year value at a given grid-point is the highest value in the 40-year period. This event has an average return period of 40 years. The second-highest event has a 20 year return period, the fourth-highest has a 10-year return period and the eighth-highest has a 5-year return period.

4.3 Projected changes in extreme rainfall

Projected changes in the characteristics of the 1-in-40 year, 1-in-20 year, 1-in-10 year and 1-in-5 year events have been calculated for annual and seasonal extremes for both 1-day and 3-day rainfall totals. Changes in the magnitude and likelihood of extreme rainfall intensity were considered.

4.3.1 1-day events

The projected changes in rainfall intensity for the 1-in-40 year, 1-in-20 year, 1-in-10 year and 1-in-5 year events have been averaged to produce the average patterns of change shown in Figure 4.1 for 2030 and 2070. The projected change in annual extreme rainfall intensity for the 1-day events shows a small region of increased rainfall in the northeast of the state and a larger region of increased extremes through the south and central regions. Decreases occur in the northwest and along the central coast. The projections for 2070 are similar to those for 2030 but with more widespread increases in annual extreme rainfall in all regions.

On a regional and seasonal basis, the following changes in extreme rainfall intensity occur by 2070:

- North-east: increases in winter, spring and summer with decreases in autumn;
- North-west: increases in autumn and winter and decreases in spring and summer;
- North central: increases in all seasons;
- South-east: increases in spring, summer and autumn, and decreases in winter;
- South-west and south central: increases in all seasons.

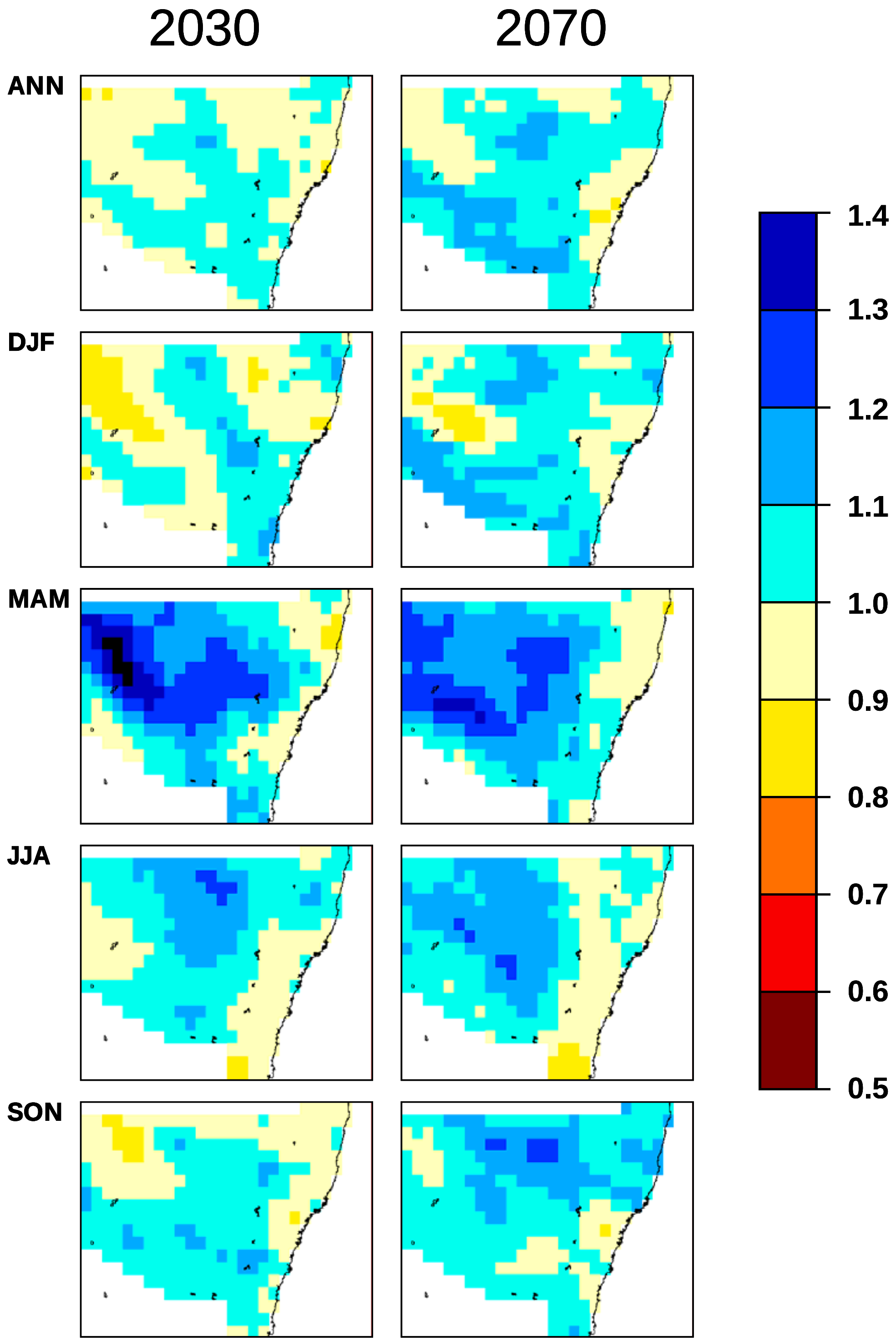

Figure 4.1. Average fractional change in the intensity of 1-day extreme rainfall events (for return periods of 5, 10, 20 and 40 years) for 2030 and 2070 relative to the current climate. Yellow regions show decreases in rainfall intensity and blue regions show increases in intensity. ANN = annual, DJF = summer, MAM = autumn, JJA = winter, SON = spring.

The projections presented in Figure 4.1 convey information about the possible direction of change in extreme rainfall intensity but they do not convey any information on the likelihood of this change occurring. The direction of the change for the four return periods under consideration for each of the four models is examined to help quantify the likelihood of an increase or decrease in the intensity of extreme rainfall events for each grid point (Figure 4.2). Likelihood is high if all four models show increases in intensity for all four return periods, and likelihood is low if all four models show decreases in intensity for all four return periods.

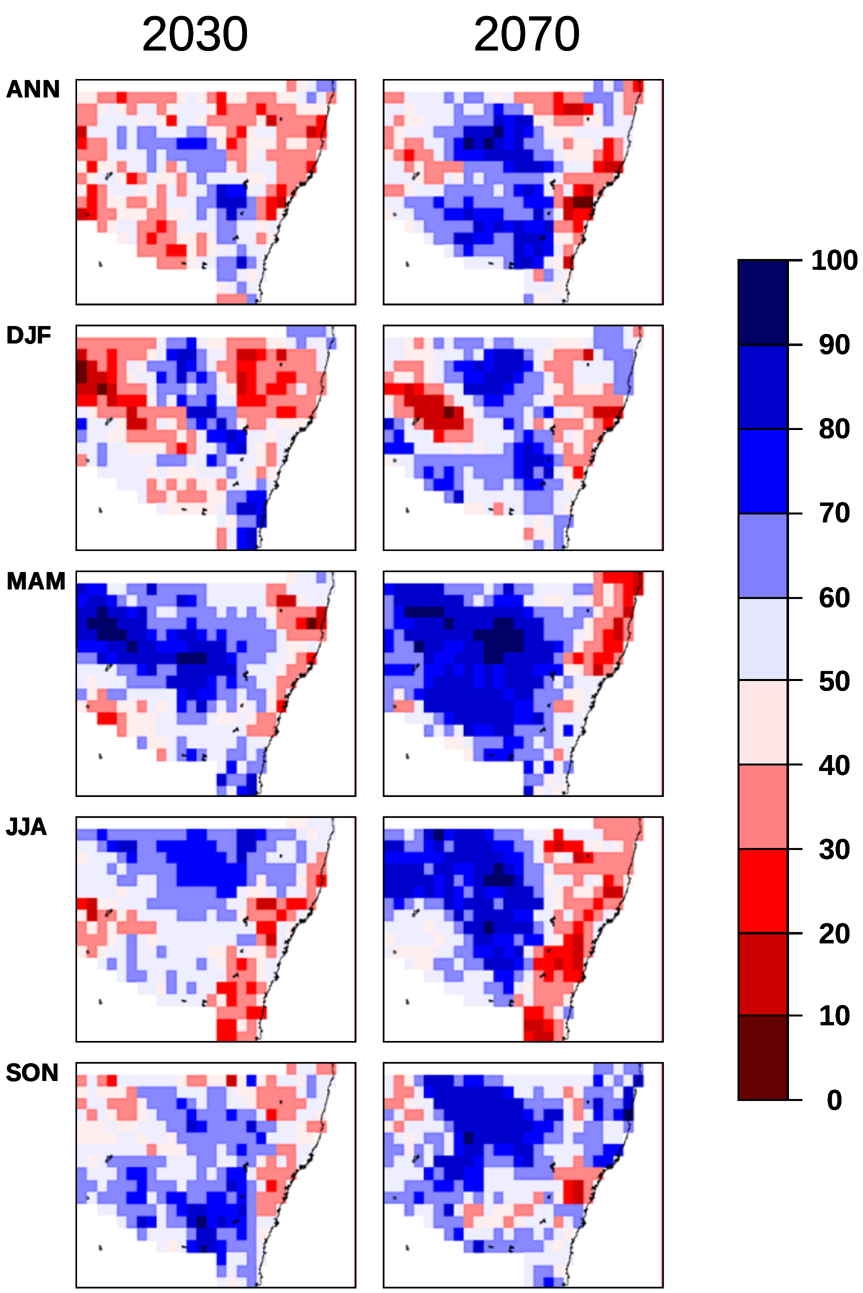

Figure 4.2. The likelihood (%) of an increase in 1-day extreme rainfall (for return periods of 5, 10, 20 and 40 years) for 2030 and 2070 relative to the current climate. Red regions denote regions of where most of the four models simulate a decrease in rainfall extremes and blue regions those where most models project an increase in extremes. ANN = annual, DJF = summer, MAM = autumn, JJA = winter, SON = spring.

The highest likelihood of an increase in annual rainfall extremes occurs in central and south-east NSW. A small region of likely increase also occurs in the north-east. These regions coincide with increases in the intensity of extreme rainfall. In contrast, the projected increase in intensity of annual extreme rainfall for the south-west of the state is less likely to occur. A similar pattern occurs in summer. Increases in the intensity of autumn and winter extreme rainfall are most likely to occur west of the Great Dividing Range in the north-central, north-west and south-central regions. The majority of models show a decrease in rainfall extremes along the coast in autumn and winter. Most models project an increase in the intensity of extreme rainfall in spring and summer on the north-east coast and decreases in winter in the southeast. The central regions of NSW are most likely to experience increased rainfall extremes, especially in autumn and winter. By 2070, the agreement between models is much stronger regarding the direction of changes in extreme rainfall intensity.

4.3.2 3-day events

Similar diagrams have been prepared, but are not shown, for 3-day rainfall events. The patterns of change for the 3-day extreme rainfall events are mostly similar to those of the 1-day events. However, the fractional changes are, in general, slightly weaker and there is less agreement between the models in the western regions. The greatest agreement between models is along the coastal regions, where 3-day events are projected to decrease in intensity in autumn, winter and spring but increase in summer. The main difference between the 1-day and 3-day events occurs in spring, with most models simulating a decrease in the intensity of the extreme 3-day events.

4.3.3 Regional-average changes in intensity

Plots of extreme rainfall intensity versus return period have been calculated for 1-day and 3-day events for each of the six regions in Figure 1.1, seasonally and annually, for three 40-year periods centred on 1980 (current), 2030 and 2070 for each model. These plots have been created by averaging the gridded values for each model and region for each of the 1-in-40, 1-in-20, 1-in-10 and 1-in-5 year events.

An example of the intensities derived using this method is shown in Figure 4.3 for the 1-day extreme events occurring in the south-east region. These plots show a small increase, of approximately 5%, in annual 1-day extreme rainfall intensity by 2030 and 2070. This increase is due almost entirely to increases in intensity of the summer events, with the autumn, winter and spring events showing little change or a slight decrease in intensity.

Figures 4.1 and 4.2 show that in autumn and spring, the southern portion of the region experiences increases in extreme rainfall intensity, but this increase is not captured in the return period plots. This is due to the averaging of changes over a large region. It also highlights the need to consider relatively small regions when studying extreme rainfall events, as local terrain features play an important role in extreme rainfall distribution.

The average projected changes in the 1-in-40 year intensity for each region is presented in Table 4.2 for the 1-day events, and in Table 4.3 for the 3-day events. In most regions, annual intensities are projected to increase. By 2070, the increases reach 15% for some locations. The largest increases in seasonal extremes are projected to occur in autumn in the central and western regions. In the south-east, rainfall extremes are projected to decrease in all seasons except summer. During summer, increases in intensity of 10-15% are projected for the 1-day events and of up to 20% for the 3-day events. Three-day spring rainfall events are projected to decrease in intensity in all regions

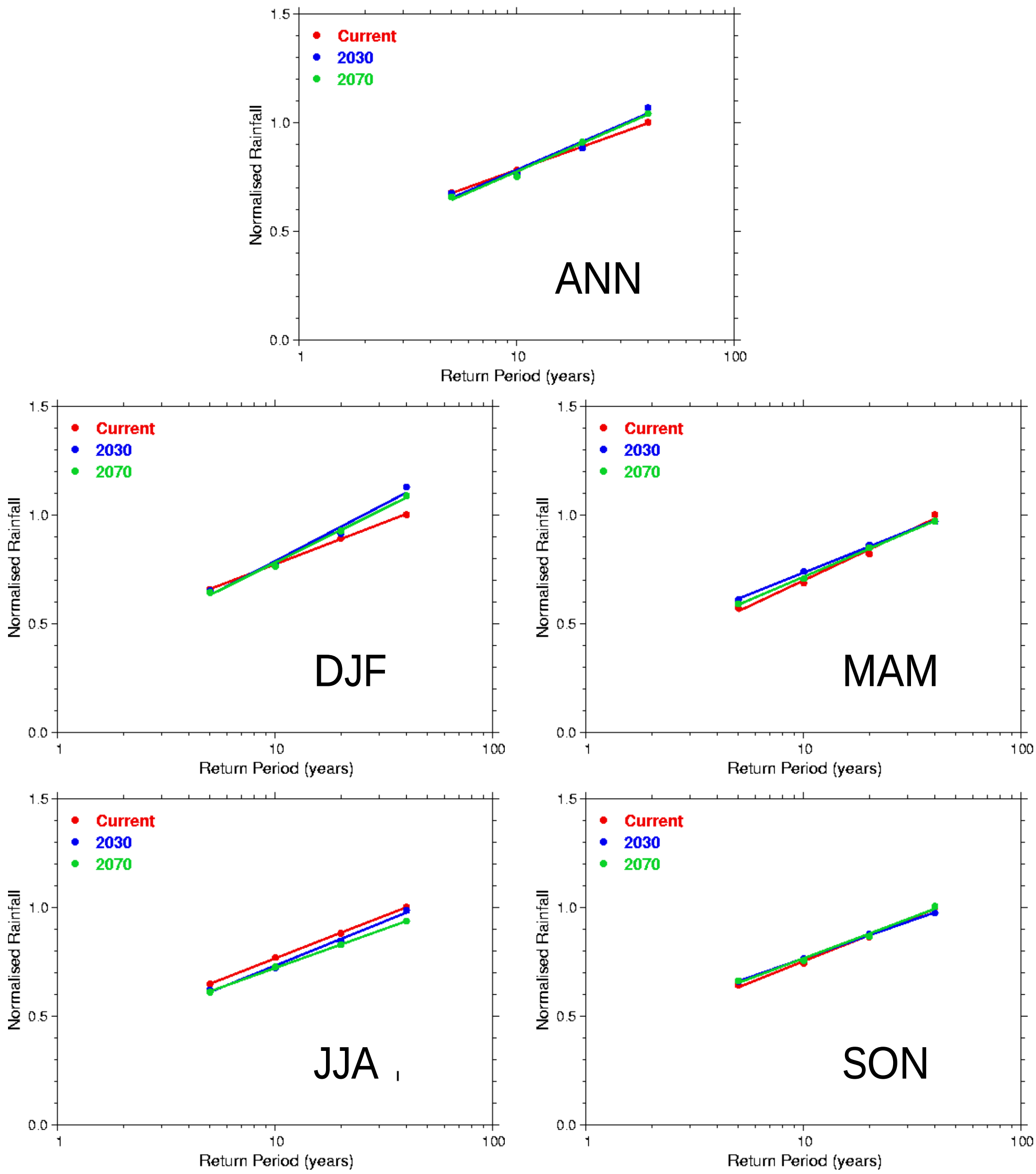

Figure 4.3. Changes in extreme rainfall intensity averaged over the south-east region for four return periods for the current climate, 2030 and 2070. ANN = annual, DJF = summer, MAM = autumn, JJA = winter, SON = spring.

The rainfall simulated by climate models contains variations due to both inter-decadal climate variability and climate change. The inter-decadal variations are important as they affect the conclusions that may be drawn when considering data or model outputs from 40-year periods. Some of these effects may be seen when comparing the changes projected in some regions for 2030 and 2070. For this reason, the changes tabulated in Tables 4.2 and 4.3 should be used with caution.

In some regions, the projected regional average change is quite large. In regions such as the northwest, the hydrological impacts from these large percentage changes are relatively small since the baseline rainfall intensity is small. For instance, in Tibooburra the historic autumn maximum daily rainfall is 86 mm. In other regions, such as the Northern Rivers and southeast coast, historic maximum daily rainfalls of over 300 mm have occurred, so moderate percentage changes in extreme rainfall will produce greater hydrological impacts with the potential for increased flooding and landslides in some areas.

Table 4.2: Projected regional changes in intensity of the 1-in-40 year 1-day rainfall events for each season and annually for 2030 and 2070. All changes are relative to the climate of 1961-2000.

Region	ANN		DJF		MAM		JJA		SON	
	2030	2070	2030	2070	2030	2070	2030	2070	2030	2070
NE	+5%	+5%	+5%	+5%	+5%	=	+5%	+5%	-10%	+10%
NC	+3%	+10%	+3%	+15%	+13%	+10%	+12%	+10%	=	+10%
NW	-10%	-7%	-10%	=	+34%	+16%	+5%	+7%	-5%	+10%
SE	+7%	+5%	+12%	+10%	-3%	-3%	=	-7%	=	=
SC	=	+13%	+5%	+15%	+20%	+10%	+7%	+5%	=	=
SW	=	+15%	=	+17%	+25%	+29%	+5%	+5%	+10%	+5%

Table 4.3: Projected regional changes in intensity of the 1-in-40 year 3-day rainfall events for each season and annually for 2030 and 2070. All changes are relative to the climate of 1961-2000.

Region	ANN		DJF		MAM		JJA		SON	
	2030	2070	2030	2070	2030	2070	2030	2070	2030	2070
NE	=	+5%	=	=	+20%	=	+5%	=	-10%	+10%
NC	-3%	+3%	-3%	+10%	+3%	-5%	+10%	+15%	-20%	-7%
NW	-3%	+3%	-7%	+15%	+37%	+10%	+11%	+20%	-20%	-15%
SE	+10%	+3%	+22%	+15%	-5%	-5%	-5%	-8%	-5%	-8%
SC	+12%	+4%	+13%	+10%	+17%	+10%	+3%	+5%	-10%	-10%
SW	=	+10%	=	+15%	+30%	+10%	+10%	+5%	=	-10%

5. Extreme winds

Projected changes in wind patterns across New South Wales were analysed in a range of climate model simulations. Scenarios of average and extreme wind conditions are presented and discussed.

5.1 Model selection

As reported in Hennessy *et al.* (2004), a wide range of climate simulations from international modelling groups are available to CSIRO for developing regional climate projections. A summary of the 19 available simulations is given in Table 5.1. Note that for some models there exists an older simulation conducted using an emissions scenario based on IS92a or a 1% per annum compounding increase in CO_2 as well as the more recent simulations carried out using various different SRES scenarios. In Hennessy *et al.* (2004), each of the simulations were subjected to quality control procedures leading to the exclusion of several poorer performing models from the scenarios. The excluded models were CCSR, NCAR-CGM, GFDL and ECHAM3. The same set of models selected for the projections of temperature, rainfall and potential evaporation in that study are used for the projection of mean and extreme winds in the current study.

Table 5.1: Climate model simulations analysed in this report. Note that D125 and CC50 are Regional Climate Models. Further information about the non-CSIRO simulations may be found at the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk).

Centre	Model	Emissions Scenarios post-1990 (historical forcing prior to 1990)	Years	Horizontal resolution (km)	Symbols used in the report
Canadian CC	CCCM1	1% increase in CO_2 p.a.	1900–2100	~400	CM1
Canadian CC	CCCM2	IS92a	1961-2100	~400	CM2
Canadian CC	CCCM2	CO_2+ aerosol SRES, A2, B2	1900-2100	~400	CM2S
CCSR, Japan	CCSRNIES	SRES, A1, A1F1,A1T,A2,B1,B2	1890-2100	~500	CCSRS
CSIRO, Aust	Mark2.1	IS92a	1881–2100*	~400	MK2
CSIRO, Aust	Mark2.2	SRES A2 (four simulations), SRES B2	1881–2100*	~400	MK2S
CSIRO, Aust	DARLAM	IS92a	1961-2100	125	D125
CSIRO, Aust	Mark3	SRES A2	1961-2100	~200	MK3
CSIRO, Aust	CC	SRES A2	1961-2100	50	CC50
DKRZ, Germany	ECHAM3/LSG	IS92a	1880-2085	~600	ECM3
DKRZ, Germany	ECHAM4/OPYC3.1	IS92a	1860–2099	~300	ECM4
DKRZ Germany	ECHAM4/OPYC3.2	CO_2+O_3 + aerosol, SRES A2, B2	1990-2100	~300	ECM4S
GFDL	GFDL.1	1% increase in CO_2 p.a.	1958–2057	~500	GFDL
GFDL	GFDL.2	Varying insolation + aerosol, SRES A2, B2	1961-2100	~500	GFDLS
Hadley Centre, UK	HadCM2	1% increase in CO_2 p.a. (four simulations)	1861–2100	~400	HCM2
Hadley Centre, UK	HadCM3.1	IS92a	1861-2099	~400	HCM3
Hadley Centre, UK	HadCM3.2	CO_2+O_3 + aerosol, SRES, A2, B2	1950-2099	~400	HCM3S
NCAR-CGM	NCARCSM	SRES A2	2000-2099	~300	NCARCS
NCAR-PCM	NCARPSM	CO_2+ aerosol SRES, A1B, A2, B2	1980-2099	~300	NCARPS

5.2 Global patterns of change

It is instructive to examine the broad patterns of change simulated by the models in variables such as winds and pressure to provide a context for understanding the changes on the local scale. Figure 5.1 represents the agreement between models on changes in near-surface wind-speed across the globe using the ten global climate models selected in Hennessy *et al.* (2004) (note that the two regional models are omitted from this analysis). While the magnitude of the change is generally small (less than 3% per degree of global warming), there is agreement between models on changes across a large part of the globe. Increases in wind speed occur over the southern ocean south of about 50°S. Increases in wind speed are also indicated over the southern Tasman Sea and across the Australian mainland. Changes are less certain immediately to the southwest of Tasmania while decreases are indicated over the Bight extending into the Indian Ocean.

The change in wind pattern in the southern hemisphere is strongly related to the pattern of pressure change (Figure 5.2) with the band of increasing winds in the southern ocean overlapping and extending slightly to the north of the band of decreasing pressure. Decreasing pressure is also indicated across Australia while decreasing pressure occurs to the southwest of Australia and across the southern Pacific Ocean.

The pattern of pressure change in the southern hemisphere is one of increasing pressure in the vicinity of the sub-tropical ridge and decreasing pressure in the sub-polar trough which leads to stronger winds in the regions between. The reason for this pattern of change is not well understood, but there is evidence that the tendency toward increased pressure in the 40-60ºS latitude band is related to the delayed warming in southern high latitudes due to the downward transport of heat by the ocean (see Whetton *et al.*, 1996). There is also some agreement amongst models on decreased pressure over Australia. Both these features are also present in the seasonal analyses, although the increased pressure band extends slightly further north in winter and the decreased pressure over the continent is stronger in summer.

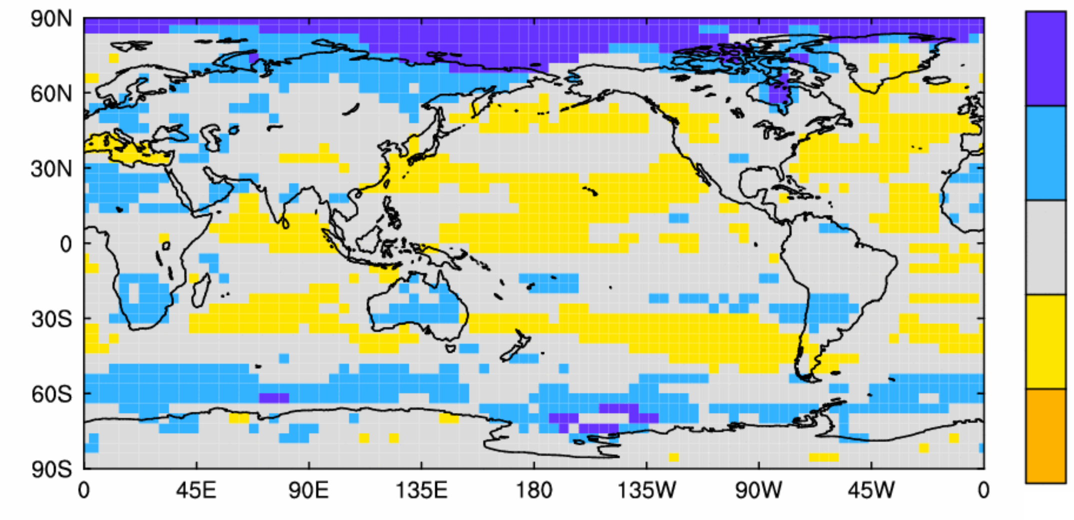

Figure 5.1. Agreement between ten models in the direction of simulated annual near-surface wind change. Large changes are defined as greater than 3 % per °C of global warming.

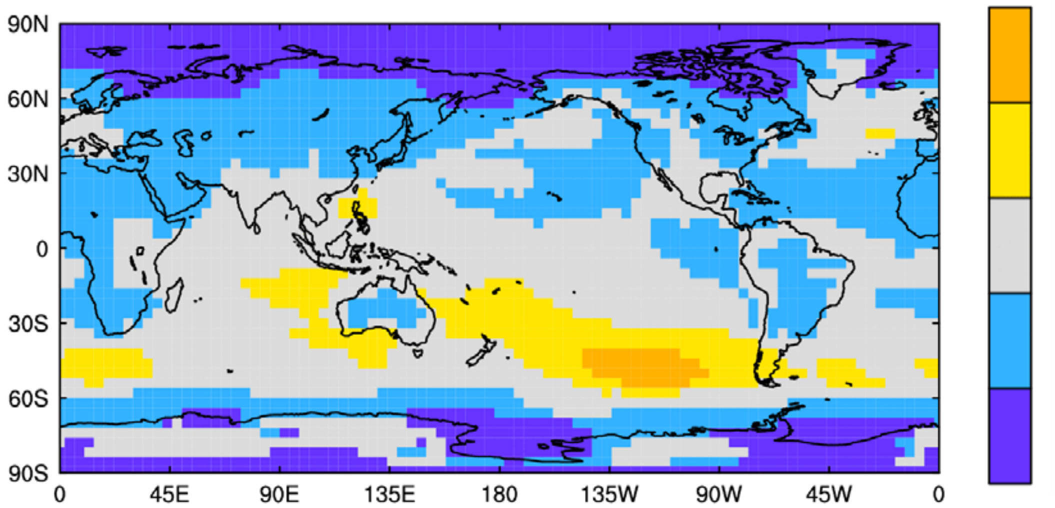

Figure 5.2. Agreement between ten models in the direction of simulated annual pressure change. Large changes are defined as greater than 50 Pa per °C of global warming.

5.3 Projected changes in wind over NSW

Scenarios of wind changes were developed from the twelve patterns of change per degree of global warming by multiplying the maps by the range of global warming projected at a particular future date under a particular emissions scenario. Three different scenarios are considered:

- the IPCC SRES scenarios without policies to reduce greenhouse gas emissions;
- the IPCC scenario for stabilising CO_2 concentrations at 550 ppm by the year 2150;
- the IPCC scenario for stabilising CO_2 concentrations at 450 ppm by the year 2090.

Regional scenarios for mean wind speed over NSW are presented in Figure 5.3 as colour-coded maps representing the range of possible change. The colour coding incorporates the quantifiable uncertainties associated with:

- Uncertainty in scenarios of future growth in greenhouse gases and aerosols:
- The climate sensitivity, i.e. the amount of global warming that will occur for a given atmospheric concentrations of greenhouse gases
- Differences between the climate model simulations in terms of regional climate change.

5.3.1 Mean wind changes

Wind-speed changes across NSW contain large uncertainty in most seasons in that the range of possible change spans zero for five of the seven categories shown in Figure 5.3. The ranges of change for the two stabilisation scenarios are narrower than those for the SRES scenarios illustrating the marked effect that deliberate attempts to limit greenhouse gas emissions will have on future climate change particularly by 2070. The remaining discussion is limited to the range of future change pertaining to the SRES scenarios.

Annual-average wind-speed shows a tendency for decreases in coastal regions, the range being -2.6 to +1.3% by 2030 and -8 to +4% by 2070. The western half of the state has a tendency for increases in wind-speed with the range being -1.3 to +2.6% by 2030 and -4 to +8% by 2070, although the range of uncertainty is greater in the south-west (-2.6 to +5.2% by 2030 and -8 to +16% by 2070).

In summer, the southern coastal regions are likely to undergo wind increases in the range of -1.3 to +2.6% by 2030 and -4 to +8% by 2070 under the full range of SRES scenarios. Northern coastal regions are more likely to undergo average wind speed reductions in the range of -2.6 to 1.3%. In the south of the state, wind increases in the range of -2.6 to +5.2% by 2030 and -8 to +16% by 2070 are indicated. Changes across much of inland NSW are uncertain with increases or decreases in the range of ±2.6% by 2030 and ±8%°C by 2070 possible. The exception is a small region across the centre of NSW extending into south-west Queensland where decreases are in the range of -5.2 to +2.6% by 2030 and -16 to +8%.

During autumn, increases in the range of -2.6 to +5.2% by 2030 and -8 to +16% by 2070 occur over the north of the state while the south-east of the state undergoes decreases in the range of -2.6 to +1.3% by 2030 and -16 to +8% by 2070.

In winter more consistent decreases in wind are indicated across the north-east of the state in the range of -5.2 to 0% by 2030 and -16 to 0% by 2070. Increases in wind are likely only in the far north-west and south-east of the state.

In spring, wind increases are likely across all of the state particularly in the north-west where the range of possible change is 0 to +5.2% by 2030 and 0 to +16% by 2070.

The projections in Figure 5.3 convey information about the range of change but no information on the likelihood of any particular change taking place. In the absence of probabilistic projections, and in view of the fact that for wind both increases and decreases are possible, it is informative to also present the wind change as an average of the 12 models noting that there is large uncertainty in doing this. The average wind change (Figure 5.4) shows strong qualitative similarity to the projections in Figure 5.3. Areas that were highly uncertain (grey in Figure 5.3) show weak decrease in all seasons except spring where all areas show weak increase. Note that the averages in Figure 5.4 have not been scaled to a represent a particular future date under a warming scenario and so the units are percentage change per degree of global warming.

Figure 5.4 also presents the number of models, out of the 12 considered, that agree on an increase in wind. This provides information on whether the ranges of change are influenced by outlier results. For example, the average increases in annual wind in the south-west occur despite the fact that only four or five of the models simulated increasing wind in this region. Therefore, the large positive range indicated in Figure 5.3 is the result of a minority of models that simulated increasing winds in this region. A similar situation occurs for summer in the north of the state where a broad range centred on decreasing winds occurs despite the majority of models indicating wind increases.

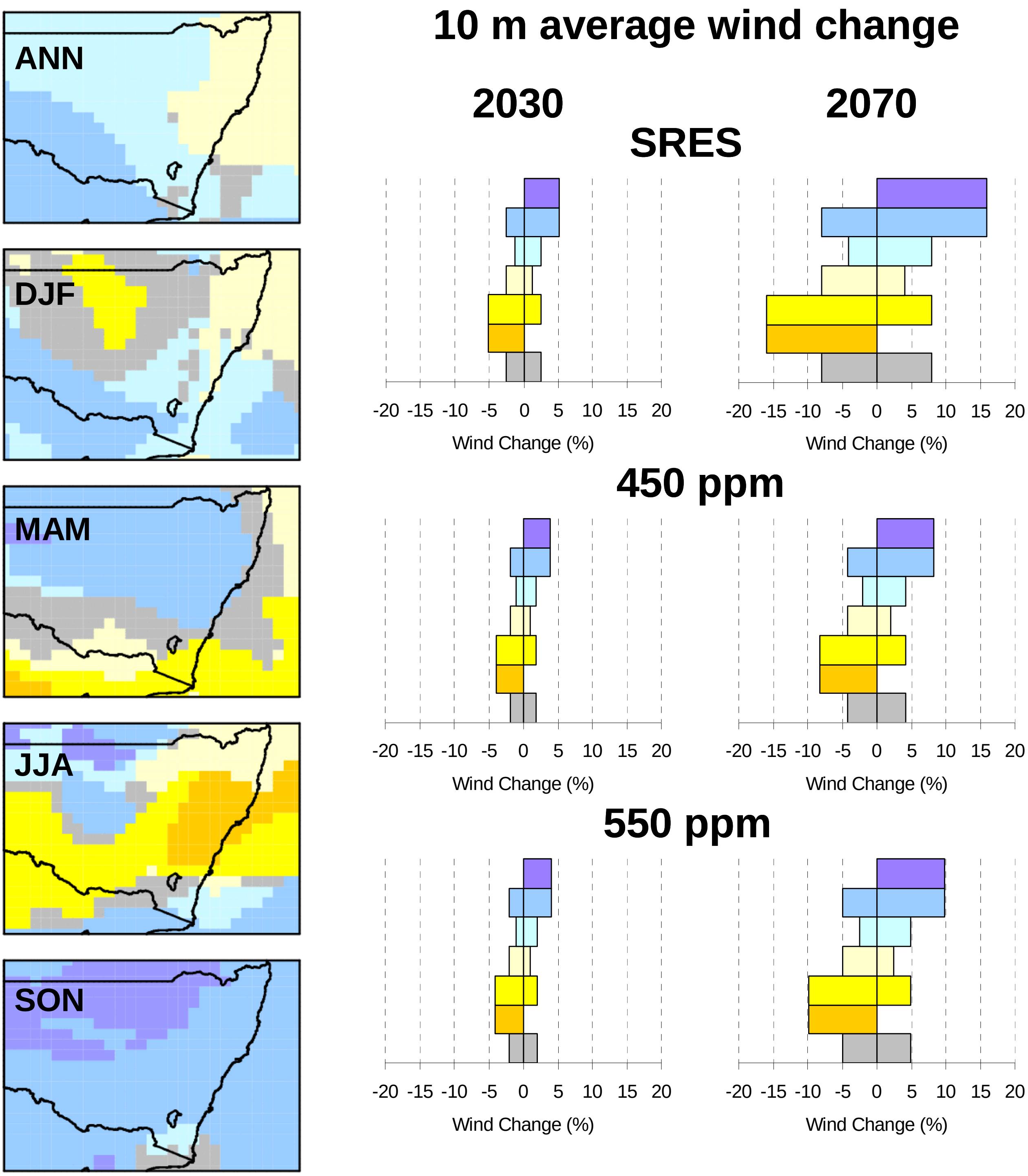

Figure 5.3. Ranges of change in near-surface (10 metres above ground) wind (% per °C of global warming) for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios. ANN = annual, DJF = summer, MAM = autumn, JJA = winter, SON = spring.

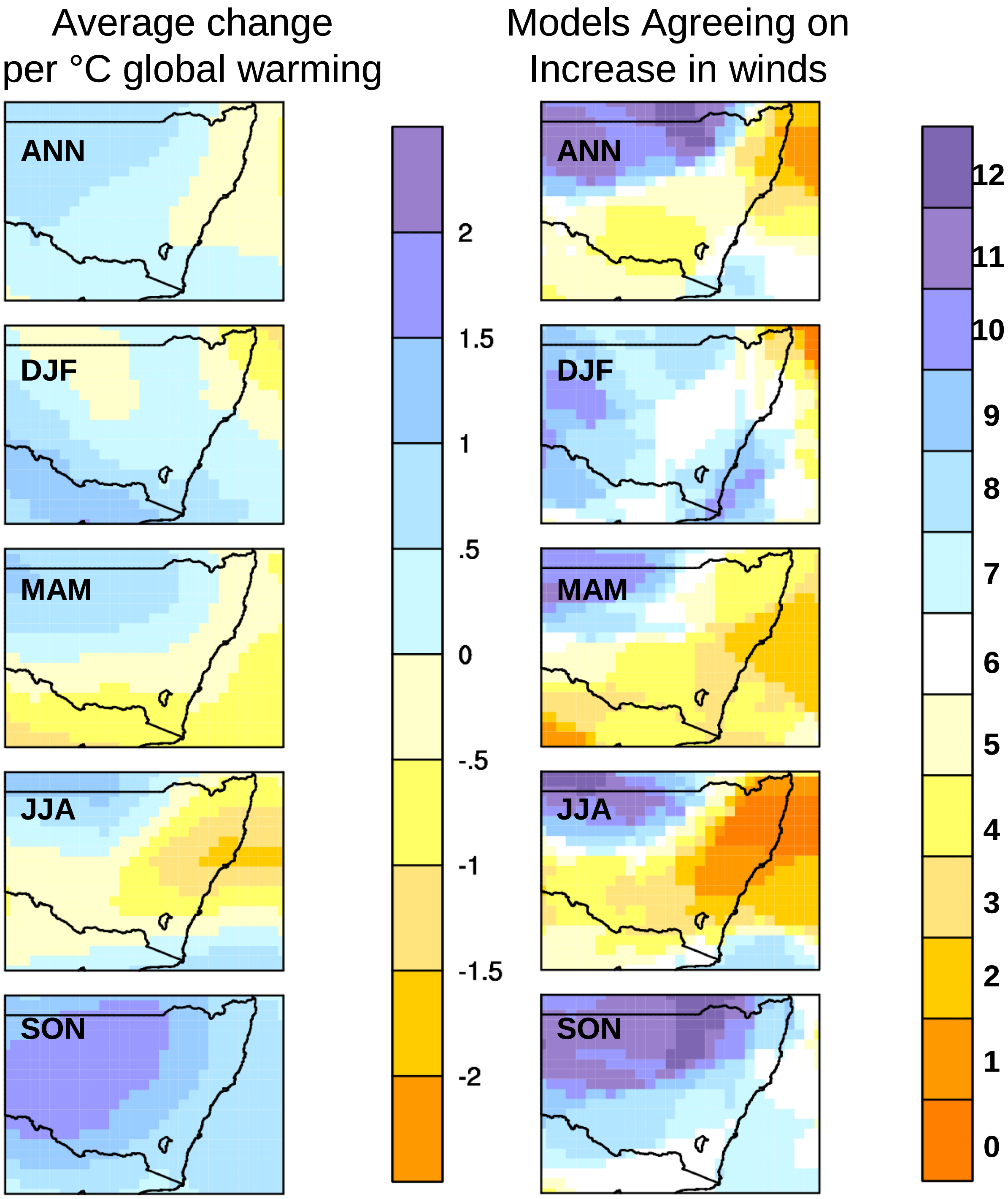

Figure 5.4. Left panels: The change in mean wind speed derived by averaging the twelve model results. Units are % change per °C of global warming. Right panels: The number of models agreeing on an increase in winds. The scale can be reversed to indicate the number of models agreeing on a decrease in winds. ANN = annual, DJF = summer, MAM = autumn, JJA = winter, SON = spring.

5.3.2 Extreme wind projections

Extreme wind was defined as the 95th percentile, i.e. the monthly wind–speed exceeded only 5% of the time. This was determined for each year by ranking monthly values in all of the months in a given season within a window of several years either side of the year of interest. For models in which only monthly averaged values of winds were available, a window of seven years centred on the year of interest was used (i.e. current year ± 3 years). This yielded 21 months that could be ranked, with the highest ranking season equating to the 95th percentile. Results were based on data from the same 12 climate models used above.

Projections for the 95th percentile wind-speeds are shown in Figure 5.5. As with the mean wind projections, the discussion of these projections will focus on the SRES scenarios for 2030 and 2070, acknowledging that changes in wind under the CO_2 stabilisation scenarios have smaller ranges of uncertainty.

During summer, much of the state, particularly to the southwest, experiences changes in extreme winds in the range -2.5 to +7.5% by 2030 and -8 to +24% by 2070, i.e. a bias toward increasing wind-speeds. Most of the coastal area and the northeast experiences changes that are relatively small and centred on 0%. Compared with the mean wind projections shown in Figure 5.3, extreme wind-speeds are biased toward increases over a larger portion of the state and the magnitude of the increase is greater.

In autumn, extreme wind-speeds are biased toward decreases across much of the state. In the northern coastal regions, the changes are projected to be in the range of -5 to +2.5% by 2030 and -16 to +8% by 2070. In southern coastal regions, the magnitude of the change is larger, in the range of -10 to +5% by 2030 and -32% to +16% by 2070.

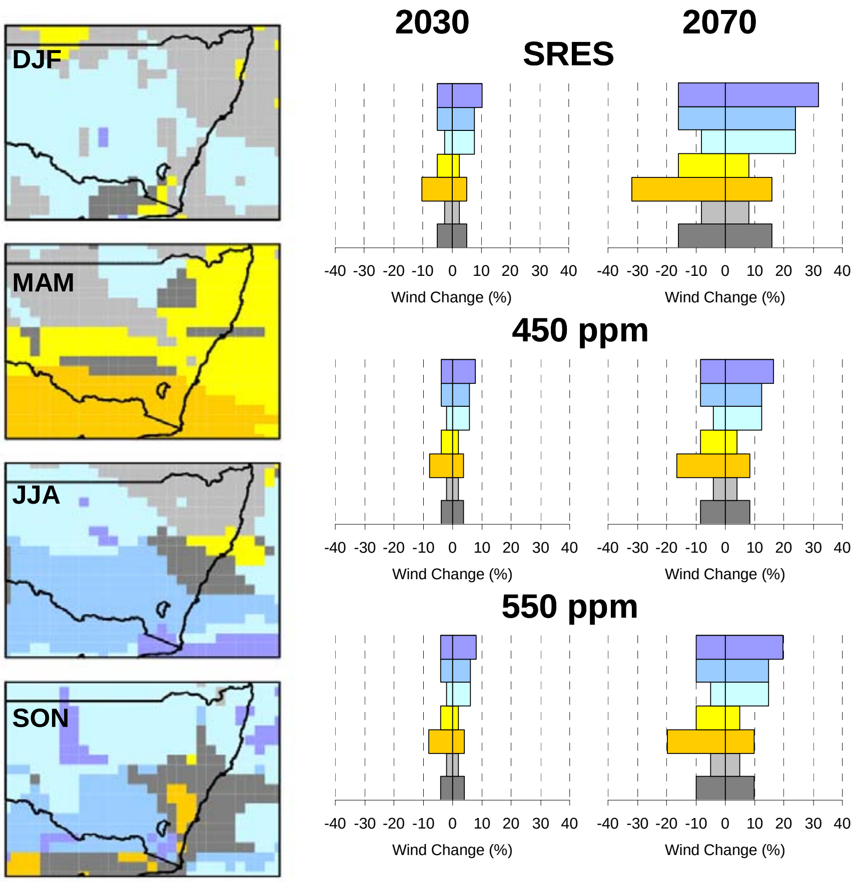

Figure 5.5. Ranges of change (%) in the 95th percentile of monthly near-surface wind-speed for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios. DJF = summer, MAM = autumn, JJA = winter, SON = spring.

In winter, there is a greater tendency toward extreme wind-speed increases across the state except in the far northeast where the direction of change is uncertain. In the southern half of the state, the changes are in the range -5 to +7.5% by 2030 and -16 to +24% by 2070. In the northwest, the range is -2.5 to +7.5% by 2030 and -8 to +24% by 2070.

The projections for spring also show a bias toward increases, with the range being -2.5 to +7.5% across much of the north by 2030 and -8 to +24% by 2070, while the south shows considerably greater variation in the direction of change.

Figure 5.6 shows the projected change in extreme wind-speed based on the average of all 12 models. This represents a simplified version of Figure 5.5, with the effect of differences between models removed and all changes scaled to a percent change per degree of global warming. In summer, much of the state, except the extreme northeast, shows increasing winds of up to 1.5% per °C of global warming towards the southwest of the state. Autumn extreme winds decrease across most of the state, except in the northwest. In winter, extreme winds increase in the west and decrease in the east, but the decreases are less marked than was seen for the mean winds in Figure 5.4. In spring, most of the state undergoes an increase in extreme winds, reaching more than 2% per °C of global warming in the northwest.

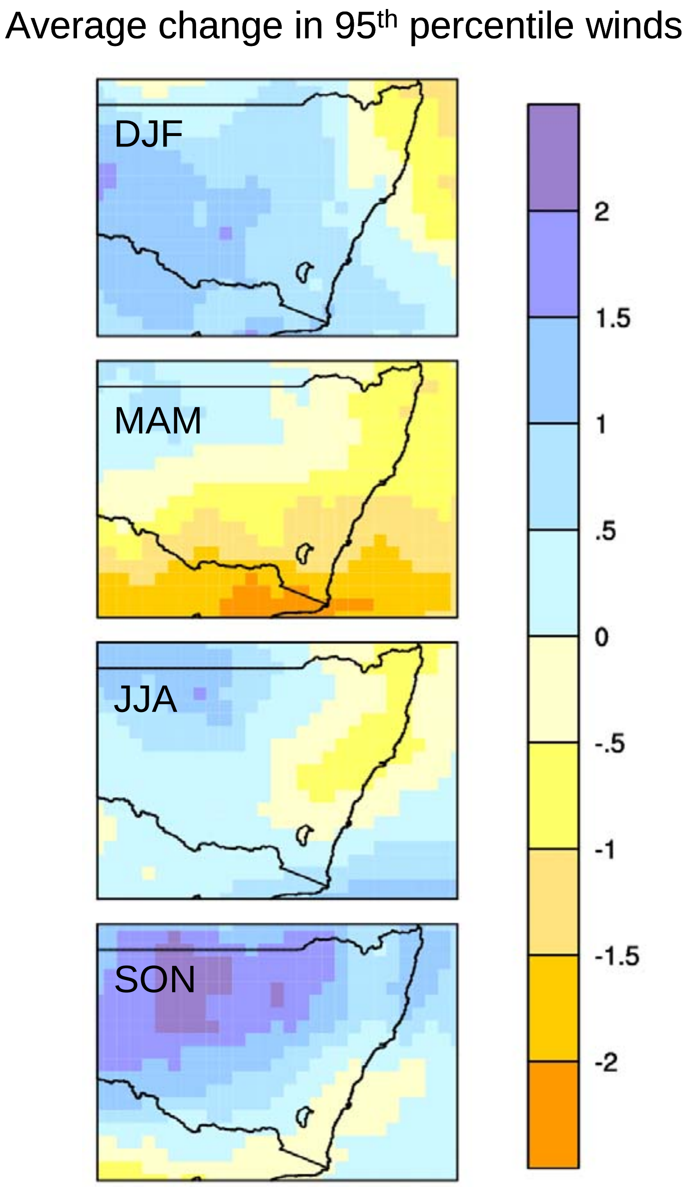

Figure 5.6. The change in the 95th percentile of monthly wind speed derived by averaging the 12 models results. Units are % change per °C of global warming.

5.3.3 Summary

Mean wind-speed projections show a tendency for increases across much of the state in summer, with decreases in the north-east. In autumn, there is a tendency toward weaker winds in the south and east, and stronger winds in the north-west. The tendency in winter is toward increases in the far north-west and south and decreases elsewhere. A tendency for stronger winds is evident in spring, with greatest increases across central NSW.

Projected changes in extreme monthly winds (strongest 5%) showed similar patterns to the mean wind-speed changes in summer and autumn, except that the magnitude of the increases and decreases tended to be larger. However, it should be noted that these larger increases mostly occur over the continent where wind-speeds are lower due to higher surface friction, and this leads to larger percentage changes in wind-speed. In winter, changes in extreme winds differed from changes in mean winds in that most of the state and the ocean in the south showed a tendency for increasing extreme winds with only the north-east indicating decreasing winds. In spring, extreme winds tended to increase, in agreement with the mean wind speed changes except in a small area on the southern half of the coast where there was a tendency towards decreasing extreme winds.

6. Extreme weather patterns

The extreme rain and wind events described in previous chapters are associated with extreme weather patterns. The performance of CSIRO's Mark3 and CC50 climate models has been validated against observations regarding the types of weather patterns most conducive to extreme weather in the NSW coastal zone. Changes to the dominant synoptic events by 2030 and 2070 are then investigated.

6.1 Data

The observed data used for the analysis of synoptic weather events along the NSW coast is the National Centers for Environmental Prediction (NCEP) reanalysis data set. The NCEP re-analyses consist of the output of a global weather prediction model into which all available global weather observations throughout the simulation period have been assimilated. The output of the model is therefore dominated by the observations over the regions for which observations are available and provides a dynamically consistent representation of the weather conditions in data-sparse parts of the globe. The near-surface (10 metres above ground) winds from this data set are available in a gridded format at a horizontal resolution of approximately 200 km every six hours from 1958 to the present.

The climate models used in this study are the CSIRO Mark3 and CC50 global climate models. Mark3 has been used to simulate the climate from 1961 to 2100 under an SRES A2 greenhouse gas emission scenario. It has a horizontal resolution of approximately 200 km and has 18 levels in the atmosphere and 30 levels in the ocean. Winds and rainfall from this model have been archived at coarser resolution and were available once daily over a 400 km grid. The CC50 atmospheric model was driven by boundary conditions from the CSIRO Mark2 global ocean-atmosphere model under an SRES A2 emission scenario from 1961 to 2100. CC50 resolution over Australia is approximately 50 km.

Extreme events were defined as the wind values falling in the top 1% of values for the particular model or data set used. The upper percentile winds were used since the magnitude of the extreme winds in model simulations is resolution dependent. The coarser the resolution of the model, the lower the wind speed is likely to be for a given synoptic weather situation. For example, the small scales and severe intensities of tropical or east coast cyclones cannot be captured by the Mark3 model, although it can capture the broader synoptic features associated with the cyclone. The winds that occur in conjunction with the system will nevertheless be extreme in a comparative sense to other synoptic weather situations produced by the model.

The selection of extreme wind days was undertaken on a seasonal basis. In other words, over the 40-year period from 1961-2000, the winds at each grid point over the months comprising the season were pooled, sorted and ranked, and the top 1% of winds (i.e. approximately the top 36 values depending on the season) and their associated dates were stored. Alternatively, the top 1% of values to occur in the year could have been selected, however, it was decided that this would lead to a much smaller number of events occurring during some seasons where climatic conditions are calmer. However, the sensitivity of the event selection process to the subsequent synoptic classification procedure warrants further investigation, which is beyond the scope of the present study.

The dates on which the extreme winds occur are then extracted over a region of interest, pooled and sorted into a list of extreme wind events. For events effecting winds along the NSW coast, the selected region of interest was chosen to span latitudes 28°S to 39°S and longitudes 150°E to 158°E. Depending on the resolution of the model, the number of events selected from this region differed. Figure 6.1 shows the placement of the grid-points in the NCEP re-analyses and the Mark3 model that fall within the region of interest, with 20 grid-points for NCEP and nine grid points for Mark3. The CC50 model with its finer spatial resolution had 165 grid-points located in the region. Although this means that potentially the CC50 model can contribute a significantly larger pool of extreme wind events for synoptic classification (165 grid-points x 36 values per season), in reality, the spatial scale of the synoptic systems that often cause extreme winds usually means that large numbers of grid-points register extreme winds on the same date, so the difference in the number of events selected for the different models is not as large as might be expected. For example, the number of events (i.e. dates) selected for synoptic typing in the CC50 model was only between 50 and 60% higher than Mark3 despite there being more than 18 times the number of grid-points in the region.

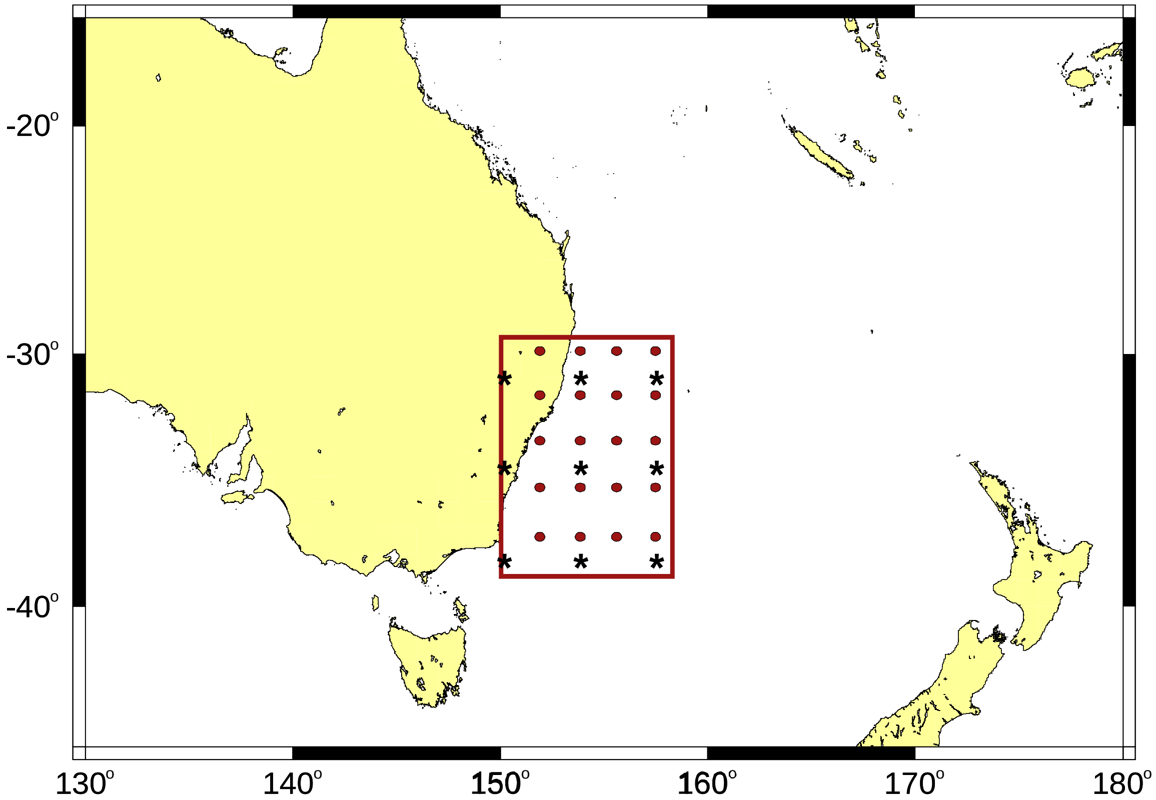

Figure 6.1. The region from which wind extremes from the NCEP re-analyses (observations) and the CSIRO Mark3 climate model were analysed. Circles indicate NCEP points and asterixes indicate Mark3 model points.

Once the set of events was selected, mean sea level pressure (MSLP) data from the NCEP dataset are used to characterise the synoptic scale weather systems that occurred on the extreme wind days identified in the study region over the 1961 to 2000 period. The synoptic classification was carried out over two half-year periods; the summer half-year from November to April, and the winter half-year from May to October. The region over which the synoptic typing was carried out covered a broader region than that over which extreme wind days were extracted, encompassing 25-45°S and 145-165°E. The number of days synoptically typed in the NCEP data was 362 days for summer and 429 days for winter. The extreme wind days in the Mark3 and CC50 models were extracted over three 40-year periods; 1961 to 2000, 2011 to 2050 and 2051 to 2090 representing present, 2030 and 2070 climates respectively. The MSLP maps for each of the dates extracted in the models were then correlated against the key synoptic types found in the analyses. This enabled an assessment of how well the climate model represented the synoptic situations responsible for extreme wind conditions and whether the frequency of the synoptic situations changed with global warming. The synoptic typing technique is a correlation-based, gridded map-typing technique following the method of Yarnal (1993) (see Appendix C for further details).

6.2 Observed extreme wind events

In this section, the results of synoptic typing procedure in the NCEP reanalysis data are presented and discussed. The correlation-based classification procedure for the observed extreme wind days was applied to two half year intervals. Table 6.1 provides a description of each of the synoptic patterns and the percentages of each type for the summer and winter half-years.

Table 6.1: A description of the main synoptic weather events associated with extreme wind days over the summer and winter half-years in the vicinity of the NSW coast. The percentage of the total number of days in which the particular synoptic type is observed is also given.

Type	Name	Description of synoptic event and coastal winds	Obs (NCEP) % of days	
			Summer	Winter
1	Tasman High	Ridge of high pressure to the south of continent or southern Tasman Sea. Coastal winds south-easterly to north-easterly depending on position of ridge.	40	10
2	Front	Front or trough situated over south-eastern Australia or further eastwards over the Tasman. Pre-frontal winds NW shifting progressively SW through S to SE as front passes and moves east	22	31
3	Tasman Low (not cut-off)	Low situated in Tasman to east or southeast, winds SSW to SSE	15	30
4	Cut-off low	Low centre situated in Tasman with winds southerly along coast or south-easterly depending how far to the east the low is situated	17	28
5	Tropical low	Low centre situated further north along NSW coast. Winds SE affecting mainly north of coast	1	0
	Un-classified		5	3

For the summer half-year, 12 distinct synoptic patterns were identified from the MSLP patterns on which extreme winds occurred. Of these, the synoptic classification was further simplified by combining some synoptic patterns into a single class of event as summarized in Table 6.1. This was because some of the patterns were similar but displaced relative to each other, as might be expected for a mobile system such as a cold front which moves progressively eastwards with time. In the winter half-year, 11 synoptic patterns were identified. They were similar to those identified for the summer half-year except that the percentages of each type were different. The only pattern that was present in summer but absent in winter was type 5. Figure 6.2 illustrates a selection of the patterns identified by the synoptic classification scheme. Each generic pattern is created by compositing all MSLP patterns that were identified as being of similar type. Note that while the Figure 6.2 examples were selected from the summer patterns, the winter patterns showed strong similarity to the equivalent summer patterns.

Synoptic type 1 in Table 6.1 is shown in Figure 6.2a and consists of a ridge of high pressure to the south of the continent or southern Tasman Sea. A depression (low pressure) often occurs to the north, strengthening the pressure gradient in NSW latitudes. The coastal winds are mainly easterly varying from NE to SE depending on the location of the ridge. This class of synoptic event accounted for 40% of extreme wind days in summer and 10% of extreme wind days in winter in the NCEP re-analyses.

Synoptic type 2 consisted of a frontal type pattern traversing the south of the continent and moving into the Tasman Sea, with winds on the NSW coast varying from pre-frontal north-westerlies through to post-frontal winds ranging from south-westerlies through to south-easterlies depending on the position of the front. They accounted for 22% of extreme wind days in summer and 31% of extreme wind days in winter. Examples of this synoptic type at different stages of progression are shown in Figure 6.2b. The remaining synoptic types are low pressure systems. Type 3 is a typical mid-latitude depression, type 4 a cut-off low in which the low is cut-off from the westerlies to the south by a ridge of high pressure, and type 5 is a low with tropical origins. Tasman lows accounted for 15% of severe wind days in summer and 30% of severe wind days in winter, and cut-off lows accounted for 17% of summer severe wind days and 28% of winter severe wind days. Lows originating from further north only occurred in summer and accounted for only 1% of extreme wind days. These three types are illustrated in Figures 6.2c-e.

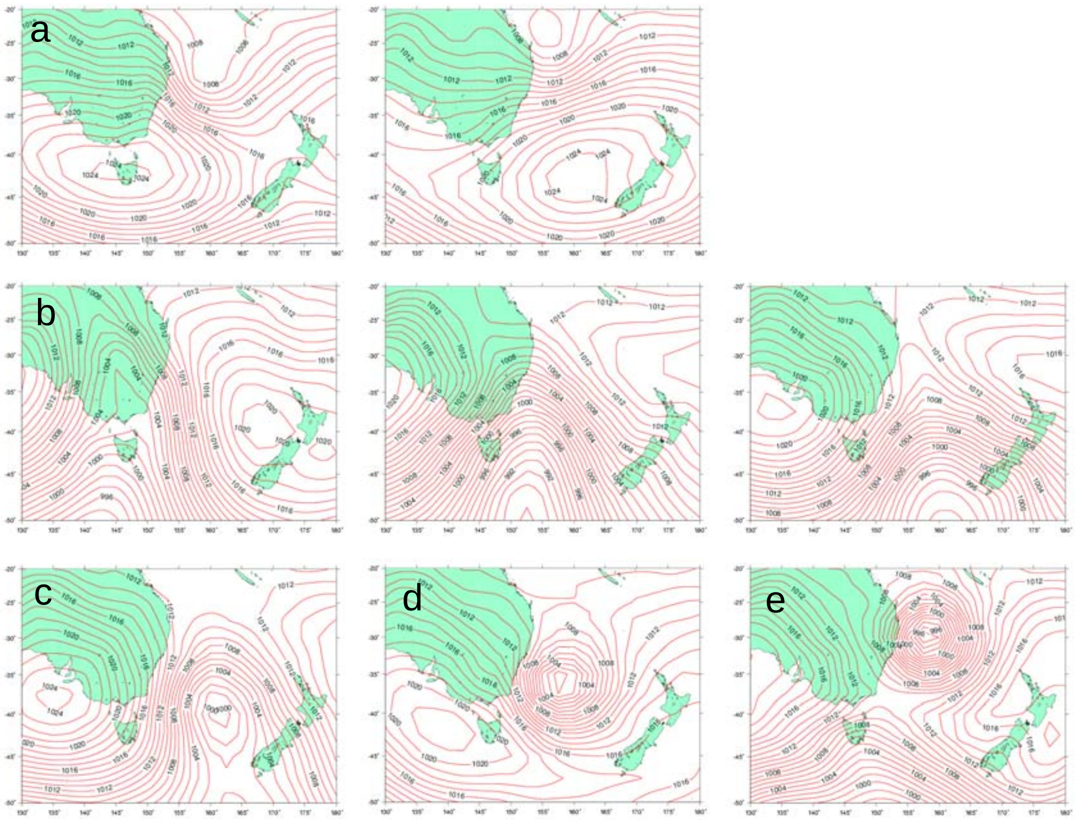

Figure 6.2. Examples of synoptic types from the summer half-year for (a) type 1, Tasman high with the ridge located at different positions relative to the NSW coast, (b) type 2, cold front at different stages of progression across south-east Australia, (c) type 3, Tasman high, (d) type 4, Cut-off low and (e) type 5, tropical low.

The synoptic types identified in this study are compared with a previous study by PWD (1985), in which six synoptic situations leading to extreme sea levels along the NSW coast were identified from manually drawn synoptic charts as follows:

- Highs;
- Easterly trough lows;
- Inland trough lows;
- Continental lows;
- Tropical cyclone;
- Secondary lows.

The larger number of synoptic classes, particularly in relation to lows, comes about because of the strong focus on the formation mechanisms and locations of the storm systems compared to the present study where the synoptic pattern only at the time of extreme winds was analysed. The anticyclones were similar to the type 1 systems identified in the present study. Easterly trough lows developed in an easterly trough situated at the coast, while inland trough lows formed over inland Australia and moved to the coast. Continental lows formed between anticyclones over the Indian Ocean or the Bight. By the time they reached the east coast, the surface synoptic patterns of the three classes were somewhat similar to each other and to the type 4 cut-off low systems identified in the present study. However, the location of the low was generally closer to the coast in the PWD study and the spatial scale of the low pressure system was sometimes of smaller scale. A reason for this result may lie in the fact that the present study utilised gridded analyses at a fairly low horizontal resolution and may fail to identify particularly small scale intense systems situated at the coast. Secondary lows were intense small scale lows that developed in association with larger eastward moving depressions in the southern Tasman. The larger southern depressions were excluded from the study unless they were intense enough to generate significant wave heights in excess of 2.5m. Frontal systems were ignored in the PWD study because the orientation of the winds was not considered to be conducive to elevated sea levels along the east coast.

6.3 Representation of extreme weather patterns in CSIRO climate models

The performance of the CSIRO Mark3 and CC50 models was assessed in terms of their ability to represent the main synoptic types identified in the NCEP re-analyses under present climate conditions. This was accomplished by correlating synoptic patterns from the model simulation against each of the patterns identified in the NCEP re-analyses for the particular half-year. A good correlation coefficient was 0.7 or greater. The results are presented in Table 6.2.

The Mark3 model performed poorly during the summer half-year because it significantly underestimated the number of Tasman highs (type 1) and the number of lows that were not cut-off (type 3). On the other hand, it overestimated the patterns associated with frontal passage (type 2) and cut-off lows (type 4). In the winter half-year, synoptic types 2 and 3 consisting of fronts and Tasman lows were underestimated while Tasman Highs were significantly overestimated.

The reasons for this result were investigated by carrying out the synoptic typing on the Mark3 maps themselves and comparing these with the synoptic maps for the NCEP re-analyses. During the summer half-year, Mark3 overestimates frontal situations while significantly underestimating all other synoptic types. In the winter half-year, Mark3 performs better with respect to Tasman lows but still dramatically underestimates Tasman highs and cut-off lows. The underestimated types consist of all of the situations that produce onshore to southerly winds to the east coast and therefore potentially hazardous ocean conditions. In both half-years, 33% of extreme wind days in Mark3 did not correlate with the key synoptic patterns associated with extreme winds in the analyses.

Table 6.2: The representation of synoptic types associated with extreme wind days in the Mark3 and CC50 models in summer and winter half-years during the period 1961-2000.

Type	Name	Summer half-year			Winter half-year		
		Obs (NCEP) %	Mark3 %	CC50 %	Obs NCEP) %	Mark3 %	CC50 %
1	Tasman High	40	16	13	10	4	14
2	Frontal	22	45	53	31	40	25
3	Tasman Low (not cut-off)	15	4	19	30	24	26
4	Cut-off low	17	4	5	28	1	26
5	Tropical low	1	0	1	0	0	0
	Unclassified	5	33	17	3	33	10

When synoptic classification was undertaken on the summer half-year Mark3 extreme wind day synoptic patterns themselves (rather than correlating them against the NCEP reanalyses), it was found that about 84% of the patterns that emerged consisted of patterns of high and low pressure at various stages of progression across the east of the continent and the Tasman Sea. These were similar to those illustrated in Figures 6.2a and 6.2b. The main difference was a tendency for the high to be located slightly further north than the observations which would account for the relatively large number of events to be unclassified when compared with the NCEP observations for which the high tends to be situated further south.

In the winter half-year, when the high is situated further north over the continent, the Mark3 model again tends to have a narrower high situated further north than the observations and the isobars to the south of the continent were particularly zonal (i.e. aligned in an east-west direction), indicating that strong westerlies were a major source of extreme winds in the Mark3 model. Figure 6.3 compares some examples of the winter half-year synoptic patterns obtained from the Mark3 model with those from the observations. The pattern in Figure 6.3a accounted for 59% of Mark3 wintertime extreme wind days but had no analogue in the observations. It illustrates the zonal orientation of the isobars to the south of the continent and therefore the high frequency of westerly winds.

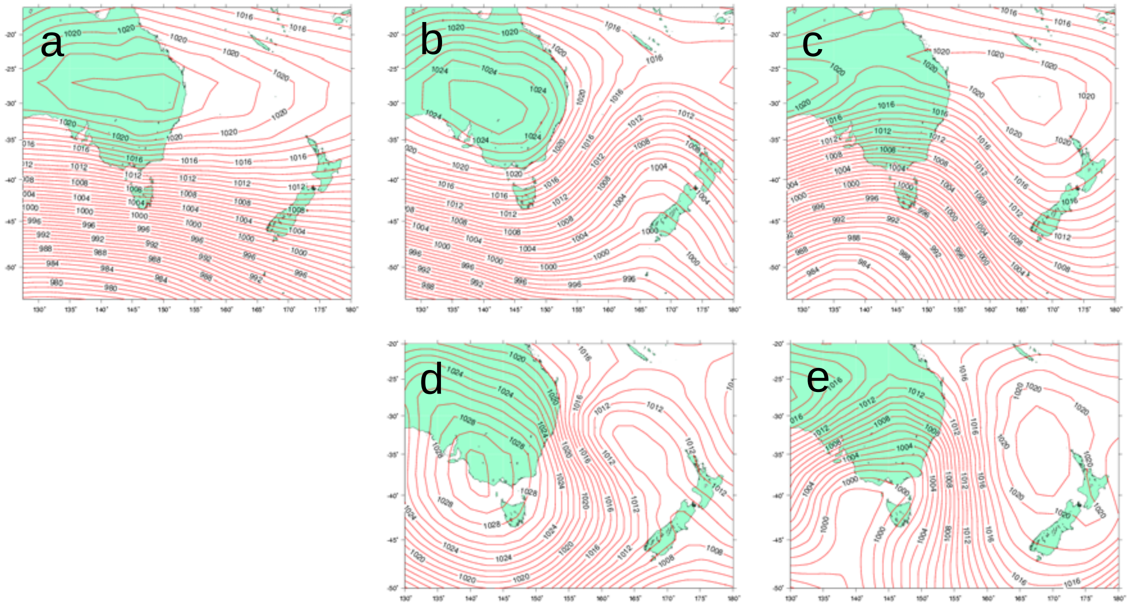

Figure 6.3. (a) the dominant synoptic pattern identified in the Mark3 model accounting for 59% of winter half-year extreme wind days; (b) and (c), two other synoptic classes in Mark 3 which are similar to two patterns identified in the observations (d) and (e) but high-lighting the tendency in Mark 3 for patterns to be more zonal in structure and for the anti-cyclones to be situated further to the north.

Figures 6.3b and 6.3c show weather patterns from the Mark3 model that are similar to two of the patterns identified in the NCEP observations shown in Figures 6.3d and e. However, the Mark3 model situates the high further to the north and again there is less structure in the isobars to the south of the continent.

One contributing factor in the performance of the Mark3 model is a bias in the sea surface temperature (SST) patterns which results in temperatures that are up to 3°C too cool off the east coast of Australia and up to 3°C too warm in the southern ocean to the south of Australia. This bias in temperatures arises from the coupling of the ocean model to the atmospheric model via temperature and momentum fluxes. Small discrepancies in the fluxes that are exchanged between the ocean and atmosphere can produce large discrepancies in SSTs. Many climate models apply a flux correction to avoid such a bias although the argument against doing this is that the correction may constrain the response of the coupled model to enhanced greenhouse forcing. The goal of the modelling community is to improve the coupling between ocean and atmospheric models so that flux correction is not necessary.

In relation to the Mark3 model performance in the east Australian region, the presence of a cool bias is likely to suppress the intensification of low pressure systems travelling across the region and possibly even suppress the formation of intense cut-off lows. Modelling and observational studies have established a strong relationship between warm SSTs off the east coast and the formation of intense east coast low pressure systems (e.g. McInnes and Hess, 1992; McInnes *et al.*, 1992; Lynch, 1988; Hess, 1990; Holland *et al.*, 1987; Leslie *et al.*, 1987). It is therefore not surprising that most of the extreme wind days in the model in this region are made up of a smaller proportion of intense low pressure systems off the east coast and that other systems such as fronts are making up a larger percentage of the extreme wind days.

As with the Mark3 model, the CC50 model also produces a large percentage of frontal events during the summer half-year while Tasman highs and cut-off lows that are associated with extreme winds are produced in smaller numbers than found in the observations (Table 6.2). Overall, however the CC50 model performs better than Mark3 in that only 17% of events cannot be classified against the synoptic types identified in the observations. In the winter half-year, the CC50 model performs extremely well. The ratios of the different classes of system are close to those found in the observations and only 10% of synoptic types were not classified against the observations.

6.4 Impact of climate change

The CC50 model demonstrated superior performance in representing observed weather patterns associated with extreme wind days. Therefore, only this model will be considered under enhanced greenhouse conditions. The results of the synoptic typing for the 2030 and 2070 climates are presented in Table 6.3.

During the summer half-year, slight decreases occurred in the numbers of type 1 events with a decrease from 13% to 9% by 2070. Since about 625 days were synoptically typed in 40-year period centred on 2070, this amounts to about 25 fewer of type 1 events contributing to the top 1% of wind conditions in the 40-year period. This could mean either a reduction of the intensity or frequency of these events. The numbers of type 3 events dropped from 19% to 9% by 2070 which amounts to about 63 fewer events over the 40-year period or reduction of between 1 and 2 events per year. Again this could mean a decrease in the intensity of Tasman lows so that fewer are registering in the top 1% of wind days or a reduction in frequency of events. Changes in the other types of events were generally small and showed no clear trend.

In the winter half-year, type 2 and 3 events showed an increase while the other types were largely unchanged. The type 2 events increased by 4% by 2070. Since about 690 days were synoptically typed in the 40-year period centred on 2070, a 4% increase amounts to about 28 more events over the 40-year period or an extra event every 1 to 2 years by 2070. For the type 3 events, a 5% increase amounts to almost one extra Tasman low pressure system each year by 2070. Cut-off lows increased marginally from 26% to 27% which amounts to about six extra events occurring over the forty year period. These results may occur either because the lows are becoming more intense or more frequent. Previous analysis of the frequency of depressions in the Mark2 model (whose boundary conditions drive CC50) found that the number of low pressure systems off the east coast of Australia increased although the increases were generally associated with the number of weaker systems. However examination of the most extreme events showed that these too were intensified (Whetton *et al.*, 2002). The analysis conducted here is focussed only on the extreme events and is consistent with this earlier result.

Table 6.3: The representation of synoptic types associated with extreme wind days in the Mark 3 and CC50 models in the summer and winter half-years, for 40 years centred on present, 2030 and 2070.

Type	Name	Summer			Winter		
		CC50 Present %	CC50 2030 %	CC50 2070 %	CC50 Present %	CC50 2030 %	CC50 2070 %
1	Tasman High	13	11	9	14	13	13
2	Frontal	53	53	56	25	24	29
3	Tasman Low (not cut-off)	19	11	9	26	28	31
4	Cut-off low	5	7	6	26	27	27
5	Tropical low	1	0	1	0	0	0
	Unclassified	17	18	19	10	9	7

6.5 Conclusions and future work

In this section, a new approach has been developed to examine the performance of climate models in terms of their ability to realistically represent the variety and frequency of synoptic weather patterns contributing to extreme wind events. This approach has also been used to examine how such events may change under enhanced greenhouse conditions. It combines an event selection procedure with a synoptic typing procedure and provides a useful method for extracting information about the specific types of synoptic weather situations associated with extremes of variables such as wind.

Assessment of CSIRO's Mark3 and CC50 models using this approach revealed that the Mark3 model does not adequately reproduce the key weather patterns that are responsible for extreme winds. It was postulated that a cool bias in SSTs off the east coast of Australia in that model may have contributed to this result. CC50 on the other hand represented the main weather patterns much more realistically, particularly in the winter half-year. Therefore, this model was used to examine how the patterns may change under enhanced greenhouse conditions.

During the summer half-year, the frequency of Tasman lows that contribute to extreme wind days decreased from 19% at present to only 9% by the year 2070. The frequency of Tasman highs also decreased from 13% at present to 9% by 2070. Frontal system frequency increased slightly by 2070 and the number of unclassified systems increased by 2%. In the winter half-year, Tasman Lows contributing to extreme winds increased in frequency from 26% at present to 31% by 2070. Frontal systems also increased from 25% of extreme wind days at present to 29% by 2070.

An increase in the frequency of a particular weather pattern may occur due to one or more of the following reasons:

- The weather pattern is becoming more frequent overall with no change in the shape of the frequency distribution, so that a higher frequency of severe examples of the weather pattern occur
- The intensity of the weather pattern is increasing while the frequency remains uniform so that the shape of the distribution changes to increase the proportion of events exceeding the extreme wind threshold
- Other weather systems may be weakening or becoming less frequent so that they are failing to satisfy the extreme wind threshold, thereby enabling a greater number of a different weather pattern to satisfy the selection criteria.

Further analysis of the different weather patterns identified by the synoptic typing procedure would be required to address the reasons for the changing proportions of weather types under enhanced greenhouse conditions. While it is beyond the scope of the present study to do this, it is useful to interpret the results in terms of the extreme wind changes projected by the CC50 model. Figure 6.4 shows the change in 95^{th} percentile wind-speed for summer and winter in CC50.

In summer (Figure 6.4a), winds are generally decreasing in magnitude except for a region between latitudes 40 and 45°S and to the east of Tasmania. The region of decreasing winds off the east coast between 30 and 40°S is consistent with weakening of the pressure gradients associated with the Tasman high event, and therefore a reduction in the frequency of this event causing extreme winds in the enhanced greenhouse climate. The tendency toward weaker winds in the Tasman is consistent with a reduction in frequency of this type of event contributing to extreme wind days.

In winter (Figure 6.4b), there is a wedge of increasing 95^{th} percentile winds adjacent to the east coast and extending southwards. Elsewhere decreases in extreme winds are indicated. This pattern of change is consistent with an intensification of Tasman low systems which would result in stronger pressure gradients on the northwest side of the low and stronger winds. Similarly intensification of frontal systems would lead to stronger pressure gradients to the west of the front and stronger associated winds. For cut-off lows, the synoptic typing for winter identified four synoptic maps which differed mainly in the location of the low pressure centre (the positions are indicated by dots in Figure 6.4b). Clearly, the locations of the lows occur in regions of increasing winds and decreasing winds. Presumably the changing wind patterns would favour a tendency for more intense cut-off lows located further south and closer to the coast and weaker lows elsewhere.

Finally, the results presented here are based on a single model simulation. It would be preferable to consider the results of additional model simulations to establish how general the findings are and to better quantify the range of possible change.

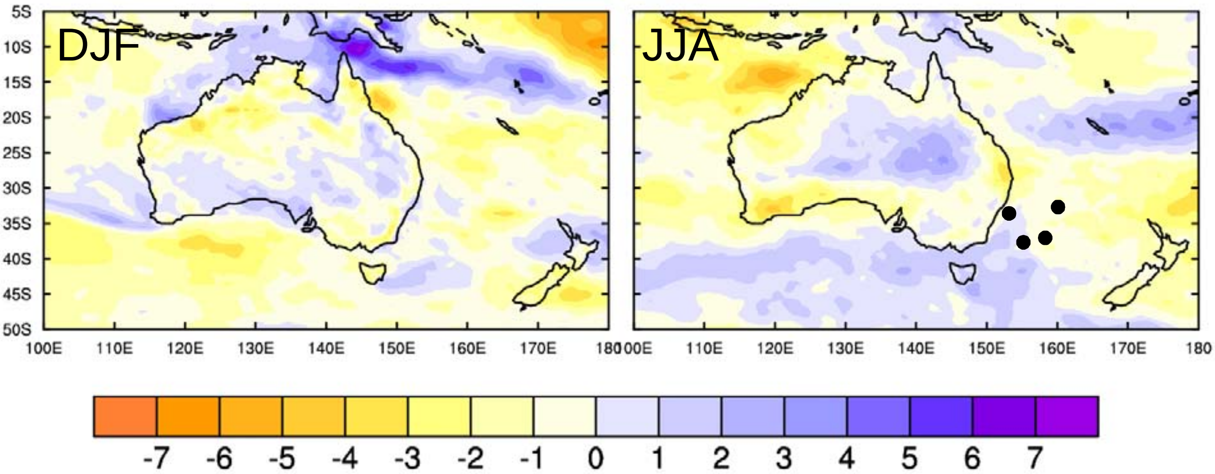

Figure 6.4. The 95th percentile wind speed change per degree of global warming for summer (DJF) and winter (JJA) in the CC50 model. Units are % per degree of global warming. Black dots in (b) indicate low pressure centres of cut-off lows.

7. Storm surges

This chapter provides a discussion of the results of chapters 5 and 6 in relation to the likely effect of climate change on storm tides on the NSW coast. Where results are inconclusive, additional studies are outlined that may help to clarify the results.

7.1 Components of storm surges

Severe storms can produce temporary increases in sea-surface height. These increases may occur as a result of several different mechanisms such as wind setup, inverse barometer effect, current setup, wave setup and wave run-up. Falling atmospheric pressure produces an increase in sea level at the rate of 1 cm per hPa fall in pressure and is known as the inverse barometer effect or barometric setup. Winds exert a drag on the ocean surface which induces an ocean current in the same direction. Wind setup occurs when winds are directed towards the shore and the induced currents encounter shallow coastal waters, the friction of the ocean floor slows the currents and coastal sea levels increase as a result. When winds are directed alongshore and are sustained for more than a day, the Earth's rotation produces a deflection of the currents to the left (right) in the southern (northern) hemisphere. If the coast lies in the path of the deflected flow an increase in coastal sea levels occurs, which is known as current setup.

Winds also produce ocean waves. As the waves move progressively into shallower water, they break and lose energy. Some of this energy is transferred into a shoreward momentum flux which acts to raise the mean sea level close into shore. This sea level increase is called wave setup and typically ranges from about 10 to 15% of the deep water significant wave height where the significant wave height is, by definition, the average height of the top one third of waves occurring at a particular deep water location (WMO, 1988). Wave run-up is the maximum inland point reached by a wave when it breaks at the shore. These various effects are illustrated in Figure 7.1.

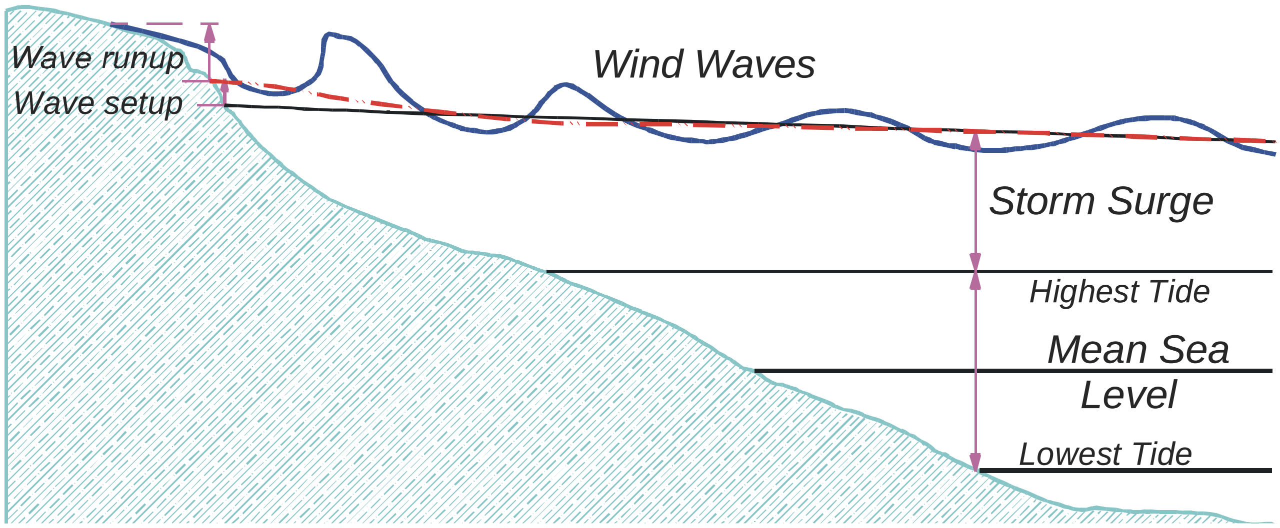

Figure 7.1: Diagram illustrating the contributions to sea level due to tides, storm surge and wind-generated waves.

While wind and pressure are responsible for generating sea level extremes, other factors such as coastal geometry and the presence and width of the continental shelf play a crucial role in determining the relative contribution by waves and storm surge. Wide shallow continental shelves favour large storm surges while narrow or non-existent continental shelves favour large waves. This is because waves steepen and break as they encounter shallow coastal waters. The wave breaking leads to loss of energy and loss of wave height. Conversely, deeper waters lying adjacent to coastlines enable waves to travel closer into shore before finally breaking. These two situations are illustrated in Figure 7.2.

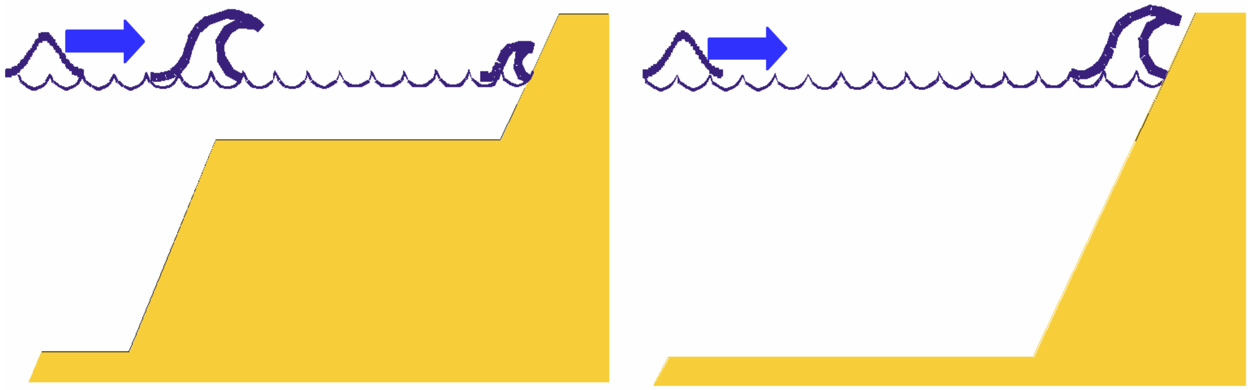

Figure 7.2: Illustration showing how shallow coastal waters (left) cause wave breaking and reduction of wave energy to occur further offshore while deeper coastal waters (right) allow higher energy waves to reach the shore.

7.2 Causes of extreme sea levels along the NSW coast

The NSW coast features a relatively narrow continental shelf of between 30 and 50 km. This means that storm surge magnitudes will be limited. Typically the magnitude of the storm surge is the sum of the inverse barometer effect and either wind or current setup, and is in the range of 0.3 to 0.6 metres (Table 7.1). The magnitude of the wave effects is in the range of 4.0 to 8.1 metres, with wave-breaking being the largest contribution to sea level extremes.

Table 7.1: Typical magnitudes of the contributions to sea level extremes on the NSW coast based on MHL (1992) and McInnes and Hubbert (2001).

	Component	Typical Range (metres)
Storm Surge	Barometric setup	0.2 – 0.4
	Wind setup	0.1 – 0.2
	Current setup	0.1 – 0.2
Waves	Wave setup	0.7 – 1.5
	Wave breaking and run-up	3.0 – 6.0

Storm surges occur as a result of localized wind and pressure conditions. Ocean waves on the other hand can be produced by local storms or remote systems since waves in deep water can travel thousands of kilometers from their point of origin with little loss of energy arriving at the coast as swell.

Wave-breaking is a transient effect of storm conditions, whereas wave setup produces a temporary increase in still water conditions close to the coast and therefore can be considered to contribute to the overall inundation produced by the storms along with the surge and tide components. However, the relative contributions of storm surge and wave setup along the NSW coast are not fully understood. Wave setup makes a significant contribution to elevated sea levels recorded along the NSW coast. This is supported by analysis of sea levels recorded at tide gauges along NSW and modeling undertaken by McInnes and Hubbert (2001) using a coastal ocean model (Hubbert *et al.*, 1990; Hubbert and McInnes, 1999) and a one dimensional wave setup model. However, measurements undertaken by Hanslow and Neilsen (1992; 1993) do not find evidence of wave setup influencing sea levels within river systems. This led McInnes and Hubbert

(2001) to suggest that in severe storms, down-gradient flow produced by extreme sea levels at the coast may be a possible mechanism whereby wave setup could influence sea levels recorded at sheltered tide gauges.

Based on a study by Short and Trenaman (1990), the total annual wave climate for the central coastal region of NSW is made up of waves originating from the northeast (17%), east (42%) and southeast (41%). Northeast waves occur predominantly in summer, are of relatively low amplitude (1.25 metres) and have relatively short wave periods (7-8 seconds). Easterly waves occur year round with peaks in March and November and amplitudes predominantly 1.5 metres high (but reaching 3 metres on occasion) with a 9 second period. Southeast waves have a broader spectrum of wave heights reaching summer and winter maxima of 4 metres. Five dominant weather systems were identified as contributing significantly to the overall wave climate in this region. These were tropical cyclones, east coast lows, mid-latitude cyclones, anticyclones and sea breezes.

The weather types identified in Chapter 6 can be related to their capacity to generate extreme sea levels on the NSW coast. Type 1, consisting of an anticyclone in the southern Tasman sea and strong onshore winds along much of the NSW coast, would be expected to generate adverse wave conditions but any storm surge effect would be minimal. Type 2, consisting of frontal systems traveling along the south coast, are generally associated with northwesterly winds ahead and southwesterly winds behind, the orientation of which is not conducive to extreme sea levels along the NSW coast. This weather system is commonly responsible for elevated sea levels along the south coast however (McInnes and Hubbert, 2003), and it is possible that some events could produce a sea level disturbance along the east coast due to the propagation of coastally trapped waves (e.g. Church and Freeland, 1986; Middleton, 1988). Synoptic type 3, consisting of a mobile low pressure system in the southern Tasman Sea, may generate swell that could impact upon the NSW coast. Type 4 systems or cut-off lows which, once formed, may persist just off the east coast for several days. McInnes and Hubbert (2001) found that these weather systems generate elevated sea levels along the NSW coast that had both a storm surge and wave setup component. The location of the centre of the low in relation to the coast determines where the greatest impact will be. The cases studied by McInnes and Hubbert (2001) had the low centred offshore and the storm surge was found to develop in the region of intense flow parallel to the coast, between the low and the coast (current setup). Clearly, when the low centre is actually at the coast, barometric setup and some wind setup to the south of the low would be expected. The mechanism for elevated sea levels from type 5, which occurred only in summer, would be similar.

7.3 Conclusions

The storm systems most conducive to elevated sea levels, through both storm surge and high waves along the NSW coast, are slow-moving low-pressure systems such as cut-off lows or lows of tropical origin that travel south along the NSW coast (PWD, 1991; MHL, 1992; McInnes and Hubbert, 2001). The remaining weather patterns also play a role in contributing to the wave climate of the east coast.

Cut-off lows contributing to the top one percent of wind speeds showed small increases in frequency in both summer and winter halves of the year. While the cause of the increase cannot be determined precisely in the present study, the spatial distribution of wind speed change in the model indicates that these systems may exacerbate extreme winds and sea levels along the southern half of the NSW coast.

The changes in frequencies of other weather patterns suggest a shift in wave climate with waves from the southeast becoming more prevalent and waves from the northeast and east becoming less prevalent. In summer this change comes about from a reduction in Tasman highs coupled with an increase in intense frontal systems. In winter, there is a smaller reduction in Tasman highs but larger increases in the numbers of intense winter fronts and Tasman lows. Based on the spatial pattern of change of extreme wind in the future, the increase in waves originating from the south would be expected to have greater impact on the southern half of NSW.

8. Risk assessment approaches

The conventional approach to impact and adaptation assessment has been to construct scenarios of climate change, then apply them to impact models to determine how impacts may change. Adaptations are then designed to manage those changes. While this approach is broadly predictive in its structure, the outcomes are contingent upon the input scenarios, so are limited by scenario uncertainty. An alternative is to apply risk assessment methods that utilise multiple scenarios. The conventional approach has also often neglected the relationship between current climate risks, vulnerability to those risks and adaptations developed to manage those risks. How society has coped in the past will influence how it copes in the future, even if future adaptation strategies are very different to those of today. Therefore, adaptation will be more successful if it manages both current and future climate risks, requiring an understanding of how climate-related risks may change over time.

8.1 Risk

Risk is a combination of two factors:
- The probability that an adverse event will occur,
- The consequences of that adverse event (USPCC RARM, 1997).

That combination can be expressed as:

Risk = probability $\times$ consequence

The probability of an adverse event can be expressed as the likelihood of a given climate hazard. The consequences of that adverse event are measured in social terms and can be characterised as vulnerability.

A hazard is *an event with the potential to cause harm*. Examples of climate hazards are tropical cyclones, droughts, floods, or conditions leading to an outbreak of disease-causing organisms (plant, animal or human). Vulnerability is measured by indicators such as monetary cost, human mortality, production costs, ecosystem damage or any other metric that is considered important. Climate risk assessment involves identification of the relevant climatic hazards, how often they will occur and what the resulting consequences may be. Although the details of a risk assessment will be specific to a particular project, there are two major pathways for assessing climate risk. One is the natural hazards-based approach that tests the effect of climate on society; the other is the vulnerability-based approach that begins with damages, then diagnoses the climatic conditions that contribute to particular levels of damage. These methods are complementary.

8.2 The coping range

Over time, societies have developed an understanding of climate variability in order to manage climate risk. People have learnt to modify their behaviour and their environment to take advantage of their local climatic conditions and reduce the harmful impacts of climate hazards. They have observed biophysical and socio-economic systems responding automatically to climate, and have tried to understand and manage these responses. This social learning is the basis of planned adaptation. *Planned adaptation* is undertaken by all societies, but the degree of application and the methods used vary from place to place. Modern societies rely most on science and government policy and traditional societies rely most on narrative traditions and local decision-making, but both approaches are based on a common structure.

This structure has a range of climate where the outcomes are beneficial, a range where the outcomes are negative but tolerable, and a range where the outcomes are harmful. Beneficial and tolerable outcomes form the *coping range* (Hewitt and Burton, 1971). Beyond that range, a society is said to be vulnerable. This structure is shown in Figure 8.1. The coping range is usually specific to an activity, group and/or sector, though society-wide coping ranges have been proposed by some researchers (Yohe and Tol, 2002).

Figure 8.1 illustrates a simple coping range using a time series of single variable under a stationary climate. If we imagine a cropping system represented by its response to a single variable e.g., temperature or rainfall, the greatest yields will be in the range to which that system is adapted. If conditions get too hot (wet) or cold (dry), then outcomes become negative. The response curve on the upper right shows a schematic relationship between climate and levels of profit and loss. Under normal circumstances, outcomes are positive but become negative in response to large extremes in variance. Using that response relationship, we can select criteria or indicators, for the purposes of assessing risk.

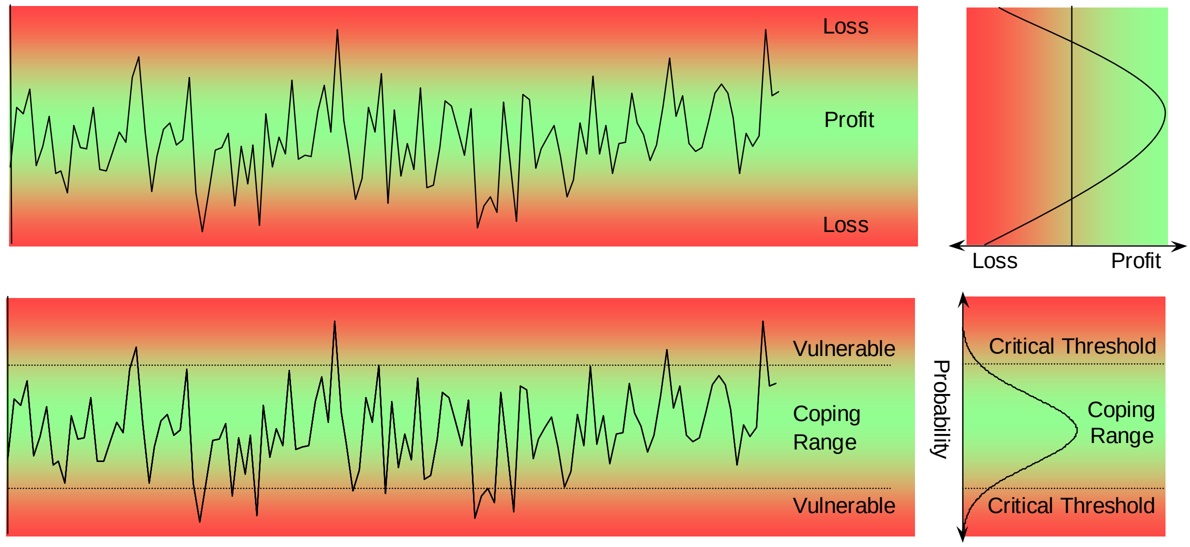

Figure 8.1. Simple schematic of a coping range under a stationary climate representing a driving variable such as rainfall or temperature and an output such as crop or water yield. Vulnerability is assumed not to change over time. The upper time series and chart shows a relationship between climate and profit and loss. The lower time series and chart shows the same time series divided into a coping range using critical thresholds to separate the coping range from a state of vulnerability. Source: McInnes et al (2002).

When climate impacts within a system can be quantified, a response relationship and one or more criteria representing different levels of performance can be constructed (Figure 8.1, lower left). For example a yield relationship can be divided into good, poor or disastrous outcomes. Other criteria may be decided on the ability to break even economically, or produce sufficient surplus to pay for next year's sowing, or in terms of water provide sufficient demand for a season. While farmers try to maximise their production, from experience they also know the consequences of not meeting such criteria. One way of deciding how the coping range is separated from the area of vulnerability, is to determine the critical threshold, which is defined as the *tolerable limit of harm*. Knowledge of the level of performance within a system allows us to set criteria, such as critical thresholds, and therefore to assess risk (Figure 8.1, lower right).

8.3 Assessing current climate risks

The most basic elements needed are a model of the system (a mental, or conceptual, model), and a basic knowledge of the hazards and vulnerabilities in order to prioritise risk. Both qualitative and quantitative methods can be used to assess risk depending on the quality of information needed by stakeholders and the data and knowledge available to provide that information.

8.3.1 Building conceptual models

The first step in an assessment is to establish an understanding of the important climate–society relationships within the system being investigated. Those relationships are dominated by the climate impacts within the system and the sensitivity of the system response. Climate sensitivity is defined as the degree to which a system is affected, either beneficially or adversely, by climate-related stimuli. The effect may be direct (e.g. a change in crop yield or response to a change in mean range or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea level rise; IPCC, 2001b). Vulnerability is the propensity of the system towards damage in response to climate sensitivity.

Climate–society relationships can be identified through stakeholder workshops, or may be well known from previous work. The creation of lists, diagrams, tables, flow charts, pictograms and word pictures will create a body of information that can be further analysed. Establishing a conceptual model in the early stages of an assessment can help the different participants develop a common understanding of the main relationships and can also serve as the basis for scientific modelling. The coping range is valuable because of its utility as a template for understanding and analysing climate risks but it is not the only such model that can be used.

8.3.2 Characterising climate extremes and hazards

Are the climate hazards (affecting the system) well understood? There are two steps to this: the identification of the relevant climate hazards and their analysis. If the hazards for a system need to be identified, or their sensitivity on the system investigated, the following questions can be addressed:

- Which climate variables and criteria do stakeholders use in managing climate-affected activities?
- Which climate variables most influence the ability to cope (i.e. are those linked to climate hazards)?
- Which variables should be used in modelling and scenario construction?

These questions can be investigated by ways such as:

1. Moving through a comprehensive checklist of climate variables in stakeholder workshops
2. Literature search, expert assessment and information from past projects
3. Exploring climate sensitivity with stakeholders, through interview, survey or focus groups
4. Building conceptual models of a system in a group environment

Different aspects of climate variability will need to be examined. For example, rainfall can be separated into single events, daily variability and extremes, seasonal and annual totals and variability, and changes on longer (multi-annual and decadal) timescales. Daily extremes are important in urban systems for flash-flooding, inter-annual variability for disease vectors, and seasonal rains for dryland agriculture. Temperature can be divided into mean, maximum and minimum daily averages, variability and extremes. In each system, people will have a different set of variables that they use to manage that system. Even though this management may not be 'scientific', it may be very sophisticated. Each of these climate variables has a different level of simulation skill and has different degrees of predictability, which is critical for building climate scenarios.

Relationships between climate variables and impacts can be analysed by a number of methods such as ranking in order of importance, identifying critical control points within relationships, and quantifying interactions through sensitivity modelling. Often, this knowledge exists in institutions (e.g., agricultural extension networks) where important relationships are well known. In such cases, stakeholder workshops will allow the information to be gathered relatively easily. In other situations, several stakeholder workshops may be needed; the first to introduce stakeholders to the issue of climate change and to establish areas of shared knowledge and gaps, before investigating the specifics of a particular activity.

8.3.3 Impact assessment

In assessing current risk, impact modelling may need to concentrate on assessing the impacts of extreme events and variability, perhaps undertaking modelling to extend the results based on relatively short records of historical data (e.g. through statistical analysis) This approach was undertaken in McInnes *et al.* (2002). Sensitivity modelling in testing changes to variability and investigating extreme-event probabilities can be of benefit later on when climate scenarios are being constructed. Given the difficulty in combining the various types of uncertainty, sensitivity modelling of impacts under climate variability will help identify which uncertainties need to be represented in scenarios.

Impacts can also be assessed from the socio-economic point of view by assessing vulnerability. The interactions between socio-economic factors and sensitivity as it affects vulnerability will also affect the ability to cope, and identifying such interactions are likely to be important for identifying possible adaptations.

8.3.4 Risk assessment criteria

Risk assessment criteria can be measured as a continuous function and/or in terms of limits or thresholds. For example, in farming, crop yields can be divided into good, moderate, poor and devastating yields depending on yield per hectare, per family or in terms of gross economic yield. This can allow a picture to be developed of the distribution of good and bad years and which combinations are sustainable. There is also a minimum level of yield below which hardship becomes intolerable. If this level is identified then it can become a criterion by which risk is measured, marking a reference point with known consequences to which probabilities can be attached.

Levels of criteria that attach outcomes to impacts and climate are known as impact thresholds. An impact threshold is any change in state associated with a given impact that can be linked with climate. They can be grouped into two main categories:

1. Biophysical thresholds represent a distinct change in conditions, such as the drying of a wetland, floods, breeding events. Climatic thresholds include frost, snow and monsoon onset. Ecological thresholds include breeding events, local to global extinction or the removal of specific conditions for survival.
2. Socio-economic thresholds are set by benchmarking a level of performance. Exceeding a socio-economic threshold results in a change of legal, regulatory, economic or cultural behaviour. Examples of agricultural thresholds include the yield per unit area of a crop in weight, volume or gross income (Jones and Pittock, 1997).

Critical thresholds are defined as any degree of change that can link the onset of a given critical biophysical or socio-economic impact to a particular climatic state (Pittock and Jones, 2000). They can be assessed through vulnerability assessment and mark the limit of tolerable harm. Critical thresholds mark the limits of the coping range; the point where climate drives impacts beyond a level that is considered tolerable (Smit *et al*., 1999; Pittock and Jones, 2000). For any system, a critical threshold is the combination of biophysical and socio-economic factors that marks a transition into vulnerability.

Stakeholders and investigators jointly formulate criteria that become a common and agreed metric for an assessment (Jones, 2001). These may link a series of criteria ranked according to outcomes (e.g., low to high), or be in the form of thresholds. Critical thresholds can be defined simply, as in the amount of rainfall required to distinguish a severe drought, e.g. less than 100 mm rainfall over a dry season, or can be complex, such as the accumulated deficit in irrigation allocations over a number of seasons (Jones and Page, 2001). Each assessment needs to develop its own criteria for the measurement of risk. For example, given a continuous function between climate and yield as in Figure 8.1, it is possible to assess the likelihood of any outcome within that relationship. It is also possible to calculate a particular threshold and calculate the probability of exceeding that threshold under a given set of conditions. There are no hard and fast rules for constructing thresholds – they are flexible tools that mark a change in state that is considered important.

8.3.5 Risk assessments

Current climate risks mainly deal with the recurrence of climate hazards within a stationary climate. The methods for risk assessment are well developed within some sectors (e.g. agriculture and water resources) and poorly developed within others (e.g. biodiversity).

Risk assessments range from those that are purely qualitative to those that apply numerical techniques. As uncertainty decreases, analytic and numerical methods increase in importance as does the capacity to understand the system over changing circumstances. The following list outlines this progression:

1. Understanding the relationships contributing to risk
2. Being able to relate given states with a level of harm (e.g. low, medium and high risk)
3. Statistical analysis, regression relationships
4. Dynamic simulation
5. Integrated assessment (multiple models or methods)

These methods can be used to undertake the following investigations:

- Understanding the relationship between climate and society at a given point in time
- Establishing current climate and society relationships prior to investigating how climate change may affect these relationships (e.g. setting an adaptation baseline or reference)
- Developing an understanding of how past adaptations have affected climate risks
- Assessing how technology, social change and climate are influencing a system in order to be able to separate changes due to climate variability and changes due to ongoing adaptation (e.g. Viglizzo *et al*., 1997)
- Assessing how known adaptation strategies can further reduce current climate risks.

8.4 Assessing future climate risks

To assess future climate risks, climate scenarios and planning horizons need to be incorporated into the analytic framework. This requires the management of large uncertainties. The exact methods used depend on the type of assessment, how much information is needed to manage risk and the tolls and resources available to carry out the assessment. Table 8.1 shows a number of climate risk assessments classified according to their major area of focus.

Table 8.1. Types of climate risk assessments

Type of assessment	Basic method	Examples
Natural hazards based	Investigate whether a specific climate hazard may change over time	Hurricanes (Lugo, 2000; Singh, 2002a, b), Health (Hales *et al.*, 2002)
Vulnerability based	Investigate whether a particular social outcome assessed as a given level of damage or "natural disaster" is likely to change over time	Social vulnerability (Adger, 1999a); Methods (Dilley and Boudreau, 2001)
Policy-based	Investigate existing or proposed policy to determine whether it may need to be modified under climate change	Water (Stakhiv, 1998), Political Structure (Adger, 1999b), Development Policy (Beg *et al.*, 2002)
National/Regional assessment (e.g., catchment, bioregion, international region)	Investigate a region to determine what the major future risks may be and assess adaptation options	National Communications
Sustainable development	Investigate joint needs based on climate risks and development needs and integrate adaptations into the development agenda	Uganda (Apuuli *et al.*, 2000)
Development proposal	Investigate a specific development proposal to determine whether anticipated adaptation is cost effective	Water storage (Harrison and Whittington, 2002)
Maladaptive practice	Determine whether a social trend is increasing climate risk	Desertification (Imeson and Lavee, 1998; Sivakumar *et al.*, 2000), catchment degradation (Chen *et al.*, 2001)
Sector-based	Investigate changing risks to a particular sector (e.g. health, agriculture, water)	Agriculture (Matthews *et al.*, 1997; Lansigan *et al.*, 2000; Kumar and Parikh, 2001; Jones and Thornton, 2002); Human Settlements (Magadza, 2000); Water resources (Tung, 2001; Mehrotra, 1999), Forestry (Fearnside, 1999)

When carrying out a risk assessment, the team needs to be aware of what type of information is needed to communicate the results. In some cases, qualitative information is all that is needed. For instance, an indication that current risks are likely to continue in future may be sufficient to warrant adaptation. In other cases, decisions about natural resource allocation based on climate change may be open to legal challenge, requiring the best possible science (e.g. the allocation of or a change in water rights). However, uncertainty also limits choice. Sometimes, although stakeholders want accurate answers, uncertainty may only allow qualitative responses. In this case, an assessment will rely less on analytic techniques and modelling, and rely more on techniques from the social sciences, such as eliciting information from different stakeholders on how they perceive climate risks.

8.4.1 Dealing with uncertainty

Risk assessment utilises a formalised set of techniques for managing uncertainty. Uncertainty under climate change is significant, and requires the use of specialised methods, such as the development and use of climate scenarios. The large uncertainty in predicting future climate is one reason why we recommend that assessments be anchored with an understanding of current climate risk. The understanding of uncertainty and its communication between all parties is very important. Moss and Schneider (2000) prepared a cross-cutting paper on uncertainty for the IPCC Third Assessment Report that provides valuable guidance on framing and communicating uncertainty. Further guidance on managing uncertainty within assessments is provided by Morgan and Henrion (1990).

The tool used to explore future climate is the climate scenario. A scenario is a coherent, internally consistent and plausible description of a possible future state of the world. They can range from simple to complex and from narrative descriptions of a possible future to complex mathematical description combining mean climate changes with climate extremes. A scenario is not a prediction, and has no likelihood attached beyond being plausible. However, it is the basic building block of risk assessment approaches under climate change that use scenarios, ranges of uncertainty and probability distribution functions.

8.4.2 Using coping ranges to measure future climate risks

The coping range as introduced in Figure 8.1 can be used to assess how climate or the ability to cope, or both is changed over time. The next step is to see how the ability to cope is affected by a perturbed climate. Figure 8.2 (upper panel) shows how a coping range may be breached under climate change if the ability to cope is held constant. Represented in terms of temperature (or rainfall), the upper hot (or wet) baseline threshold is exceeded more frequently while the exceedance of the lower cold (or dry) baseline threshold reduces over time. Vulnerability will increase to extreme levels for the hot (wet) threshold over time. Figure 8.2 (lower panel) represents the expansion of the coping range through adaptation and the consequent reduction of vulnerability. The amount of adaptation depends on the planning horizon under assessment and the likelihood of exceeding given criteria over a given planning horizon.

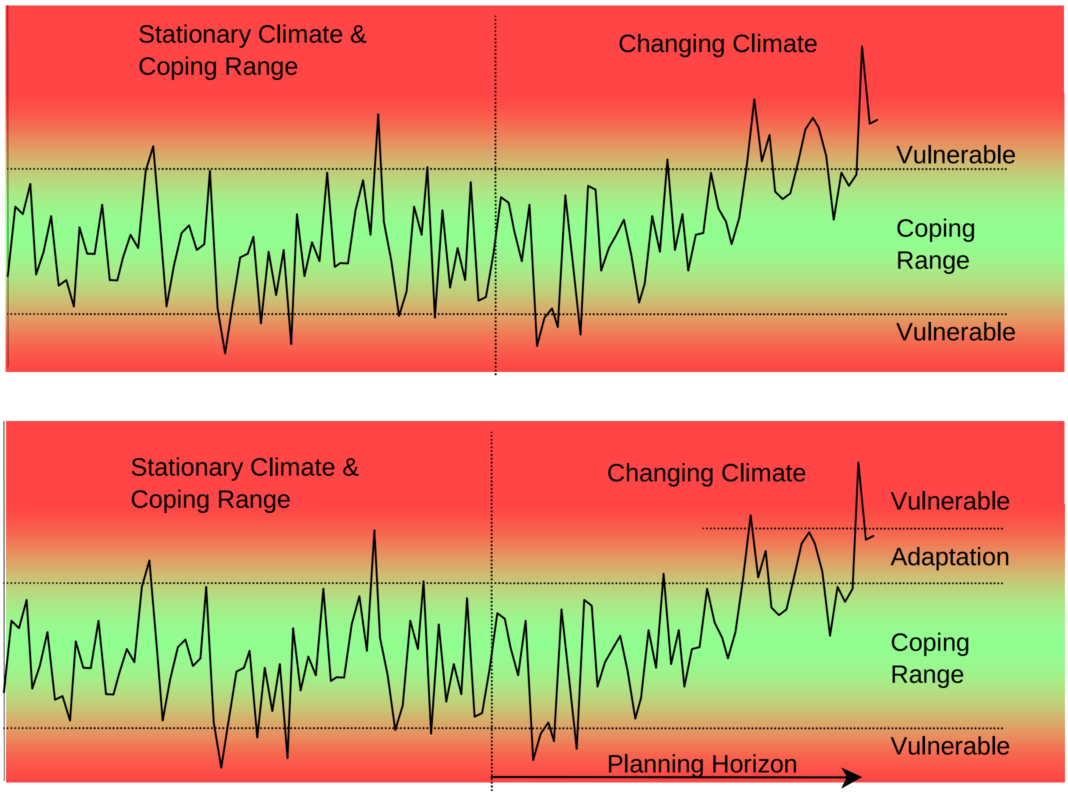

Figure 8.2. Coping range showing the relationship between (a) climate change and threshold exceedance, and (b) how adaptation can establish a new critical threshold, reducing vulnerability to climate change. Source: McInnes et al (2002).

The coping range can also be used to see how both climate and the ability to cope may change. For example, an agricultural assessment could account for projected growth in technology, yield and income that broadens the coping range. An assessment could then determine whether these changes are adequate to cope with projected changes in climate. These assessments should be carried out on an appropriate planning horizon.

8.4.3 Planning and policy horizons

Planning horizons will affect how far into the future a risk assessment may be projected. Planning horizons relate to the lifetime of decision-making associated with a particular activity – how far into the future is it planned? Do current planning decisions assume the continuation of historical conditions? How do we incorporate climate change into long-term planning? The same activity can be affected by several planning horizons used by different stakeholders (e.g. financial, urban planning and engineering horizons for infrastructure). For example, in a water resource or catchment-based assessment, the planning life of water storages may be 50+ years, but planning for supply may only be 5–15 years (Figure 8.3). A risk assessment may then want to create scenarios based on two time horizons such as 2020 and 2050 to accommodate both infrastructure and water policy horizons.

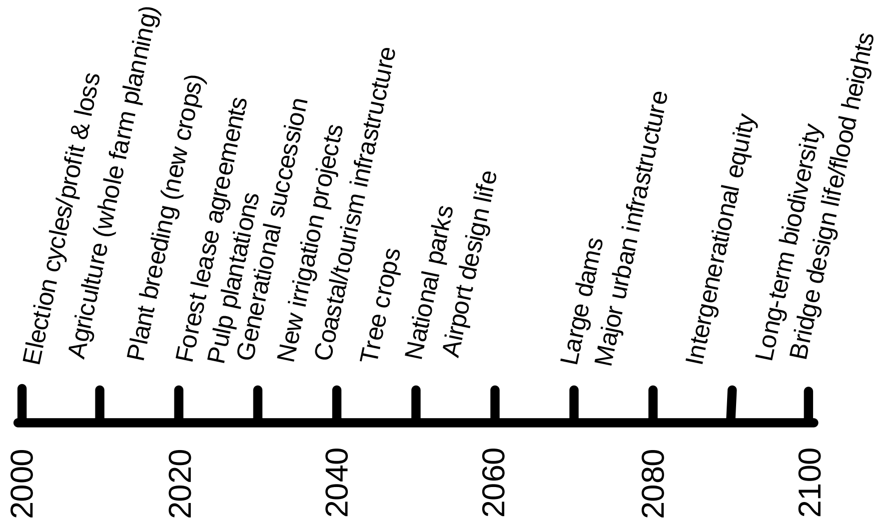

Figure 8.3. Planning horizons relevant to climate risk assessments.

The policy horizon is related to the period of time that a particular policy is being planned for. It is not always the same as a planning horizon. For instance, the infrastructure affecting an activity will have an engineering life of many decades, but the policy horizon that affects the operation of that infrastructure may only be a handful of years. Most natural resource policy is implemented over several years and may be reviewed or updated over time but is expected to manage resources over a much longer planning horizon. A risk assessment may extend over the longer planning horizon, but adaptations developed to manage those risks are likely to be applied over a much shorter policy horizon. Sometimes the policy horizon is the planning horizon; in such circumstances a risk assessment can be used to inform policymakers of the value of taking a longer-term view.

Likelihoods of climate change are constructed of frequency-based uncertainties of recurrent climate hazards and single event uncertainties associated with climate change; from a range of possible outcomes, only one can come true. Ranges such as temperature change, rainfall change and sea level rise are typical. Each range of uncertainty has three components: there is a full range of change that is unknown, a less extensive but quantifiable range that may or may not have a known probability distribution, and individual climate scenarios, which are the building blocks of these ranges (Jones, 2000). A climate scenario can serve as an individual sample or a set of scenarios can be used to construct a range, which can then be re-sampled using bayesian techniques. If each scenario within an assessment is applied as a plausible sample with no attached likelihood, each outcome will have a different level of vulnerability (or potential benefit), suggesting different rates and magnitudes of adaptation. Without any means to prioritise these results, the fallback position is to suggest adaptations that will work across a wide range of possibilities (Lempert and Schlesinger, 2001)

8.4.4 Risk assessments under future climates

Risk assessment under climate change is a measure of how likely various activities are to be taken beyond their coping range. This is easiest if impacts can be expressed as a function of global warming and are likely to change in only one direction (e.g. increase or decrease). For example, for sea level rise we intuitively know that the lowest areas of coast will be inundated first and are the most likely to be inundated over the long term. Given the IPCC range of sea level rise of 9 to 88 cm at 2100, a section of coast with a critical threshold of 25 cm is much more likely to be inundated by 2100 than a section with a critical threshold of 75 cm. In terms of risk, hazard may be experienced as a storm surge, vulnerability can be measured through a given combination of surge and damage that exceeds tolerable levels (e.g., loss of important coastal ecosystems or infrastructure) and likelihood is the probability of threshold exceedance at a particular time.

This principle extends to all activities where it is possible to characterise critical thresholds or other risk-based criteria as a function of global warming. Coral reefs that repeatedly bleach at a warming threshold of 1°C are more likely to be damaged than those that will bleach at 2.5°C. Alpine ecosystems close to their marginal limits will be affected at much lower temperatures than at higher altitudes. Activities affected by rainfall change, though less directly linked than temperature, will also fit this general framework. Climate models indicate that once a direction of rainfall change is established, the magnitude increases with global warming. Therefore, drought and/or floods will intensify over time, requiring adaptation before damage can be alleviated or benefits realised. The regions where small changes in climate breach a critical threshold will be those that face the greatest risk.

Figure 8.4 shows how thresholds can be related to global warming and sea level rise in a probabilistic sense. Risk is calculated as the probability of threshold exceedance and is highest at the minimum limit, nearest to the current coping range and lowest at the maximum limit away from the coping range. Figure 8.4 also shows how probability distribution functions based on two or more input uncertainties can be recast.

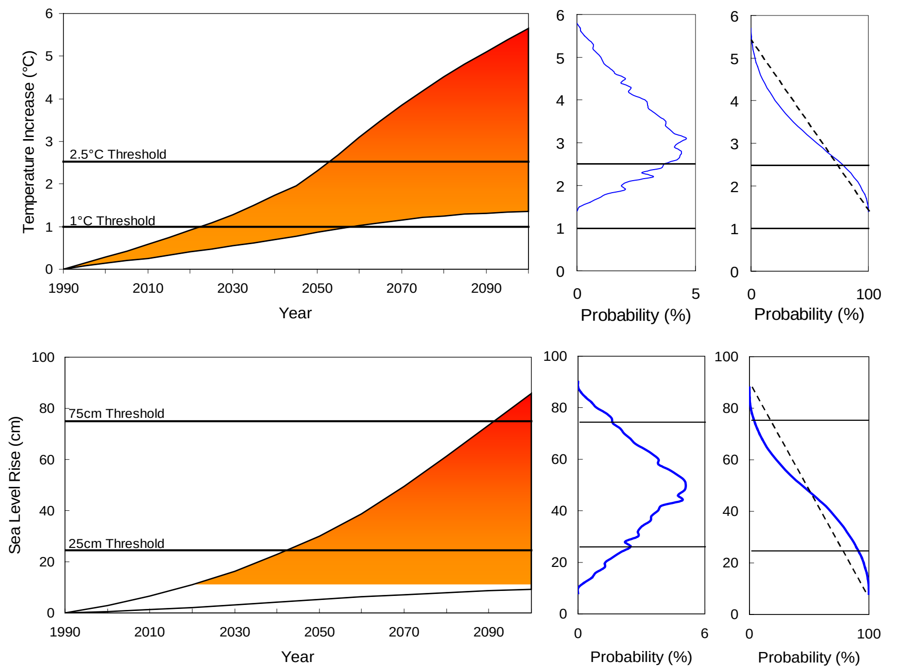

Figure 8.4. The left hand panels show ranges of temperature increase (upper) and sea level rise (lower) 1990–2100 (IPCC 2001), showing a 1°C and 2.5°C warming threshold (upper) and a 25 cm and 75 cm sea level rise threshold (lower). The centre panels show a probability distribution combining two ranges of uncertainty for temperature and sea level rise. The right hand panels show the same probability distributions recast to assess the likelihood of threshold exceedance. The dashed line represents a uniform probability distribution (all points equally likely in the central panels). These charts shows the probability of threshold exceedance manages input uncertainties in a far more robust manner than the prediction paradigm, represented in the centre panels, as it less sensitive to changes in the probability distribution.

Activities with critical thresholds that will be exceeded at low levels of warming will be the most at risk, requiring risk management in the form of adaptation, mitigation or "do nothing". Those exceeded at moderate levels of global warming are less likely to occur and those close to the upper limit least likely to be exceeded. At increasing levels of warming the number of coping ranges being exceeded will increase, as will the damage to each activity already affected.

The role of vulnerability assessment is to identify the systems most sensitive to climate change, those with narrow coping ranges, those with low adaptation capacity and those exposed to current climate risks that are likely to be exacerbated under warming. Direct adaptation or increasing adaptive capacity (the ability to respond to an experienced or anticipated stress) can reduce net damages or even increase net benefits in many systems, but as global warming increases, the rate and magnitude of adaptation required will increase. Mitigation of greenhouse gases will reduce the risk of global warming. If mitigation is sustained, it will act from the top down, reducing the highest potential temperatures first, then successively lower temperatures as mitigation continues.

The relationship between adaptation and mitigation and global warming in terms of risk assessment is shown in Figure 8.5. Adaptation will either reduce damages or provide net benefits for impacts affected by the warming that does occur, and mitigation will reduce the likelihood of even higher temperatures occurring. The two columns on the right side of Figure 8.5 provide guidance on how risk can be assessed. Likelihood goes from most likely to least likely with increasing global warming. Its probability distribution is unknown, but statistical techniques can be used to assess different realisations of that distribution based on prior assumptions.

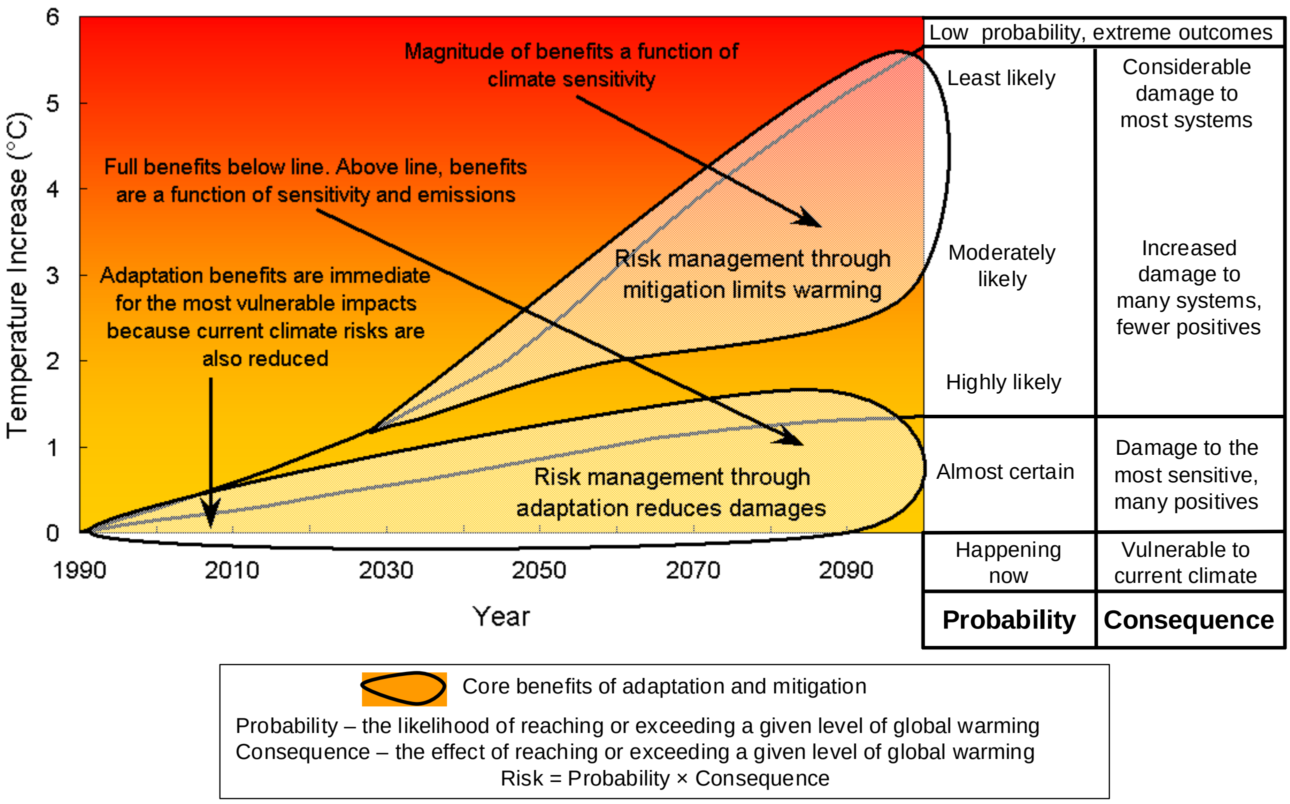

Figure 8.5. Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on the six SRES greenhouse gas emission marker scenarios with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold exceedance as a function of global warming and the consequences of global warming reaching that particular level. Risk is a function of probability and consequence.

8.5 Case study for water resources in NSW

Water supply and quality is one of the primary areas of risk under climate change, because of its importance in both natural and managed systems and sensitivity to climate. Although a well-managed system can cope with a wide range of climate variability, climate change has the potential to threaten water resources in both developed and undeveloped systems. This case study uses a series of assessments, mainly carried out in the Macquarie River Catchment in NSW, part of the Murray-Darling Basin, to demonstrate how uncertainty can be managed using risk assessment techniques (Jones and Page, 2001).

Step 1: Project Scope

Objective: To determine whether climate change poses a sufficient risk to water resources in the Murray-Darling Basin, requiring climate change to be incorporated into water policy and integrated catchment management plans.

Project Design: The project utilised a catchment water management model operated by the state water management authority. This model was used because of its credibility with the managers and water users. Water management allocates irrigation supply from a dam with one year's streamflow each irrigation season depending on availability. Some environmental flows and all domestic and industrial flows are high security. Excess supply may be sold as low security 'off-allocation' water. The method of assessment was to take the existing model and perturb it by climate change scenarios for 2030 and 2070.

Step 2: Current vulnerability

A baseline climate record of rainfall and potential evaporation (A-Class Pan extended using temperature regression), allowed a 100+ year record of flows to be analysed, although only the past 50 years have good streamflow records. The widespread development of irrigation systems has occurred since the 1950s and irrigation development was largely uncontrolled until capped in the late 1990s. Extractions in the Macquarie catchment are above their sustainable limit (NLWRA, 2001).

The 20th century can be divided into a dry period for the first half and a wet period during the second half. These are described as drought-dominated and flood-dominated rainfall regimes and denote a period of several decades where average rainfall decreases by more than about ±20% from the long-term mean. However, irrigation development has seen flows decrease throughout the twentieth century, seriously threatening the Macquarie Marshes, a Ramsar wetland of international significance. This has united local graziers and conservationists, both concerned over wetland degradation.

Irrigation has been economically successful, and cotton growing has expanded and moved south due to climate change and improved varieties. However, the catchment is threatened by both irrigation and dryland salinity, with elevated levels of saline discharge threatening future water supply. Irrigators who learned their craft during the wetter second half of the 20th century may not yet have developed the adaptations to deal with reduced water supply if climate variability and/or climate change reduces supply below the current capped levels.

Step 3: Future climate-related risks

Several levels of climate change information have contributed to the assessment of climate change risks.

Climate Projections: Climate change projections for rainfall and potential evaporation from the set of climate models stored on the IPCC Data Distribution Centre were calculated for region in question. Rainfall was taken directly and potential evaporation was calculated from model output. These changes were converted into change per degree of global warming and scaled for the IPCC range of global warming in 2030 and 2070. They show the spread of models in terms of rainfall increase and decrease and which models are the driest and wettest for the region. Robust findings were 1) that late winter-spring rainfall usually decreased relative to summer-autumn rainfalls in most models and 2) potential evaporation change could be related to rainfall change across all models – where rainfall increased, the increase in potential evaporation was smaller than it was for rainfall decreases. This information was communicated to stakeholders.

Sensitivity assessment: A series of sensitivity experiments showed that this catchment was much more sensitive to cool season changes in rainfall than warm season changes in rainfall, and that low flows were much more sensitive to changes than median or high flows.

Vulnerability assessment: Critical thresholds defining vulnerability in terms of irrigation supply and environmental flows were set as five years of irrigation allocations below 50% of the water right and ten years of low flows into the Macquarie Marshes insufficient to trigger waterbird breeding. They were found to be breached when mean annual streamflow decreased by more than 10% in a drought-dominated rainfall regime, more than 20% in a normal regime and more than 30% in a flood-dominated regime. The assessment showed that both long-term rainfall variability and climate change acting together should be assessed as part of long-term climate risks. This is probably true for many regions in the world but is made difficult by the need for long-term baseline data.

Natural hazard-based assessment: A natural hazard-based assessment projected a number of scenarios through the model to estimate the most likely outcomes. Ranges of uncertainty for input variables describing changes in mean global warming, rainfall and potential evaporation were randomly sampled and used to perturb a simple algorithm relating rainfall and potential evaporation change to change in mean annual streamflow. The result was a probability distribution describing a wide range of possible changes that favored the central tendencies at the expense of the extremes.

Figure 8.6 shows the results for 2030. Although there is an increased flood risk with increased flows, the drier outcomes are considered worse in terms of lost agricultural and environmental productivity. The extremes of the range are about +10% to –30% but the most likely outcomes range from about 0% to –15%.

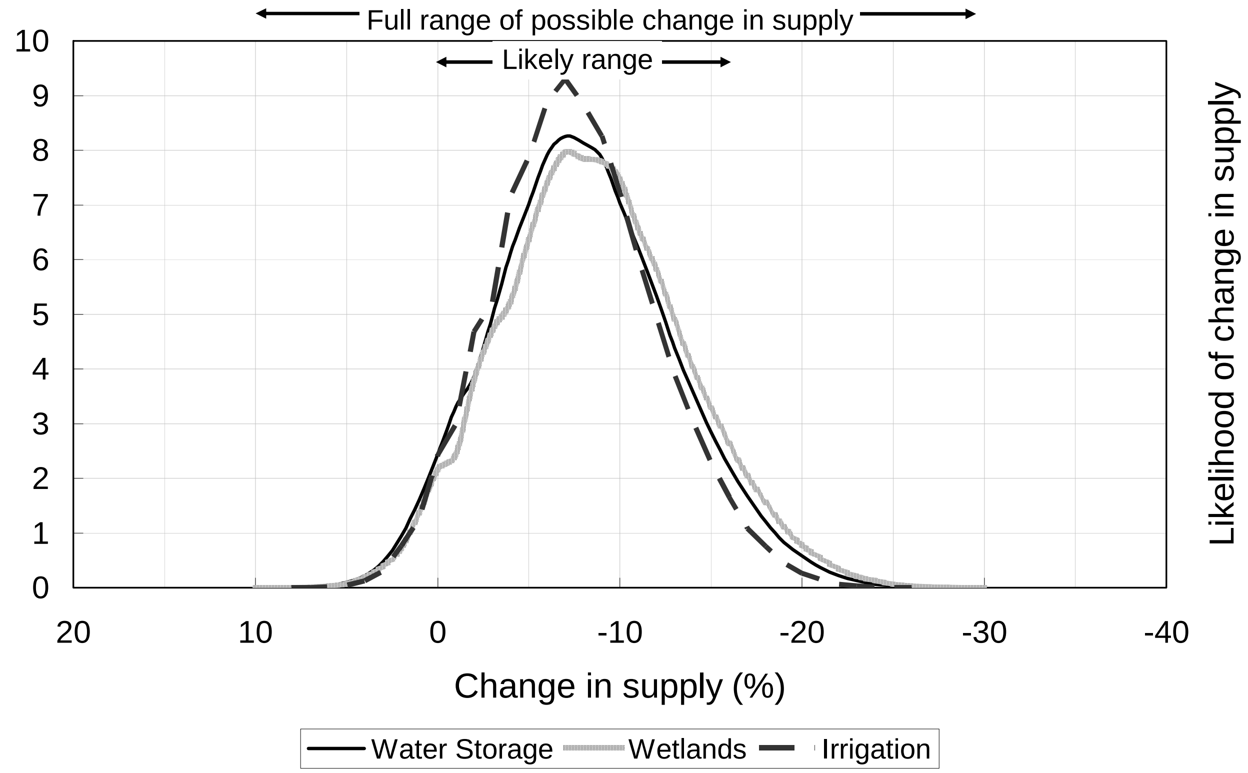

Figure 8.6. Likelihood (%) of changes to mean annual water supply, Macquarie Marsh inflows and irrigation allocations for the Macquarie catchment in 2030

Vulnerability-based assessment: Probabilities of exceeding the critical thresholds described earlier were assessed in a vulnerability-based risk assessment. These showed that the likelihood of exceeding a critical threshold was subject to both the decadal rainfall regime and to the mean change in climate. The likelihood of exceeding the critical thresholds in 2030 in a drought-dominate rainfall regime is about 25% for irrigation and 35% for environmental flows, showing that environmental flows are subject to a higher risk. In a normal climate, these likelihoods are about 2% and 1%.

In 2070, likelihoods of critical threshold exceedances are much higher: 70% and 75% for irrigation and environmental flows respectively in a drought-dominated rainfall regime, 30% and 40% in a normal climate and 3% and 6% in a flood-dominated rainfall regime (Figure 8.7). Without adaptation, vulnerability becomes more likely as climate change progresses.

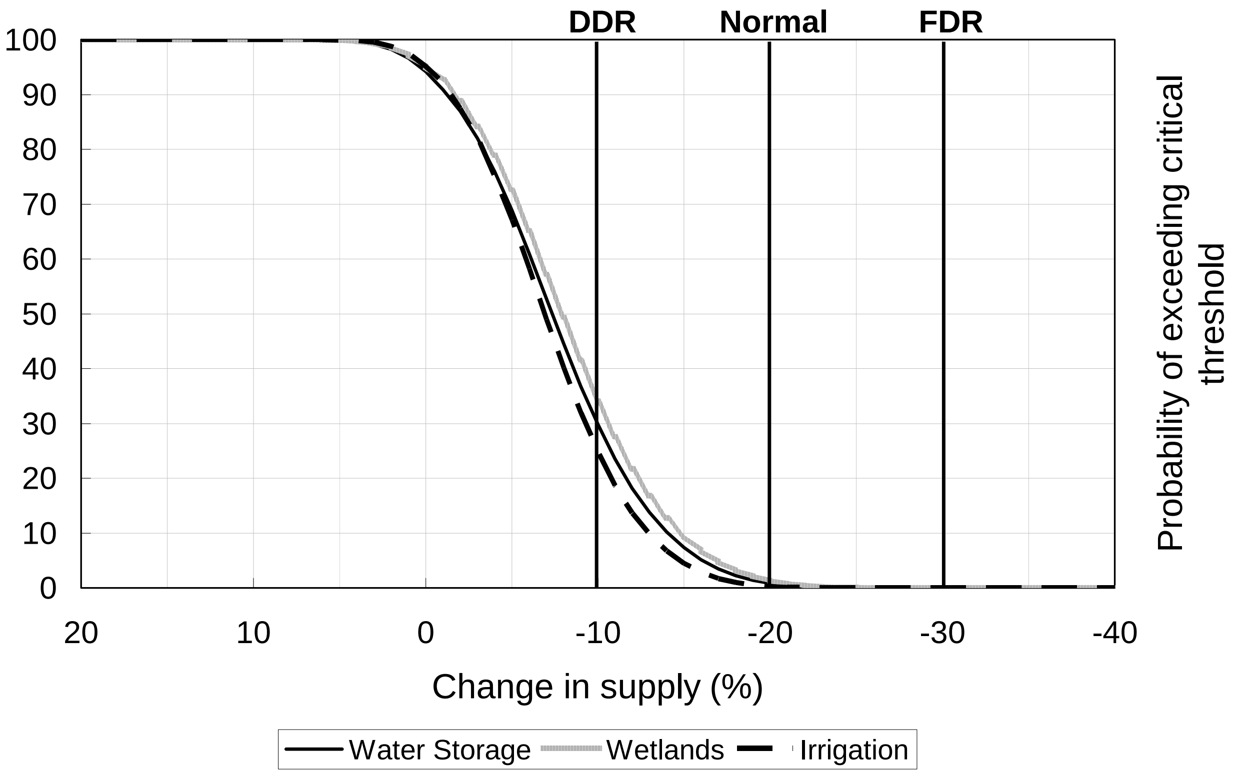

Figure 8.7. Probability of exceeding critical thresholds under a drought-dominated climate (DDR), flood-dominated climate (FDR) and normal climate (Normal) for the Macquarie catchment in 2030

Integrated assessment: Limited integrated assessment was carried out looking at the combined impacts of climate change and re-forestation on streamflows. For a 10% increase in tree cover in the headwaters of the Macquarie, a 17% reduction in inflows to Burrendong Dam was estimated and for a 2% increase a reduction of 4% was estimated. Changes in flows shown in Figure 8.5 would add directly onto these changes except for large reductions in flow. Therefore, if revegetation and carbon sequestration aims are both pursued in the upper catchment they will combine with climate change to reduce flows. Revegetation targeted for mid-catchment areas to control dryland salinity has less of an effect on streamflow but are commercially sub-economic because of the lower rainfall in these areas.

Step 4: Developing adaptation strategies

A number of strategies to manage water resources more sustainably are currently underway or have been recently implemented. A cap on extractions has been imposed in the Murray-Darling Basin and is being extended to the rest of Australia as part of the National Water Reform Policy. The ultimate intention is that sustainable limits of extraction be set in each catchment. The Living Murray project is assessing environmental flows for the Murray River, where over 70% of the available flow is currently being extracted. As part of the investigations Jones *et al.* (2002) extended the results from the Macquarie Study, to the Murray River to determine whether climate change could threaten the allocation of environmental flows. As a result, climate change was identified as a risk requiring further management by the catchment management authority, the Murray-Darling Basin Commission and further investigations are underway.

Step 5: Continue the adaptation process

Actions consistent with adaptation to climate such as capped allocations, better environmental flows, improved irrigation management and moves to improve water quality are ongoing. Climate change has been recognised as having an impact on the success of all these measures.

A recent stakeholder workshop identified the following items for further research:

- Prediction of inflows to dams and water allocations with three to six months lead times to help manage cropping risks;
- Forecast temperatures and potential evaporation with three to six week lead times;
- Prediction of flows in unregulated streams and link with environmental flow requirements;
- Build climate variability and climate change research inputs into key national water reforms;
- Program for integrated research into recent rainfall reductions in eastern Australia, similar to that instituted to south-west Western Australia.

9. Recommendations for future research

The climate change projections presented in this report represent the most up-to-date information available for NSW from a range of recent climate model simulations. However the relevance and reliability of climate change projections for NSW could be enhanced through further work in a number of priority areas, which are outlined below.

The IPCC (2001a) assessed the performance of global and regional climate models in simulating observed climate features. The following recommendations were made by the IPCC to improve model reliability:

- Understand better the mechanisms and factors leading to changes in radiative forcing. This includes better observations of the spatial distribution of greenhouse gases and aerosols, improvements in deriving concentrations from emissions of gases and aerosols, improving the ability to model the carbon cycle, and better assessment of direct and indirect aerosol forcing.
- Understand and characterise the important unresolved processes and feedbacks, both physical and biogeochemical, in the climate system. In particular, improve the understanding of cloud, ocean and biospheric feedbacks.
- Address more completely patterns of long-term climate variability including the occurrence of extreme events. It is important to understand this variability and to expand the emerging capability of predicting patterns of organised variability such as El Niño-Southern Oscillation (ENSO).
- Improve methods to quantify uncertainties of climate projections and scenarios, including development and exploration of long-term ensemble simulations using complex models. The focus must be upon the estimation of the probability distribution of the climate system's future possible states.
- Improve the integrated hierarchy of global and regional climate models with a focus on the simulation of climate variability, regional climate changes, and extreme events. This will require improvements in the understanding of the coupling between the major atmospheric, oceanic and terrestrial systems, and extensive modelling and observational studies that evaluate and improve simulation performance.

Large uncertainties still remain in the average climate projections for NSW in Appendix A. This is partly due to the fact that the simulations used in the climate projections are all given equal weight. This is also true of the range of models used by the IPCC to evaluate global climate sensitivity. A method of analysis could be developed that reduces the range of uncertainty by developing criteria that would enable probabilities to be assigned to the likelihood occurrence of any particular value within the range.

The development of projections of climate extremes under enhanced greenhouse conditions is less advanced than the projections of changes to average climate conditions and further work is needed in this area. Some priority research topics for assessing NSW climate extremes are:

- A more rigorous assessment of potential changes in extreme daily temperatures should include the effect of small changes in diurnal temperature range and daily temperature variability.
- Future research should aim to develop methods that minimise the impact of inter-decadal variability in projections of changes to extreme rainfall due to global warming. The development of a means of estimating likely change in extreme rainfall for a given change in average rainfall and global temperature is required. This would enable the preparation of ranges of change in extreme rainfall similar to those provided in the present report for average rainfall. Climate scenarios could then be developed for sectors where changes in both the average and extreme rainfall are essential components (e.g. water resources). In addition, robust statistical techniques for extreme value distributions should be employed.
- An analysis of changes in extreme weather patterns in a larger sample of climate model simulations is needed to improve the robustness of projections.
- The synoptic typing techniques used in Chapter 6 and described in Appendix C are currently being used to identify the weather patterns that produce extreme rainfall in 3 regions – the Northern Rivers, Hunter-Sydney-Illawarra and the lower Murray-Murrumbidgee region. The ability of the climate models to simulate these features will be assessed, and future changes in their frequency of occurrence determined. High-resolution downscaling, with a grid spacing of 4km, is in progress for these three regions to quantify likely changes in extreme rainfall intensity and frequency for 2030 and 2070.
- The robustness of the model results for severe winds needs to be determined by analysing the results of addition models.

- The effects of changes in wind and storm events and rising sea levels on coastal inundation through changes in storm surges could be undertaken using statistical methods that relate changes in broadscale atmospheric circulation to the risk of storm occurrence. Such studies would enable the relative impacts of storm frequency changes and mean sea level rise to be assessed for specific coastal locations.

In addition, new climate projections may be required to service the specific needs of priority impact research areas. This will involve the development of methods to characterise climate risk based on the modes of climate variability and extremes affecting coping ranges of key activities. Key uncertainties include the effect of climate change on the incidence of bush fires, flood frequency, water quality and biodiversity.

The best source of information on climate change impacts for Australia is “Climate change: an Australian guide to the science and impacts”, published by the Australian Greenhouse Office (Pittock, 2003). The guide contains substantial material on potential impacts in NSW. Extracting and synthesizing the NSW material in a separate report would be a valuable exercise, highlighting the major vulnerabilities, opportunities, gaps in knowledge and priorities for further research on impacts and adaptation.

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Appendix A: Past climate variability and projected changes in average climate

Global climate change

The IPCC's 2001 reports concluded that:

- An increasing body of observations gives a collective picture of a warming world and other changes in the climate system;
- Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that affect the climate system;
- There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities;
- Recent climate changes have already affected many physical and biological systems;
- Some human systems have been affected by recent increases in floods and droughts;
- Natural systems are vulnerable to climate change and some will be irreversibly damaged;
- Many human systems are sensitive to climate change and some are vulnerable;
- Confidence in the ability of models to project future climates has increased;
- Atmospheric composition will continue to change throughout the 21st century;
- By the year 2100, global average temperature may rise 1.4 to 5.8^{o}C and global-average sea level may rise 9 to 88 cm, relative to 1990, if there are no explicit policies to limit greenhouse gas emissions;
- Projected changes in climate extremes could have major consequences;
- If carbon dioxide (CO_2) concentrations are stabilised through reductions in net emissions, some of the more serious damage associated with high rates of warming may be avoided;
- Since global warming cannot be avoided completely, adaptation will be necessary to complement efforts to reduce net greenhouse gas emissions.

It is important to note that reductions in CO_2 emissions do not immediately lead to reductions in the CO_2 concentrations that influence global warming. This is because there are time lags in the global carbon cycle. For example, only half the CO_2 emitted by human activities is absorbed by the oceans and biosphere, leaving half in the atmosphere where it has a lifetime of 50 to 200 years.

Observed climate variability in NSW

From 1950 to 2003, the NSW annual mean maximum temperature rose 0.15^{o}C/decade and the NSW annual mean minimum temperature rose 0.19^{o}C/decade. There has been an increase in hot days (35^{o}C or more) of 0.10 days per year, an increase in hot nights (20^{o}C or more) of 0.26 nights per year, a decrease in cold days (15^{o}C or less) of 0.22 days per year and a decrease in cold nights (5^{o}C or less) of 0.29 nights per year.

NSW annual total rainfall has decreased 14.3mm/decade since 1950, dominated by high year-to-year variability. Many El Niño years (such as 1965, 1982, 1994 and 2002) were associated with very low rainfall. The highest recorded proportion of the state with extremely low annual rainfall is 76% in 2002. During the 2002 drought, the low rainfall was accompanied by the highest mean maximum temperatures on record, but close to average mean minimum temperatures. Temperature increases in NSW mean that there is a tendency for more recent dry periods to be accompanied by warmer temperatures than in the past. This suggests that the impact of the 2002 drought would have been exacerbated by temperature rises resulting in increased evaporation and water demand. Decreases in the annual intensity and frequency of extreme daily rainfall events in NSW are consistent with the decline in annual mean rainfall since 1950, with strongest decreases at coastal locations.

Mean relative sea-level rise (including land movement) around Australia of about 1.2mm/year was recorded over the period 1920 to 2000. In Sydney, the frequency of extreme sea-level events reaching 2.1 or 2.2 m has doubled or tripled, respectively, since 1950.

Future climate change

Method

The complexity of processes in the climate system means it is inappropriate to simply extrapolate past trends into the future. To estimate future climate change, scientists have developed scenarios. These are not predictions of what will actually happen. They allow analysis of "what if?" questions based on various assumptions about demographic change, economic growth and technological development.

Two types of scenarios were considered by IPCC:

1. SRES scenarios that *exclude* specific actions to reduce greenhouse gas emissions (although emissions may change indirectly due to other environmental policies),
2. a range of carbon dioxide emission reduction scenarios that slow global warming by stabilising carbon dioxide concentrations at various levels.

The SRES scenarios envisage an increase in carbon dioxide concentration from the present concentration of 370 parts per million (ppm) to 430–455 ppm by 2030, 525–705 ppm by 2070 and 540-960 by 2100, leading to a global average warming of 1.4-5.8°C by 2100. The other scenarios stabilise carbon dioxide at 450 ppm by 2090, or 550 ppm by 2150, or 650 ppm by 2200, or 750 ppm by 2250, or 1000 ppm by 2375, leading to a global warming of 1.2-3.5°C by 2100. Hence, stabilisation scenarios reduce the upper limit of global warming, but have little effect on the lower limit.

The greater the reductions in emissions and the earlier they are introduced, the smaller and slower the projected warming. For example, stabilisation of the CO_2 concentration at 450 ppm by the year 2090 would require global CO_2 emissions peaking at 20% above present by the year 2010, followed by a reduction to 38% below present by 2050 and 70% below present by 2100, limiting global warming to between 1.2 and 2.3°C by 2100. Stabilisation at 550 ppm by the year 2150 would require global emissions peaking at 40% above present by 2025, dropping to 20% above present by 2050 and falling to 35% below present by 2100, giving a global warming of 1.5 to 2.9°C by 2100.

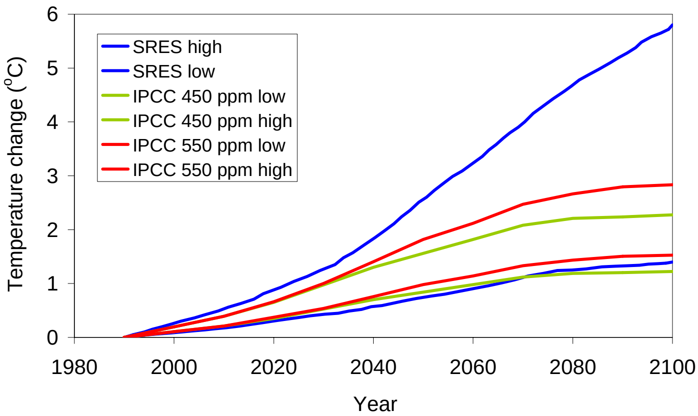

Figure A1. Comparison of projected global warming based on various assumptions about greenhouse gas emissions: SRES and CO_2 stabilisation at 550 ppm and 450 ppm. The low and high limits for each set of scenarios account for uncertainty in climate model projections.

Regional scenarios for NSW are presented below with ranges of uncertainty, rather than a central estimate. The ranges allow for:

- Uncertainty in scenarios of future growth in greenhouse gases and aerosols, and resultant global warming:
    - the IPCC SRES scenarios without policies to reduce greenhouse gas emissions;
    - the IPCC scenario for stabilising CO_2 concentrations at 550 ppm by the year 2150;
    - the IPCC scenario for stabilising CO_2 concentrations at 450 ppm by the year 2090.
- Differences between 12 climate model simulations of regional climate change.

Results from the simulations were expressed as a change per degree of global warming, then converted to a map of change in 2030 or 2070 using IPCC global warming values.

Temperature projections

NSW is likely to experience greatest warming west and north of the highlands, and least in southern and coastal areas. Most warming is expected to occur in spring and summer, and least in winter. Figure A2 and Table A1 show that by the year 2030, the SRES scenarios give an annual-average warming of 0.2 to 1.6°C in coastal and southern regions, relative to 1990, 0.2 to 1.8°C in the central-west, and 0.3 to 2.1°C in the north. By 2070, the warming increases to 0.7 to 4.8°C in coastal and southern regions, 0.7 to 5.6°C in the central-west, and 0.9 to 6.4°C in the north. If CO_2 concentrations are stabilised at 550 ppm by the year 2150, the upper limit of warming is reduced by 23% by 2030 and 38% by 2070. If CO_2 concentrations are stabilised at 450 ppm by the year 2090, the upper limit of warming is reduced by 25% by 2030 and 48% by 2070.

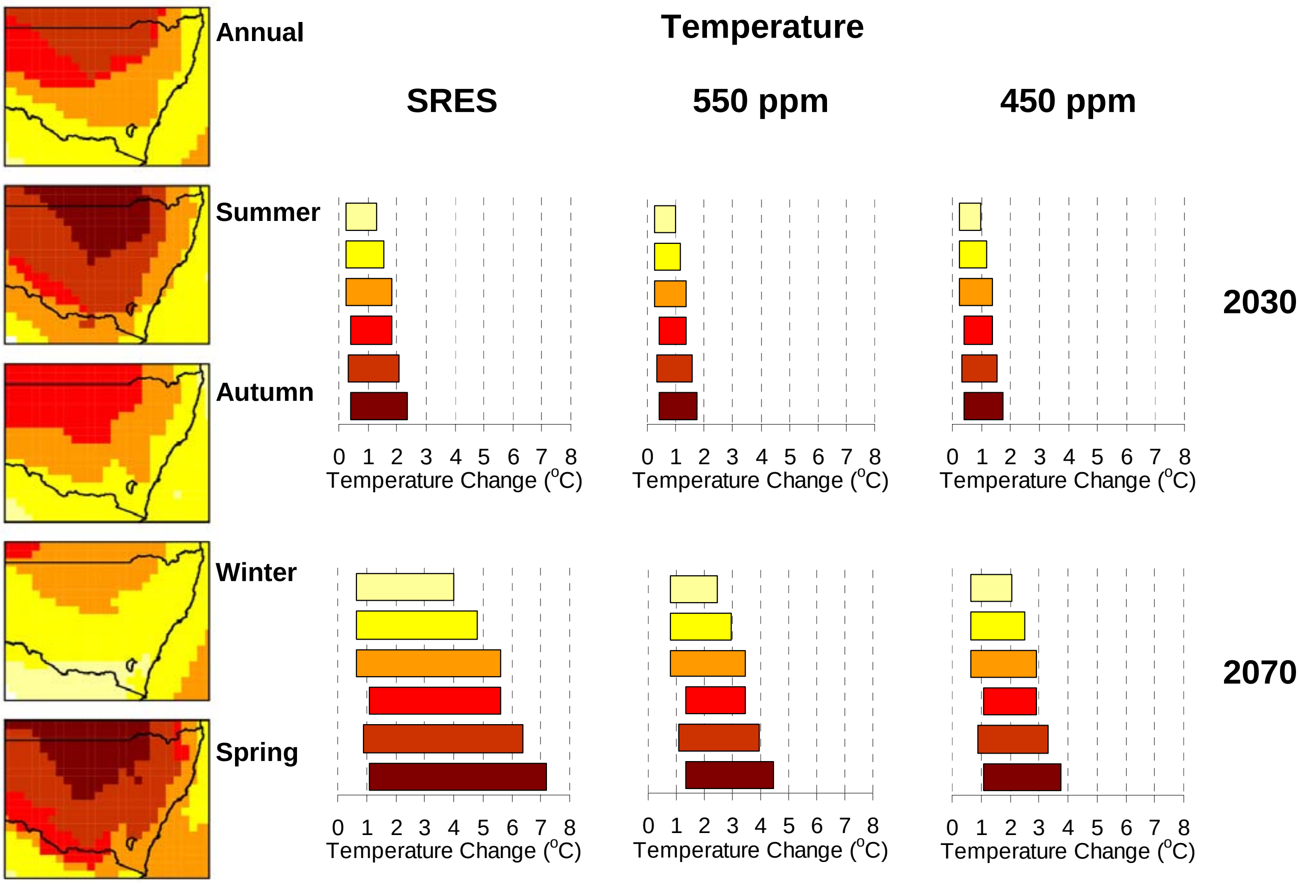

Figure A2. Projected change in average annual and seasonal temperature (°C) for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios exclude explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

Table A1. Projected change in annual average temperature (°C) for the years 2030 and 2070 relative to 1990.

Region	SRES	550 ppm	450 ppm
2030			
Coastal and southern	0.2 to 1.6	0.3 to 1.2	0.2 to 1.2
Central-west	0.2 to 1.8	0.3 to 1.4	0.2 to 1.4
North	0.3 to 2.1	0.4 to 1.6	0.3 to 1.6
2070			
Coastal and southern	0.7 to 4.8	0.8 to 3.0	0.7 to 2.5
Central-west	0.3 to 5.6	0.8 to 3.5	0.7 to 2.9
North	0.9 to 6.4	1.1 to 4.0	0.9 to 3.3

Rainfall projections

There is a general tendency for decreasing annual-average rainfall (Figure A3). This is mainly confined to winter and spring. In autumn, the direction of rainfall change is uncertain over most of the State, with a tendency for decreases in the north and increases in the far west. Summer rainfall changes are uncertain over much of southern and western NSW, with a tendency for increases along the coast and in the north-east, and a tendency for decreases in the north-west.

The magnitude of rainfall change depends on the scenario. By the year 2030, the SRES scenarios give changes of -13% to +7% in winter, in the north-west in summer and in the north in autumn, relative to 1990; -20% to +7% in spring; -7% to 13% along the coast and north-east in summer and in the far west in autumn. By 2070, these ranges of change triple, e.g. -13% to +7% becomes -40% to +20%. If CO_2 concentrations are stabilised at 550 ppm by the year 2150, the limits of the SRES rainfall changes are reduced by 23% by 2030 and 38% by 2070. If CO_2 concentrations are stabilised at 450 ppm by the year 2090, the limits of the SRES rainfall changes are reduced by 25% by 2030 and by 48% by 2070.

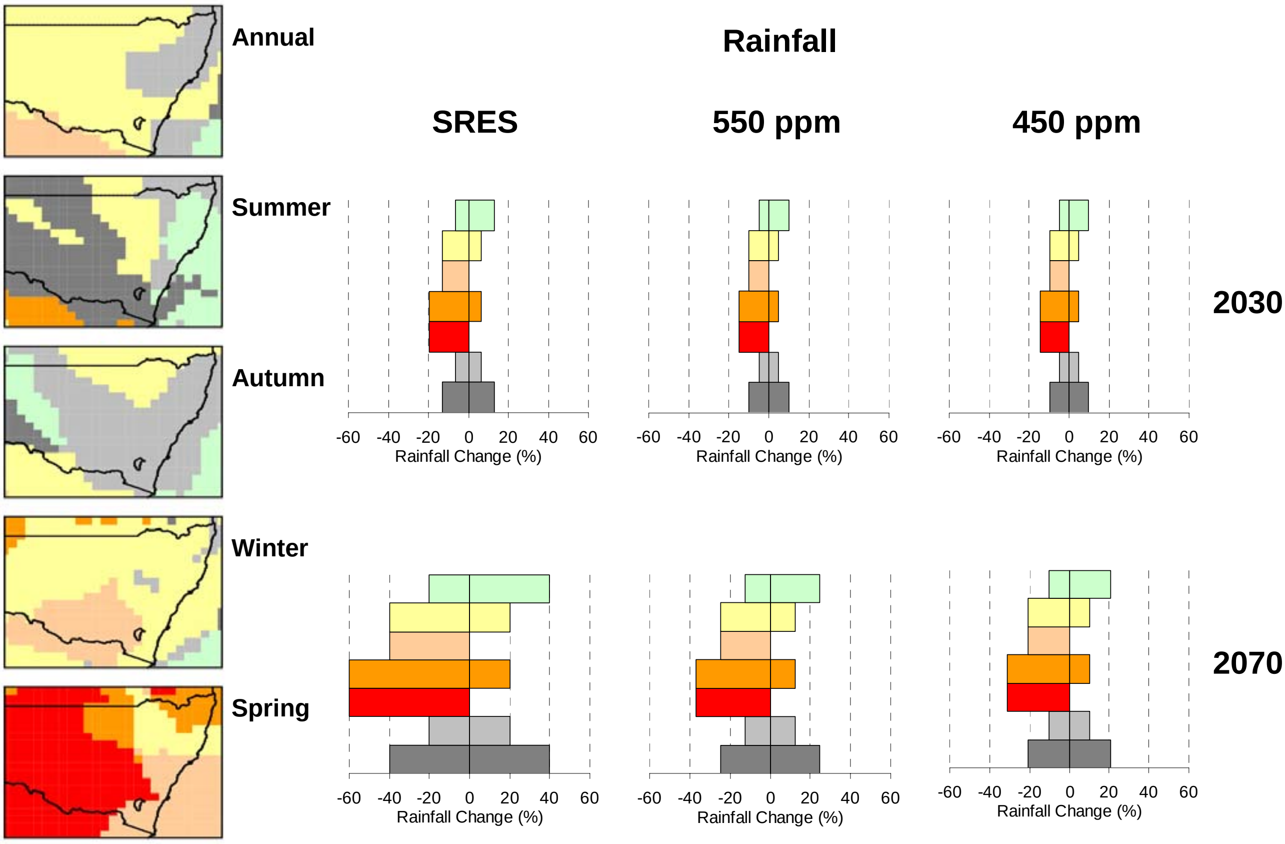

Figure A3. Ranges of change in average rainfall (%) for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

Atmospheric moisture balance projections

Atmospheric moisture balance is the difference between rainfall (supply) and potential evaporation (demand). Potential evaporation is the potential of the local air to evaporate available water from open water or soil, and transpire water from plants. Enhanced greenhouse simulations indicate that potential evaporation will increase. By the year 2030, the SRES scenarios give annual-average increases of 1.5 to 13% west of the highlands and 1 to 8% along the coast, relative to 1990. By 2070, the increase is 4 to 40% west of the highlands and 2 to 24% along the coast. Smaller increases are estimated if CO_2 concentrations are stabilised at 450 or 550 ppm.

Using projections of potential evaporation and rainfall, the change in the atmospheric moisture balance was calculated. Decreases in moisture balance were simulated on a national basis. Over NSW, average decreases in annual moisture balance are largest in the north and smallest along the coast. By 2030, annual average decreases range from 0 to 195 mm along the coast and 20 to 325 mm in the north, relative to 1990. By 2070, the coastal decreases are 0 to 600 mm and the northern decreases are 55 to 1000 mm. If CO_2 concentrations are stabilised at 550 ppm, the lower limits of the SRES changes are reduced by 23% by 2030 and 38% by 2070. If CO_2 concentrations are stabilised at 450 ppm, the lower limits of the SRES changes are reduced by 25% by 2030 and by 48% by 2070. The implied increase in moisture stress is obviously very important and is being addressed further in ongoing research.

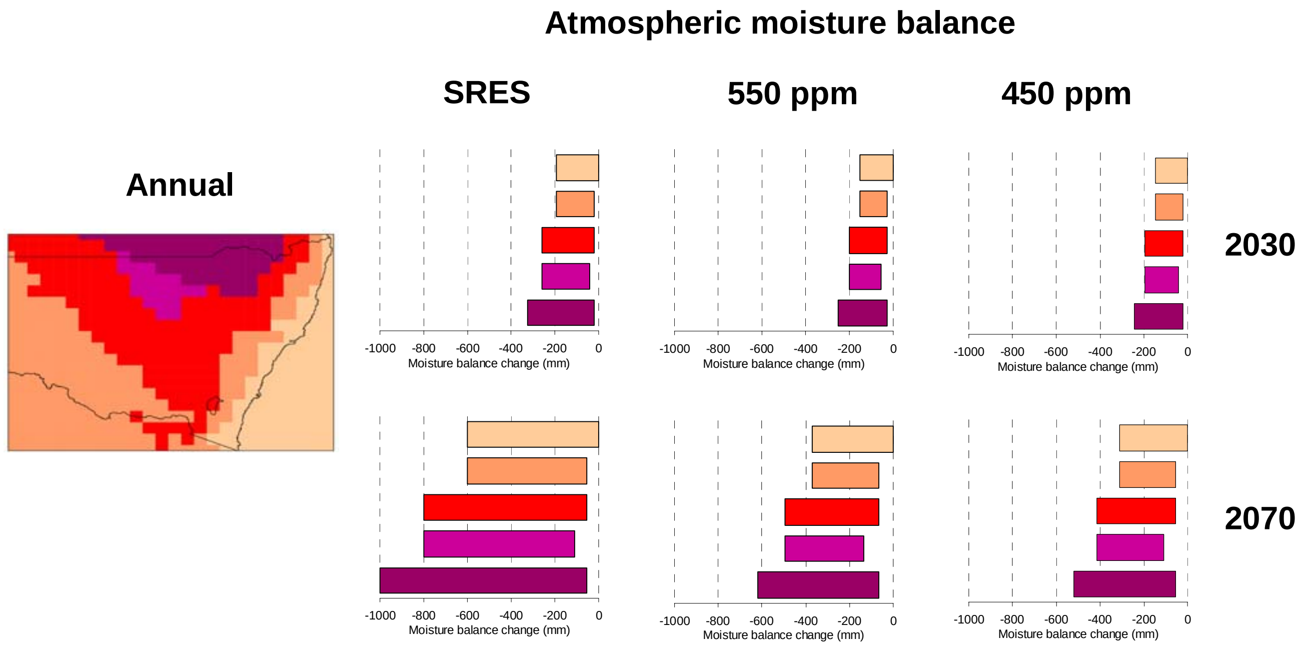

Figure A4: Patterns of change in annual average atmospheric moisture balance (mm) for the years 2030 and 2070, relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

Appendix B: Greenhouse gas emission scenarios and global warming

The complexity of processes in the climate system means it is inappropriate to simply extrapolate past trends to forecast future conditions. To estimate future climate change, scientists have developed scenarios. These are not predictions of what will actually happen. They allow analysis of “what if?” questions based on various assumptions about human behaviour, economic growth and technological change.

Some IPCC scenarios assume “business as usual” without explicit policies to limit greenhouse gas emissions, although some scenarios include other environmental policies that indirectly affect greenhouse gases. These are described in the Special Report on Emission Scenarios (SRES, 2000). Other IPCC scenarios include actions to reduce CO_2 emissions and stabilize CO_2 concentrations at some level above the current value of 375 ppm. These would postpone or avoid some of the more serious damages associated with higher rates of warming. Probabilities have not been assigned to any of the scenarios. Sections 4.1 and 4.2 will describe the SRES (2000) and CO_2 stabilization scenarios in some detail, since they underpin climate change projections for NSW.

SRES emission scenarios

To estimate future climate change, the IPCC developed a set of scenarios to represent a broad range of the main demographic, economic and technological driving forces of greenhouse gases and sulphur emissions for the 21st century. The Terms of Reference for the scenarios required that they do not include additional climate initiatives that explicitly assume implementation of the United Nations Framework Convention on Climate Change (UNFCCC) or the emission targets of the Kyoto Protocol. Each of the forty scenarios represents a variation within one of four 'storylines': A1, A2, B1 and B2. The experts who created the storylines were unable to arrive at a most likely scenario, and probabilities were not estimated.

- A1 describes a world of very rapid economic growth in which the population peaks around 2050 and declines thereafter and there is rapid introduction of new and more efficient technologies. The three sub-groups of A1 are fossil fuel intensive (A1FI), non-fossil fuel using (A1T), and balanced across all energy sources (A1B).
- A2 depicts a world of regional self-reliance and preservation of local culture. In A2, fertility patterns across regions converge slowly, leading to a steadily increasing population and per capita economic growth and technological change is slower and more fragmented slower than for the other storylines.
- B1 describes a convergent world with the same population as in A1, but with an emphasis on global solutions to economic, social and environmental sustainability, including the introduction of clean, efficient technologies.
- B2 places emphasis on local solutions to economic, social and environmental sustainability. The population increases more slowly than that in A2. Compared with A1 and B1, economic development is intermediate and less rapid, and technological change is more diverse.

Figure B1 shows the SRES (2000) anthropogenic (human-induced) emission scenarios for carbon dioxide, methane, nitrous oxide and sulphur dioxide. Carbon cycle models are used to convert emissions into well-mixed atmospheric concentrations, allowing for uptake of emissions by the land and ocean, land and ocean climate feedbacks, and chemical reactions in the atmosphere. By the year 2100, carbon cycle models give estimates of atmospheric CO_2 concentrations ranging from 540 to 970 ppm (an increase of 44 to 159% relative to 375 ppm at present) (Figure B2; IPCC, 2001a). Methane concentrations are projected to change by -11 to +112% and nitrous oxide concentrations may rise 12 to 46%. Concentrations of tropospheric ozone, hydrofluorocarbons and perfluorocarbons are also projected to increase. The SRES (2000) scenarios include the possibility of increases or decreases in anthropogenic aerosols (e.g. black carbon, sulphate aerosols, biomass, aerosols and organic carbon aerosols) depending on the extent of fossil fuels use.

The gas concentrations are converted to a radiative forcing of the climate system using mathematical formulae. Positive forcing warms the Earth, while negative forcing cools the Earth. CO_2 dominates the radiative forcing and has a warming effect. At present, CO_2 accounts for 56% of the total greenhouse gas forcing (including tropospheric ozone), but by 2050 and 2100 CO_2 may represent about 70-80% of the total forcing (IPCC, 2001a). The next most influential gas, methane, accounts for 17% of the present forcing, decreasing to about 10% by 2050, and 0 to 10% by 2100. All SRES scenarios give positive forcing for the well-mixed greenhouse gases, except for methane in the B1 scenario by the year 2100.

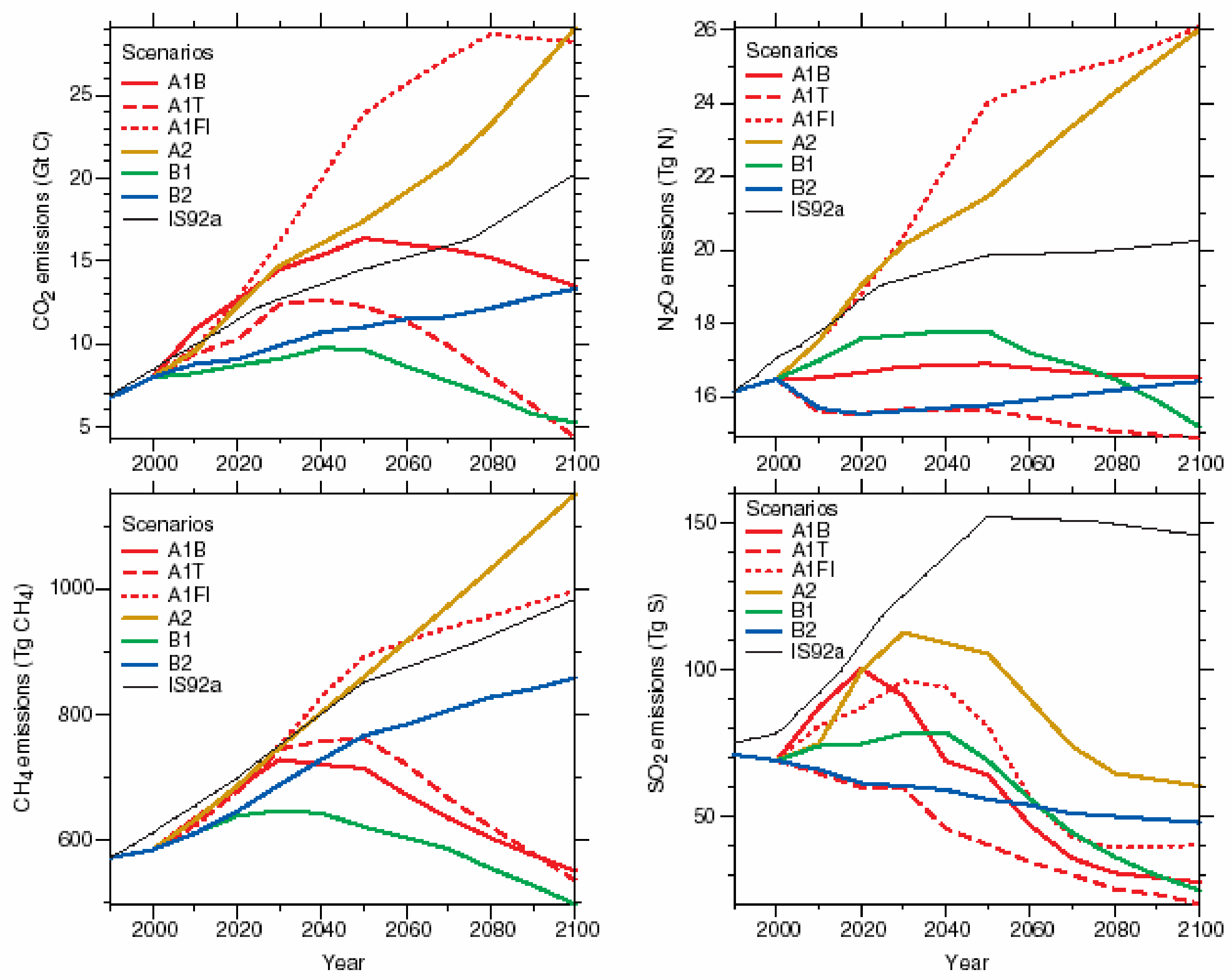

Figure B1. Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulphur dioxide (SO_2) for six SRES scenarios. The IS92a scenario is also shown (from the IPCC Second Assessment Report in 1996). Source (IPCC, 2001a).

To estimate the effect of changes in radiative forcing on climate, we use mathematical models of the climate system. These models, run on extremely fast "super computers", are the best tools we have for forecasting weather and climate. The key components are the atmosphere, ocean, polar ice and land surface. The ability of a model to simulate interactions in the climate system depends on the level of understanding of the geophysical, chemical and biological processes that govern the climate system. Our understanding of these processes has gradually improved, along with our ability to represent them in climate models. Ongoing improvements in available computing power have allowed these processes to be represented in models with greater complexity and detail. A wide variety of weather elements, like temperature and rainfall, are computed over an array of grid-cells covering the Earth in three dimensions. Most models have a time-step of about 30 minutes with grid-cells spaced about 300-500 km apart over the surface, 10-20 layers in the atmosphere and 20-30 layers in the ocean.

Climate models need massive computing resources to perform a simulation with just one emission scenario. Each simulation has a unique climate sensitivity and pattern of climate change. Comparing and synthesising results from different models is a big job. Much simpler climate models have been developed to allow exploration of the sensitivity of climate to a wide range of inputs and assumptions. These simple models can be run on a desktop computer. They provide information about global-average warming and sea-level rise for various emission scenarios and other parameters. The simple models rely on the more-complex climate models for climate sensitivity, rates of ocean heat uptake and patterns of climate change. The SRES results for global-average warming and sea-level rise are shown in Figure B3.

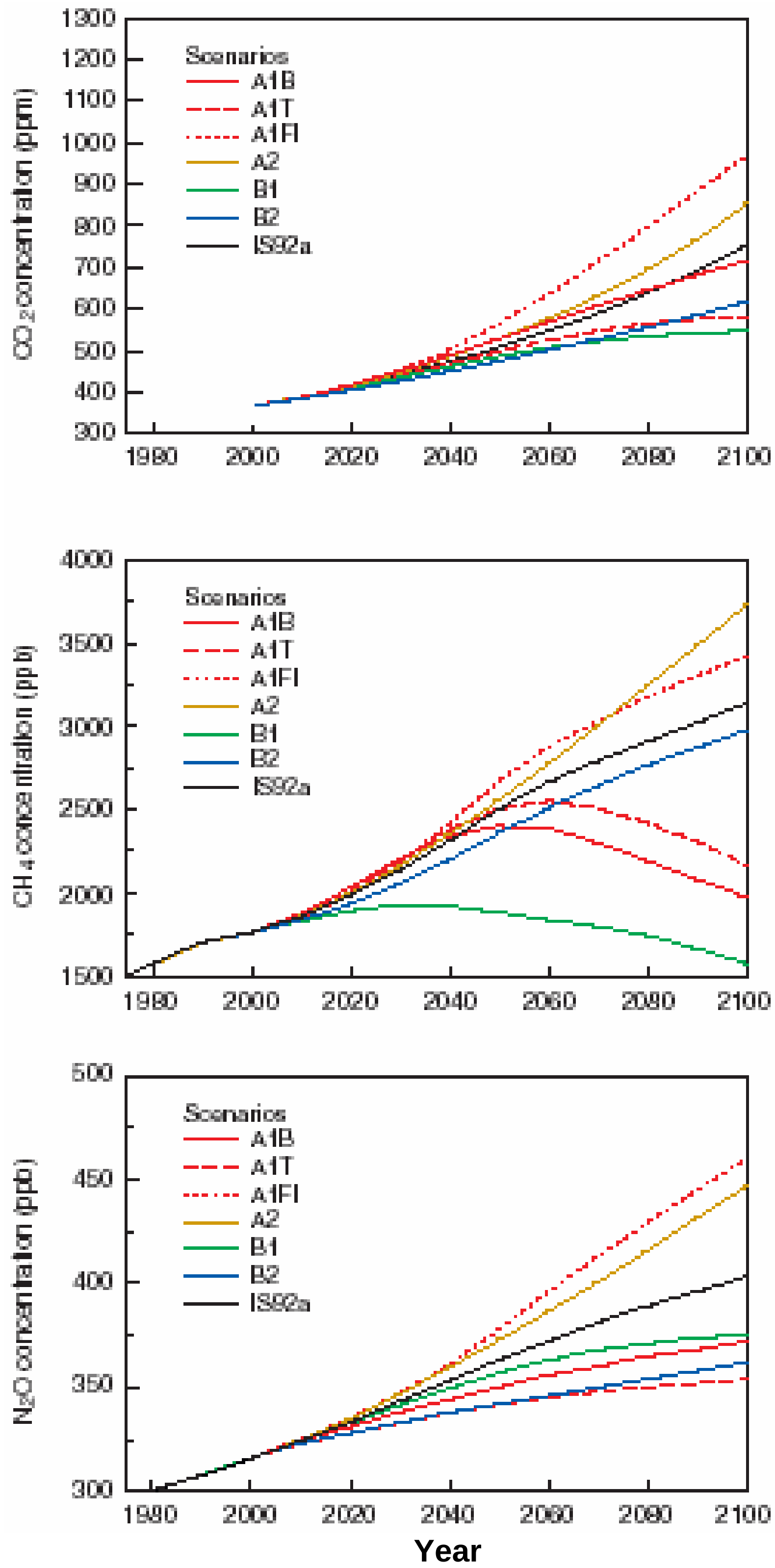

Figure B2. Atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) resulting from the six SRES scenarios. The IS92a scenario is also shown (from the IPCC Second Assessment Report in 1996). Source (IPCC, 2001a).

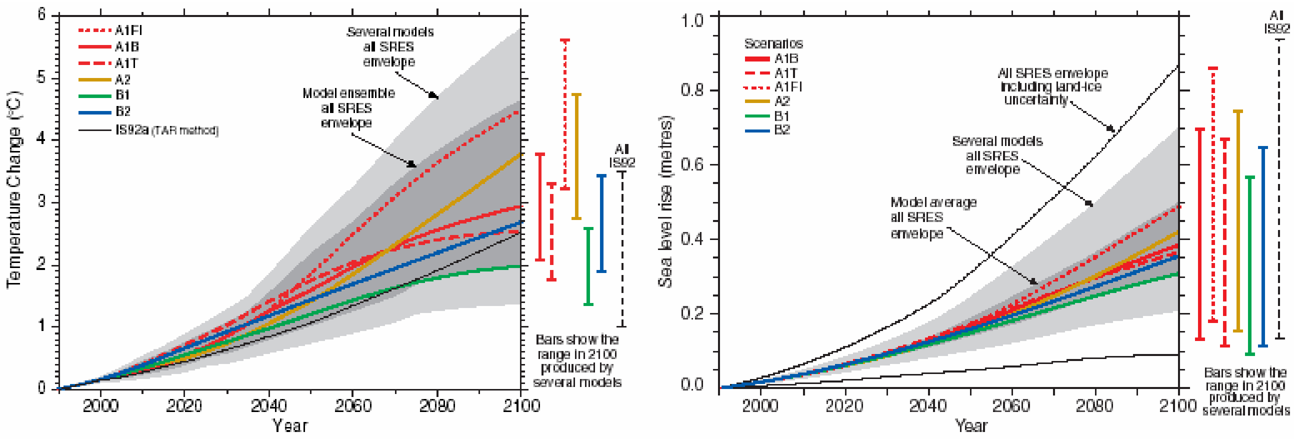

Figure B3. Projected changes in global-average temperature and sea level resulting from the six SRES scenarios, based on a simple climate model tuned to a number of complex climate models with a range of climate sensitivities. The IS92a scenario is also shown (from the IPCC Second Assessment Report in 1996). Source (IPCC, 2001a).

The global average warming for the SRES scenarios is 0.4 to 1.3°C by the year 2030, 0.75 to 2.6°C by 2050, 1.1 to 4.0°C by 2070 and 1.4 to 5.8°C by 2100, relative to 1990. Global-average sea-level rise is 3 to 17 cm by 2030, 5 to 32 cm by 2050, 7 to 52 cm by 2070 and 9 to 88 cm by 2100, relative to 1990. In the past 100 years, the global-average temperature increased about 0.6°C and sea level rose about 15 cm, so the SRES-based projections represent an acceleration of past changes.

Emission reduction scenarios

It is important to remember that the SRES scenarios do not include explicit policies to limit greenhouse gas emissions. Hansen (2004) believes that emphasis on non-mitigation scenarios may have been appropriate in the past, "when the public and decision-makers were relatively unaware of the global warming issue". He argues that there is now a need to shift the focus to "scenarios that are consistent with what is realistic under current conditions" bearing in mind that the impacts of unabated global warming may be harmful in some regions. The United Nations Framework Convention on Climate Change (UNFCCC) (ratified by 186 countries) addresses this issue and entered into force in 1994. Article 2 of the UNFCCC states:

"The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

At this stage, 'dangerous anthropogenic interference' is not well defined and will involve a mixture of scientific, economic, political, ethical and cultural considerations. However, it is clear that greater emission reductions will slow climate change more effectively, leading to a lower probability of dangerous impacts. O'Neill and Oppenheimer (2002) proposed three examples of 'dangerous' environmental consequences:

1. sustained global warming in excess of 1°C, which would cause coral bleaching to become an annual event in most oceans;
2. complete disintegration of the West Antarctic Ice Sheet (WAIS) could occur for a 2°C warming, raising sea level by 4 to 6 metres; and
3. a warming in excess of 3°C could weaken or shut down the large-scale thermohaline circulation of the oceans, which regulates the distribution of heat and other properties over the global oceans.

Hansen (2004) suggested that a 1°C warming could cause significant rapid melting of polar ice and a 5 metre rise in sea level. He estimated that the current energy imbalance of the Earth of about 0.75 W/m^2 implies that a warming of 0.5°C is unavoidable. WBGU (2003) estimated that dangerous climate change may occur for a global warming of about 2°C above pre-industrial levels, i.e. 1.4°C above present.

Article 3 of the UNFCCC refers to the precautionary principle, which states:

"*Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost*".

One way of slowing global warming is to stabilise greenhouse gas concentrations. A range of CO_2 stabilisation scenarios were considered by the IPCC (2001a). Figure B4 shows the time paths of CO_2 emissions that would lead to stabilisation of CO_2 concentrations at 450, 550, 650, 750 and 1000 ppm sometime between the year 2090 and 2300. Lower CO_2 concentration targets would require an earlier reversal of emissions growth and earlier decreases to levels below current emissions. The shaded area shows the range of uncertainty in estimating CO_2 emissions corresponding to each concentration scenario, as represented in carbon cycle models. Also shown for comparison are CO_2 emissions for the A1B, A2, and B1 SRES scenarios. In all cases except the 1000 ppm scenario, stabilising CO_2 concentrations at a higher level than present (375 ppm) would require a reduction from the current level of 8 GtC (million tonnes of carbon) per year to around 3 GtC per year within the next 100 to 300 years, i.e. at least a 60% reduction in global emissions relative to present. For example, the path to stabilising at 550 ppm by 2150 would require emissions to peak at 40% above present (11.2 GtC) by the year 2025, then drop to 20% above present (9.5 GtC) by the year 2050, falling to 35% below present (5.2 GtC) by the year 2100. Alternatively, the path to stabilising at 450 ppm by the year 2090 would require emissions to peak at 20% above present (9.5 GtC) by the year 2010, then decrease to 38% below present (5.0 GtC) by the year 2050, and 70% below present (2.3 GtC) by the year 2100.

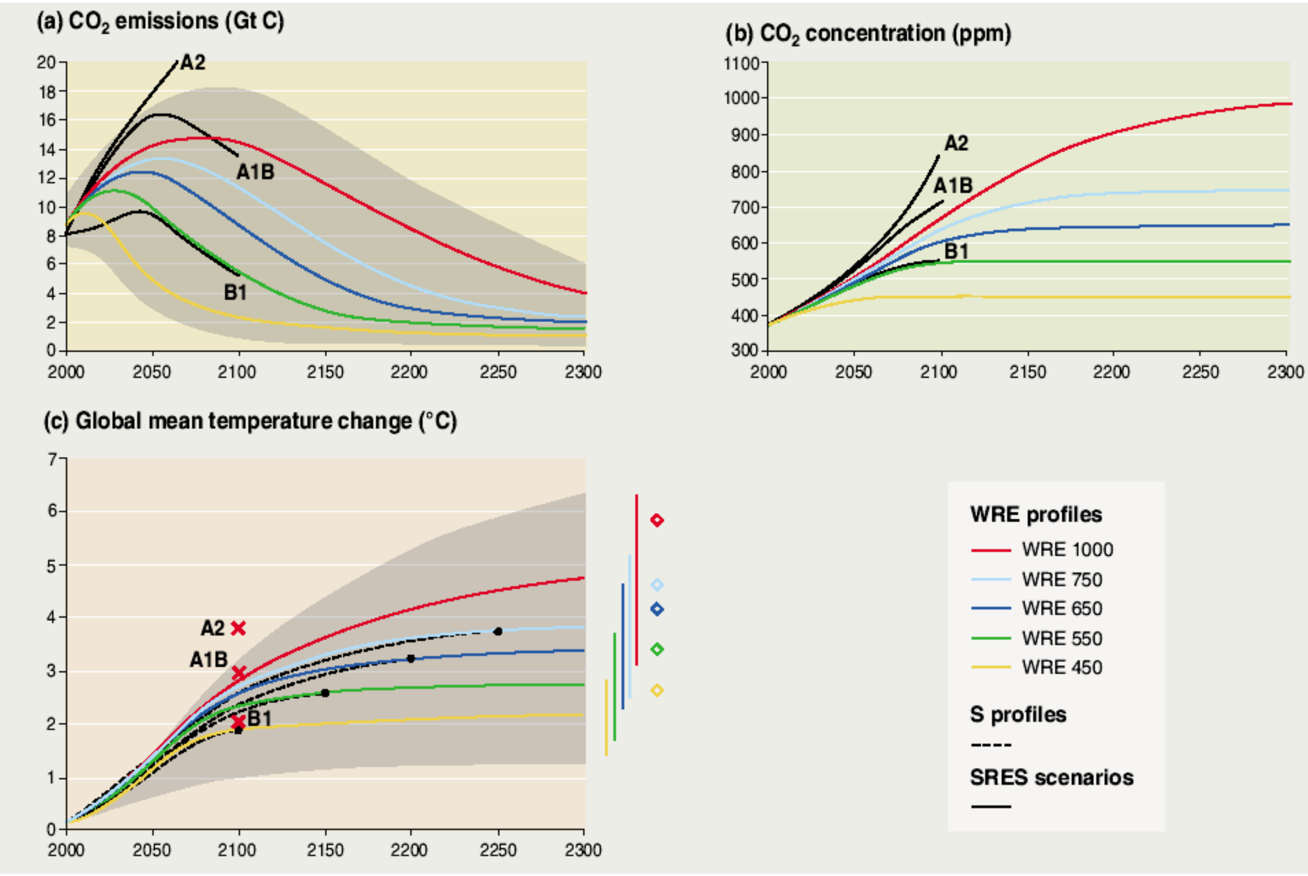

Figure B4. (a) Time paths of CO_2 emissions that would lead to (b) stabilization of the concentration of CO_2 in the atmosphere at 450, 550, 650, 750, and 1000 ppm. The shaded area shows the range of uncertainty in estimating CO_2 emissions corresponding to each concentration scenario. CO_2 emissions for the A1B, A2, and B1 SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. (c) The corresponding global warming includes coloured bars on the right-hand side showing the range at the year 2300 and the diamonds show the equilibrium (very long-term) warming. Red crosses show warmings in the year 2100 for the A1B, A2, and B1 scenarios and the dashed lines show warmings for the S profiles, an alternate set of CO_2 stabilization profiles (not shown in panels (a) or (b)). From IPCC (2001d).

In the IPCC (2001a) warming projections for CO_2 stabilisation, it is assumed that emissions of gases other than CO_2 follow the mid-range A1B scenario until 2100 and are constant thereafter. The global warming slows as growth in CO_2 concentration slows, and warming continues after the time at which the CO_2 concentration is stabilized (indicated by black spots in Figure B4c) but at a much weaker rate. For the 550 ppm stabilisation path, the warming by 2100 is reduced to between 1.5 and 2.9ºC, compared with 1.4 to 5.8ºC without emission reductions (O'Neill and Oppenheimer, 2002). For the 450 ppm stabilisation path, the warming by 2100 is reduced to between 1.2 and 2.3ºC.

Hansen (2004) proposed two "alternative" emission reduction scenarios. The first stabilises CO_2 at 475 ppm by 2100 and gives a global warming peaking at 1ºC in the period 2125-2150. The second stabilises CO_2 at 560 ppm by 2100 and gives a warming peaking at 2ºC by 2125-2150. While the CO_2 concentration targets are almost the same as the IPCC (2001a) targets described above, the resultant global warming value are slightly lower. This is because the time paths for Hansen's (2004) CO_2 and non-CO_2 gases emissions differ from those of the IPCC (2001a). Figure B5 shows that emission reductions clearly have a major impact on the upper limits of the SRES unmitigated global warming, but a minor effect on the lower limits.

Hansen's (2004) first "alternative" scenario assumes CO_2 emissions decline after 2020, followed by a linear slow-down in the CO_2 growth rate until the CO_2 concentration is stabilised at 475 ppm by 2100. Methane concentrations start to decline after 2015, reaching 1515 ppm by 2050. Nitrous oxide continues to increase at a slowly declining rate. The other well-mixed gases are assumed to increase so as to provide a radiative forcing that balances expected decreases in chlorofluorocarbons (CFCs), i.e. the net forcing due to CFCs and other well-mixed gases is held constant after 2000. This requires at least a 50% reduction in fossil fuel use or CO_2 capture and sequestration. The second "alternative" scenario allows for more rapid CO_2 growth from 2000-2050, followed by a slow-down in the growth rate until the CO_2 concentration stabilises at 560 ppm by the year 2100.

Hansen (2004) notes that methane, a precursor of ozone, offers a great opportunity to slow the growth of a gas that has been expected to contribute to global warming. Actions to reduce methane include methane capture at landfills, waste management facilities and fixing leaky gas pipes, each of which have economic benefits that partially offset costs. However, carbon dioxide will be the dominant human-induced forcing in future. The "alternative' scenarios would require a near-term levelling off of carbon dioxide emissions from burning fossil fuel and a decline in emissions before mid-century, heading toward stabilisation by the end of the century. The near-term levelling would require improved energy efficiency and increased use of renewable energies, but a long-term decline will require development of energy technologies that produce little or no carbon dioxide, or that capture or sequester carbon dioxide. Hansen (2004) adds that it would not be easy to move from the unmitigated 1-1.5% per year carbon dioxide growth rate to the 0% per year of the "alternative" scenarios. It would require "a concerted global effort of developed and developing countries".

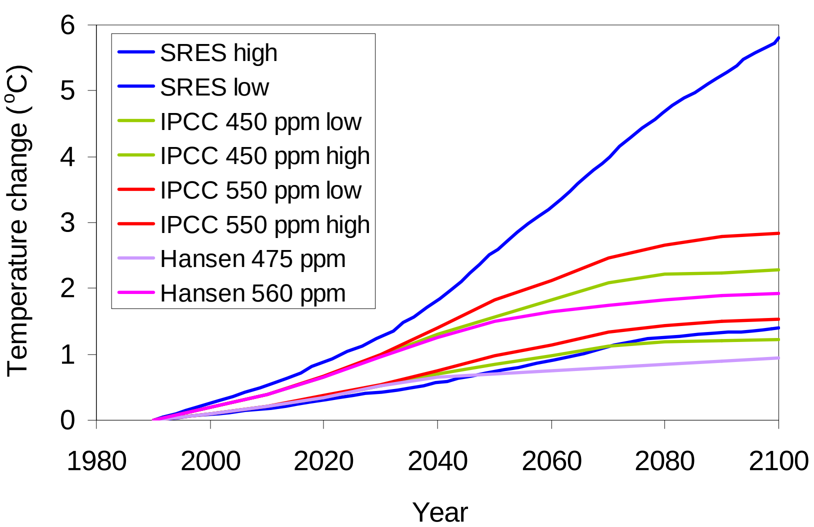

Figure B5. Comparison of projected global warming based on various assumptions about greenhouse gas emissions: SRES, IPCC scenarios for CO_2 stabilisation at 550 and 450 ppm, and Hansen's "alternative" scenarios for CO_2 stabilisation at 560 and 475 ppm.

Therefore, slowing global warming will require significant emission reductions while regions simultaneously prepare for the impacts of climate change that are already in the pipeline. The IPCC (2001d) concluded that the greater the reductions in emissions and the earlier they are introduced, the smaller and slower the projected warming and consequent impacts.

The Kyoto Protocol is focussed on the period 2008-2012, with the aim of reducing CO_2 emissions from developed countries by 5%. Ratification of the Kyoto Protocol requires a "double trigger" (UNFCCC, 2002). The first trigger is ratification by 55 governments - a requirement that was met in 2002. The second trigger is that the ratifying governments must include developed countries representing at least 55% of that group's 1990 CO_2 emissions. Since the USA (36%) is not intending to ratify, the 55% threshold can only be met with the participation of Russia (17%). The President of Russia signed the federal law to ratify the Kyoto Protocol on 4 November 2004 (UNFCCC, 2004). The final step in the ratification process will be the deposit of the formal instrument of ratification with the Secretary-General of the United Nations in New York. The Kyoto Protocol will enter into force 90 days later. Further commitments would be needed so that developed countries reduce emissions substantially after 2012, and so that emissions from developing countries do not grow as much as expected. Various approaches are being considered (WBGU, 2003).

Appendix C: Synoptic typing

The pressure patterns associated with heavy rainfall days have been analysed to determine the synoptic-scale weather patterns that are conducive to extreme rainfall in the study region. The technique is known as synoptic typing and follows the method of Yarnal (1993). This is a correlation-based, gridded map-typing technique in which days are grouped based on the Pearson product-moment correlations (r_{xy}) to establish the degree of similarity between map pairs. Similar fields are identified on the basis of similar spatial structures (i.e. highs and lows in similar positions) with little emphasis on the magnitude of the patterns.

To establish a synoptic climatology compatible with the CSIRO Mark 3 model output, this technique was first applied to NCEP 00 UTC MSLP fields valid for the extreme rainfall days for the study region. These fields were extracted for the 49 points (7×7) in the region between 140 and 165°E and 35 and 20°S, and were further divided in summer (Oct-Mar) and winter (Apr-Sep) series. The following steps were then applied:

Each daily MSLP grid is first normalised:

$$Z_i = \frac{x_i - \overline{X}}{s} \qquad 3.1$$

where Z_i is the normalised value of grid-point i, x_i is the observed value at grid-point i, $\overline{X}$ is the mean of the N-point grid and s is the standard deviation of the grid. The effect of this normalisation is to eliminate the seasonal impact on pressure pattern intensity, thus permitting direct inter-seasonal map comparisons.

Once nomalised, each daily map pattern in the extreme rainfall subset is compared with all other maps in the subset using Pearson product-moment correlations (r_{xy}).

$$r_{xy} = \frac{\sum_{i=1}^{N}\left[\left(x_i - \overline{X}\right)\left(y_i - \overline{Y}\right)\right]}{\sqrt{\sum_{i=1}^{N}\left(x_i - \overline{X}\right)^2 \sum_{i=1}^{N}\left(y_i - \overline{Y}\right)^2}} \qquad 3.2$$

In this formula, x_i and y_i represents the variable at each of the N grid points of the two maps being compared. $\overline{X}$ and $\overline{Y}$ represent the means of the N-point grids. Pairs of MSLP maps are considered similar if $r_{xy} \geq 0.7$. Yarnal (1993) discusses the numerous sources of subjectivity in choosing a correlation threshold. The value of 0.7 was chosen after experimentation showed that it provided an acceptable balance between the number of patterns produced and the number of days that were not classified.

Once all days have been compared with all other days in the dataset, the day with the largest numbers of r_{xy} values meeting the threshold criteria is designated “key day” 1 and is considered representative of the first map type. This “key day’ as well as all the days with which it is considered to be similar on the basis of the correlations are then removed from the analysis. All days deemed to be similar to each of those days are also removed. The analysis is then repeated with the reduced dataset to find “key day 2”, and so on, until all days are classified into m groups of 3 days or more. The remainder are considered unclassified.

Once the “key days” are established, a second pass over the entire data set is made. This is necessary because it is possible for any grid to be significantly correlated with more than one grid. In this step, each map pattern is assigned to the map pattern represented by the “key day” for which it produces the highest correlation. After the typing procedure was completed for the NCEP extreme rainfall dataset, the “key days” produced were used to type the gridded MSLP fields for “extreme” rainfall days extracted from the Mark3 climate model, for the present, 2030 and 2070 climates.