Climate change in South Australia

Report on:

Assessment of climate change, impacts and possible adaptation strategies relevant to South Australia

Undertaken for the South Australian Government by the Climate Impact Group, CSIRO Atmospheric Research

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Important Disclaimer

This report relates to climate change scenarios based on computer modelling. Models involve simplifications of the real physical processes that are not fully understood. Accordingly, no responsibility will be accepted by CSIRO or the South Australian Government for the accuracy of projections in this report or actions on reliance of this report.

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EXECUTIVE SUMMARY

This report presents results of a project undertaken by CSIRO for the South Australian Government to assess observed and projected climate change in South Australia, its impacts and potential adaptations. The assessment draws upon the latest findings of the Intergovernmental Panel on Climate Change (IPCC), as well as regionally-specific analyses of a broad range of climate modelling results.

IPCC

The Third Assessment Report of the IPCC (2001) 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.
- Confidence in the ability of models to project future climates has increased.
- Atmospheric composition will continue to change throughout the 21st century.
- Global average temperature and sea level are projected to rise.

It is thus appropriate to identify how South Australia may be affected by future climate change, and to identify adaptations needed to reduce vulnerability and to maximise potential benefits.

Observed climate trends in South Australia

- Over the period spanning 1910 to 2000, Australia's average temperature increased by 0.76ºC (0.08ºC per decade), with the minimum temperature increasing by 0.96ºC (0.11 per decade) and maximum temperature by 0.56ºC (0.06ºC per decade). The rate of increase has been more rapid in the period since 1950 (0.13ºC per decade for maximum temperature and 0.21ºC per decade for minimum temperature). The frequency of extremely warm days and nights has increased while that of extremely cool days and nights has decreased since 1957.

- Since 1950, South Australia's average maximum temperature has increased by 0.17ºC per decade, the minimum by 0.18ºC per decade and the average temperature by 0.17ºC per decade. Thus, compared to national trends, South Australian maximum temperature indicates a faster rate, while minimum temperature shows a slower rate.

- Sea surface temperatures in the region have risen at about half the rate of the land-based temperatures.

- Trends in South Australian annual rainfall since 1910 are generally weaker than other parts of the continent. Most of the northern half of the state has experienced an increasing rainfall trend while southern coastal regions around the Eyre Peninsula and the far south-east of the State have experienced drying trends since 1950.

Climate models' representation of South Australia's climate

- An assessment of ten global climate models (GCMs) (including two CSIRO GCMs, Mark2 and Mark3) and two CSIRO regional climate models (RCMs) in their ability to simulate observed patterns of mean sea level pressure, temperature and rainfall indicated that all but two models performed satisfactorily. All of the CSIRO models performed well.

- Analysis of the relationship between simulated pressure and rainfall revealed strong variations from model to model and also from season to season. The Mark3 model was the best performer over spring, summer and autumn while most models performed poorly during winter.

Average regional temperature, rainfall and potential evaporation projections

Ranges of change in average rainfall and temperature for South Australia have been prepared from the latest simulations of ten climate models and include the key uncertainties such as the IPCC range of future greenhouse gas emission scenarios, the IPCC range of global warming, and the model-to-model differences in the regional pattern of climate change. The results are shown in Figure A1 and may be summarised as follows:

- Annual average temperatures over the north of the state are 0.4 to 2.0°C higher by 2030 and 1.0 to 6.0°C higher by 2070. In the south temperatures increase by 0.2 to 1.4°C by 2030 and 0.6 to 4.4°C by 2070 and these changes are almost uniform throughout the year. Patterns of warming in summer and autumn are similar to the annual patterns. In the north of the state in winter, the range of possible warming is smaller (0.4 to 1.7°C by 2030 and 1.0 to 5.2°C by 2070) while in spring, it is greater (0.4 to 2.2°C by 2030 and 1.2 to 6.8°C by 2070).

- In summer over most of the north-east of the state, increases and decreases of rainfall in the range of –13 to +13% by 2030 and –40 to +40% by 2070 are equally likely. In other areas, projected summer ranges tend towards decreases (-13 to +6%). Autumn sees broad ranges of change apply over much of the north-east of the state, (–13 to +13% by 2030 and –40 to +40% by 2070) although some areas tend towards increase. In the south of the state, narrower ranges of change apply, tending mostly towards rainfall decreases. In winter the tendency is towards decreases in rainfall, with larger ranges of uncertainty in the north of the state. In spring, decreases in rainfall of up to –20% by 2030 and –60% by 2070 are indicated. In the north of the state, changes are indicated in the range of –13 to +6% by 2030 and –60 to +20% by 2070.

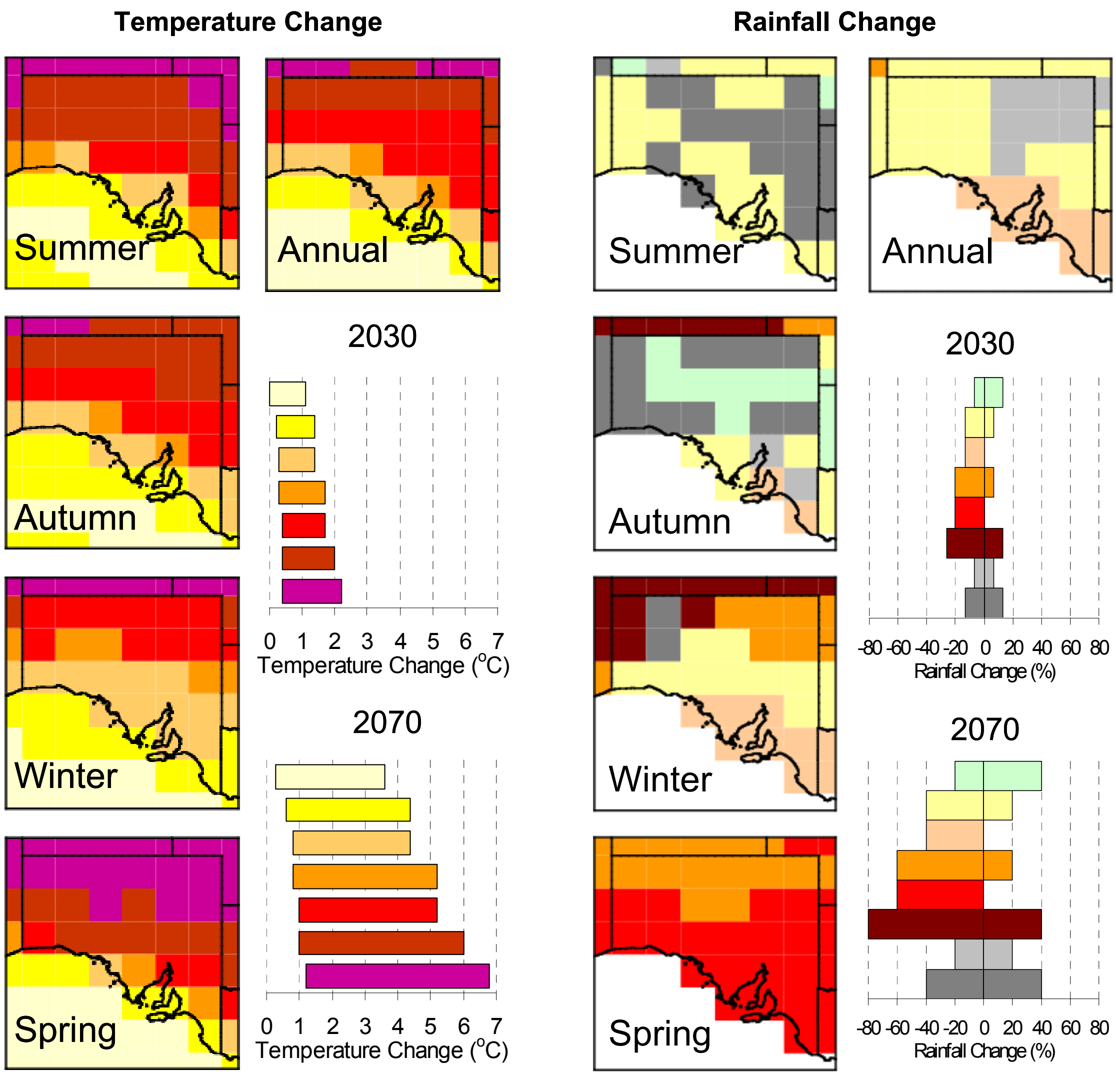

Figure A1: *Ranges of change in average temperature (°C) and rainfall (%) for around 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the seasonal and annual maps.*

- Over the ocean, surface air temperature changes reflect those of sea surface temperature. Much of the continental shelf including Spencer Gulf, indicates temperature increases in the range of 0.2 to 1.2°C by 2030 and 0.6 to 3.6°C by 2070. The Gulf of St Vincent in winter exhibits a narrower range of warming of 0.3 to 1.2°C by 2030 and 0.8 to 3.6°C by 2070.

- Projections of annual potential evaporation indicate increases across the state with the largest increases seen in the far east and north-west of the state and the smallest increases in coastal regions around Adelaide and the Eyre Peninsula. Average annual water balance show deficits throughout the state with the largest values in the south-east of the state and the smallest in the west of the state.

Changes in extreme temperature, rainfall and drought

- Model results indicate that future increases in daily maximum and minimum temperatures will be similar to the changes in average temperature. The frequency of extreme maximum temperatures will increase while the frequency of extreme minimum temperatures will decrease.

- The frequency of hot spells above 35°C and 40°C are projected to increase across most of the state with the largest increases in the north. Little or no change in hot spells is likely in the far south-east of the state or Kangaroo Island.

- Despite decreases in average rainfall over most of South Australia in most seasons by 0 to 30%, extreme rainfall is found to increase by between 0 to 10%. The specific weather patterns associated with heavy summer rainfall in the north of the state are projected to increase both in terms of frequency of events and magnitude of rainfall, with a projected 20% increase in flood frequency in northern South Australia.

- All climate models show an increase in the frequency of droughts towards the end of the century.

Extreme events at the coast

Storm surges of at least half a metre in height occur year round along the South Australian coast with the greatest frequency of events occurring during the winter and spring months. They are caused by the westerlies or south-westerlies following the passage of cold fronts and their associated mid-latitude low pressure systems further to the south.

- The frequency of wintertime low pressure systems (lows) decreases by about 20% in the vicinity of South Australia under enhanced greenhouse conditions. Central pressures of the most extreme lows were lower by about 2 hPa on average indicating slightly more intense lows under enhanced greenhouse conditions. Accumulated rainfall accompanying the lows in the South Australian region decreased by between 10 and 20% under enhanced greenhouse conditions owing to the fewer low systems occurring The amount of rainfall per low however tended to increase by up to 10% over the Bight and coastal regions in the western half of the state. The frequency of mid-latitude lows in spring increased by 2% while the most extreme lows deepened by about 1 hPa.

- Extreme wind speeds were found to decrease across much of South Australia and the Bight in winter and summer. Increases in extreme wind speed occurred over the north of the state in autumn and spring while decreases occurred in the south of the state and over the Bight.

- Examination of wind direction changes, particularly in westerlies, south-westerlies and southerlies, that can be responsible for storm surge occurrence in South Australia, revealed only minor changes in winter in South Australian with south-westerly coastal regions tending towards decreases in frequency. However, there were relatively larger increases in frequency of westerlies, south-westerlies and southerlies in eastern coastal regions in spring. Patterns of change were qualitatively similar in autumn but weaker than spring while in summer, increases occurred only in the frequency of southerlies.

Impacts and adaptation strategies for climate change in South Australia

A vulnerability-based approach to risk assessment, which begins with the damages or consequences and diagnoses the climatic conditions that contribute to particular levels of damage, is outlined. This approach requires significant stakeholder input and benefits from the development of close collaborative links between stakeholders and climate scientists.

Sector-based issues were discussed with stakeholders in workshops conducted during the course of the project with a view to identifying priority areas for future research. Some key issues for the different sectors are presented in the following table:

Sector	Key Issues
Water and Catchments	Although the adaptive capacity of water management is high owing to large interannual climate variability, projected long term reductions in water supply due to climate change need to be assessed
Agriculture	This sector is generally well adapted to climate variability but further work is needed on how climate change may affect production systems to maximise agricultural performance under future climate conditions
Biodiversity	Understanding of the relationships between biota and climate change at the species and community level is generally poor and needs improvement in order to develop options for planned adaptation
Coasts	Rising sea levels in the future combined with storms of possibly greater intensity will increase the vulnerability of low lying coasts with little setback to allow for adaption
Health	With trends in South Australia towards an aging population, the major risks of climate change in this sector are likely to be heat stress while health impacts associated with floods, such as drowning and vector-bourne diseases, are likely to increase only in the north of the state.
Energy and Urban Settlement	Increasing frequencies of high temperatures will increase energy usage in warmer months and the capacity of increased energy demands may require assessment. More extreme rainfall events in the future may require the implementation of adaptation and mitigation strategies in low-lying suburbs of Adelaide.

Recommendations for further research

Recommendations for future research based on the results of the present study, as well as feedback from stakeholder workshops, include:

- Development of techniques that enable probabilities to be attached to the range of possible change in future climate that accompanies climate projections;
- Analysis of additional climate variables such as humidity and coastal water temperatures;
- Improved analysis techniques for extreme rainfall change;
- Analysis of storm tracks and extreme winds in other available models to determine the generality of the changes seen in the present study;
- An impact study to assess the relative effects of rising sea levels and changes in storm and wind frequencies on storm surge return periods.

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1. Introduction

Substantial increases in carbon dioxide concentrations are inevitable during the course of the 21st century, despite international efforts to reduce emissions of greenhouse gases. Consequently some global warming and climate change will continue to occur. It is therefore appropriate to identify how South Australia may be affected by future climate change, and to identify adaptations to reduce vulnerability and to maximise potential benefits. This task requires the best available estimates of the future regional climate change and its impacts and the casting of this information, including uncertainties, in a form that is relevant to current planning and decision-making. This report presents results from a study undertaken by CSIRO for the South Australian Government aimed at providing these requirements for adaptation planning.

The aims of the research activities are:

- An assessment of how climate change is likely to affect South Australia;
- Identification of vulnerable areas that need to be addressed in ongoing research so that adaptation strategies can be developed;
- Increased knowledge amongst stakeholders of the risks and opportunities posed by climate change and of the need to consider adaptation strategies.

The research activities undertaken for this study include:

- An assessment of how well current climate models simulate the climate of South Australia;
- Analysis of enhanced greenhouse changes over South Australia in terms of mean temperature, rainfall, potential evaporation and water balance;
- Analysis of enhanced greenhouse changes over various regions of South Australia in terms of extremes in temperature and hot spells, rainfall extremes, droughts and weather systems responsible for heavy summer rain in the north;
- Analysis of changes in climate relevant to coastal impacts including winds and weather systems responsible for storm surges and the scoping of a research project for quantifying changes in storm surge risk.

Inherent in the projections of future climate change are large uncertainties that must be incorporated into impact and adaptation assessments. To facilitate the planning, development and prioritisation of such assessments, a framework for risk assessment being developed at CSIRO and internationally is also presented in this report. This framework utilises a formalised set of techniques for managing uncertainty. This section is complemented by a report of two workshops undertaken with stakeholders to identify and communicate potentially vulnerable impact areas.

2. Global climate change and observed regional trends

In February 2001, Working Group One of the Intergovernmental Panel on Climate Change (IPCC) released a summary of its Third Assessment Report (IPCC, 2001). This report provides a comprehensive and authoritative assessment of the science of climate change, and is essential background material for analysing climate change in South Australia.

The key findings of the IPCC regarding climate change up to the present are as follows:

- 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.

Figure 1 is based on results used in the Third Assessment Report and shows atmospheric concentrations of carbon dioxide (CO_2) over the past thousand years based on ice-core data combined with direct measurements for the recent period. This illustrates the recent increase in CO_2 concentrations, which is largely a consequence of rapidly increasing fossil fuel use since the Industrial Revolution. CO_2 concentration has risen from a background level of around 280 parts per million (ppm) to its current level of around 370 ppm and is now higher than at any time over the past 420,000 years. The rate of increase of CO_2 is also higher than at any time in at least the past 20,000 years. Also shown in Figure 1 is a record of Northern Hemisphere temperatures based on proxy records combined with direct measurements for the most recent period. The recent increase in temperature is also unusual relative to hemispheric temperature variations over the past one thousand years.

With regard to future climate change, the IPCC's key findings were:

- Confidence in the ability of models to project future climates has increased.
- Atmospheric composition will continue to change throughout the 21st century.
- Global average temperature and sea level are projected to rise.

The IPCC provided a range of projected global average warming and sea-level rise, based upon a set of future emission scenarios of greenhouse gases and sulphate aerosols, known as the 'SRES' scenarios and on the results of global climate modelling. These scenarios allowed for a broad range of plausible future technology-population-economy pathways, and updated an earlier set of emission scenarios known as the 'IS92' scenarios (IPCC, 1996). Representative carbon dioxide emissions for the A1B, A1T, A1F, A2, B1 and B2 scenarios are shown in Figure 2a and the associated atmospheric concentrations in Figure 2b. Note that even for scenarios such as B1 that show a reversal in the rate of emissions around 2040, CO_2 concentrations will still increase throughout this century from about 370 ppm in the year 2000 to 550 ppm by 2100 for the B1 scenario. For the SRES scenarios, concentrations of other greenhouse gases also increase. A key difference between the SRES scenarios and the earlier IS92 scenarios is that projected increases in sulphate aerosols, associated with tropospheric cooling, are now expected to be much smaller than had been previously estimated.

The IPCC used the SRES scenarios in combination with the results of range of climate models to give ranges of projected future global average warming and sea-level rise. Figure 2c shows the IPCC range of projected global warming based on the range of SRES scenarios and average response of a group of global climate models (pink lines) and the range where model-to-model variations are allowed for as well (blue lines). The pink lines show that about half of the warming stems from uncertainty about future human behaviour (variations in emissions). Global average warming ranges from 1.4 to 5.8ºC by the year 2100, relative to 1990, which is a warming rate of 0.1 to 0.5ºC per decade. The observed warming rate since the 1970s has been 0.15ºC per decade. Associated with this warming is a rise in sea level of 0.09 to 0.88 m by 2100, or 8 to 80 mm per decade (Figure 2d). The observed sea-level rise over the 20th century has been 10 to 20 mm per decade. Australian stations, after correction for geological effects and data quality, indicated a sea level rise of 0.12 to 0.16 m during the past century (Lambeck, 2001).

The IPCC also noted that various gaps in information and understanding remain. These particularly concern the need for better estimates of emissions of greenhouse gases and their associated climate forcings and more complete understanding of key atmospheric feedback processes such as those involving clouds, sea-ice and the oceans.

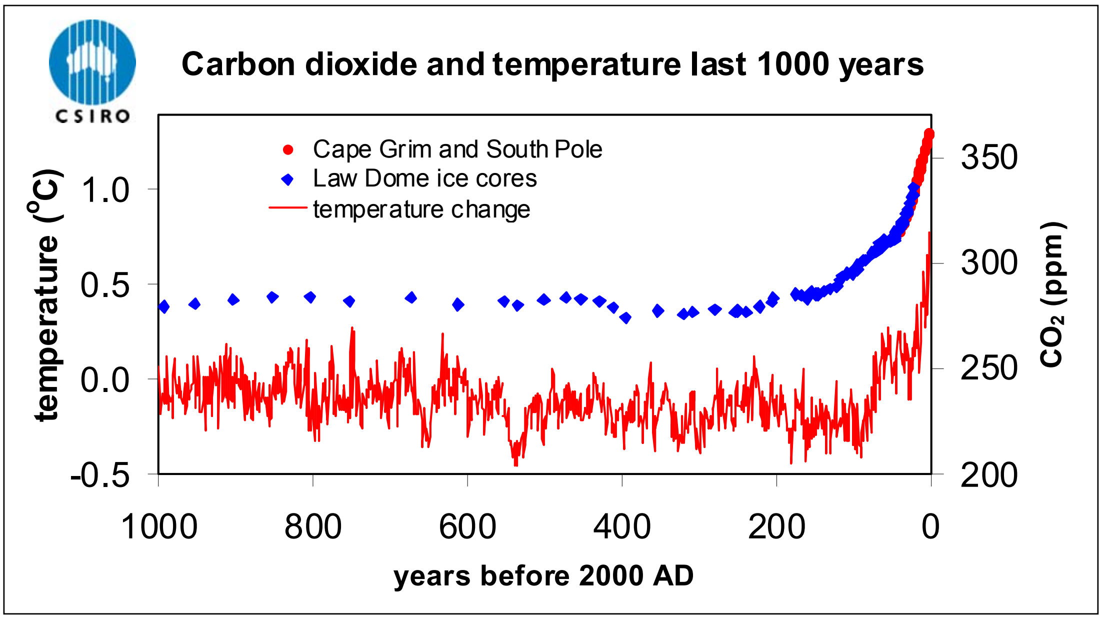

Figure 1: *Global CO_2 concentrations (direct observations and ice core data) and Northern Hemisphere temperature anomaly (direct observations and proxy, mainly tree-ring, data). Sources: Mann et al. (1999) and Etheridge et al. (1996).*

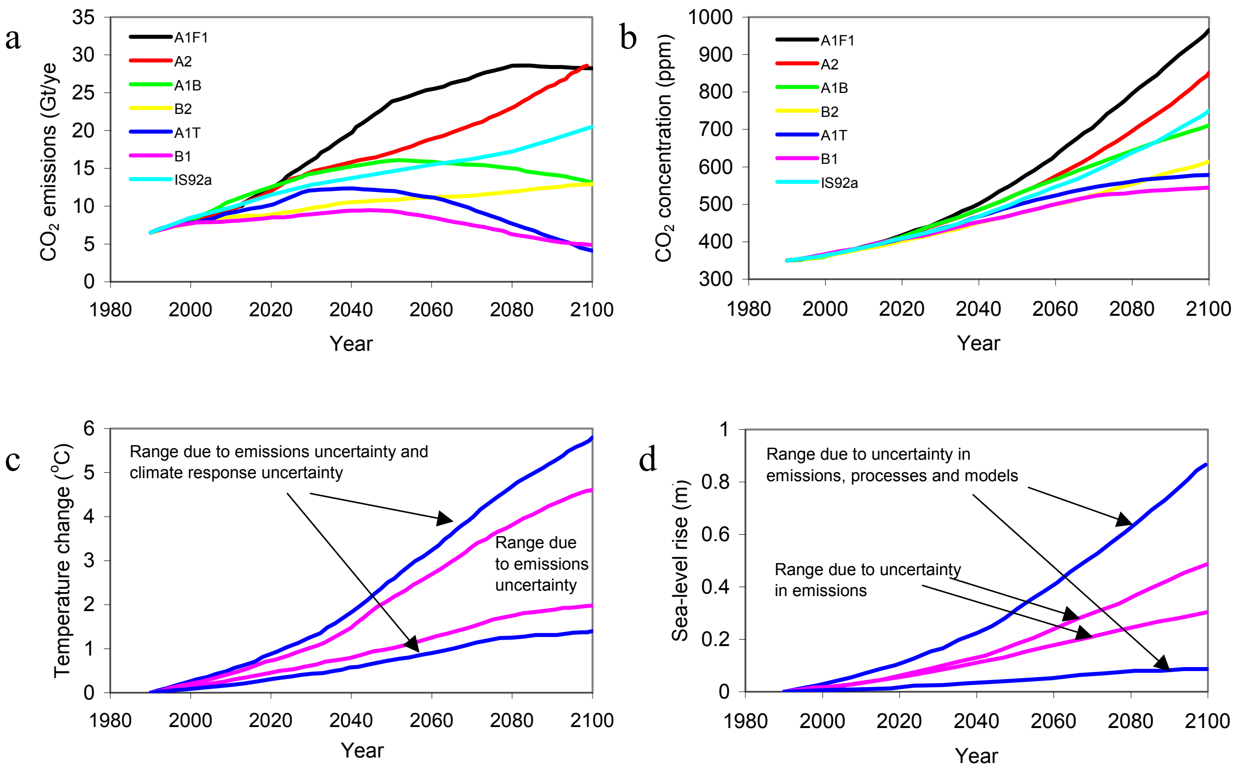

Figure 2: *(a) Six of the SRES emission scenarios for carbon dioxide (CO_2), plus the IS92a mid-case scenario used by the IPCC in 1996, (b) corresponding atmospheric concentrations, (c) ranges of global-average warming relative to 1990 and (d) ranges of global average sea-level rise relative to 1990. From IPCC (2001).*

South Australia's climate is strongly influenced by the continental air mass and surrounding oceans. Dominant weather systems that affect South Australia during the winter half of the year include frontal systems in the mid-latitude westerlies and sometimes cloud bands extending from the north-west of the continent. In spring and summer, there is a considerable influence from tropical air masses particularly over the north of the state, but frontal systems may still bring rainfall and cool weather. The interplay of these various influences results in South Australia having a climate that is highly variable in space and on time scales from the daily to decadal and longer. Natural climatic variability is thus a strong element of the observed climatic record of the region and provides the background against which any enhanced greenhouse climatic trends need to be viewed.

2.1 Temperature record

During the 20th century, the globally averaged surface temperature has increased by 0.6 ± 0.2ºC and it is very likely that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record (IPCC, 2001). Analysis of temperature trends in the Australian region for 1910 to 2000 (D. Collins pers. comm., 2002) shows that the Australian average temperature has increased by 0.76ºC over this period. Minimum temperature has increased by 0.96ºC and the maximum has increased by 0.56ºC. This warming is consistent with the global temperature trend reported by IPCC (2001), although the regional warming over the second half of the century has been stronger. For the period 1950 to 2000, Australian average surface temperature has shown an increase of 1.68ºC per century. Maximum temperatures have increased at a rate of 1.26ºC per century and minimum temperatures have increased by 2.10ºC per century.

Figures 3a and b show minimum and maximum temperature anomalies for South Australia from 1950 to 2001 based on an average of eleven stations across the state. The South Australian trends are very close to all-Australian trends. The South Australian maximum temperature has increased by 1.69ºC per century, minimum by 1.78ºC per century and the average temperature by 1.74ºC per century. As in the general pattern for Australia, minimum temperature shows slightly greater increases than maximum temperature.

The frequency of extremely warm days and nights has increased while that of extremely cool days and nights has decreased during the last five decades (Plummer et al., 1999; Collins et al., 2000). For areas affected by frost, Collins et al. (2000) found that the annual number of frost days nationally declined by an average of 5.6 from 1957 to 1996 and the average length of the frost season shortened by around ten days. These changes are qualitatively applicable to South Australia where minimum temperatures and the number of days with warm nights have increased across the State.

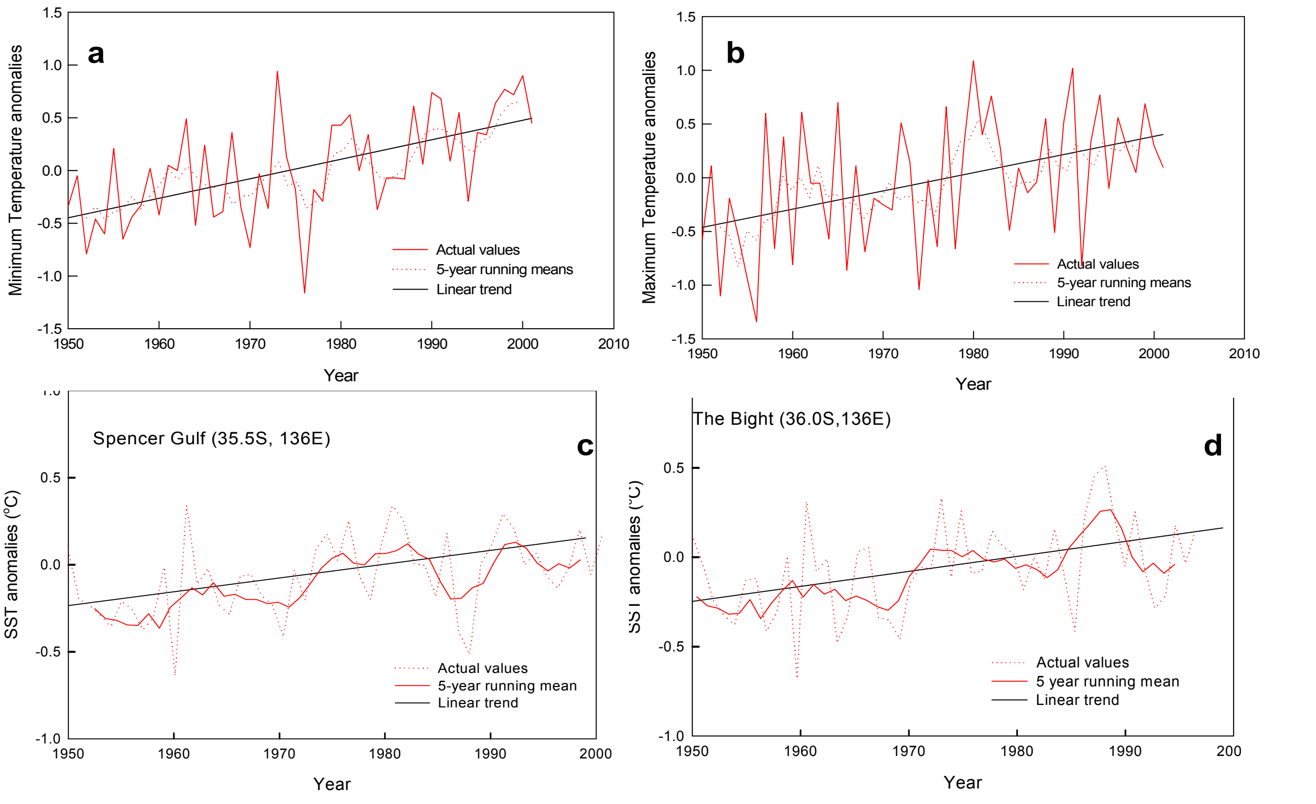

Figure 3: *Trend in (a) minimum and (b) maximum temperatures for South Australia and trends in sea surface temperature at (c) a location in the southern Spencer Gulf and (d) The Great Australian Bight.*

Figures 3c and d show changes in sea surface temperature over the interval 1950 to 2000 for a location on the continental shelf at the mouth of Spencer Gulf (35.5°S, 136°E) and in the deeper and cooler water further south in the Bight (38°S, 136°E) obtained from the most recent version (version 4) of the Global Sea-Ice and Sea Surface Temperature (GISST) data set, earlier versions of which are described in Parker et al. (1995) and Rayner et al. (1996). These data indicate that water temperatures have increased by 0.39°C and 0.43°C on the continental shelf and in the Bight respectively. These increases are about half of those seen at the aggregate of land-based stations in South Australia since 1950.

2.2 Rainfall record

At the broadest scale through the 20^{th} Century, an increasing rainfall trend has been evident for the middle to high latitude land areas in the Northern Hemisphere, and there is a weak decreasing trend across the tropics and subtropics (IPCC, 2001). Australian observed rainfall records also show a slight increasing trend over many parts of the country during the 20^{th} century, except for south-western Western Australia and some parts of inland Queensland (Figure 4a). However, during the second half of the century, there is a stronger tendency for decreased rainfall in south-western Western Australia and eastern Australia. The decreasing trend during the last 50 years over eastern Australia extends from Cape York Peninsula in the north to Victoria and some parts of Tasmania (Figure 4b). However, most of these trends are weak relative to natural decadal-scale fluctuations. In particular, the 1970s were wet in many parts of the country, while 1990s were dry in many parts. Much of the northern half of South Australia experienced an increasing rainfall trend while southern coastal regions around the Eyre Peninsula and the far south-east of the state have experienced drying trends since 1950.

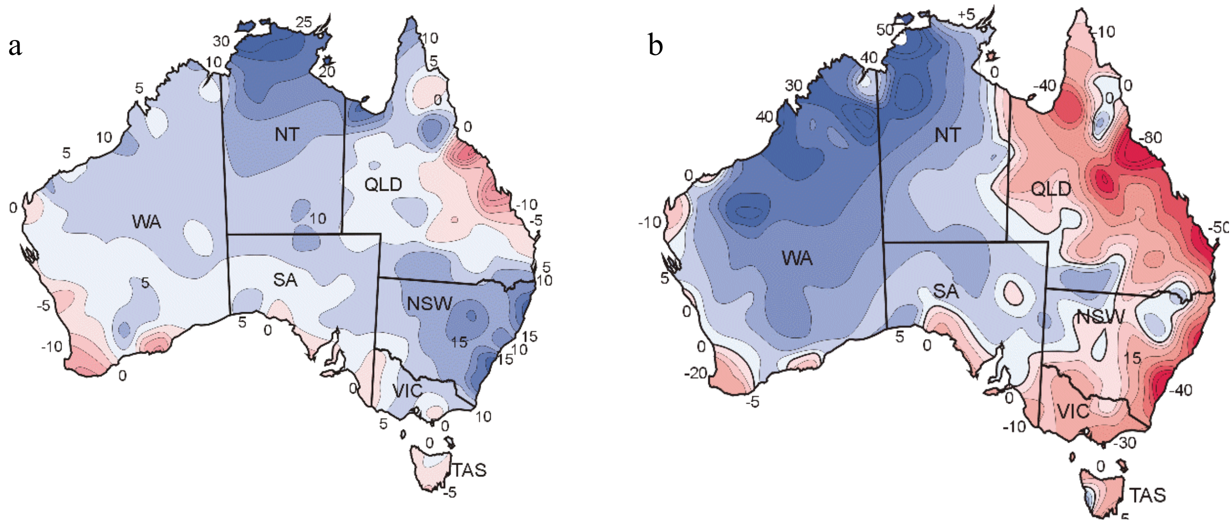

Figure 4: *Rainfall trends in Australia for (a) 1910 to 1999 and (b) 1950-1999. Trends are shown as mm per 10 years. Source: Della-Marta (pers .comm.)*

3. Simulating current regional climate

Global Climate Models (GCMs) are the best available tools to study the future climates of the earth. These GCMs solve complex mathematical equations that represent the physical processes underlying atmospheric and oceanic circulations. Meteorological variables that are available from GCMs include temperature, rainfall, surface pressure and winds. In addition to GCMs, climate change can be modelled using Regional Climate Models (RCMs). These are models that simulate the atmosphere over a smaller geographical domain at higher spatial resolution. The advantage of RCMs is that the results contain more detail particularly in the vicinity of coasts and varying topography. However, because these models are run over a subset of the globe, they are dependant on a GCM to provide boundary conditions at their lateral boundaries.

The development of climate change projections on a regional scale relies upon analysing as many GCMs and RCMs as is feasible to ensure that uncertainty due to the climate sensitivity inherent in different models is captured. A prerequisite for the inclusion of a GCM into the climate projections is that it adequately simulates present climate conditions. In this chapter, an assessment is made of the ability of a range of climate models to simulate current climate. Table 1 presents some key details pertaining to the simulations and data availability of the models considered.

Table 1: *Climate model simulations analysed in this report. Further information about the non-CSIRO simulations may be found at the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/). Note that DAR125 and CC50 are Regional Climate Models.*

Centre	Model	Emission Scenarios post-1990 (historical forcing prior to 1990)	Years	Horizontal resolution (km)	Temporal resolution available
CSIRO, Australia	Mark2	IS92a, SRES A2 (four simulations), SRES B2	1881–2100*	≈400	daily
CSIRO, Australia	DAR125 (RCM)	Nested in Mk2 with IS92a	1961-2100	≈125	daily
CSIRO, Australia	CC50 (RCM)	Nested in Mk2 with SRES A2	1961-2100	≈50	daily
CSIRO, Australia	Mark3	SRES A2	1961-2100	≈200	daily
Canadian CCCM	CCCM1	1% increase in CO_2 p.a.	1900–2100	≈400	monthly
Canadian CCCM	CCCM2	IS92a	1961-2100	≈400	monthly
DKRZ, Germany	ECHAM3/LSG	IS92a	1880-2085	≈600	monthly
GFDL	GFDL	1% increase in CO_2 p.a.	1958–2057	≈500	monthly
Hadley Centre, UK	HadCM2	1% increase in CO_2 p.a. (four simulations)	1861–2100	≈400	monthly
Hadley Centre, UK	HadCM3	IS92a	1861-2099	≈400	monthly
DKRZ, Germany	ECHAM4/OPYC3	IS92a	1860–2099	≈300	monthly
NCAR	NCAR	IS92a	1960-2099	≈500	monthly

* pre-1990 period common to the SRES simulations

3.1 Average patterns of temperature, precipitation and mean sea level pressure

Realistic patterns of mean sea level pressure are important because they are implicitly related to the circulation (i.e. wind) patterns in the models. Figure 5 illustrates the seasonal mean sea-level pressure patterns in the observations and in two models, the Mark 3 and the CC50. The movement of the subtropical ridge over the continent in winter and to the south of the continent in summer is well captured by the models although a slight overestimation in the strength of the ridge can be seen in the models across the continent, most noticeably during winter.

Statistical methods have been employed to objectively and efficiently test the performance of the model's present day climate. Observed and simulated patterns for 1961-1990 were compared by calculating the pattern correlation coefficient, which measures pattern similarity, and root mean square error (RMS), which measures magnitude differences. A pattern correlation coefficient of 1.0 indicates a perfect match between observed and simulated spatial pattern and RMS error of 0.0 indicates a perfect match between observed and simulated magnitudes. A domain bounded by 110-160ºE, 10-45ºS was used to test mean sea-level pressure and the results are presented in Figure 6. In these figures, the better the model performance, the closer to the top left-hand corner of each diagram the result will lie. The correlation coefficient of most models is above 0.8 indicating that the models simulate the observed pattern of mean sea-level pressure over a large area reasonably well. However, the RMS error is relatively large in some models, particularly in GFDL and in ECHAM3.

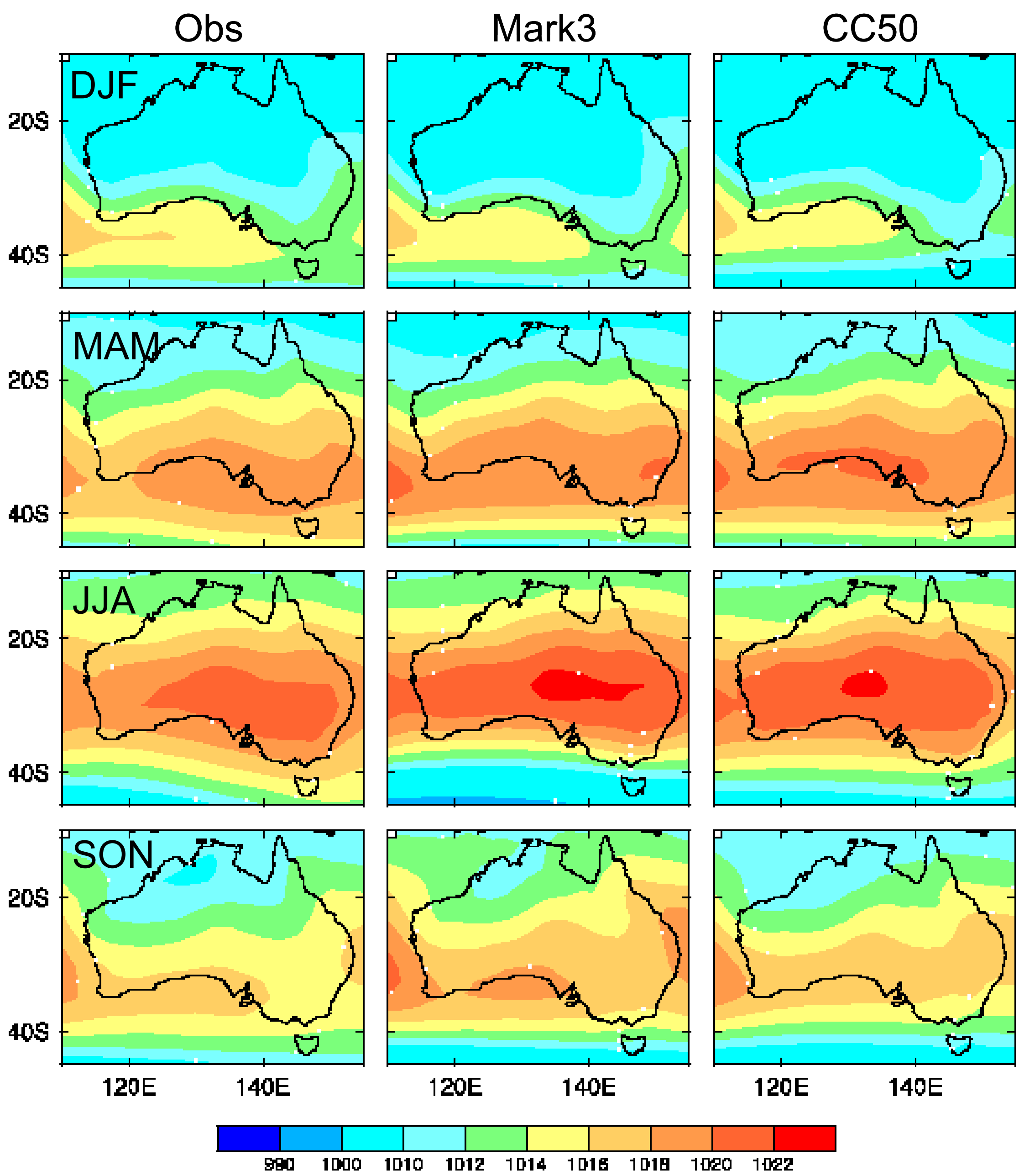

Figure 5: *Observed (left) and simulated pressure by CSIRO MARK3 (centre) and CC50 (right) for the period 1961-1990 for the four seasons summer (DJF), autumn (MAM), winter (JJA) and spring (SON).*

Figure 7 presents the seasonal observed temperature averaged over the period 1960-1990 and the corresponding patterns for the ECHAM3 and the CC50 model. The marked difference in the horizontal resolution of the models is clearly illustrated in this example with the lowest resolution ECHAM3 model unable to resolve the detailed temperature variation associated with terrain height particularly in the east of the continent. The highest resolution CC50 model, on the other hand, reproduces the observed spatial pattern of temperature remarkably well. However there is a tendency for the CC50 model to be too warm over the continent in summer and in the north of the continent in other seasons.

Figure 8 compares observed rainfall with the rainfall in DAR125 and CC50. In summer, both models produce higher rainfall over the south of the continent compared with the climatology. In autumn, DAR125 is drier over central Australia while the CC50 model is considerably wetter. Both models are wetter than the climatology over large parts of the continent in winter and spring.

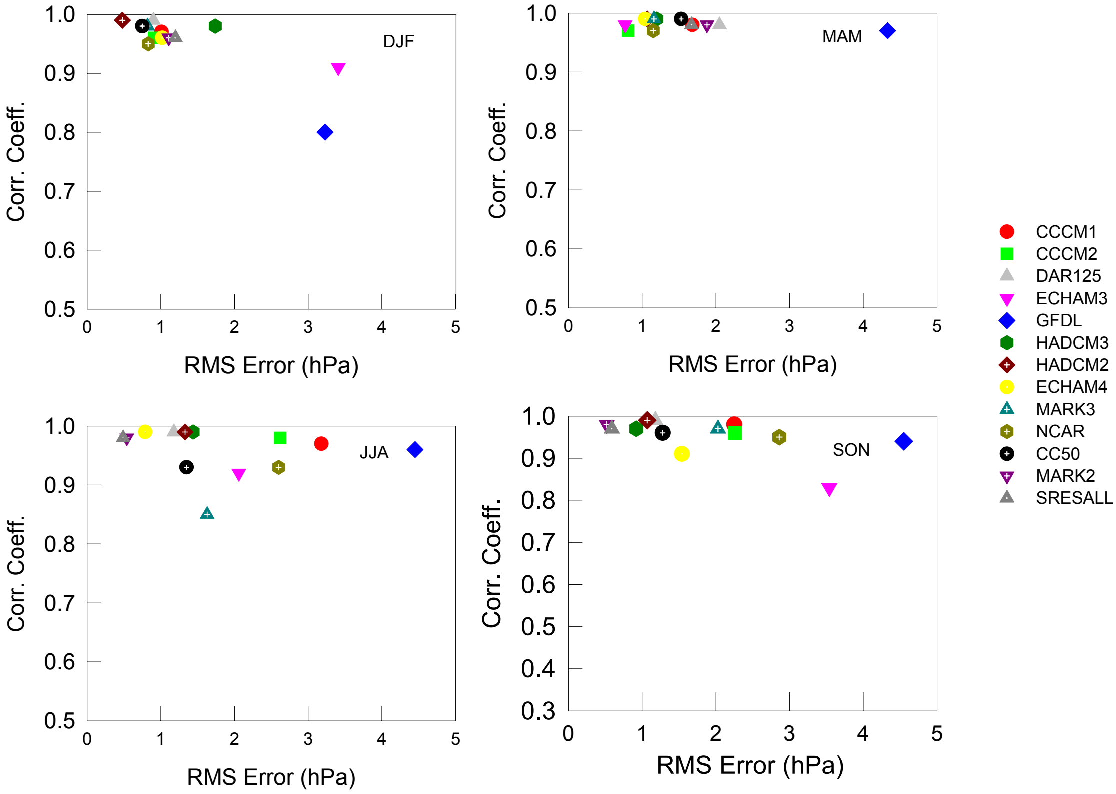

Figure 6: *Pattern correlation and RMS error for observed versus model mean sea-level pressure in each season for the models listed in Table 1.*

Figure 9 shows the pattern correlation and RMS error for temperature and rainfall for a number of models over an area that covers South Australia. In summer, autumn and spring, when the continent strongly influences temperature variations, the models perform well in representing the spatial variation of temperature. Most models simulate the temperature magnitudes well although ECHAM3 and ECHAM4 tend to be too warm over South Australia in summer and spring along with CC50 in summer and GFDL in spring. In winter, however, pattern correlations are more varied and RMS error values are larger, particularly for some of the lower resolution GCMs such as CCM1, CCM2, GFDL and NCAR. In winter, mid-latitude synoptic systems and local topography strongly drive the temperature patterns and it is therefore not surprising that the lower resolution models do not perform as well.

The simulation of rainfall by the models shows RMS errors that are less than 1 mm day^{-1} for most models and greater variation between models in representing the pattern of rainfall. In contrast to temperature, winter is the month in which all models show a high degree of skill in both pattern correlation and RMS error. Generally, it is the lower resolution GCMs that do not capture the spatial pattern of rainfall, the notable exception being the CC50 model in summer. Inspection of Figure 8 indicates that the pattern of rainfall is well captured in the east of the state but the model produces too much rain in this season in the west. In general however, the high resolution CSIRO RCM simulations perform well compared to the lower resolution GCMs.

These statistics suggest that most models capture the average climatic features reasonably well. However, some models clearly perform better than others. To compare the overall performance of each model, a simple point system based on thresholds was devised. Models with an RMS error greater than 2.0 or with a pattern correlation below 0.8 for MSLP and 0.6 for temperature and rainfall were assigned a point. A maximum of 12 points would indicate failure to satisfactorily reproduce either pattern or magnitude for each variable in each season. Using this system, the poorest performing models were ECHAM3 and GFDL with scores of nine and seven respectively. The best performing models were HADCM2 with a score of zero and HADCM3, Mark 2, DAR125 and CC50 with scores of one. On the basis of this analysis, it was decided to exclude ECHAM3 and GFDL from the scenario development carried out in the next chapter.

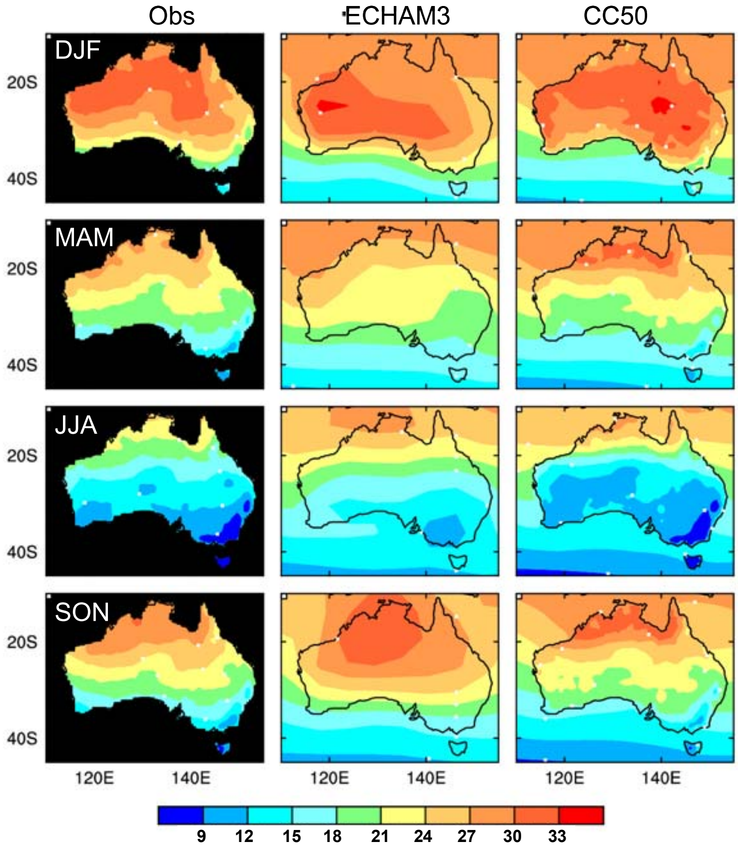

Figure 7: *Observed (left) and simulated temperature (°C) by ECHAM3 (centre) and CC50 (right) for the period 1961-1990.*

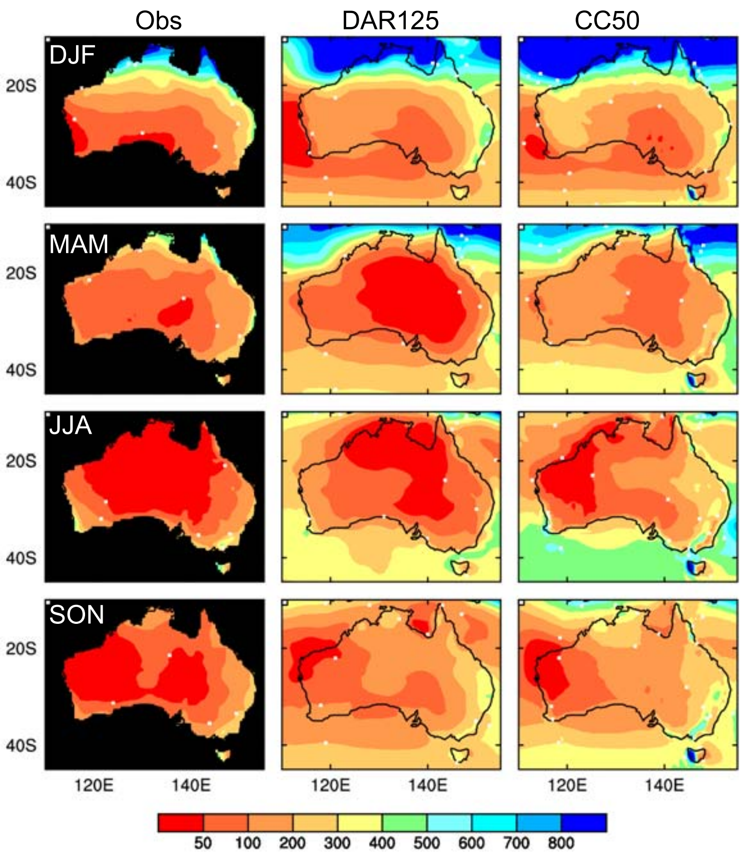

Figure 8: *Observed (left) and simulated rainfall (mm) by CSIRO DAR125 (centre) and CC50 (right) for the period 1961-1990.*

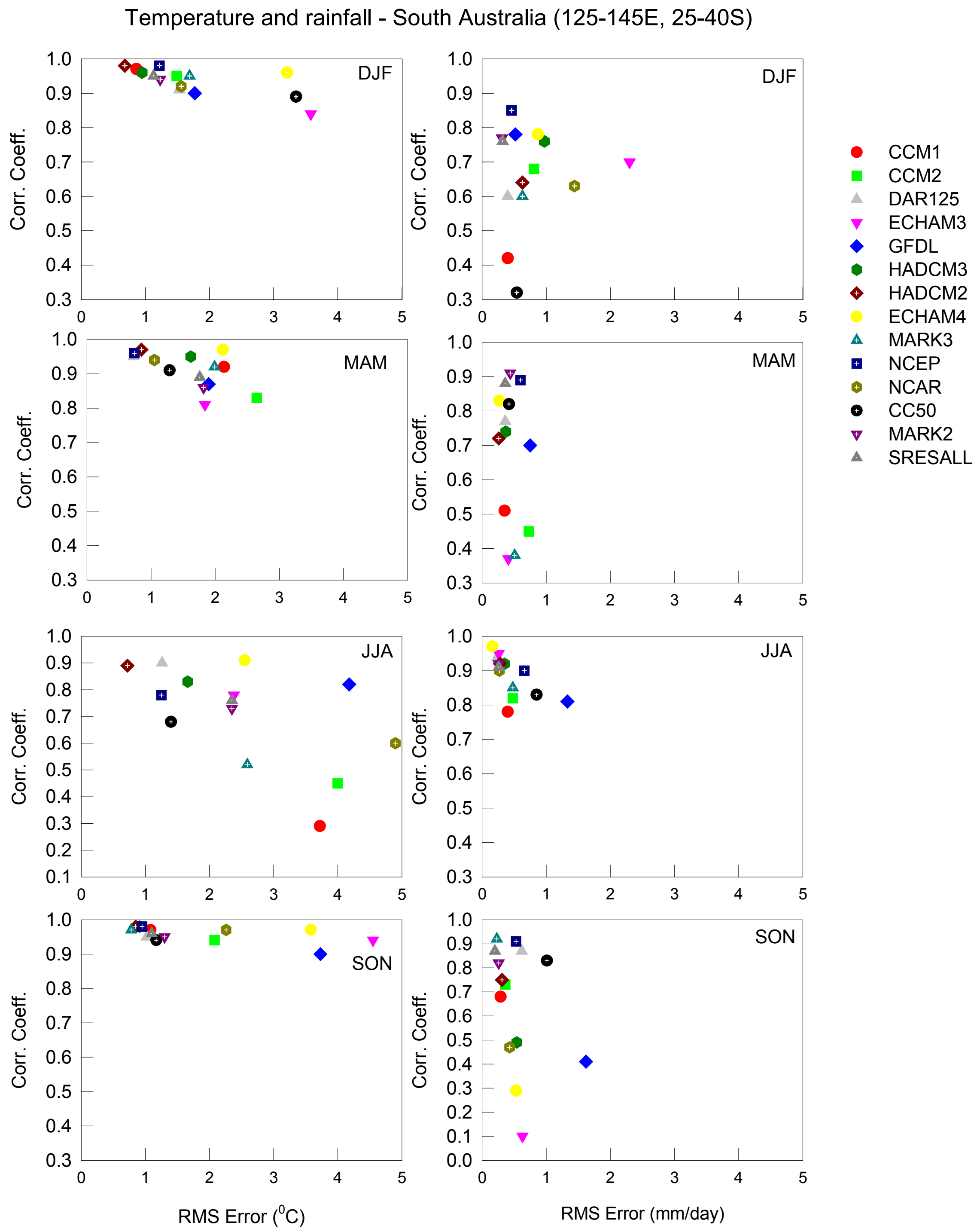

***Figure 9:** Pattern correlation and RMS error for observed versus model temperature (left column) rainfall (right column) for the models in Table 1.*

In addition to mean temperature, pattern correlations and RMS errors were calculated for maximum and minimum temperatures in seven of the twelve models for which these data were available. The spatial pattern of maximum temperature was well captured by all models with correlation coefficients all above 0.6. However, RMS errors were higher with five of the seven models producing RMS errors greater then 2°C in winter and summer. The models generally performed better in spring and autumn.

Minimum temperatures, on the other hand, had poorer spatial pattern especially in winter with correlation coefficients of less than 0.6 in five of the seven models. RMS errors were generally lower for minimum temperatures with errors of less than 2°C in five of the seven models in all seasons.

3.2 Relationship between atmospheric circulation patterns and rainfall over South Australia

The average climate of South Australia and its strong spatial and temporal variations are caused by the influences of various synoptic systems that affect the state during different seasons and by the topography of the state. During late spring, summer and early autumn, tropical air masses influence the rainfall particularly over the northern half of the state. During late autumn, winter and early spring, South Australia receives its rainfall from middle and high latitude frontal systems that originate in the Indian and Southern Ocean. In this section, the performance of the various climate models is assessed in terms of their ability to capture the relationship between the seasonal synoptic patterns and rainfall. This analysis forms the basis for choosing the most suitable model to analyse future changes to heavy summer rainfall events in the north of the state and wintertime frontal systems that influence the south of the state.

Correlation coefficients have been calculated between rainfall over South Australia and sea-level pressure over the Australian continent bounded by 110-160°E and 10-45°S over the period from 1950 to 2000 for each season. Rainfall observations are from the Bureau of Meteorology and pressure anomalies are derived from the National Center for Environmental Predictions (NCEP) reanalyses. Results of the correlation analysis are shown in Figure 10. Strengthening and weakening of correlations show the evolution of the relationship between mean sea-level pressure and rainfall from season to season. The negative correlations over the western half of the continent during summer indicate that low pressure systems associated with the Australian monsoon have a significant impact on rainfall at this time of the year. This ridge would be associated with north-easterly flow on its western flank. The cyclonic (clockwise) curvature of flow in this region can be associated with summer thunderstorms in south-eastern Australia. These conditions can often precede the passage of summertime cold fronts.

The spatial correlation pattern for autumn shows strong negative correlations with pressure anomalies over the continent and a positive relationship over mid-latitude westerly regime south of the continent. In winter, rainfall is correlated with low pressure over the entire domain. The strongest correlations of $r = -0.7$ occur over the south-east of the state and are likely to be related to the rainfall with mid-latitude lows and their associated fronts, which contribute to wintertime rainfall over the south of the continent. In spring, the correlations are mostly negative and return to a spatial pattern that is similar to autumn.

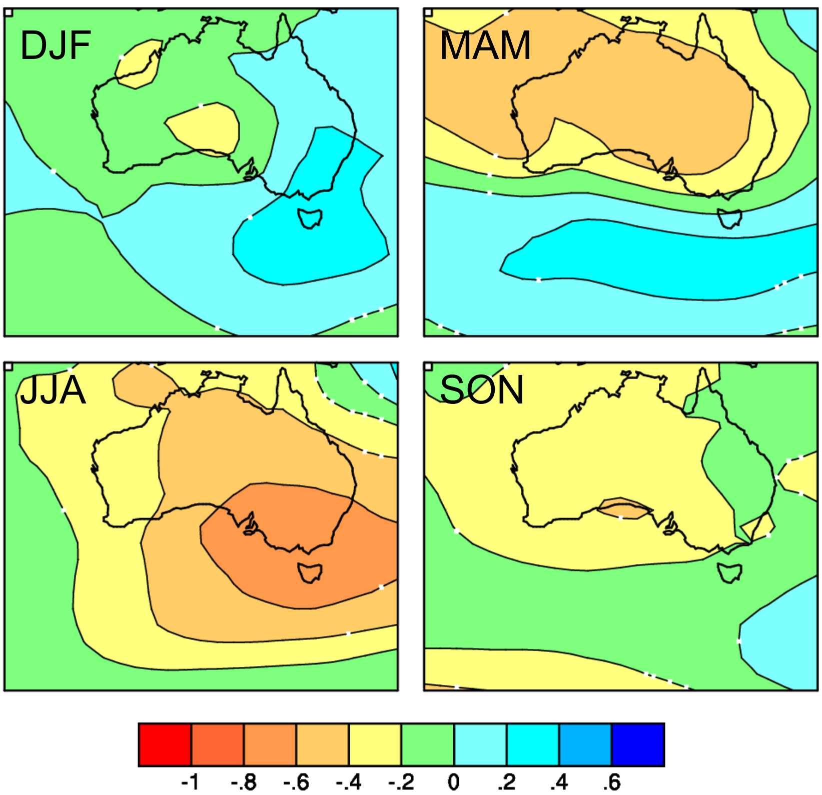

Figure 10: *Spatial correlation patterns between South Australian rainfall and sea level pressure over the region illustrated for each season.*

Correlation patterns between rainfall and sea-level pressure have also been generated for rainfall to the north and south of 31.5°S. These diagrams are reasonably similar to Figure 10 and so are not shown. The main differences are that in spring, rainfall in the southern half of the state shows stronger negative correlations with pressure over the south-east of the continent indicating that spring rainfall in the south is similar to winter rainfall in terms of how it is produced. Rainfall over the northern half of the state shows stronger negative correlations with pressure over the north-west of the continent in winter. Correlation patterns for other seasons are generally similar to Figure 10.

A similar analysis was conducted between the model simulated rainfall over South Australia and regional sea-level pressure for each of the available models. The model correlation patterns were then compared to the observed correlation patterns and a single correlation coefficient generated. Following this, the model correlation patterns for rainfall in the north and south of the state with regional sea-level pressure were compared with the equivalent patterns in the observations. The results are summarized in Table 2. Note that a value of 1.0 would indicate that the model correlations between model rainfall and pressure were identical to the observed patterns shown in Figure 10. Considering the complexity of the correlations being compared, a correlation of at least 0.5 indicates reasonable model performance. Considering first the correlations for rainfall over the whole state, it is clear that none of the models performs well in all seasons. However, almost all models simulate summer correlation patterns well with a correlation coefficient of at least 0.5 and spring spatial correlation patterns are well captured by most models. The best performing model is the CSIRO Mark 3 model, which produces correlations of 0.5 or greater in summer, spring and autumn. The correlation for summer of 0.93 is the highest value attained by any model. During winter, the best performing models are ECHAM4 and Mark 2.

We now consider the correlations for rainfall in the north of the state. Once again, summer and spring correlation patterns are reasonably well represented by most models while winter and autumn are generally poorly captured. For Mark 3 the correlations for summer, autumn and spring are 0.94, 0.70 and 0.70 respectively, which show an improvement over the statewide rainfall correlations particularly in autumn and spring. Clearly this model is the best performer with respect to circulation patterns associated with summer rainfall in the north of the state.

The final set of columns in Table 2 show the correlations between rainfall in the south of the state with regional sea-level pressure. For these correlations, we are most interested in models that perform well during winter with a view to selecting the most appropriate model for analysis of changes in frontal systems. Most models perform poorly during winter with the best performers being the ECHAM4 and DAR125. In terms of the CSIRO GCMs, the best performer is the Mark 2 model.

Table 2: *The correlation between the observed and the global and regional climate models ability to simulate the relationship between large-scale circulation patterns and rainfall over South Australia as a whole and also separately for northern and southern halves of the State. The results are shown for summer (DJF), autumn (MAM), winter (JJA) and spring (SON).*

Models	**South Australia**				**northern South Australia**				**southern South Australia**			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
CCCM2	**.92**	.27	.11	.38	**.91**	.10	.51	.33	.77	**.51**	.44	.47
CCCM1	.37	.20	-.31	**.77**	.34	-.03	**.57**	**.85**	.38	**.54**	-.28	.32
ECHAM3	**.61**	.44	-.27	**.68**	**.56**	.43	-.04	**.82**	**.78**	.36	.34	-.57
GFDL	**.59**	.36	-.71	-.40	**.66**	.31	.13	-.26	.47	.29	.37	.20
HADCM2	**.84**	.04	.28	**.64**	**.84**	-.12	.38	**.78**	**.68**	**.61**	.34	.31
NCAR	**.79**	-.29	**.56**	**.57**	**.76**	-.31	.37	**.81**	**.58**	.21	**.86**	.42
HADCM3	**.83**	.38	**-.51**	.38	**.82**	.47	.16	**.71**	**.72**	.04	.22	-.48
ECHAM4	**.60**	.38	**.90**	.16	**.59**	. 35	.31	**.53**	**.62**	.38	**.94**	-.36
DAR125	**.52**	.30	.14	**.62**	**.59**	.22	.40	**.82**	.20	**.84**	**.94**	-.17
MARK2	**.50**	-.30	**.71**	**.58**	**.63**	-.68	.48	**.76**	-.29	**.80**	**.87**	-.08
MARK3	**.93**	**.56**	-.82	**.50**	**.94**	**.72**	.03	**.73**	**.76**	-.15	.13	-.01
CC50	.49	-.02	-.44	**.56**	.43	-.25	-.13	**.66**	**.58**	**.65**	.28	.40

3.3 Summary

The performance of twelve climate models in reproducing key aspects of South Australia's current climate has been the focus of the present chapter. The rationale for this assessment is that a model should at least be able to reproduce present climate if it is to be used to provide guidance of changes in future climate. However, we cannot validate the changes to climate that are simulated by the models. The exercise of model validation should therefore be seen as necessary but not sufficient to ensure accuracy of the changes to future climate simulated by the various models. It is for this reason that a large number of climate model simulations are considered when preparing projections and that large ranges of uncertainty ensue. The suitability of the twelve models for inclusion in the climate projections will now be assessed.

Most models simulated circulation patterns, average rainfall and temperature well. However two models, ECHAM3 and GFDL, performed poorly in over half of the test conducted and so it was decided to exclude these models from the mean climate projections.

The relationship of rainfall to circulation patterns was assessed to determine the most suitable models for assessing future changes to systems responsible for summer rainfall in the north of the state and winter rainfall in the south. The more complex nature of this type of assessment precludes the assessment of more than one model. The CSIRO Mark 3 models was clearly the best performing model in relation to summer, spring and autumn rainfall circulation systems and so will be used in the analysis of summer rainfall changes in chapter 5.

Winter rainfall generally accompanies fronts and their associated mid-latitude low pressure systems. The most comprehensive means of assessing changes to low pressure systems is to find and track low pressure systems in daily fields of surface pressure. Overall, the models generally had difficulty reproducing the circulation patterns associated with winter rainfall. The best performing models were the Canadian climate models, with the Mark 2 model being the best performer amongst the CSIRO models. Owing to the fact that daily fields are required for the analysis of wintertime systems and these are only available in the CSIRO models, the Mark 2 model was selected for this analysis in chapter 6.

Changes in temperature extremes are strongly driven by changes in average temperature and the range of variability (i.e. the variance) is relatively unaffected. Therefore, projected changes to mean temperature can be applied to observed temperature records and these records are then analysed in terms of exceedences over specified thresholds. Rainfall extremes, however, do not stem directly from changes in mean rainfall. This is indicative of a change occurring to the range of variability. As such, it is inappropriate to scale observed rainfall records with average rainfall changes. Rather, daily model results are analysed directly for rainfall extremes. Wind extremes are also analysed directly from daily model results. Both these quantities are sensitive to terrain effects, and so the higher resolution RCMs are preferred for this analysis. Of the two RCMs, DAR125 was found to demonstrate higher skill than CC50 in most months and for most variables. It was therefore chosen for analysis of extreme rainfall and winds.

Some additional assessment of model performance of the selected models in their simulation of extremes under current climate conditions will be undertaken in chapters 5 and 6.

4. Enhanced greenhouse regional climate change

In this chapter, an assessment of the sensitivity of various key aspects of South Australia's climate to enhanced greenhouse effect is provided and projections of climate change for average temperature, rainfall, evaporation and water balance are evaluated and discussed. The assessment is based upon general considerations such as the conclusions of IPCC (2001), and various specific results obtained from analysing climate model output over the South Australian region. Results of climate change experiments from the ten GCMs and two CSIRO RCMs are presented for discussion. Based on the assessment of model performance under current climate conditions in the previous chapter, however, only eight of the GCMs are used in the development of projections. The RCM results provide regional detail in the patterns of change, which is more realistic than provided by GCMs, but the GCM results can illustrate the extent to which simulated regional changes in climate are model-dependent. The climate projections are presented in the form of maps of change for the state. In addition, some regionally-specific information is presented for the eight regions shown in Figure 11.

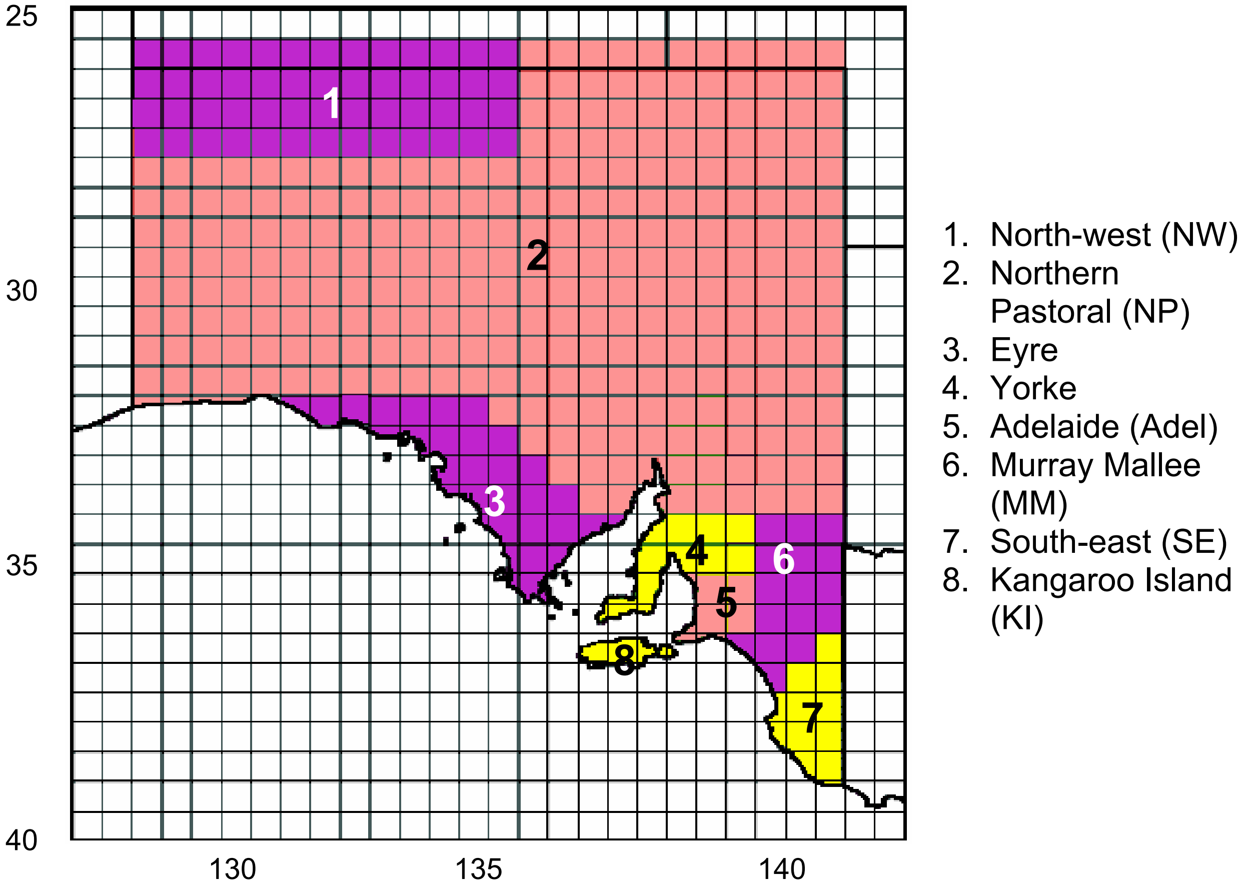

Figure 11: *Division of South Australia into eight regions for presenting various results.*

4.1 Regional average temperature change

All climate models show increases in simulated average temperature over South Australia under enhanced greenhouse conditions. However, the magnitude of regional warming is dependent upon the climate model used and the forcing scenario assumed. The range of warming over South Australia for models run with the various SRES emission scenarios is shown in Figure 12a while 12b shows the temperature simulation for models run with the IS92a emission scenario. The observed temperature between 1950 and 2000 is also shown. All climate model simulations show reasonable agreement with the observed average temperature trend over South Australia. Uncertainty due to differences in projected emissions is more pronounced later in the century as illustrated by the warming curves of the Mark 2 model under four different SRES scenarios (including an ensemble of four simulations with the A2 emission scenario). On the other hand, uncertainty due to model to model differences is evident from the first few decades of the century. This is illustrated by the Mark 3 and CC50 temperature curves in Figure 12a with Mark 3 warming at a slower rate than the CC50 model. This point is also illustrated in Figure 12b for nine models that have been run using the IS92a scenario, and indicates warming ranging from about 2.2°C for the NCAR model to 5.8°C for CCM1 by about 2100. The South Australian rate of regional warming is broadly similar to the global average rate, but models suggest systematic variations across the region.

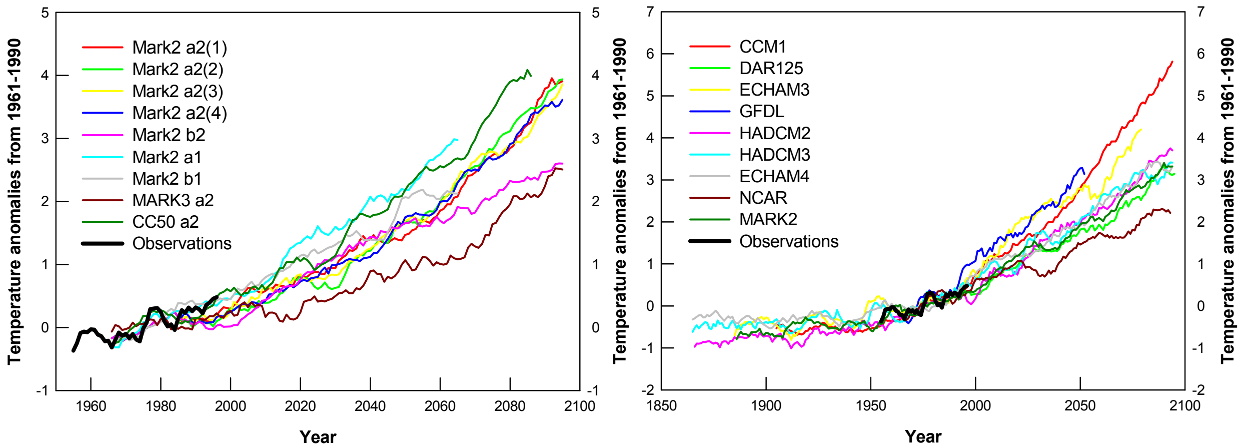

Figure 12: *Warming averaged over South Australia (relative to the period 1961-1990) in (a) the CSIRO Mark2 GCM forced by four different SRES emission scenarios including an ensemble of four simulations with the A2 scenario and the Mark 3 and the CC50 models run with the A2 emission scenario and (b) a set of nine models all forced with the IS92a scenario. All time series have been smoothed with an 11-year running mean.*

Figure 13 compares the pattern of regional average temperature change in summer and winter across the GCMs and the two RCMs, DAR125 and CC50. The results are given in local warming per °C of global warming by linearly regressing the local seasonal mean temperatures against global average temperatures smoothed with an 11-year running mean. This method assumes that the local temperature signal evolves over time like that of the smoothed global temperature. The degree of change for a particular future date can then be calculated by multiplying the particular map by the global warming curve at that date.

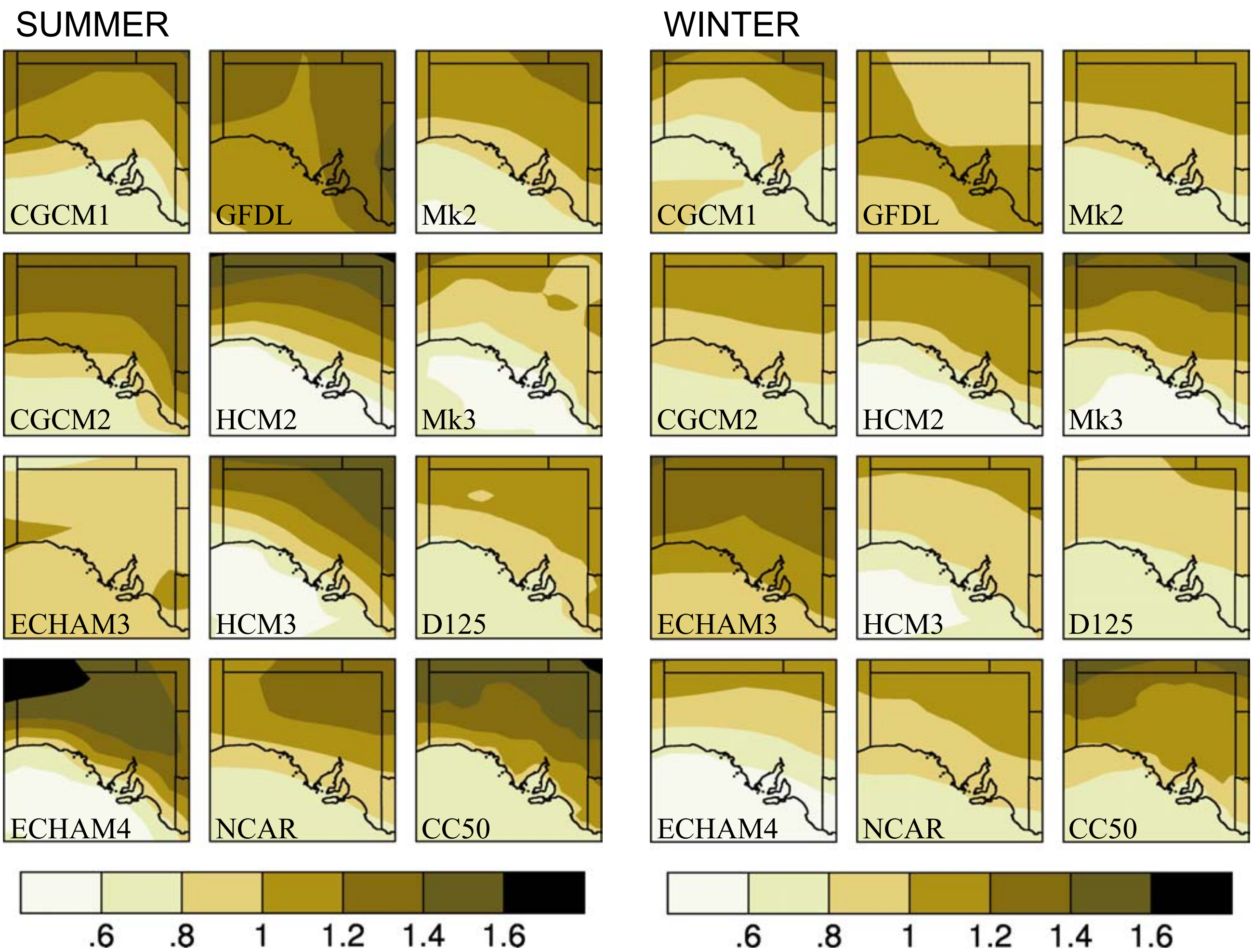

Figure 13: *Pattern of warming in ten GCMs and two RCMs for (a) summer and (b) winter. Units: C per °C of global warming. Model details are given in Table 1.*

Almost all models show a pattern of greater warming over inland South Australia compared to the coastal areas. This warming is in the range of 0.8 to 1.6°C and is more pronounced in summer. Warming is delayed in the middle to higher latitudes of the Southern Hemisphere compared to other regions (IPCC, 2001; Whetton et al., 1996) due to the high heat capacity of this largely oceanic region, and air from this zone affects southern Australia more in winter. It is noteworthy that the two warming patterns that do not show greater warming inland compared to the coast are the ECHAM3 model in summer and GFDL model in winter. On the basis of performance criteria presented in the previous chapter, it was decided to omit these models from the final production of future scenarios. Exclusion of these models will tend to reduce the range of uncertainty for temperature particularly in coastal regions.

4.2 Regional average rainfall changes

South Australia's agricultural production, natural ecosystems and water resources are highly dependent upon local rainfall and thus have the potential to be significantly affected if rainfall undergoes change under enhanced greenhouse conditions. However, uncertainty associated with estimating the sensitivity of rainfall in any region is much higher than it is for temperature. This is for at least three reasons. First, unlike temperature where increases are always indicated, regional rainfall may increase or decrease under enhanced greenhouse conditions. Secondly, the greenhouse signal is much weaker for precipitation than it is for temperature because of the much higher natural variability of precipitation. Finally, the spatial representation of precipitation occurrence by climate models is generally poorer than it is for temperature.

Current GCMs broadly simulate increases in precipitation in mid to high latitudes of both hemispheres and close to the equator, and decreases are usually confined to patches in the subtropics of both hemispheres (IPCC, 2001). Figure 14 shows the consistency amongst ten current GCMs in the direction of rainfall change across the globe. Note that the location of South Australia is such that it is affected by rainfall decrease in the south and east of the State, while in the north-west of the State, models do not portray a clear direction of change with some models indicating rainfall increases and some decreases. Previous assessments of rainfall change over Australia (e.g. CSIRO, 2001) have all indicated the potential for rainfall decreases, particularly in winter, but with increases in rainfall possible in summer.

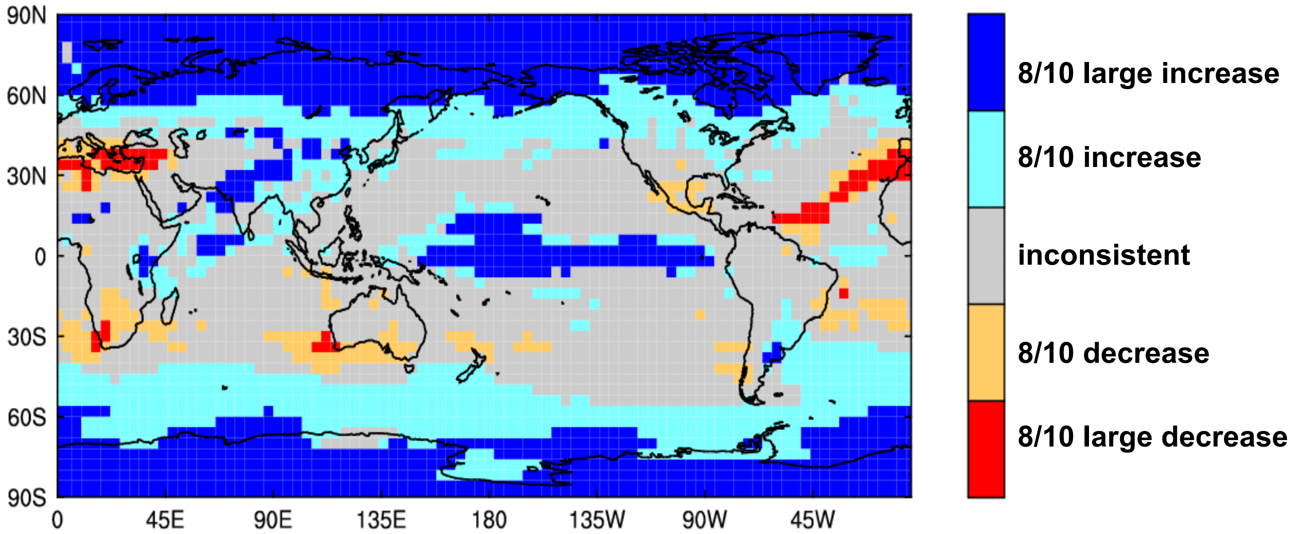

Figure 14: *Inter-model consistency in direction of simulated annual rainfall change in ten GCMs (see Table 1). Large changes are where the average change across the models is greater in magnitude than 5% per °C of global warming.*

To explain the patterns of simulated rainfall change, we also examine simulated changes in mean sea-level pressure. In the annual average, there is broad agreement amongst the models on a pattern of increased pressure in the zone 35-55°S in the southern hemisphere (Figure 15). The reason for this pattern is not well understood, but there is evidence that the increased pressure 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 seasonal analyses, although the increased pressure band extends slightly further north in winter and the decreased pressure over the continent is stronger in summer.

The band of increased pressure would weaken the westerlies across southern Australia and may be expected to lead to reductions in rainfall over South Australia, particularly in winter and spring when this rainfall source is most important.

On the other hand the tendency for lower pressure over the continent may increase rainfall, particularly in summer when this feature is more evident. The pressure changes thus seem broadly consistent with the simulated rainfall changes.

Figure 15 also shows a tendency for pressure to be decreased over the eastern tropical Pacific and increased in the western tropical Pacific. This pattern may be viewed as the atmospheric response to the El Nino-like warming pattern simulated by most models in the Pacific (see Cai and Whetton, 2000), and based on the analogy of El Nino, rainfall reductions may be expected in the Australian region. However, this feature may be less relevant to Australian rainfall than the analogy would suggest. Unlike the pattern of change during an El Nino event, the area of pressure increase does not extend far enough west to affect the Australian continent.

Finally, it should be noted that the discussion above assumes that atmospheric circulation and rainfall are realistically simulated in current GCMs. Although, the analysis presented in section 3.2 indicated that this was broadly true, it was also noted that some models showed some unusual features.

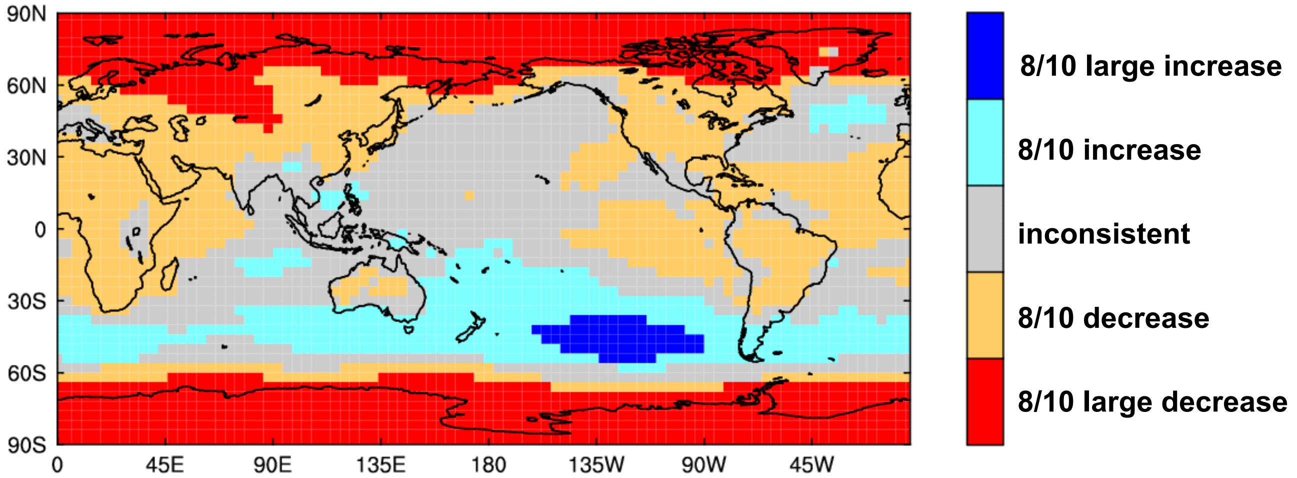

Figure 15: *Inter-model consistency in direction of simulated annual pressure change.*

Figure 16 shows the seasonal pattern of rainfall change per degree of global warming in the twelve models calculated by regressing local seasonal rainfall against smoothed global average temperatures. Unlike temperature, there is considerable variation in the patterns and sign of rainfall change from model to model. Areas of both rainfall increase and decrease are present over South Australia in most models and seasons. However, some consistent patterns emerge (i.e. patterns supported by at least ten of the twelve models). Rainfall decreases are consistently indicated for the south-east of the state in winter. In no region of the state in any season do the model results consistently indicate increasing rainfall. However, in spring and summer, at least half of the models indicate rainfall increases in the north-west of the state. One of the two models to be excluded from the scenario development simulates the strongest increases in rainfall of up to 20% in spring and summer. Exclusion of this model in the scenario development will slightly reduce the uncertainty surrounding rainfall change in these seasons. The regional model DAR125 also indicates strong increases in rainfall of up to 15% during spring and summer. On the other hand, CC50 indicates strong decreases of up to 15% in summer.

4.3 Projected changes in average temperature and rainfall for South Australia

This section provides a summary of projected future changes in South Australia's climate based on the current climate modelling. For temperature and precipitation we present ranges of change that incorporate quantifiable uncertainties associated with the range of future emission scenarios, the range of global responses of climate models, and model-to-model differences in the regional pattern of climate change.

The ranges are based on:

- the full range of IPCC global warming projections given in Figure 2c, which provide information on the magnitude of the global climate response over time. These ranges take into account a range of possible future emissions of greenhouse gases as well as uncertainty associated the sensitivity of the climate system.
- the regional response in terms of local change per °C degree of global warming. A range of local values is derived from the differing results of ten climate model simulations presented in this chapter in figures 13 and 16.

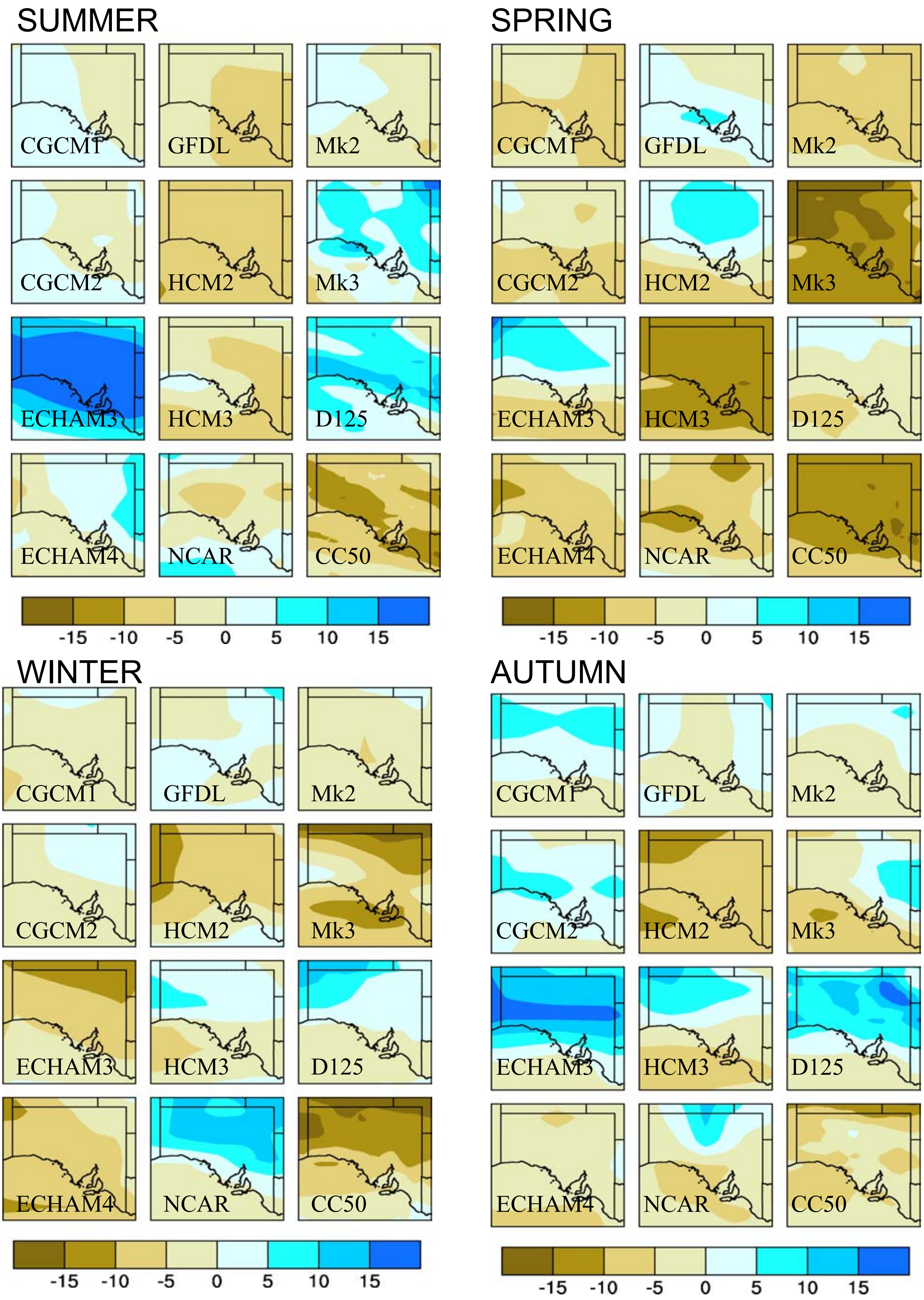

Figure 16: *Pattern of annual rainfall change in twelve climate models in percent change per °C degree of global warming for each season.*

Spatial results are presented in Figure 17 as colour-coded maps for the changes in average climate conditions by around 2030 and 2070 relative to 1990. These selected dates illustrate changes in average climate that may be expected in the next few decades and the larger changes that may occur late in the century. The conditions of any individual year will continue to be strongly affected by natural climatic variability which cannot be predicted.

Annual average temperatures (Figure 17a) over the north of state are 0.4 to 2.0°C higher by 2030 and 1.0 to 6.0°C higher by 2070. In the south temperatures become higher by 0.2 to 1.4°C by 2030 and 0.6 to 4.4°C by 2070 and these changes are uniform throughout the year. Patterns of warming in summer and autumn are similar to the annual patterns. In the north of the state in winter, the range of possible warming is smaller (0.4 to 1.7°C by 2030 and 1.0 to 5.2°C by 2070) while in spring, it is greater (0.4 to 2.2°C by 2030 and 1.2 to 6.8°C by 2070).

Over the ocean, surface air temperature changes can be considered to reflect changes to sea surface temperatures. Over much of the continental shelf including Spencer Gulf, temperatures increase in the range of 0.2 to 1.2°C by 2030 and 0.6 to 3.6°C by 2070 throughout the year. The Gulf of St Vincent in winter exhibits a slightly narrower range of warming of 0.3 to 1.2°C by 2030 and 0.8 to 3.6°C by 2070. In deeper waters further south, smaller increases in temperature are possible although the range of change increases with warmings of 0.1 to 1.2°C by 2030 and 0.3 to 3.6°C by 2070.

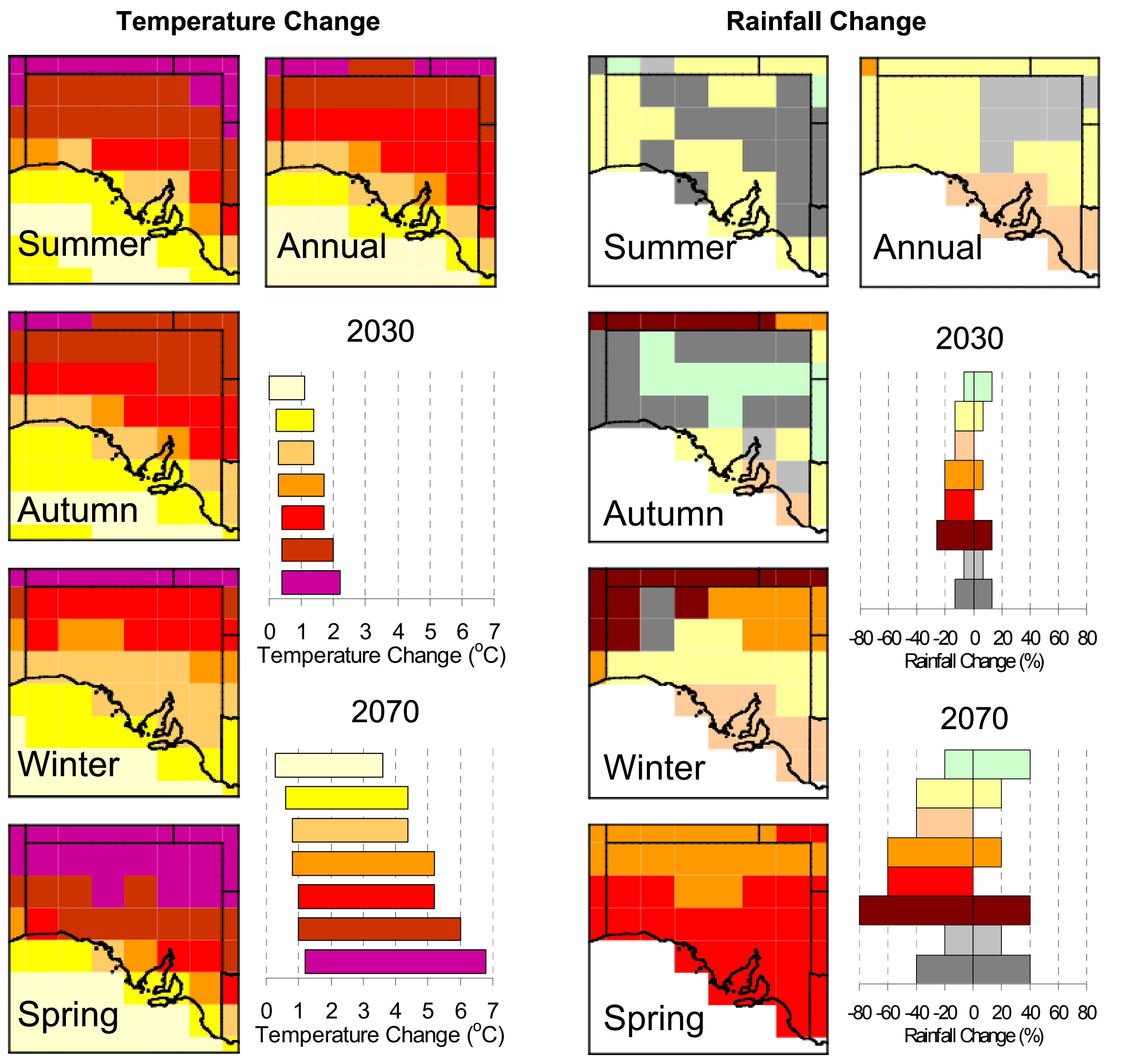

Figure 17: *(a) Average seasonal and annual warming ranges (°C) for around 2030 and 2070 relative to 1990 and (b) average seasonal and annual rainfall change (%) for 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps.*

Table 3 presents the ranges of change averaged over each of the eight regions illustrated in Figure 11. The north-west of the state (region 1) undergoes the largest range of annual warming of 0.4 to 1.8°C by 2030 and 1.2 to 5.6°C by 2070. On a seasonal basis, the range of warming is smallest in winter and largest in spring. Kangaroo Island (region 8) has the lowest range of projected warming of 0.2 to 1.0°C by 2030 and this range of warming is uniform throughout the year.

Table 3: *Average range of warming (°C) for each region indicated in Figure 11.*

Region	2030					2070				
	Annual	Summer	Autumn	Winter	Spring	Annual	Summer	Autumn	Winter	Spring
NW	0.4-1.8	0.4-1.9	0.4-1.8	0.4-1.6	0.5-2.2	1.2-5.6	1.2-5.7	1.1-5.4	1.1-5.1	1.3-6.7
NP	0.4-1.6	0.4-1.7	0.4-1.6	0.4-1.5	0.4-1.9	1.1-4.9	1.1-5.3	1.1-5.0	1.0-4.5	1.2-5.7
Eyre	0.3-1.2	0.3-1.2	0.3-1.2	0.3-1.2	0.3-1.4	0.9-3.8	0.8-3.8	0.9-3.7	0.8-3.6	0.9-4.3
Yorke	0.3-1.2	0.3-1.2	0.3-1.2	0.3-1.1	0.3-1.3	0.9-3.7	0.8-3.8	0.8-3.6	0.8-3.5	0.9-3.9
Adel	0.3-1.2	0.3-1.2	0.3-1.2	0.3-1.3	0.3-1.3	0.8-3.7	0.8-3.7	0.8-3.7	0.8-3.5	0.9-3.9
MM	0.3-1.3	0.3-1.4	0.3-1.3	0.3-1.2	0.4-1.4	0.9-4.0	0.9-4.4	0.9-4.1	0.8-3.8	1.0-4.3
SE	0.3-1.1	1.1-1.3	0.3-1.2	0.3-1.1	0.3-1.2	0.7-3.5	0.8-3.9	0.7-3.7	0.7-3.2	0.8-3.7
KI	0.2-1.0	0.2-1.0	0.2-1.0	0.2-1.0	0.2-1.0	0.6-3.1	0.6-3.2	0.6-3.2	0.7-3.1	0.6-3.1

Figure 17b shows ranges of change in South Australian rainfall for around 2030 and 2070. Projected annual average ranges tend toward decrease over most of the state (–13% to +6% in 2030 and –40% to +20% in 2070), with exceptions in the far south-east (stronger decreases) and in the north-east (increases and decreases equally likely).

In summer over most of the north-east of the state, increases and decreases in the range of –13to +13% are equally likely. In other areas, projected summer ranges tend towards decreases (–13 to +6%). Autumn sees broad ranges of change apply over much of the north-east of the state, (–13 to +13% by 2030 and –40 to +40% by 2070) although some areas tend towards increase. In the south of the state, narrower ranges of change apply, tending mostly towards rainfall decreases. In winter the tendency is towards decreases in rainfall, with larger ranges of uncertainty in the north of the state. In spring, decreases in rainfall of up to –20% by 2030 and –60% by 2070 are indicated. In the north of the state, changes are indicated in the range of –13 to +6% by 2030 and –60 to +20% by 2070.

Table 4 presents ranges of change for eight regions. These results indicate that on an annual basis, only the two northernmost regions may experience increases in rainfall as a result of climate change. All other regions indicate rainfall decreases on an annual basis. On a seasonal basis, summer indicates some potential for rainfall increases although the tendency is for rainfall decreases. Spring shows the strongest tendency towards rainfall decreases.

Table 4: *Average range of rainfall change (%) for each region indicated in Figure 11 (note that values above 20 are rounded to the nearest 5).*

Region	2030					2070				
	Annual	Summer	Autumn	Winter	Spring	Annual	Summer	Autumn	Winter	Spring
NW	-7– +1	-11– +7	-8 – +11	-15–+11	-17–+2	-25–+6	-30–+25	-25–+35	-45–+35	-55–+5
NP	-7– +1	-10 – +7	-7 – +7	-13–+5	-18 – 0	-20–+2	-30–+20	-20–+25	-40–+14	-55– -1
Eyre	-8– 0	-11 – +7	-7 – +5	-10– 0	-17– -1	-25 – 0	-35–+20	-25–+15	-30– 0	-50– -4
Yorke	-9– 0	-11 – +5	-7 – +2	-10– 0	-18– -1	-30– -1	-35–+14	-20 – +7	-30– -1	-55– -4
Adel	-9– -1	-11 – +5	-7 – 0	-9 – -1	-17– -2	-30– -2	-35–+15	-20 –+1	-30– -2	-55– -4
MM	-9– -1	-11 – +7	-6 – +2	-8 – 0	-18– -1	-30– -2	-35–+20	-20–+7	-25– -1	-55– -4
SE	-8– -1	-11 – +2	-8 – 0	-9 – 0	-15– -2	-25– -2	-35–+5	-25 – 0	-30– -1	-50– -5
KI	-9– -1	-10 – +2	-10– 0	-11– -1	-15– -2	-25– -2	-30–+5	-30– -1	-35– -2	-50– -5

4.4 Evaporation and water balance

Higher temperatures are likely to increase evaporation. In this section, changes in potential evaporation (atmospheric water demand) and water balance across South Australia are assessed in the various GCMs for which the necessary data are available. Projections of potential evaporation are prepared by multiplying the observed point potential evaporation over the period 1961 to 1990, obtained as seasonal totals from the Bureau of Meteorology, by the changes in point potential evaporation obtained from each GCM. Water balance is derived by subtracting the changes in potential evaporation from changes in rainfall. As with potential evaporation, rainfall changes are calculated by multiplying the observed precipitation from the Bureau of Meteorology over the period 1961 to 1990 with the changes in rainfall obtained from the GCM.

Figure 18a shows the simulated of change in annual potential evaporation in seven GCMs and the two RCMs. All of the models show increases in potential evaporation under enhanced greenhouse conditions. Increases range from 2 to 8% per °C of global warming. The results are similar for each season, although the tendency for increase is generally stronger in winter and spring than in summer and autumn. Across all the models, increases in potential evaporation are stronger where there are corresponding reductions in rainfall. This is illustrated further in Figure 19. The correlation for all data is –0.4 and is larger in the north and west of the state, decreasing to the south-east.

The model-simulated changes in the potential evaporation and water balance for the nine available models are shown in Figure 18. Increases in potential evaporation in the range of 2 to 8 % are simulated by the models. Despite the fact that some models (such as ECHAM3 and DAR125) simulated increases in rainfall, all models show decreases in water balance (i.e. a water deficit) in the range of 20 to 180 mm per °C of global warming. The patterns of change also apply (with some minor exceptions in some models) in each of the four seasons.

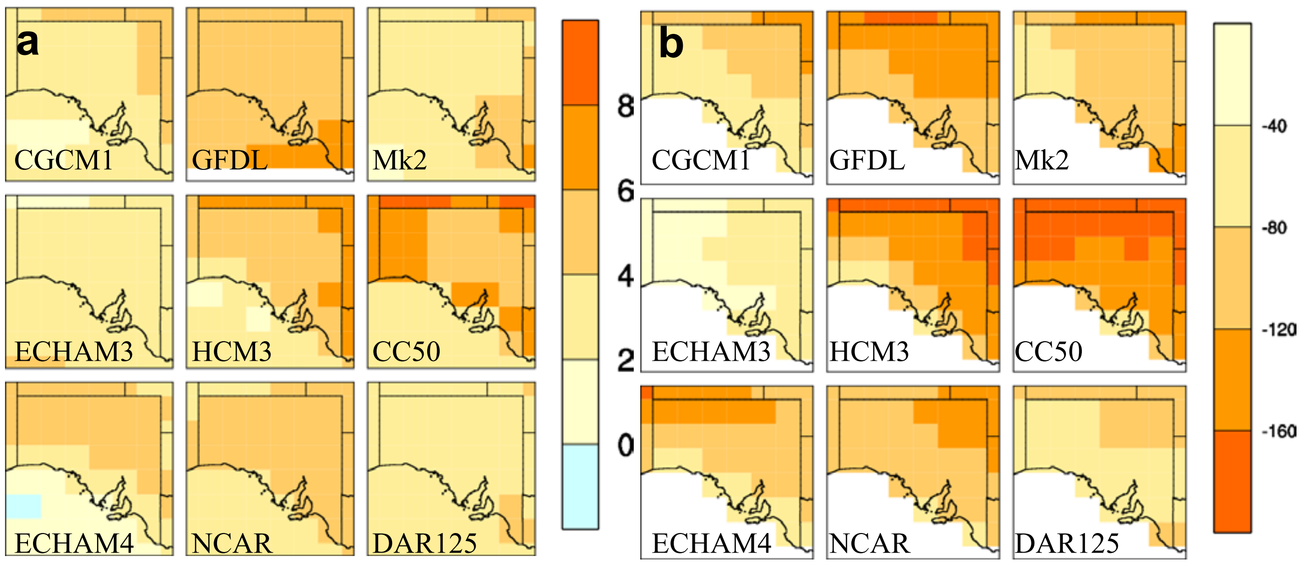

Figure 18: *Patterns of annual change in seven GCMs and two RCMs for (a) potential evaporation (% per °C of global warming) and (b) water balance (mm per °C of global warming).*

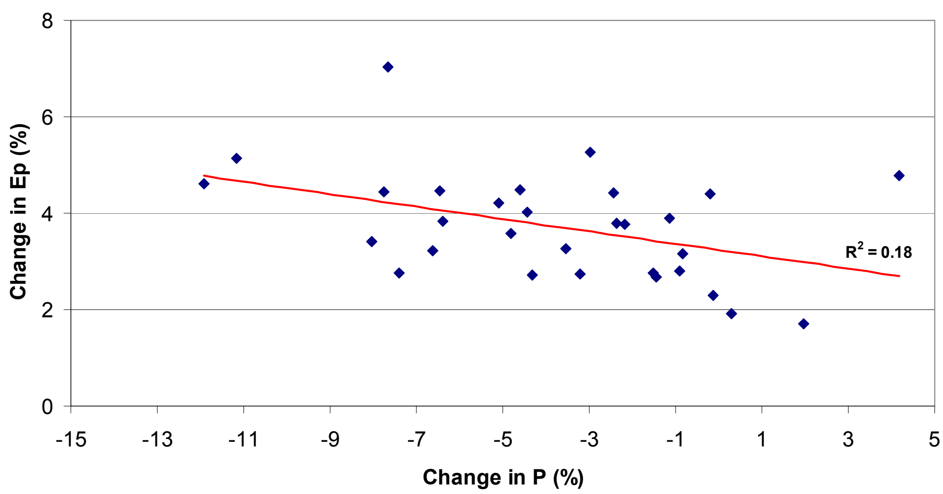

Figure 19: *Seasonal averages of precipitation (P) and potential evaporation (Ep) change in percent per °C of global warming area-averaged over South Australia, showing the inverse relationship between P and Ep change.*

Projected changes in potential evaporation and water deficit (negative water balance) based on the average of the nine available models are shown in Figure 20. Potential evaporation shows largest increases in the east and north-west of the state with values of about 2 to 7% by 2030 and 6 to 24% by 2070 in summer and autumn. Values in the centre of the state and the western coastal regions are in the range of 1 to 5 % by 2030 and 2 to 16% by 2070. In winter, and spring, potential evaporation in the east and north-west of the state increases by 2 to 9% in 2030 and 6 to 24% by 2070 with a lower range of increase for the centre and western coastal regions of 2 to 8% by 2030 and 4 to 20% by 2070. Ranges of change in potential evaporation averaged over each of the eight regions are also presented in Table 5.

In terms of moisture balance, summer exhibits the strongest deficits, which increase towards the north-east of the state and are in the range of 10 to 110 mm by 2030 and 50 to 320 mm by 2070. Patterns of change in autumn are similar to summer but the ranges are lower with deficits of 5 to 55 mm by 2030 and 20 to 160 mm by 2070. In winter, moisture deficits exhibit uniform reductions across the state of 0 to 25 mm by 2030 and 10 to 80 mm by 2070. Moisture deficits in spring are uniform across the state and of similar magnitude to autumn. Annual moisture deficits increase from the coast to produce maxima in the north-east of the state, which are in the range of 50 to 200 mm by 2030 and 150 to 650 mm by 2070. Ranges of change in moisture deficit averaged over each of the eight regions are also presented in Table 6.

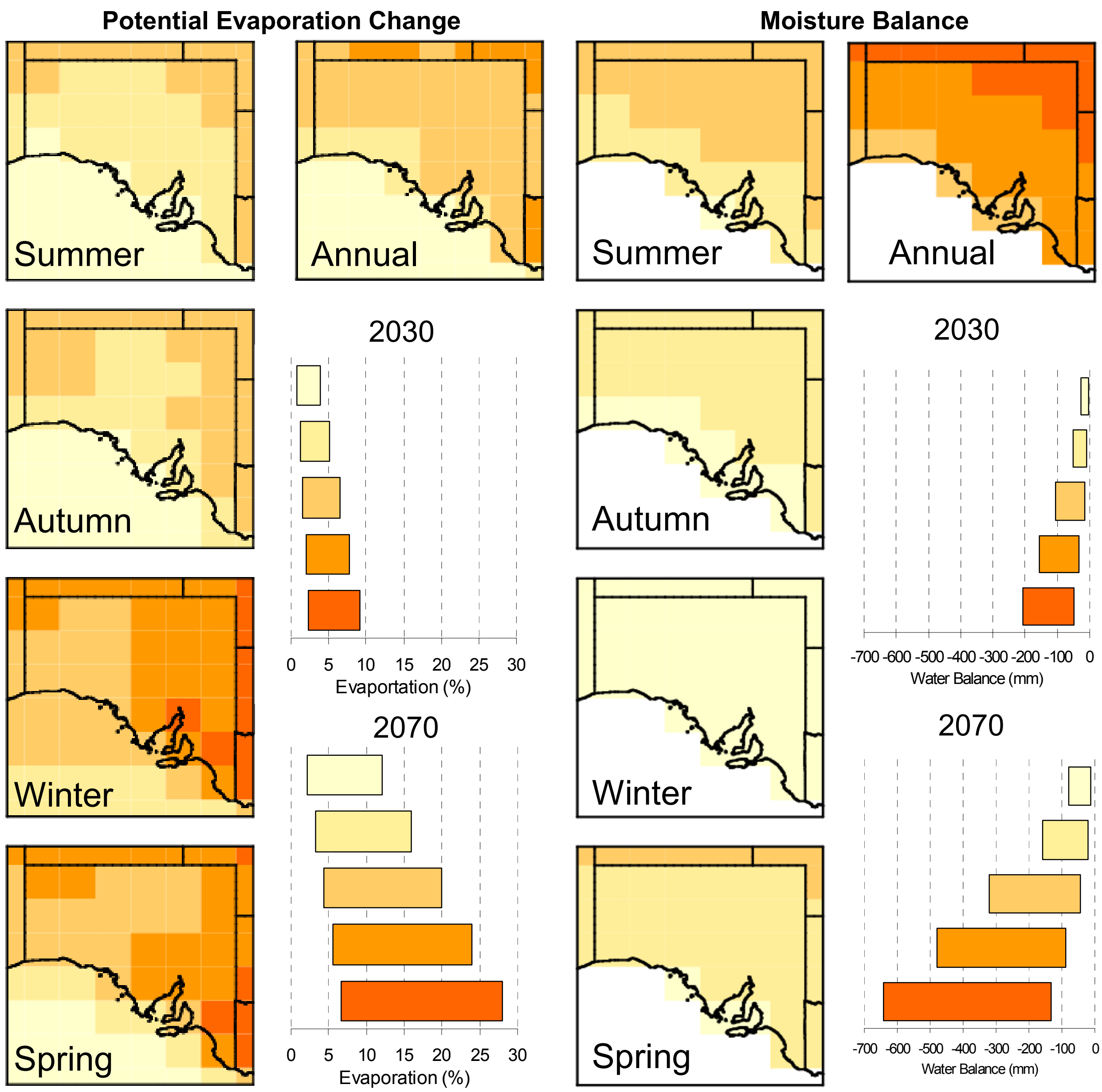

Figure 20: *Patterns of seasonal and annual change presented as ranges of change across five GCMs and two RCMs for (a) potential evaporation (% per ℃ of global warming) and (b) water balance (mm).*

Table 5: *Average range of potential evaporation change (%) for each region indicated in Figure 11.*

Region	2030					2070				
	Annual	Summer	Autumn	Winter	Spring	Annual	Summer	Autumn	Winter	Spring
NW	2-6	2-5	2-5	2-7	2-7	5-18	4-16	5-17	6-20	6-20
NP	2-6	2-5	2-5	2-7	2-7	5-17	4-15	4-16	6-21	6-20
Eyre	1-5	1-4	1-4	2-6	2-6	4-14	3-11	4-13	5-20	5-18
Yorke	2-5	1-4	1-5	2-7	2-7	4-15	3-11	4-14	6-22	6-20
Adel	2-5	1-4	1-5	2-7	2-7	4-16	3-12	4-14	6-23	6-21
MM	2-6	1-5	2-5	3-8	3-8	5-18	4-14	4-16	7-25	7-26
SE	2-6	1-4	2-5	2-8	3-8	5-17	4-14	4-16	6-23	7-25
KI	1-4	1-3	1-4	2-6	2-5	3-12	2-8	3-11	5-18	4-15

Table 6: *Average range of change of moisture deficit (or negative water balance) in mm for each region indicated in Figure 11 (note that values above 30 are rounded to the nearest 5).*

Region	2030					2070				
	Annual	Summer	Autumn	Winter	Spring	Annual	Summer	Autumn	Winter	Spring
NW	50-155	18-60	10-30	5-17	14-45	130-470	50-185	27-100	14-50	40-140
NP	45-140	17-55	9-29	4-15	12-41	120-430	50-170	25-90	12-45	35-125
Eyre	30-105	11-35	7-22	5-16	9-29	90-320	30-110	19-70	14-50	24-90
Yorke	35-105	12-40	7-24	5-16	9-29	90-330	30-120	20-70	13-50	25-90
Adel	35-105	12-40	7-23	5-16	9-29	90-330	30-115	20-70	13-50	25-90
MM	40-125	14-45	8-26	5-16	11-35	105-380	40-145	22-80	13-50	29-105
SE	35-115	12-40	8-25	6-21	9-30	95-350	35-120	21-75	18-65	26-95
KI	27-90	8-25	6-20	6-20	7-23	75-270	21-75	17-60	17-60	19-70

5. Changes in extremes: Temperature, rainfall and droughts

This chapter focuses on projections of extremes in temperature and rainfall. Specific analysis is also undertaken into the likely changes in the frequency of droughts and heavy summer rainfall events that mainly affect the northern half of the state. Unlike the development of climate projections for mean temperature and rainfall, for which a large number of international GCM simulations are available for analysis, the analysis of climate extremes is for the most part limited to models for which daily data rather than monthly averages are available. Where appropriate, information is provided on a regional basis for the eight regions represented in Figure 11.

5.1 Extreme temperature change

In this section, future changes in extreme temperatures are presented and discussed. Changes in mean temperature will be felt through changes in extremes. It is noteworthy that in mid-December, 2002, South Australia experienced record breaking hot spells over 40°C at a number of locations. Although in isolation such events cannot be attributed to changing climate, it is not unreasonable to expect that such events will occur more frequently or earlier or later in the season than have tended to occur historically.

Although changes in temperature extremes can be analysed directly from a climate model's simulation, a potential disadvantage of this approach is that the model's present climate simulation can contain biases in the frequency of extremes and this lowers confidence in the reliability of the enhanced climate situation. The alternative and preferred approach for analysing extreme temperatures is to apply the range of projected change in average temperature to observed daily records for South Australian sites and then analyse the modified record for extremes in relation to thresholds. This analysis has been applied to annual temperature records to ensure that extremes that occur in the transitional seasons are also captured. In addition to avoiding the requirement of realistic representation of extremes in the current climate, this approach is also well justified given that climate models do not give clear and consistent changes in variability and diurnal temperature range.

We note that maximum and minimum temperatures will not necessarily change at the same rate as average temperature. Indeed, minimum temperatures have been observed to increase at a slightly greater rate than mean or maximum temperatures in recent observational records. However, Figure 21 shows the change in maximum and minimum temperatures expressed as a ratio of mean temperature averaged across the seven models for which maximum and minimum temperatures were available. Here it can be seen that both maximum and minimum temperatures increase within 10% of the mean temperature increase, suggesting that scaling daily extreme temperatures with the average range of warming is reasonable. The increase in maximum temperatures is slightly less than the average temperature whereas minimum temperatures increase at a slightly higher rate and this is most pronounced in the south-east of the state.

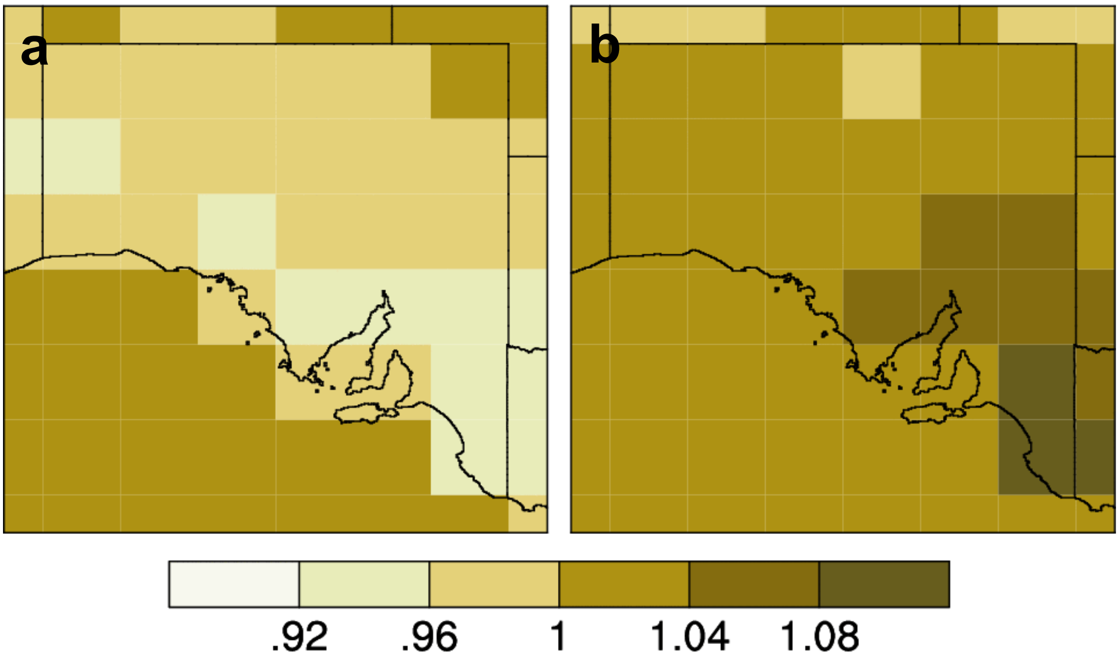

Figure 21: *The ratio of (a) maximum to mean temperature and (b) minimum temperature to mean temperature averaged across seven models for which monthly maxima and minima data were available.*

Table 7 presents the projected changes to the average number of days per year in which the temperature falls below 0°C for 23 locations in South Australia. Under the low warming scenario, many locations experience a reduction of about 15-30% in below-zero degree days by 2030 and around about 50% by 2070. Under the high warming scenario the reduction in below-0°C days is greater than 60% in 2030 with some central locations such as Marree, Oodnadatta, Cook, Adelaide and Berri ceasing to have days below 0°C in an average year. By 2070 all locations with the exception of Yongala would no longer experience days below 0°C in an average year.

These changes will reduce energy demand for heating and reduce cold stress for humans and animals. For agriculture, a reduction in frost days may affect the viability of certain crops such as stone fruits and cool climate cultivars of grapes and may increase the risk of certain agricultural weeds, pests and diseases that would otherwise be kept under control by lower winter temperatures.

Table 7: *The average number of days per year below 0°C for selected locations within South Australia.*

Region	Site	Days below 0° C		
		Present	2030	2070
1	Ernabella	19	7-15	0-12
2	Woomera	0	0	0
	Coober Pedy	0	0	0
	Tarcoola	7	1-5	0-3
	Marree	3	0-2	0-1
	Oodnadatta	1	0-1	0
	Cook	4	0-3	0-1
	Port Augusta	0	0	0
3	Ceduna	4	1-3	0-2
	Kyancutta	10	3-8	0-6
	Port Lincoln	0	0	0
	Port Pirie	0	0	0
	Maitland	0	0	0
4	Yongala	40	20-34	2-28
	Clare	19	6-15	0-10
5	Adelaide	1	0-1	0
	Eudunda	1	0	0
	Tailem Bend	3	1-2	0-1
6	Berri	1	0-1	0
	Keith	4	1-3	0-2
7	Kingscote	0	0	0
8	Robe	0	0	0
	Mt Gambier	5	1-4	0-2

For high temperatures, thresholds of 35°C and 40°C were considered. In addition to single days above the threshold, spells of three or more days were also calculated (note that five consecutive days above the threshold has been counted as a single hot spell while six days has been counted as two hot spells). Days above 35°C (Table 8) increased in the range 7 to 40% on average under the projected warming range for 2030 across the 21 sites that currently experience five or more days annually above 35°C. By 2070, the average increase in 35+°C days is between 18 and 150% across the 21 sites. Kingscote and Robe undergo considerably higher ranges of percentage change by 2070 (50 to 400% and 0 to 600% respectively) owing to the fewer days above this threshold under present climate conditions.

For locations currently experiencing five or more 35+°C spells annually (3 to 5 consecutive days above 35°C), the range of increase by 2030 is 6 to 50% and by 2070 is 22 to 170%. Locations such as Kingscote and Robe are not likely to be affected by 35°C spells even under a 2070 high warming scenario.

Table 9 presents projected temperatures over 40°C. Region 2 experiences the highest frequency of days above 40°C under present climate conditions and these are projected to increase by between 12% and 70% by 2030 and 35% and 270% by 2070. Locations such as Kingscote and Mt Gambier currently experience no days on average per annum above 40°C and this is not likely to change even under a high warming scenario by 2070.

Table 8: *The average number of days per year above 35°C for selected locations within South Australia*

Region	Site	Days above 35° C			Spells above 35° C		
		Present	2030	2070	Present	2030	2070
1	Ernabella	59	65-90	74-153	7	8-12	9-23
2	Woomera	49	54-72	60-124	10	11-16	12-33
	Coober Pedy	79	82-104	90-158	14	15-20	17-35
	Tarcoola	64	67-88	75-144	12	13-18	15-35
	Marree	96	101-123	109-178	24	26-33	28-51
	Oodnadatta	97	103-125	110-180	20	21-28	23-43
	Cook	54	57-72	63-123	9	9-13	11-28
	Port Augusta	36	38-47	42-78	4	5-7	6-14
3	Ceduna	30	31-39	34-63	3	3-5	4-9
	Kyancutta	43	45-59	50-95	7	7-11	9-21
	Port Lincoln	6	7-10	8-23`	0	0	0-2
	Port Pirie	32	34-42	37-73	5	5-7	6-15
	Maitland	17	18-24	21-44	2	2-3	3-7
4	Yongala	21	23-31	27-60	4	4-5	5-13
	Clare	18	19-27	23-52	2	2-3	2-8
5	Adelaide	14	15-20	17-38	1	2	2-6
	Eudunda	14	15-22	18-42	2	2	2-6
	Tailem Bend	25	25-31	28-55	1	1	1-2
6	Berri	33	34-45	39-76	1	1-2	2-5
	Keith	23	24-30	26-53	3	3-4	3-9
7	Kingscote	2	2-3	3-10	0	0	0
8	Robe	1	1	1-7	0	0	0
	Mt Gambier	9	10-13	12-24	1	1	1-2

Table 9: *The average number of days per year above 40°C for selected locations within South Australia*

Region	Site	Days above 40° C			Spells above 40° C		
		Present	2030	2070	Present	2030	2070
1	Ernabella	7	9-21	12-74	0	1-2	1-9
2	Woomera	11	13-22	16-60	1	2-4	2-12
	Coober Pedy	24	26-41	31-90	3	3-6	4-17
	Tarcoola	20	22-35	26-75	3	3-5	4-15
	Marree	35	40-57	45-109	7	8-12	10-28
	Oodnadatta	33	37-55	44-110	5	6-9	7-23
	Cook	18	20-29	23-63	2	2-4	3-11
	Port Augusta	10	11-15	13-32	1	1-2	1-4
3	Ceduna	9	10-15	12-30	1	1	1-3
	Kyancutta	13	14-21	16-45	1	2	2-7
	Port Lincoln	1	1-2	1-7	0	0	0
	Port Pirie	6	7-11	8-27	1	1	1-4
	Maitland	2	2-4	3-14	0	0	0-2
4	Yongala	2	2-4	3-17	0	0	0-3
	Clare	1	1-4	2-15	0	0	0-1
5	Adelaide	1	2-3	2-11	0	0	0-1
	Eudunda	1	1-3	2-12	0	0	0-1
	Tailem Bend	5	5-9	7-22	0	0	0-1
6	Berri	7	8-12	10-28	0	0-1	0-1
	Keith	4	5-7	6-19	0	0	0-2
7	Kingscote	0	0	0	0	0	0
8	Robe	0	0	0	0	0	0
	Mt Gambier	1	1-2	2-8	0	0	0

Region 2 will also be most affected by hot spells over 40°C increasing on average by 40 to 480% by 2070. By 2030 regions 4 to 8 will still be largely unaffected by 40+°C hot spells although by 2070, only regions 7 and 8 will remain unaffected with regions 4 to 6 experiencing between one and three hot spells under a 2070 high warming scenario.

Increases in hot days and hot spells can increase bushfire frequency, 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.

5.2 Extreme rainfall change

While much of South Australia shows a tendency towards drier conditions under enhanced greenhouse conditions, it does not necessarily follow that extreme rainfall events will become less frequent or less severe. Indeed previous studies based on daily rainfall data from various climate models have indicated marked increases in the magnitude and frequency of extreme daily rainfall events under enhanced greenhouse conditions for the Australian region (Whetton et al., 1993, 2000; Fowler and Hennessy, 1995). To examine the relationship between extreme and average rainfall changes, return periods (i.e. the average time between rainfall events of the same size) are analysed over two 40-year periods; 1961-2000 and 2011-2050. Events with return periods of 10, 20 and 40 years were computed for each of four seasons and eight South Australian regions. The percent change in extreme rainfall has been plotted against the percent change in average rainfall in Figure 23. Despite decreases in average rainfall over most of South Australia in most seasons by 0 to 30% extreme rainfall tends to increase 0 to 10%. These results indicate that storms may become more intense even in a climate that becomes drier on average.

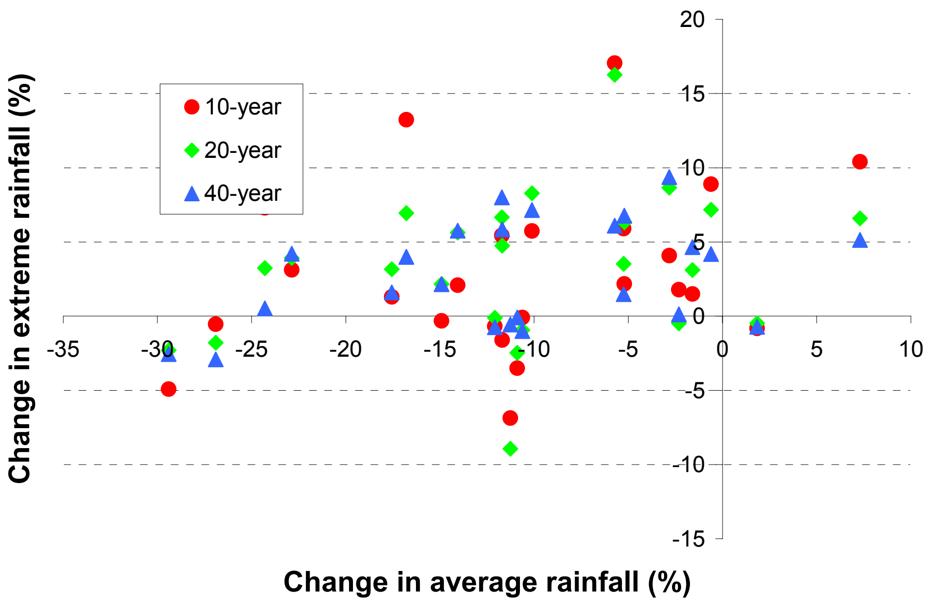

Figure 23: *Percent changes in average rainfall and extreme rainfall intensity (events with return periods of 10, 20 and 40 years) between two 40-year periods (1961-2000 and 2011-2050) simulated by DARLAM60. The 32 symbols come from eight South Australian regions and four seasons.*

Changes in extreme rainfall events by the year 2030 are substantial in most seasons and regions. They generally become more intense and more frequent in most seasons in the Yorke, Kangaroo Island and Adelaide regions, but less intense and less frequent in the north-west and northern pastoral regions (Table 10).

Table 10: *Change in extreme rainfall intensity and frequency between present and 2030 based on 20-year and 40-year return period events. Blank spaces indicate negligible change.*

	North-west	Northern Pastoral	Eyre	Yorke	Adelaide	Riverland Mallee	South-east	Kangaroo Island
Summer	↓			↑	↑	↑	↓	↑
Autumn	↓	↓	↑	↑				↑
Winter	↑	↓	↓		↑		↓	↑
Spring	↓	↓			↑		↑	

5.3 Extreme summer rainfall and circulation in northern South Australia

Extreme rainfall events and their associated flash floods in northern South Australia are major natural hazards that affect human settlements and major transportation routes. These events often occur during the Australian monsoon season when fully developed low pressure systems penetrate further south into northern South Australia. A number of climate models simulate an increase in average rainfall during the summer months and many models simulate an increase in extreme rainfall even when mean rainfall decreases under enhanced greenhouse conditions. This suggests that a more detailed analysis into the effect of climate change on the specific synoptic situations that produce extreme rainfall over northern South Australia is warranted.

In this section, circulation systems associated with heavy rainfall during are identified in the observations and these are compared to the simulation of present climate in the Mark 3 GCM and the changes due to enhanced greenhouse conditions are then examined. This model was chosen for the present analysis because it had the most realistic simulation of the circulation patterns associated with rainfall over South Australia of all models compared during the spring, summer and autumn seasons. The analysis is carried out from November to April since this period encompasses both the pre-monsoon and monsoon seasons. Anomalously wet months over the north of the state are identified as those whose rainfall totals exceed a threshold, which is defined as one standard deviation above the long-term mean rainfall. On the basis of this criterion, 43 months between 1950 and 2001 were selected from the observations. The mean sea-level pressure and rainfall for the 43 months were then averaged and these subtracted from the six-month climatologies of pressure and rainfall over the 50-year period to produce composites of the anomalies associated with extreme rainfall events. These are shown in Figures 22 a and c for rainfall and pressure respectively. The rainfall anomalies are largest over northern Australia, particularly over the north-west and the Gulf of Carpentaria although positive rainfall anomalies also extend into northern South Australia. These are associated with a region of deeper pressure anomaly that is centred over much of the state. The link between rainfall over northern Australia and northern South Australia suggests that heavy rainfall events that occur over the state are part of the larger-scale monsoonal system.

The same analysis is applied to 40 years of present climate spanning 1961 to 2000 of the CSIRO Mark 3 GCM to assess how well it can simulate atmospheric circulation patterns associated with heavy rainfall events. Using the threshold of mean plus one standard deviation derived from the rainfall of the GCM under present climate conditions, 43 months were selected in the control climate. Composites of the rainfall and pressure anomalies are shown in Figures 22 b and d. The north-west—south-east pattern of rainfall anomalies is well simulated, although the model tends to simulate more rainfall compared with the observed values. This is not surprising since the model also simulates pressure anomalies that are 1 to 2 hPa lower that the observed conditions. The simulated pressure anomaly pattern is slightly more zonal (east-west) compared to the observed north-west—south-east pattern. Overall the model simulates larger negative pressure anomalies during the months that experience heavy rainfall over northern South Australia and central Australia.

For the enhanced greenhouse conditions, the period from 2051 to 2090, centred on 2070 is selected for analysis. Changes to both the intensity and frequency of these events are considered. To examine changes in the intensity of the events, the mean plus standard deviation derived from the model's enhanced climate simulation is used to identify extreme rainfall events for compositing. The difference between the composite of this set of events and those selected under present climate conditions indicates the likely direction of intensity change. These are shown in Figure 23 for rainfall and pressure respectively. Under climate change conditions, an increase in heavy rainfall amounts under enhanced greenhouse conditions is simulated with the greatest increases occurring over the west and south of the state. This is associated with a deepening of pressure anomalies over most of the continent and stronger positive pressure anomalies over the Great Australia Bight. Overall, the model simulates an intensification of the rain-producing systems over northern South Australia and a consequent increase in rainfall intensity under enhanced greenhouse conditions.

To examine changes in the frequency of events under enhanced greenhouse conditions, the threshold of the mean plus one standard deviation derived from the model's current climate is applied to the model's enhanced greenhouse simulation. A comparison of the number of events selected in each climate then indicates how the frequency of events is changing. The number of events selected in the enhanced greenhouse climate using the control climate threshold was 52, compared with 43 events selected in the control climate. This represents approximately a 20% increase in the frequency of events under enhanced greenhouse conditions.

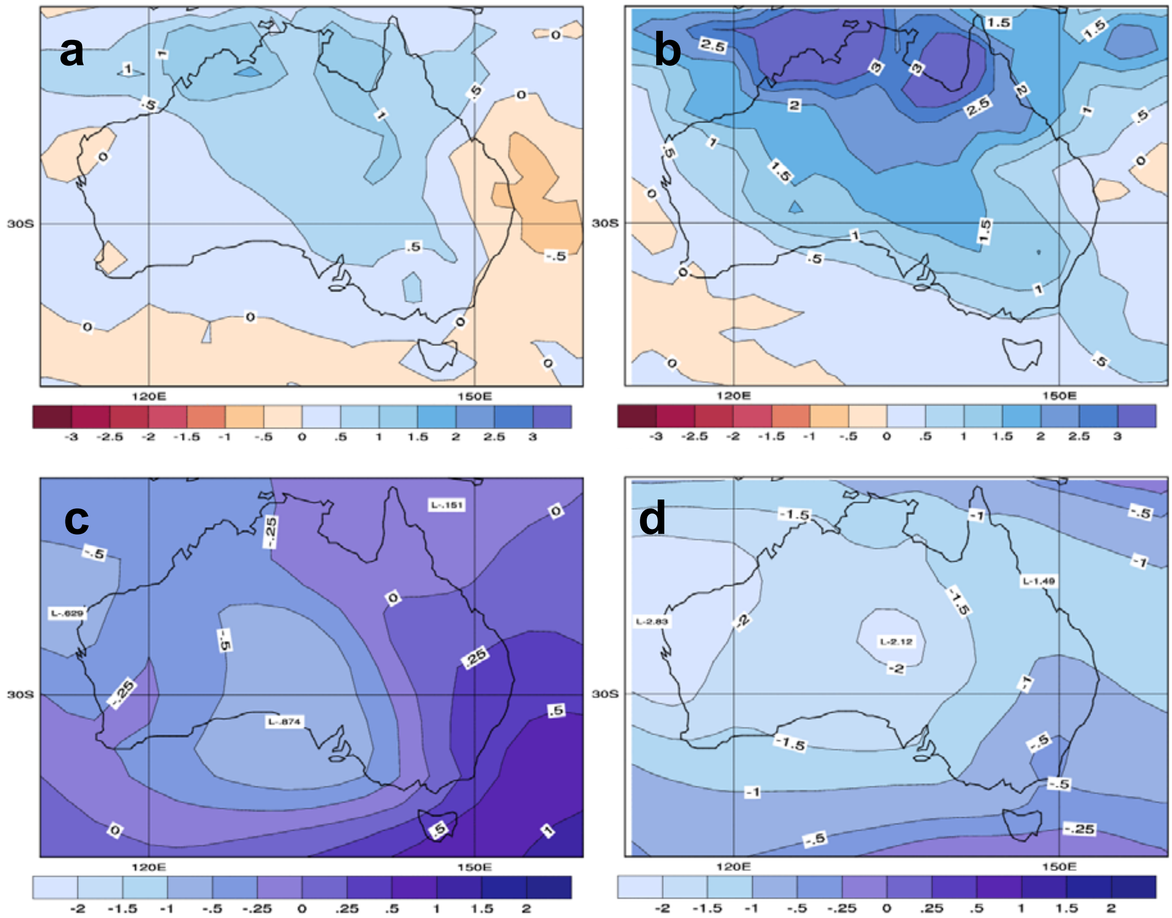

Figure 22: *(a) Observed and (b) Mark3-simulated rainfall anomalies for heavy rainfall events and (c) observed and (d) Mark3-simulated pressure anomalies for heavy rainfall events over northern South Australia. Rainfall (pressure) anomalies are calculated as the difference between composites of rainfall (pressure) during heavy rainfall events and long-term average rainfall (pressure) for six months from November to April. Units are mm per day (hPa).*

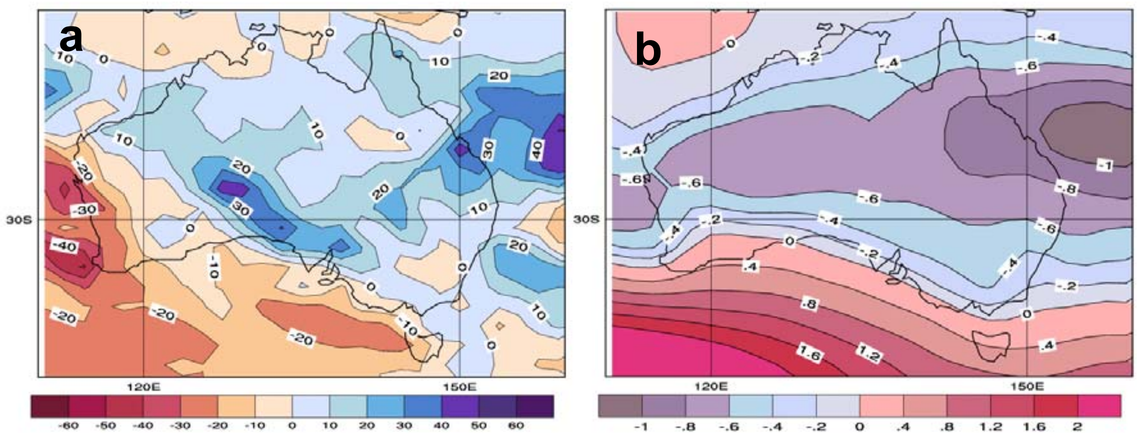

Figure 23: *(a) Mark 3-simulated rainfall anomalies and (b) pressure anomalies under enhanced greenhouse conditions. Anomalies are calculated as the difference between the composites of enhanced greenhouse and control simulations. For rainfall, units are expressed as a percentage change relative to control climate conditions and for pressure, units are hPa.*

5.4 Droughts

Serious rainfall deficiency or drought differs from most other natural hazards in that its effect is slowly accumulated and may persist over long periods of time, unlike the sudden and short-lived nature of phenomena such as storms and floods. In this section, the changes to the frequency of droughts are examined on a seasonal basis in ten of the twelve available climate models (ECHAM3 and GFDL are omitted from the analysis).

The definition of drought used in the present analysis is the Bureau of Meteorology's definition of serious rainfall deficiency, which is applied to model simulated rainfall over South Australia (Bureau of Meteorology, 1999). In this, a serious rainfall deficiency is initiated when a three-month rainfall total falls within the first decile (lowest 10% of records) and is terminated when a monthly total exceeds the average for the three-month period commencing that month, or a three month total is above average. The overall period of serious rainfall deficiency could be any number of consecutive months. Two periods are examined in the climate models, the period 1961-2000 representing present climate conditions and the period 2051-2090 representing enhanced greenhouse conditions.

The frequency of months experiencing drought conditions over the two 40-year periods is shown in Figure 24. All models tend to produce more droughts under present climate conditions than are observed, with Mark2 most closely representing observed frequencies and CC50 classifying nearly twice too many months as 'drought months'. Under enhanced greenhouse conditions, all models simulate an increase in drought frequency with the smallest increases produced by NCAR and the largest by ECHAM4. All models showed increased drought conditions during spring and summer. Four of the models, CCM1, CCM2, DAR125 and NCAR, showed a decrease in wintertime droughts whereas Mark3 and Mark2 showed little change in wintertime drought frequency under enhanced greenhouse conditions. HadCM3 and CC50 showed small increases in wintertime drought frequency and ECHAM4 and HadCM2 showed strong increases in drought frequency throughout the year. Most models showed decreases in drought frequency in Autumn, the exceptions being ECHAM4, HadCM2, and HadCM3.

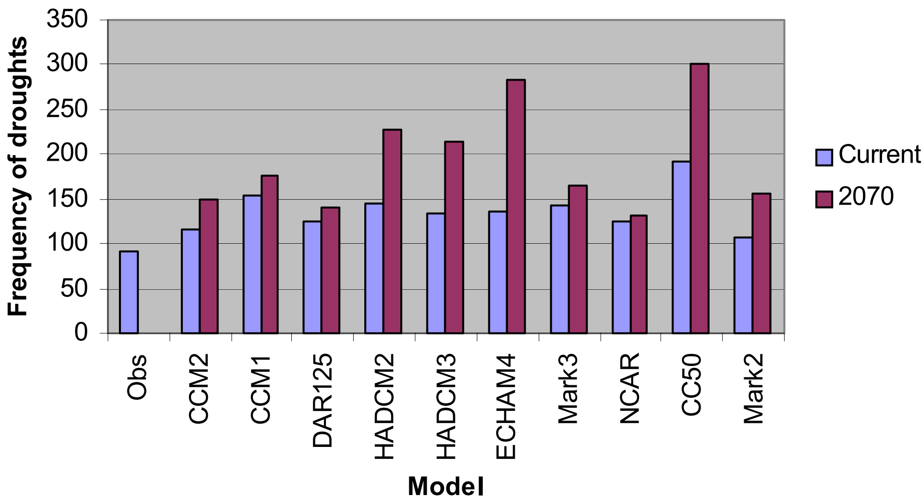

Figure 24: *The frequency of drought-classified months over the forty years of current climate (1961-2000) and enhanced greenhouse climate (2051-2090).*

6. Extreme events and the coastal zone

In the mid-latitudes, extra-tropical cyclones are the main cause of stormy weather conditions. They can produce heavy rainfall leading to flooding and strong winds that can damage the terrestrial landscape and generate hazardous ocean conditions including storm surges, heavy waves and swell. An understanding of how climate change may impact upon the behaviour of mid-latitude cyclones and extreme winds are an important aspect of climate change impact assessment particularly for coastal regions that are vulnerable to both the terrestrial and oceanic consequences of severe storms.

6.1 Storm surges in South Australia

Episodes of elevated sea level have been examined in eight years of data collected from tide gauges established by the National Tidal Facility in 1993 at Ceduna (Thevenard) and Adelaide (Port Stanvac). Sea-level residual data, in which the re-predicted tidal component is subtracted out to leave the sea-level response due to currents caused by the meteorology, are used to identify incidences where sea levels exceed 0.5 m and 1.0 m at each of the locations. A total of 43 events occurred over the 8-year period and their seasonal frequencies are represented in Figure 25. These data show that elevated sea-level events occur in all seasons, although they tend to be more frequent in winter and spring. The prevailing meteorological conditions in the majority (approximately 97%) of cases are cold fronts that traverse the south coast. Less commonly, they are caused by small-scale mesoscale low pressure systems which develop and intensify in close proximity to the coast.

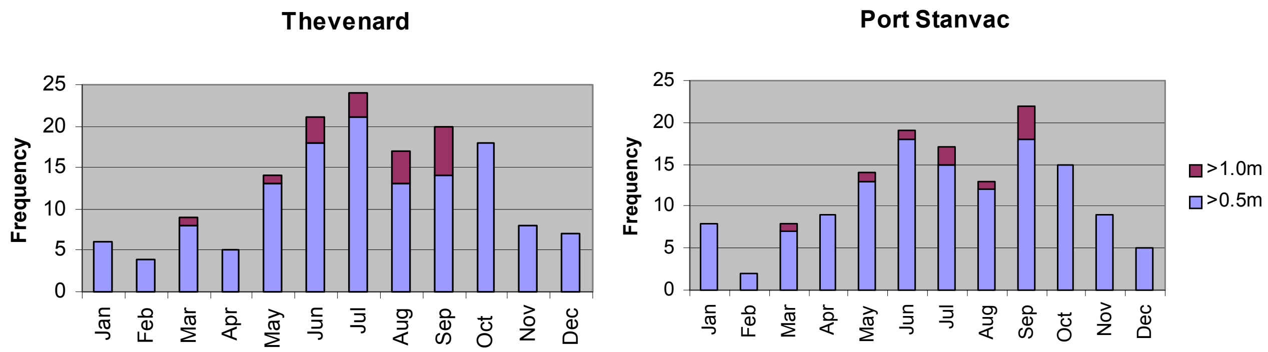

Figure 25: *Frequency of sea-level anomalies above 0.5 and 1.0 m respectively for Thevenard (Ceduna) and Port Stanvac (Adelaide) based on eight years of NTF data.*

An example of one such event, which occurred in May 1994 is shown in Figure 26. Sea levels reached about 1.1 m at both Thevenard (Figure 26a) and Port Stanvac. The synoptic situation at the time of the peak is shown in Figure 26b and illustrates a front and associated low pressure system travelling eastwards along the South Australian coast. The front was situated to the south-west of Western Australia at the commencement of the 8-day sea-level time series, and had reached the Tasman Sea eight days later. Winds during this time had a strong west to south-west component reaching 16 ms^{-1}.

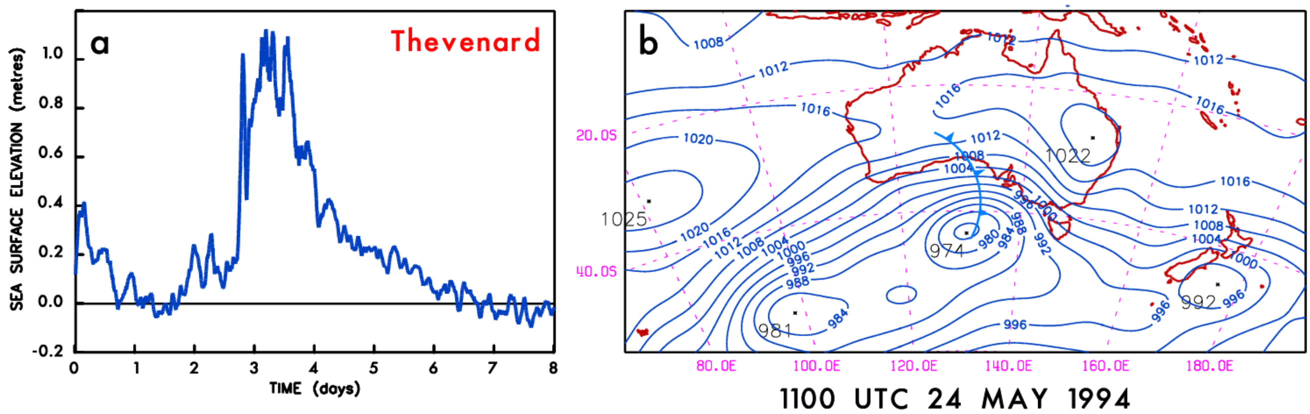

Figure 26: *(a) Sea-level anomalies at Thevenard caused by the passage of a cold front. The time series commences at 1100 UTC 21 May 1994. Note that variations in sea level due to tides have been removed. (b) the mean sea-level pressure pattern (hPa) at 1100 UTC 24 May 1994 at around the time when highest sea levels were recorded at Thevenard.*

Since low pressure systems and associated westerly or south-westerly winds are responsible for the majority of storm surges along the South Australian coast, an assessment has been made of both changes to low pressure systems and winds in the region under enhanced greenhouse conditions. Due to the complex analysis procedure involved in locating and tracking low pressure centres in daily fields, these changes are analysed on only one model simulation; the CSIRO Mark 2 climate experiment. The choice of this model was justified in that it produced the highest skill amongst the global CSIRO models in reproducing the circulation systems and rainfall patterns during the winter months (section 3.2).

6.2 Storm Tracks

There have been few studies of storm tracks carried out with a Southern Hemisphere focus and those to date have based their analyses on climate simulations performed using the older GCM experiments. While the majority of studies find an increase in storminess in high northern latitudes such as north-western Europe, all of the Southern Hemisphere studies to date find a reduction in the frequency of low pressure systems. The intensity of lows in the majority of the studies was found to increase under enhanced greenhouse conditions.

Automated counting and tracking software of Jones and Simmonds (1993) is used to identify individual centres of low pressure in daily fields of mean sea-level pressure in the GCM. Two 40-year intervals are examined, the first spanning 1960-1999 representing the control climate and the second from 2040-2079 representing the enhanced greenhouse climate at around the time of CO_2 doubling. The mid-latitude lows identified in the control climate are also compared to those identified over the same time interval in the observations.

Figure 27 compares the frequencies of lows based on observations in the NCEP reanalyses and the Mark 2 model during the winter. The GCM captures the pattern of low pressure occurrence well, although the number of lows is underestimated, particularly over south-eastern Australia and the Tasman Sea. The coarse horizontal resolution of the CSIRO GCM is a contributing factor to the reduced number of low pressure systems.

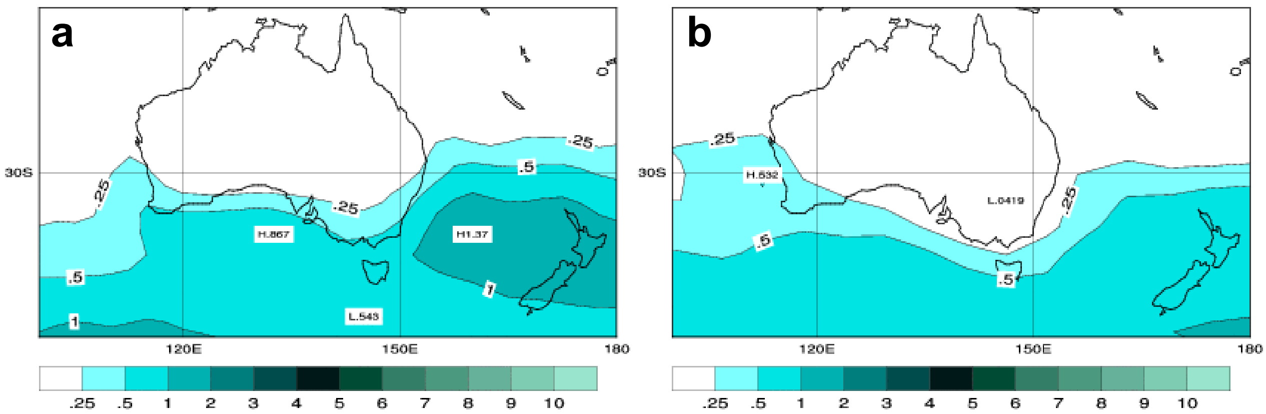

Figure 27: *Frequency of storms counted in each latitude-longitude square for (a) observed and (b) Mark 2 over the period 1960-1999 over the winter season. Units are 10^{-3} cyclones (°latitude)$^{-2}$.*

On a hemispheric scale, the frequency of lows was found to decrease under enhanced greenhouse conditions in the CSIRO Mark2 GCM. This result is likely to be associated with the general tendency for increased pressure in the midlatitudes of the southern hemisphere. Changes in the frequency of low pressure systems between the enhanced and control climates are shown in Figure 28a. The frequency of lows is found to decrease over much of the Bight. A small region of increasing low frequency occurs over the south-east coast of Australia. This pattern is attributed to an increase in the low level temperature gradient across Australia and is consistent with results obtained from DAR125 using alternative measurements of storm tracks (Whetton et al., 2002). Over the region bounded by 30-50°S and 125-145°E, the number of lows over the 40 year interval decreases by 20% from 754 lows under present climate conditions to 612 lows under enhanced greenhouse conditions.

A brief analysis of change in cyclone frequency and intensity during spring was also undertaken since this season indicates a reasonably high incidence of storm surges as well. Lows were found to increase slightly in frequency (2%) from 565 under control climate conditions to 576 under enhanced greenhouse conditions. The average intensity of the top one percent of events increased slightly in intensity from 971.5 to 970.5 hPa under enhanced greenhouse conditions.

Cyclone intensity is calculated as the central pressure of the cyclone on each day of its existence relative to the climatological mean sea-level pressure. This is to ensure that the results are not biased by large changes in the climatological pressure means that also may have occurred as a result of enhanced climate change. Differences in cyclone intensity between enhanced greenhouse and present climate conditions are shown in Figure 28b. These results indicate that low pressure centres have deepened (i.e. intensified) by up to 2 hPa everywhere except across Bass Strait and off the east coast of Australia. The average intensity of the most intense lows in each climate defined as the top one percent of lows is 969.5 hPa in the control climate and 968 hPa in the enhanced greenhouse climate.

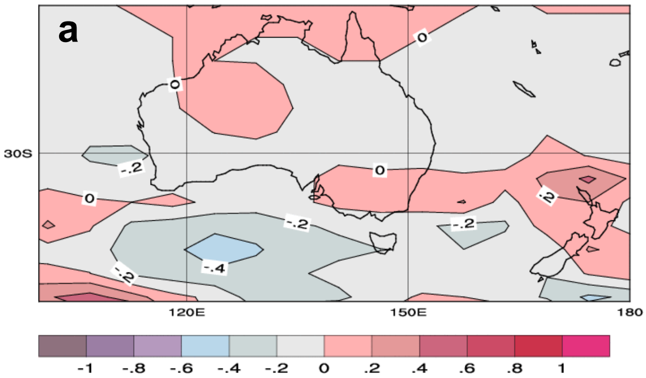

Figure 28: *Difference between CSIRO Mark2 simulated present and future (a) storm frequency and (b) relative storm intensity. Note that blank areas in diagrams of storm intensity indicate areas where lows did not occur and for which frequency and central pressure data do not exist.*

Finally, the likely changes in rainfall associated with wintertime lows are examined. Rainfall for all days in which a low pressure system was located within the region bounded by 125-145°E and 30-50°S in both present and enhanced greenhouse climates were composited. Figure 29a shows the rainfall pattern due to mid-latitude lows under present climate conditions. A rainfall maximum in excess of 100 mm is situated in the Bight and little rainfall penetrates inland. The spatial pattern of rainfall from the lows is similar to that of total winter rainfall simulated by the Mark 2 model although the magnitudes are only about a quarter of the total value. This may be because rainfall occurs before the low moves into the region and continues for several days after the low has moved away from the area.

The difference between the accumulated rainfall from the wintertime lows in the present and enhanced climates is shown in Figure 29b. Owing to the 20% fewer lows that occur under enhanced greenhouse conditions, total rainfall from this source is around 10 to 20% lower over the Bight and more than 20% lower over the south-east of the state by around 2060. On the other hand, the average rainfall associated with each low is up to 20% higher under enhanced greenhouse conditions over the Bight and western coastal region, although still shows decreases of between 10 and 20% over the eastern coastal region (Figure 29c).

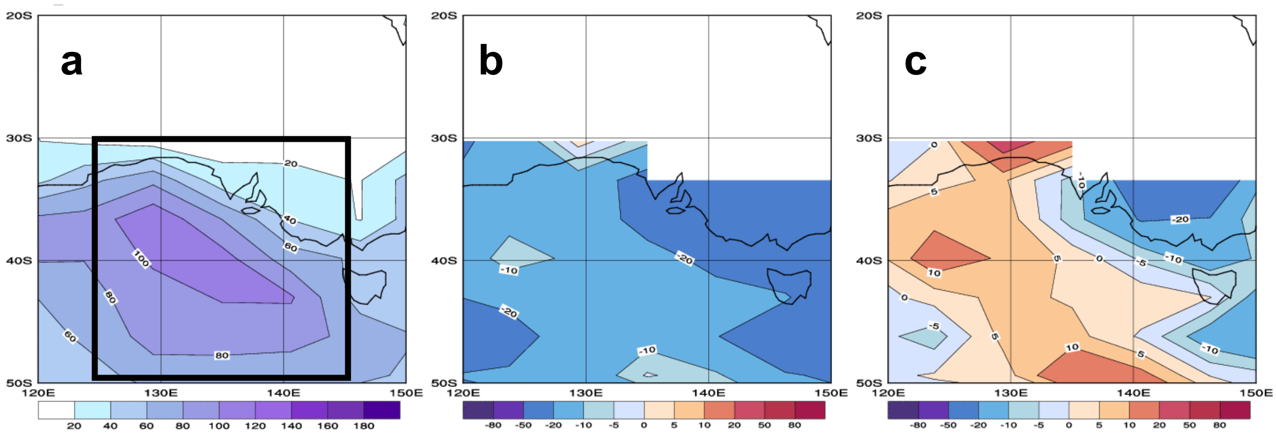

Figure 29: *(a) composite of rainfall for all days in which a low pressure system was located between 125 and 145°E and 30 and 50°S over the forty years of model simulated current climate, (b) the percentage change in rainfall composites between enhanced greenhouse and current climate (c) the percentage change in rainfall per low pressure system between enhanced greenhouse and current climate.*

6.3 Extreme Winds

The largest contribution of energy from the sea to the coast, which drives erosion and transport of sand and sediment, is from wind-generated waves. Therefore, an understanding of the likely changes to wind climate and in particular, extremes in wind due to enhanced greenhouse change is important for understanding the likely impacts on the coastal zone. In this section, wind extremes are analysed in the regional climate model DAR125. Note that this model was nested within the Mark2 GCM but owing to its higher resolution, is likely to simulate more realistic extremes in wind particularly in the vicinity of the coast.

Figure 30 presents a comparison between average wind speed in forty years of DAR125 from 1961 to 2000 with the equivalent years of observed wind from the NCEP reanalyses for summer and winter. There is good agreement between the model and the observations over South Australia and the Bight both in terms of wind magnitudes and spatial patterns. A comparison of extreme winds, defined as the upper percentile or the top one percent of wind speeds in the model and observations showed that the model extremes tended to be underestimated, particularly in the southern ocean.

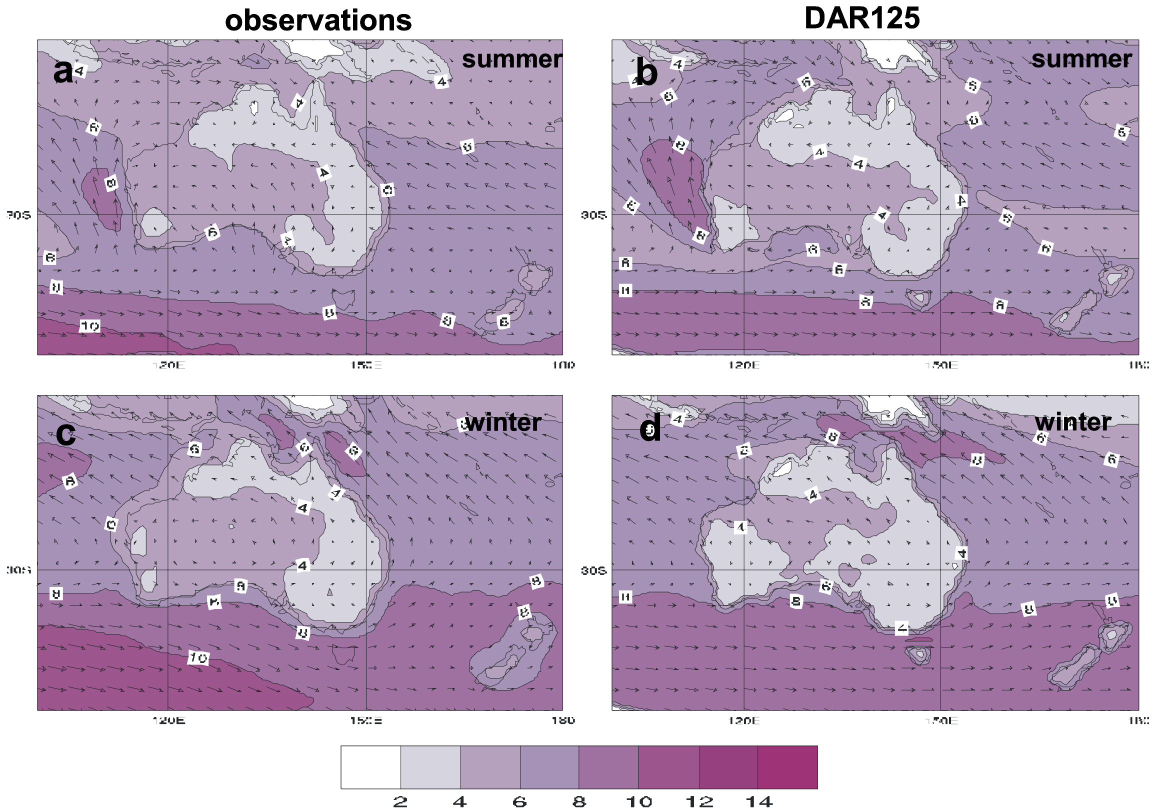

Figure 30: Comparison between seasonally averaged winds from observations and the control climate of the DAR125 simulation for summer (a) and (b) and winter (c) and (d). Contour intervals are 2 m s^{-1}.

The frequency of winds from eight compass directions (north, north-east, east, south-east, south, south-west, west and north-west) were also compared. During summer, winds over the state are dominated by winds from the east, south-east, south and south-west, while over the Bight, winds from the west, south-west and north-west dominate. The model captures the directional frequencies of winds over the state reasonably well although some spatial variation occurs in the partition of winds from these directions. Over the Bight, the model over estimates the frequency of westerly winds by between 10 and 15% at the expense of winds with an easterly, north-easterly and south-easterly component.

Enhanced greenhouse conditions are analysed over the 40-year period from 2041 and 2080. Over this period, average wind speeds and standard deviations are found to decrease over most of South Australia in all seasons. Extreme winds also tended to decrease over the southern pards of South Australia in all seasons with reductions of up to 60% over the Bight (Figure 31).

Changes in wind direction under enhanced greenhouse conditions were fairly minor over much of the state and coastal waters. Winds from the west, south-west, south and north-west are most relevant in terms of their ability to generate storm surges along the South Australian coast and so these directions will be the focus of the analysis of changes under enhanced greenhouse conditions. Changes in wind frequencies for these directions in winter are shown in Figure 32.

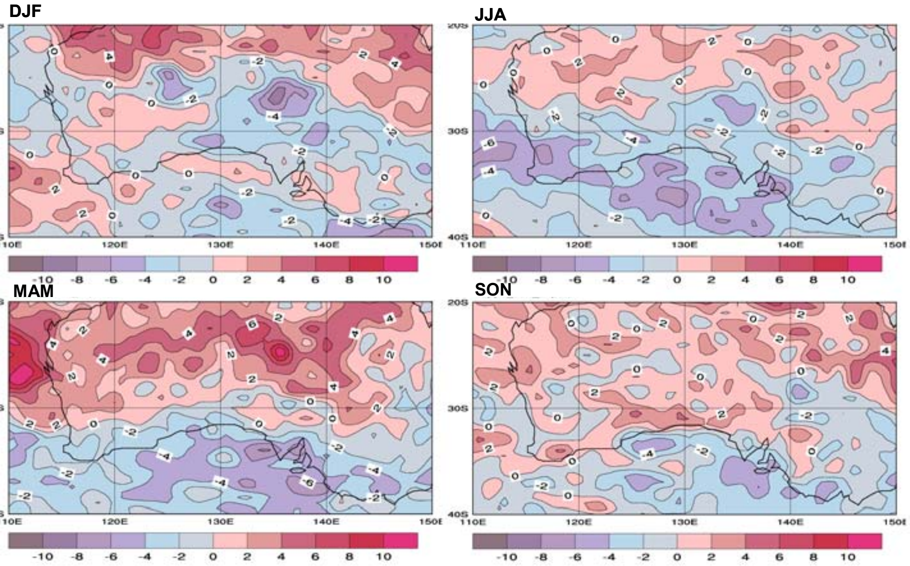

Figure 31: *DAR125 simulated differences between upper percentile winds for 2030-2069 and 1960-1999 for the four seasons. Units are percentage change relative to 1960-1999.*

Under enhanced greenhouse conditions, westerlies and north-westerlies indicate decreasing frequencies of occurrence over South Australia and the Bight with strong increases further to the south of the continent. Southerlies show slight increases of around 1% over the South Australian coast and the Bight. The decreases in westerly and north-westerly winds are largely compensated for by increases in easterlies, north-easterlies and south-easterlies (not shown).

In spring (Figure 33), westerlies, southerlies and south-westerlies show stronger increases in frequency, particularly along the eastern coastal regions with Adelaide experiencing an increase of about 4% (approximately 4 days per season) of winds from these directions. Autumn shows similar but weaker patterns of change to spring. It is noteworthy that slight increases in the frequency of south-easterlies also occur during summer and autumn along the Bonney Coast to the east of Adelaide. Winds from this direction are associated with upwelling (rising of nutrient rich water) at the edge of the continental shelf along this part of the coast and provides favourable conditions for fish spawning.

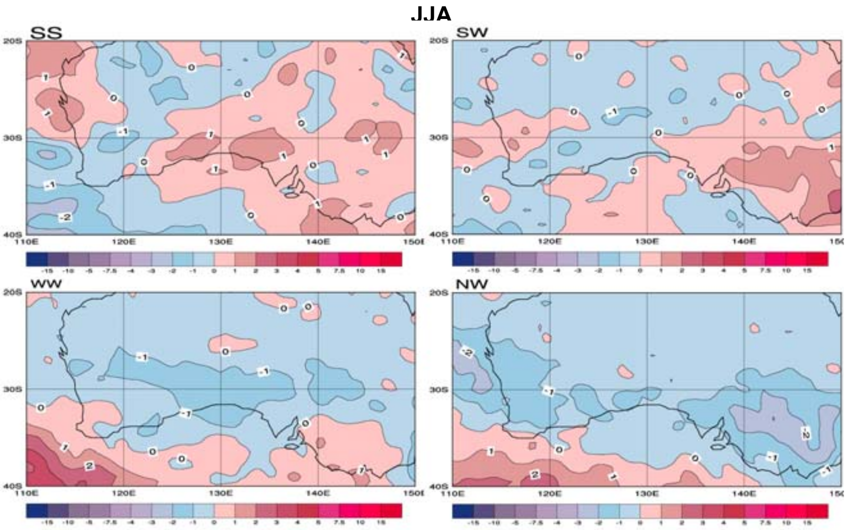

Figure 32: *DAR125 simulated differences between 2040-2079 and 1960-1999 wind frequency from the south (SS), south-west (SW), west (WW) and north-west (NW) directions in winter. Units are percentage of days per season.*

6.4 Implications for storm surges and coastal flooding

This chapter has examined changes to storm tracks in Mark 2 and extremes in winds in DAR125. In winter, mid-latitude cyclones, which produce storm surge-conducive westerly and south-westerly winds along the south coast, were found to decrease in frequency by about 20% in the South Australian region but increase slightly in intensity. The changes in the frequency of lows were consistent with extreme wind changes in this season. These results tend to imply reduced frequency and severity of storm surge under enhanced greenhouse conditions. However, analysis of wind direction changes in spring and autumn showed increases in the frequency of winds that can cause storm surges suggesting that further analysis is needed of changes occurring in the transitional seasons. Furthermore, there is also evidence that the rainfall associated with lows increased over parts of the coast suggesting that flooding due to the combination of rainfall and storm surge could increase. Finally, it is also important to bear in mind that the analysis in this chapter was undertaken only on one model experiment. Analysis of storm tracks and winds in the other models for which daily data exist would provide greater confidence in the robustness of the changes and their spatial variations.

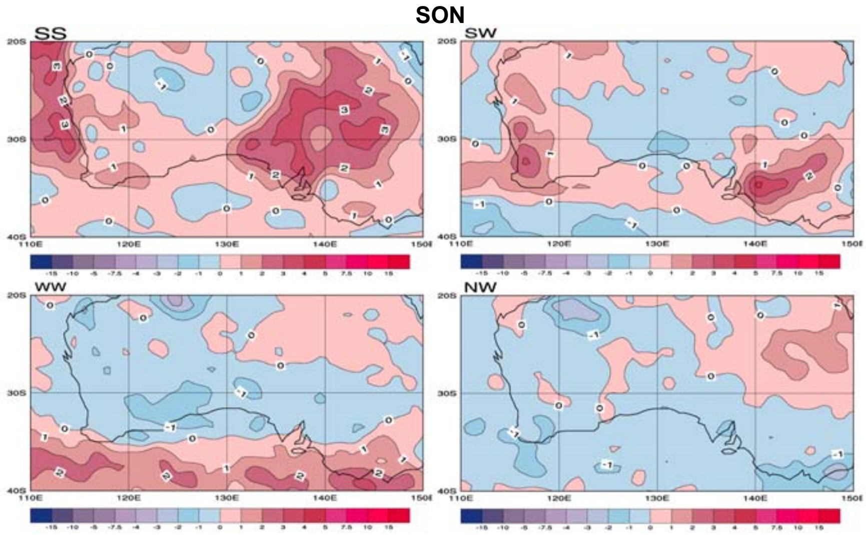

Figure 33: *DAR125 simulated differences between 2040-2079 and 1960-1999 wind frequency from the south (SS), south-west (SW), west (WW) and north-west (NW) directions in spring. Units are percentage of days per season.*

Despite the possibility of decreasing storm frequency and wind extremes in winter, the net effect of rising sea levels (and possibly land subsidence in the vicinity of Adelaide) with changes in storm frequency is unknown. A more targeted impacts study that integrated all the effects together would be required to gain greater understanding of the various contributions to extreme sea-level events. A study of this nature has been undertaken for storm surges in Cairns under enhanced greenhouse conditions (McInnes et al., 2003) and could also be undertaken for specific regions along the South Australian coast such as the Gulf of St Vincent. A brief outline of the approach of this study is presented below.

The approach requires developing a statistical model of the extreme weather conditions that cause storm surges based on the observational records of weather conditions in the region. For example, in Cairns, it is tropical cyclones whereas in South Australia, severe westerly and south-westerly winds are the cause. The statistical model is then used to randomly generate a large number of plausible 'storm events' for the region and these conditions are used to drive a high resolution coastal ocean model capable of modeling currents, sea level heights and overland inundation due to the effects of tides and storm surges. The model-simulated events are then analysed to produce storm surge average recurrence intervals (ARIs).

There are a number of advantages to this approach as outlined below:

- Whilst tide gauge records can be used to derive ARIs for extreme sea level events, the reliability of such analyses are dependent on the length of the tide gauge record in relation to the frequency of severe weather events that produce the extreme sea levels.
- The ARI's for storm tides can be evaluated at each grid point of the model's two-dimensional computational grid rather than just at the location of the tide gauge so that return period contours can be developed over the geographical region of interest.
- By modelling the tides and surge together ensures that the non-linear interaction between the tide and storm surge currents is taken into account.
- Enhanced greenhouse changes to meteorological extremes that cause storm surges can easily be incorporated into the statistical model governing severe weather conditions enabling the impact of different climate change scenarios on the return periods of extreme sea levels to be explored.

7. Impacts and adaptation strategies for climate change in South Australia

The purpose of this chapter is twofold. The first is to outline a framework in which climate change information may be incorporated into impact and adaptation assessments. Methods are being developed at CSIRO with international collaborators to identify vulnerability of different sectors to climate change through risk assessments. These approaches are reliant upon creating links between climate and impact scientists and stakeholders. This chapter also reports on the outcomes of two stakeholder workshops conducted during the course of this project.

7.1 Assessing current and future climate risks

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. This is a 'top-down' approach for which an example was presented in the previous chapter for evaluating storm surge risk. 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 approach, which is the focus of the present chapter, is the vulnerability-based approach that begins with the damages or consequences, and diagnoses the climatic conditions that contribute to particular levels of damage. In this, the problem is treated from the 'bottom-up' where a particular adverse event or threshold is identified and the probability of that situation being realized through climate change is evaluated by applying risk assessment methods that utilise multiple scenarios. An advantage over the conventional approach is that it incorporates 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.

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).

Such a combination can be expressed as:

Risk = probability × 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.

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 34. 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 34 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 become 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.

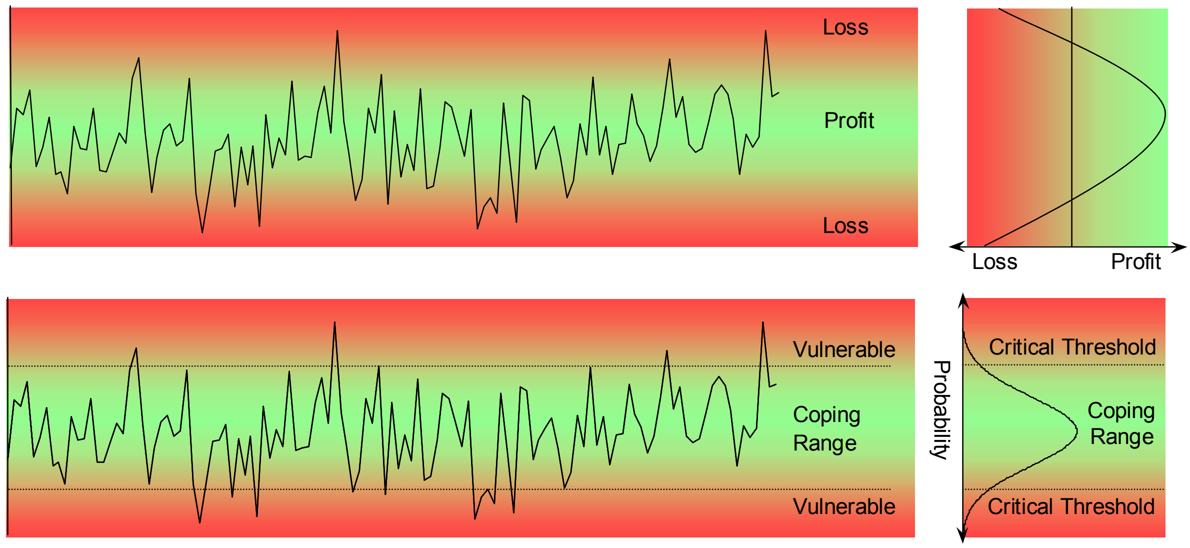

***Figure 34:** Simple schematic of a coping range under a stationary climate representing a driving variable such as rainfall or temperature and an output such as crop or water yield. Vulnerability is assumed not to change over time. The upper time series and chart shows a relationship between climate 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.*

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 34, 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 34, lower right).

7.2 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.

Building conceptual models and characterizing climate extremes and hazards

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, 2001). 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.

The characterisation of climate extremes and hazards commences with an identification of how well the climate hazards (affecting the system) are 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, interannual 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 variables has a different level of skill in terms of climate modelling and has different degrees of predictability, information that 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.

Impact assessment and risk assessment criteria

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 is undertaken in McInnes et al. (2003). 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 effects vulnerability will also affect the ability to cope, and identifying such interactions are likely to be important for identifying possible adaptations.

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. <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 34, 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.

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.

7.3 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 11 shows a number of climate risk assessments classified according to their major area of focus.

***Table 11**: 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.

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.

Using coping ranges to measure future climate risks

The coping range as introduced in Figure 34 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 35 (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 35 (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.

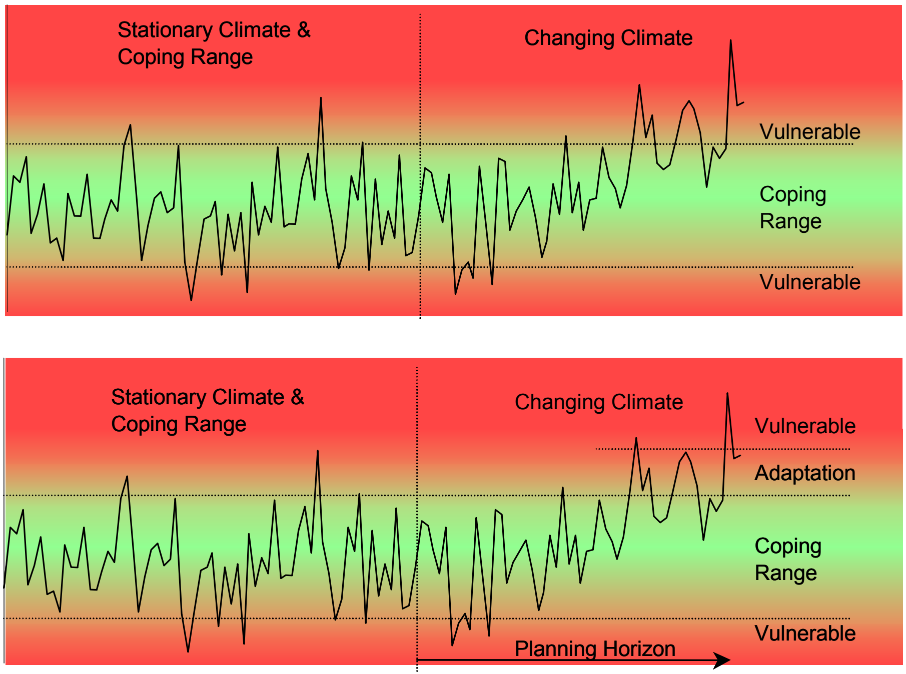

Figure 35: *Coping range showing the relationship between (a) climate change and threshold exceedance, and (b) how adaptation can establish a new critical threshold, reducing vulnerability to climate change.*

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.

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 or more years, but planning for supply may only be 5–15 years (Figure 36). 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.

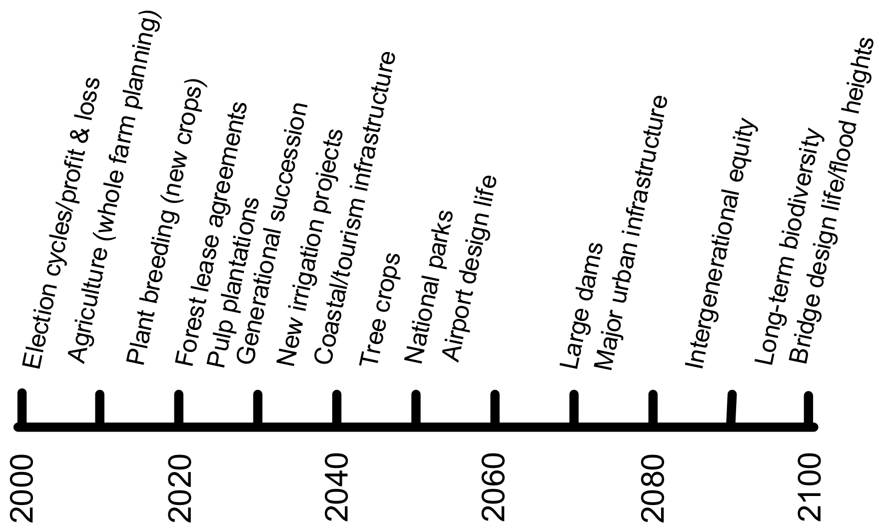

Figure 36: *Planning horizons relevant to climate risk assessments.*

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 resampled 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)

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 0.09 to 0.88 m at 2100, a section of coast with a critical threshold of 0.25 m is much more likely to be inundated by 2100 than a section with a critical threshold of 0.75 m. 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 37 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 37 also shows how probability distribution functions based on two or more input uncertainties can be recast.

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.

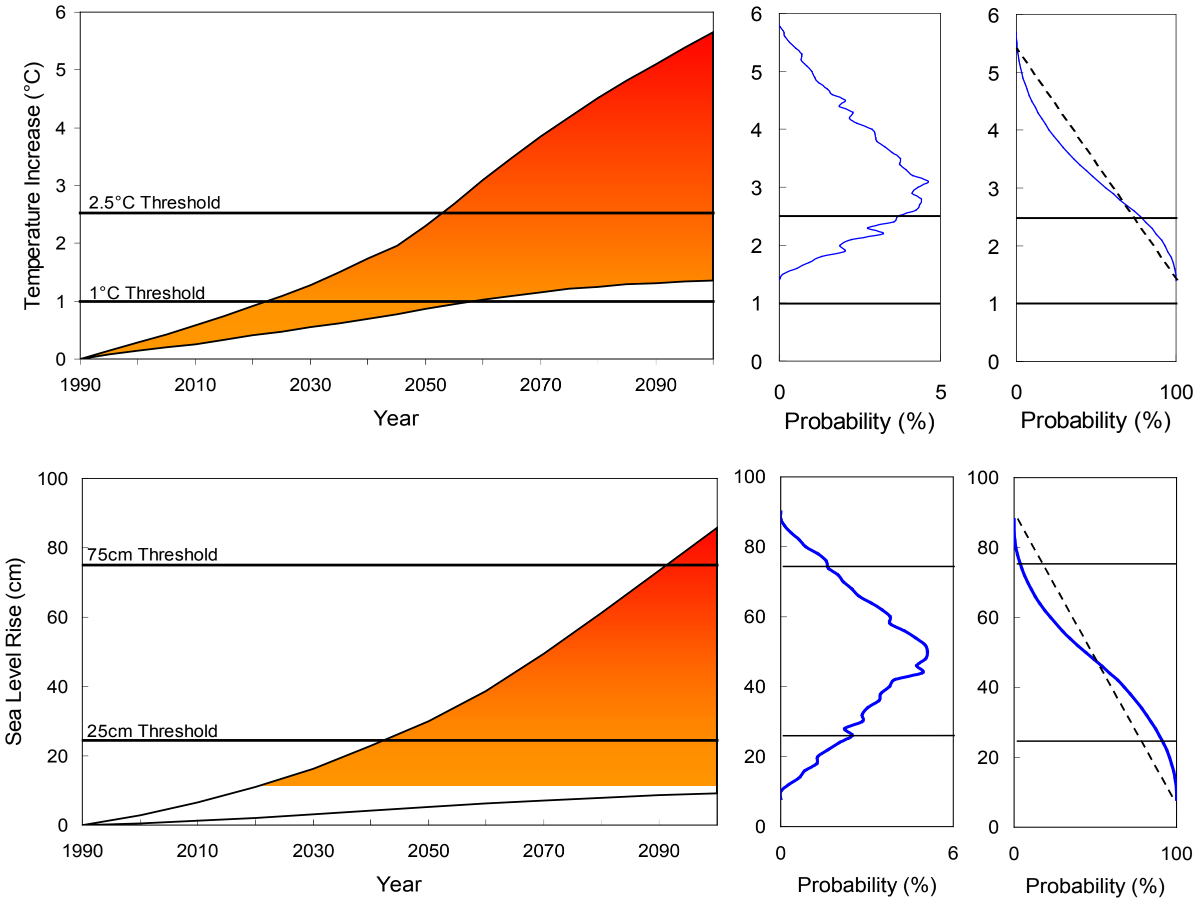

Figure 37: *The left hand panels show ranges of temperature increase (upper) and sea level rise (lower) 1990–2100 (IPCC 2001), showing a 1°C and 2.5°C warming threshold (upper) and a 0.25 m and 0.75 m sea level rise threshold (lower). The centre panels show a probability distribution combining two ranges 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.*

The relationship between adaptation and mitigation and global warming in terms of risk assessment is shown in Figure 38. 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 38 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.

7.4 Summary of Sectoral Issues

This section reports on the issues raised in two workshops conducted with stakeholders during the course of the present study. The purpose of the workshops was to engage stakeholders in identifying the different sectors that are potentially vulnerable to climate change and the various issues within each sector. These issues are reported under sectoral headings below and are based on information gained from the workshops and from other studies. Details of the attendees at the workshops are given in Appendix 1.

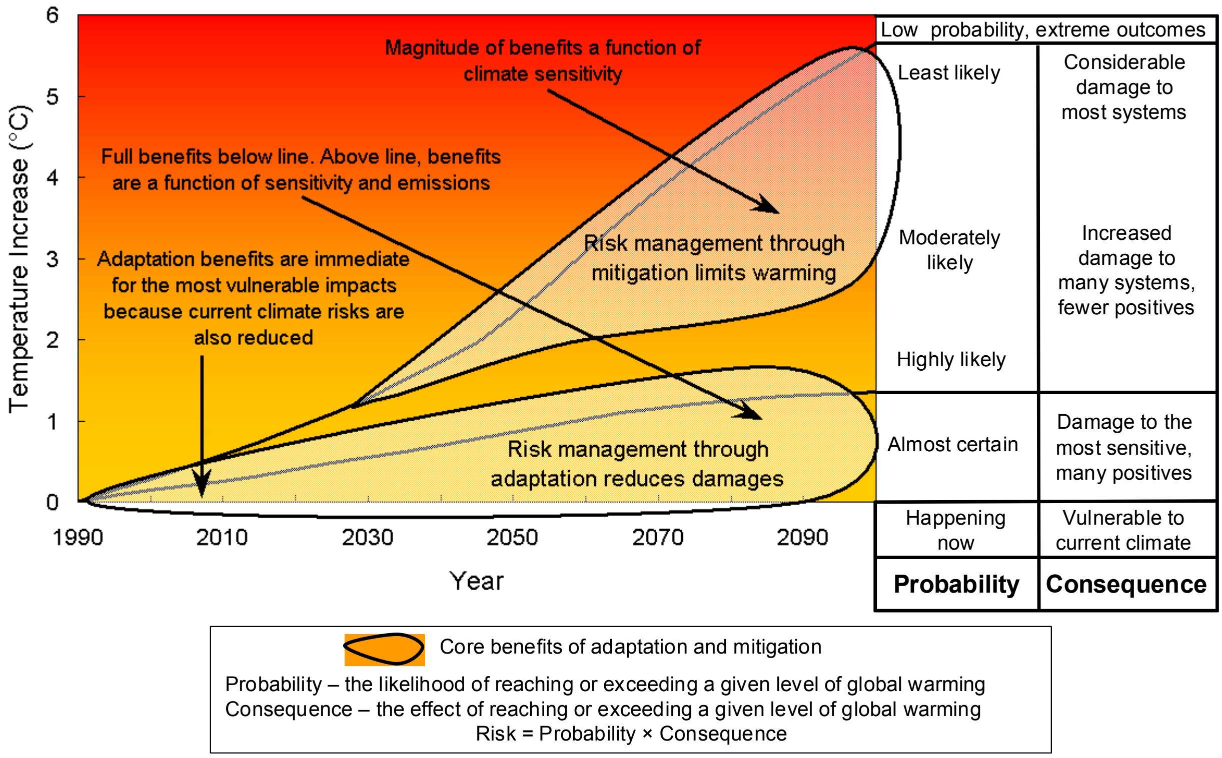

***Figure 38:** Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on the six SRES greenhouse gas emission marker scenarios with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold 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.*

Water and catchments

The recent CSIRO (2001a) climate projections and summary of impacts (CSIRO, 2001b) indicate that reductions in water supply are likely for South Australia. Generally, the adaptive capacity of water management is high owing to the large interannual climate variability in the region. However, the risks of longer-term, sustained reductions of water supply remain unknown. As the most downstream region in the Murray-Darling Basin with limited surface resources elsewhere, what happens in South Australia is dependent on climate change upstream as well as the actions of New South Wales, Victoria and Queensland. Climate change needs to be factored into ongoing water reform processes including market development, planning for water quality, river health and environmental flows. Possible interactions between climate change and salinity, including how they may influence salinity management options, is a key long term issue for catchment management.

Agriculture

The agricultural sector in general is well adapted to climate variability. The cropping area for wheat has changed in response to past rainfall shifts (e.g. Goyder's Line) and a study into the distribution of wheat cropping under various climate change scenarios by Reyenga et al. (2001) indicate an expansion of wheat cropping in South Australia to the north under all scenarios except that of reduced rainfall. Viticulture, another major agricultural activity in South Australia, is likely to have greater adaptive capacity to climate change than most other agricultural activities. For example, increases in atmospheric carbon dioxide will increase plant productivity, which is likely to counterbalance the impacts of lowered available moisture, as long as temperature effects remain tolerable. Experiments in partial root zone drying, in which vine water use efficiency is enhanced, show promise in reducing the overall water requirements of this industry.

Further work on how climate change may affect production systems will be needed to maximise agricultural performance under such conditions, particularly at higher temperatures. Adaptation will be required for longer-lived crops near the boundaries of their current climatic limits. The impact of agriculture on land systems at the catchment scale, the risks of long-term water supply to irrigated agriculture and the long-term threats of dryland salinity under climate change require further research.

Biodiversity

The relationships between biota and climate change are poorly known at the species level and largely unknown at the community level. The resilience of ecosystems to natural climate change is high if they are allowed time and space to respond. However, in a landscape where many systems are fragmented and subject to weed and pest invasion, ecosystems will be much more vulnerable. Furthermore, rising sea levels and the possibility of increasingly severe storm surges combined with limited scope for retreat mean that biodiversity in intertidal zones will increasingly come under threat with changing climate with areas of mangroves and samphires particularly vulnerable. Increases in water temperature along the coasts and in the Gulf of St Vincent and Spencer Gulf could also have serious implications for coastal and marine biodiversity with possible impacts on algal recruitment, spawning and migration of marine fauna and health of sea grasses. The relationships between water temperature and marine biology are generally poorly understood yet impacts on marine biota will almost certainly impact upon aquaculture in the region. Estuarine processes under climate change are poorly understood. Natural estuarine systems are biologically very important, so setback strategies will be needed rather than hard barriers such as sea walls, but will be limited where prior development has occurred. Clearly the most vulnerable areas are those that are low-lying with very little setback to allow for adaptation.

The impacts of increased CO_2 on ecosystem functions of natural communities and on species distribution is largely unknown. In order to develop options for planned adaptation, research needs include a better understanding of the dynamics between climate and biodiversity and processes of autonomous adaptation within the modern landscape. Fragmentation issues, and pests and weeds will need to be actively managed because the latter's invasive potential will be enhanced by higher CO_2, nutrient changes and increased ecosystem turnover. Although South Australia's reserve system is large, many biotic communities are not adequately represented in that system (H. Possingham pers. comm., 2002). Adaptation will require management on both public and private land, where species may need to shift to respond to a changing climate.

Coasts

New IPCC (2001) projections of sea-level rise are slightly lower than previous estimates, being 0.09–0.88 m by 2100. The regional rate of risk remains unknown. Sea-level rise is also expected to rise for centuries after stabilisation of greenhouse gases, so emissions over the next century will contribute to long-term risks. The effects of sea level rise in the Adelaide region, particularly across Lefevre Peninsula and Barker Inlet will be exacerbated by a subsiding coastline, making relative sea level rise larger than eustatic sea-level rise. Low-lying sections of the coast will be the most vulnerable.

The impacts of sea-level rise will also be felt through storms and related surge events, with mean sea-level rise adding to their severity. Storm patterns may not change greatly, but may become slightly less frequent and slightly more intense in South Australia. Wind generated waves are the main mechanism by which energy of the ocean is transferred to the coastal zone and small changes in wind climate can bring about large coastline modification. Strong winds likely to cause storm surges were found to weaken over South Australian coastal regions in winter but strengthen in spring and autumn possibly leading to a broader distribution of storm surge occurrence throughout the year. Although the models do not indicate a drastic change in winds in the region of the Bonney coast, increases in south-easterlies during the summer months indicate that some alteration in strength or frequency of the upwelling is not implausible. These issues should be considered in relation to the conservation values of the area and how they should be managed.

The most vulnerable coasts are those what are low-lying with little setback to allow for adaptation. Estuarine processes under climate change are poorly understood. Natural estuarine systems are biologically very important, so setback strategies will be needed rather than hard barriers such as sea walls, but will be limited where prior development has already occurred.

Health

Trends in South Australia at present are towards an ageing population that is generally less heat tolerant. The relationship between climate extremes and human mortality has been investigated by McMichael et al. (in press) using scenarios from the CSIRO Mark2 and ECHAM4 global climate models. The CSIRO model simulates wetter conditions in central Australia and drier conditions in the eastern States, while ECMAH4 simulates wetter conditions for north-eastern Australia. The observed temperature and mortality data for each Australian capital city were combined to determine temperature-related mortality relationships. At temperate locations like Adelaide, Canberra, Hobart, Melbourne, Brisbane and Perth, they found a 1% increase in mortality per degree of daily maximum temperature above 20^{o}C. Perth and Adelaide showed the highest number of heat-related deaths per capita in the 65+ age-group. In Adelaide, the annual death-rate was 127 per 100,000 people. After adjusting for the effect of air-pollution, very few cold-related deaths were found, e.g. 3 per year in Canberra.

Climate change and population change scenarios were included in estimates of heat-related deaths in people aged at least 65 for 2020 and 2050. The results for 2050 in Adelaide show that the annual mortality rate increases to 154-187 deaths per 100,000 people – an increase of 21-47%. Allowing for population growth, this means 523-633 heat-related deaths per year in Adelaide's older people by 2050. Adaptation measures include development of heat-forecasting systems, community-wide heat-emergency plans, heat-illness management plans, increased use of air conditioning, increased intake of fluids, changed working hours, and better building insulation and design.

Also considered by McMichael et al., (in press) were the health impacts of extreme rainfall and flooding, although these assessments were made on the basis of monthly rainfall data and therefore may underestimate the increases in extreme daily rainfall and associated floods. Direct effects include injury or death by drowning or being hit by debris. Indirect effects include water-borne diseases such as leptospirosis and hepatitis A, disruption of water purification and sewage disposal systems, psychological stress and depression. By 2050, the estimated risk of flood-related death or injury tends to decrease in regions near Adelaide (−24 to -44%), Eyre Peninsula (−2 to −28%), Coonawarra (+4 to −29%), and Ceduna (+1 to −21%), while increases were found near Renmark (+15 to +46%) and in the northern-half of the State (+72 to +108%).

Energy and Urban Settlement

Increasing frequencies of temperature extremes will lead to greater energy demand for cooling, both peak demand and summer base load. However, these stresses may be partially offset by increasing dependence on energy supplies from wind farms whose output is typically higher on hot days owing to the fact that days of extreme temperature often coincide with strong northerly winds. Adaptations may also include a greater use of photovoltaic energy, peaking with summer demand, and the construction of more energy efficient buildings. This is a key development where mitigation and adaptation coincide.

Parts of Adelaide are low-lying and vulnerable to floods although flooding occurs infrequently enough (less than once every three years on average) that flood events are generally tolerated. However, more extreme rainfall events projected to occur in the future may increase the frequency of flooding in low-lying suburbs sufficiently that adaptation or mitigation strategies need to be implemented. It is possible that a major driver of change in low-lying, flood prone coastal suburbs may be the increasing cost of insurance premiums.

7.5 Conclusions

Adaptation to climate change will involve significant changes in behaviour. Therefore, the assessment of climate change risks in the future needs to incorporate our understanding of current climate risks. This is the underlying principal of the approach to impact and adaptation studies proposed in the present chapter. In this, the biophysical and socio-economic aspects of risk under current climate are analysed and incorporated into an assessment of how climate and other drivers of change may alter future risks.

There are still instances where traditional 'top-down' impact studies are required. These include areas where basic deficiencies exist in our understanding of the impacts of present climate conditions on systems or activities. Long-term observations of natural systems are needed to observe change and to record system behaviour across a range of climate variability.

Integration between natural resource sectors is also very important in the long term. For agriculture, the largest challenges are at the landscape rather than the enterprise scale. Agriculture is vulnerable to loss of water supply and salinity, biodiversity is vulnerable to land-use change and the impacts of altered nutrients and pest plant and animals, some areas of coast are vulnerable to increasing sea level and subsidence. The largest challenges are for collaboration across different disciplines, integrating the various biophysical disciplines, economics and social sciences.

Priority research areas were identified in the workshops for which risk assessments could be undertaken. These include the effect of rising temperatures on the incidence of bush fires, algal blooms and water quality in general. Also important were the impact of changes in flood frequency in the arid zone on biodiversity and the impact of changing frequency of severe weather events on the insurance industry. These changes will also impact significantly on management of transport infrastructure, particularly in the arid zone (due to increased flood frequency) and marine assets (due to severe weather events, intensity of storm surges etc)

Further work is also needed to determine how to incorporate climate change into policy that is designed to increase the sustainability of natural and human systems. This requires bringing climate change into mainstream policy development and application.

8. Recommendations

The climate change projections presented in this report represent the most up-to-date information available for South Australia from a range of recent climate model simulations. However the relevance and reliability of climate change projections for South Australia could be enhanced through further work in a number of priority areas, which are outlined below. A number of these research areas would also help address the concerns raised in the workshops that the ranges of uncertainty surrounding projected changes to climate are in some instances too large to enable the formulation of policy.

The climate projections for average temperature and rainfall incorporate the ranges of change that span the changes simulated over South Australia by a number of recent available climate model simulations as well as the IPCC ranges of uncertainty for CO_2 emissions and global climate sensitivity. While some attempt was made to reduce the range of uncertainty in the present study by excluding two of the twelve available models on the grounds of inadequate performance in reproducing South Australia's present climate, large uncertainties still remain in the projections. This is partly due to the fact that the simulations of the models included 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 workshops highlighted additional climate variables that would be relevant to particular sectors, the analysis of which was beyond the scope of the present study. These included climate change projections for humidity which would be relevant for health impacts as well as the viticulture industry. Also rising water temperatures were of concern for biodiversity in the Spencer Gulf and Gulf of St Vincent.

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

- 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).

- An analysis of mid-latitude cyclones undertaken in a single climate model simulation revealed possible adverse changes in cyclone behaviour under enhanced climate change, particularly in spring. The generality of this result requires analysis of additional climate models.

- As with mid-latitude cyclones, the generality 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. Some specific concerns raised in the workshops, that could be addressed in future studies were the effect of rising temperatures on the incidence of bush fires, algal blooms and water quality in general. In addition, an assessment of the impact of changes in flood frequency in the arid zone on biodiversity and transport infrastructure should be assessed and finally, the impact of changing frequency of severe weather events on the insurance industry could be undertaken.

9. References

Adger, W.N. (1999a) Evolution of economy and environment: an application to land use in lowland Vietnam, Ecological Economics, 31, 365–379

Adger, N.W. (1999b) Social vulnerability to climate change and extremes in coastal Vietnam, World Development, 27, 249–269

Apuuli, B., Wright, J., Elias. C. and Burton, I. (2000) Reconciling national and global priorities in adaptation to climate change: With an illustration from Uganda, Environmental Monitoring and Assessment, 61, 145–159

Beg, N., Morlot, J.C., Davidson, O., Afrane-Okesse, Y., Tyani, B., Denton, F., Sokona, Y., Thomas, J.P., La Rovere, E.L., Parikh, J.K., Parikh K. and Rahman, A.A. (2002) Linkages between climate change and sustainable development, Climate Policy, 2, 129–144

Bureau of Meteorology (1999) Droughts. Bureau of Meteorology, Melbourne.

Cai and Whetton (2000) Evidence for a time-varying pattern of greenhouse warming in the Pacific Ocean. Geophysical Research Letters, 27, 2577-2580

Chen, X., Zong, Y., Zhang, E., Xu, J. and Li, S. (2001) Human impacts on the Changjiang (Yangtze) River basin, China, with special reference to the impacts on the dry season water discharges into the sea, Geomorphology, 41, 111–123

Collins, D. A, Della-Marta, P. M., Plummer, N. and Trewin, B. C. (2000) Trends in annual frequencies of extreme temperature events in Australia. Australian Meteorological Magazine, 49, 277-292

CSIRO (2001a): Climate Change Projections for the Australian Region. Climate Impact Group, CSIRO Division of Atmospheric Research, Melbourne, 8pp. http://www.dar.csiro.au/publications/projections2001.pdf

CSIRO (2001b): Climate Change Impacts for Australia. CSIRO Impacts and Adaptation Working Group. CSIRO Sustainable Ecosystems, Aitkenvale, Queensland, 8pp. http://www.marine.csiro.au/iawg/impacts2001.pdf

Dilley, M. and Boudreau, T.E. (2001) Coming to terms with vulnerability: a critique of the food security definition, Food Policy, 26, 229–247

Etheridge, D. M., Steele, L. P., Langenfelds, R. L., Francey, R. J., Barnola, J.-M., and Morgan, V. I., (1996) Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn. Journal of Geophysical Research, 101 (D2): 4115-4128

Fearnside, P.M. (1999) Plantation forestry in Brazil: the potential impacts of climatic change, Biomass & Bioenergy, 16, 91–102

Fowler, A.M. and Hennessy, K.J. (1995) Potential impacts of global warming on the frequency and magnitude of heavy precipitation, Natural Hazards, 11, 283-303

Hales, S., de Wet, N., Maindonald, J. and Woodward, A. (2002) Potential effect of population and climate changes on global distribution of dengue fever: an empirical model, The Lancet, 360, 830–834

Harrison, G.P. and Whittington, H.W. (2002) Susceptibility of the Batoka Gorge hydroelectric scheme to climate change, Journal of Hydrology, 264, 230–241

Hewitt, K. and Burton, I. (1971) The Hazardousness of a Place: A Regional Ecology of Damaging Events, University of Toronto, Toronto

Imeson, A.C. and Lavee, H. (1998) Soil erosion and climate change: the transect approach and the influence of scale, Geomorphology, 23, 219–227

IPCC (2001) Summary for Policymakers, in Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van Der Linden, P.J. and Xioaosu, D (eds.) Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 944 pp.

IPCC, (1996) Climate Change 1995, The Science of Climate Change. J. T. Houghton, Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A. and Maskell, K. (Eds.), Cambridge University Press, 572 pp.

IPCC, (2001) Climate Change 2000. The Science of Climate Change. Summary for Policymakers and Technical Summary of Working Group. Cambridge University Press, 98 pp.

Jones, D. A. and Simmonds, I. (1993) A climatology of southern hemisphere extratropical cyclones. Climate Dynamics, 9, 131-145

Jones, P.G. and Thornton, P.K. (2002) Spatial modelling of risk in natural resource management, Conservation Ecology, 5 (2), Art. No. 27

Jones, R.N. (2000) Analysing the risk of climate change using an irrigation demand model, Climate Research, 14, 89–100

Jones, R.N. (2001) An environmental risk assessment/management framework for climate change impact assessments, Natural Hazards, 23, 197–230

Jones R.N. and Pittock, A.B. (1997) Assessing the impacts of climate change: the challenge for ecology, in Klomp N. and Lunt, I, (eds), Frontiers in Ecology: Building the Links, Elsevier Science Ltd, Amsterdam, 311–322

Jones, R.N. and Page, C.M. (2001) Assessing the risk of climate change on the water resources of the Macquarie River Catchment, in Ghassemi, F., Whetton, P., Little, R. and Littleboy, M. (eds.), Integrating Models for Natural

Resources Management across Disciplines, issues and scales (Part 2), Modsim 2001 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, Canberra, 673–678

Kumar, K.S.K. and Parikh, J. (2001) Indian agriculture and climate sensitivity, Global Environmental Change, 11, 147–154.

Lambeck, K. (2001) Sea-level change from mid-Holocene to recent time: An Australian example with global implications. In: Glacial Isostatic Adjustment and the Earth Systems, Eds. J. X. Mitrovica. and B. Vermeersen, American Geophysical Union, Geodynamic Monograph Series

Lansigan, F.P., de los Santos, W.L. and Coladilla, J.O. (2000) Agronomic impacts of climate variability on rice production in the Philippines, Agriculture Ecosystems and Environment, 82, 129–137

Lempert, R. and Schlesinger, M.E. (2001) Climate-change strategy needs to be robust. Nature 412, 375

Lugo, A.E. (2000) Effects and outcomes of Caribbean hurricanes in a climate change scenario, The Science of the Total Environment, 262, 243–251

Magadza, C.H.D. (2000) Climate Change Impacts and Human Settlements in Africa: Prospects for Adaptation, Environmental Monitoring and Assessment, 61, 193–205

Mann, M.E., R.S. Bradley, and M.K. Hughes, (1999) Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations, Geophysical Research Letters, 26, 759-762

Matthews, R.B., Kropff, M.J., Horie, T. and Bachelet, D. (1997) Simulating the Impact of Climate Change on Rice Production in Asia and Evaluating Options for Adaptation, Agricultural Systems, 54, 399–425

McInnes, K.L., K.J.E. Walsh, G. D. Hubbert and T. Beer, (2003) Impact of Sea-level Rise and Storm Surges on a Coastal Community. Natural Hazards, (in press)

McMichael, A., Woodruff, R., Whetton, P., Hennessy, K., Nicholls, N., Hales, S., Woodward, A. and Kjellstrom, T. (in press): Risk assessment regarding human health and climate change in Australasia. Consultancy report for the Australian Greenhouse Office, published by the National Centre for Epidemiology and Population Health, Australian National University, 116 pp.

Mehrotra, R. (1999) Sensitivity of Runoff, Soil Moisture and Reservoir Design to Climate Change in Central Indian River Basins, Climatic Change, 42, 725–757

Morgan, M.G. and Henrion, M. (1990) Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press, Cambridge, 332 pp.

Moss, R.H. and Schneider, S.H. (2000) Towards Consistent Assessment and Reporting of Uncertainties in the IPCC TAR: Initial Recommendations for Discussion by Authors. New Delhi: TERI

Parker, D. E., P. D. Jones, C. K. Folland, and A. Bevan, (1995) Marine surface data for analysis of climate fluctuation on interannual-to-century time scales. Natural Climate Variability on Decadal-to-Century Time Scales, National Research Council, USA.

Pittock A.B. and Jones R.N. (2000) Adaptation to what, and why? Environmental Monitoring and Assessment, 61, 9–35

Plummer, N., Salinger, M. J., Nicholls, N., Suppiah, R., Hennessy, K. J., Leighton, R. M., Trewin, B. and Lough, J. M. (1999) Twentieth century trends in climate extremes over the Australian region and New Zealand. Climatic Change , 42, 183-202

Rayner, N. A., E. B. Horton, D. E. Parker, and C. K. Folland, (1996) Version 2.2 of the global sea-ice and sea surface temperature data set, 1903-1994. Climate Research Technical Note, CRTN74, Hadley Centre, Meteorological Office, Bracknell, UK.

Reyenga, P.J., Howden, S.M., Meinke, H. and Hall, W.B. (2001) Global change impacts on wheat production along an environmental gradient in South Australia. Environment International., 27, 195-200

Singh, O.P. (2002a) Interannual variability and predictability of sea level along the Indian Coast, Theoretical and Applied Climatology, 72, 11–28

Singh, O.P. (2002b) Predictability of sea level in the Meghna estuary of Bangladesh, Global and Planetary Change, 32, 245–251

Sivakumar, M.V.K., Gommes R. and Baier, W. (2000) Agrometeorology and sustainable agriculture, Agricultural and Forest Meteorology, 103, 11–26

Smit, B., Burton, I., Klein, R.J.T. and Street, R. (1999) The science of adaptation: a framework for assessment, Mitigation and Adaptation Strategies, 4, 199–213

Stakhiv, E.Z. (1998) Policy implications of climate change impacts on water resources management. Water Policy, 1, 159–175.

Tung, C.P. (2001) Climate change impacts on water resources of the Tsengwen creek watershed in Taiwan, Journal of the American Water Resources Association, 37, 167–176

USPCC RARM (1997) Framework for Environmental Health Risk Management, Final Report Volume 1, US Presidential/Congressional Commission on Risk Assessment and Risk Management, Washington DC.

Viglizzo, E.F., Roberto, Z.E., Lértora, F., Gay, E.L. and Bernardos, J. (1997) Climate and land-use change in field-crop ecosystems of Argentina, Agriculture, Ecosystems and Environment, 66, 61–70

Whetton, P. H., England, M. H., O'Farrell, S. P., Watterson, I. G., and Pittock, A. B. (1996) Global comparison of the regional rainfall results of enhanced greenhouse coupled and mixed layer ocean experiments: implications for climate change scenario development. Climatic Change, 33 (4): 497-519

Whetton, P. H., Fowler, A.M., Haylock, M.R. and Pittock, A.B. (1993) Implications of climate change due to the enhanced greenhouse effect on floods and droughts in Australia. Climatic Change, 25, 289-317

Whetton, P. H., Katzfey, J. J., Nguyen, K., McGregor, J. L., Page, C. M., Elliot, T. I. And Hennessy, K. J. (2000) Climate averages and variability based on a doubled CO2 simulation. Fine resolution assessment of enhanced greenhouse climate change of Victoria. Annual Report 1996-97., Dept. Natural Resources and Environment Report, Victoria. 48 pp.

Whetton, P. H., Suppiah, R., McInnes, K.L., Hennessy, K.J. and Jones, R.N., (2002) Climate change in Victoria: High resolution regional assessment of climate change impacts. Dept. Natural Resources and Environment Report, Victoria. 44 pp.

Yohe, G. and Tol, R.S.J. (2002) Indicators for social and economic coping capacity - moving toward a working definition of adaptive capacity, Global Environmental Change, 12, 25–40

Appendix 1 – Attendees at workshop sessions

Table A1: *Attendees at Climate Projections workshop, July 30, 2002*

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Mr Robert Hall	Director of Public HealthDHS 31 Markham Avenue Enfield 5085	08 8269 7025	Hall.Robert@saugov.sa.gov.au
Mr Keith Jones	SA Wine & Brandy National Wine Centre Botanic Rd, Adelaide SA 5000	08 8222 9273	Keith@winesa.asn.au
Mr Peter Alexander	DEH (NPWSA) GPO Box 1047 Adelaide 5001National Parks	08 8124 4831	Peter.alexander@state.sa.gov.au
Mr Dr Phillip Morgan	Transport SA PO Box 1 Walkerville 5081	08 8343 2827	Phil.morgan@transport.sa.gov.au
Ms Fiona Selleck	Transport SA PO Box 1 Walkerville 5081	08 8343 2723	Fiona.selleck@transport.sa.gov.au
Mr Keith Plastow	EPA GPO Box 2607 Adelaide 5001	08 8204 2023	Keith.plastow@state.sa.gov.au
Dr Andrew Lothian	Environmental Policy Solutions PO Box 385 Mitcham 5062	0439 872 226	Alothian@senet.com.au

Table A2: *Attendees at Climate Projections workshop, November 27, 2002*

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Mr David Cresswell	DWLBC GPO Box 1047 Adelaide 5001	08 8463 6989	David.cresswell@state.sa.gov.au
Ms Tineta Ellis	DECS GPO Box 1152 Adelaide 5001	08 8226 1018	Ellis.Tineta@saugov.sa.gov.au

Mr Murray Hutchesson	DHS SA HT GPO Box 1669 Adelaide 5001	08 8207 0666	Hutchesson.murray@saugov.sa.gov.au
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Abbreviations:

DWLBC	Department of Water Land and Biodiversity Conservation
DECS	Department of Education and Children's Services
DHS:SAHT	Department of Human Services: South Australian Housing Trust
DTF	Department of Treasury and Finance
DAIS	Department of Administrative and Information Services
EPA	Environment Protection Authority
NPWSA	National Parks and Wildlife South Australia