Climate Change in New South Wales

Part 1: Past climate variability and projected changes in average climate

Consultancy report for the New South Wales Greenhouse Office

by

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Important Disclaimer

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

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For more information about climate change, see http://www.dar.csiro.au/information/climatechange.html

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EXECUTIVE SUMMARY

This report presents results of a project undertaken by CSIRO for the New South Wales Greenhouse Office to assess past climate variability and projected changes in average climate. Information is drawn from the global findings of the Intergovernmental Panel on Climate Change (IPCC), and independent research undertaken by CSIRO on regionally-specific changes in temperature, rainfall, potential evaporation and sea level.

Global climate change

The IPCC's 2001 report concluded that:

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

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

Observed climate variability in NSW

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

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

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

Future climate change

Method

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

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

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

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

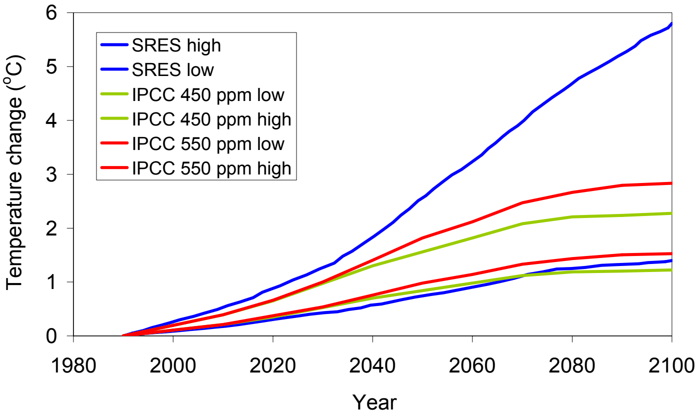

Figure S1. Comparison of projected global warming based on various assumptions about greenhouse gas emissions: SRES and CO_2 stabilisation at 550 ppm and 450 ppm. The low and high limits for each set of scenarios account for uncertainty in climate model projections.

Regional scenarios for NSW are presented below with ranges of uncertainty, rather than a central estimate. The ranges allow for:
- Uncertainty in scenarios of future growth in greenhouse gases and aerosols, and resultant global warming:
    - the IPCC SRES scenarios without policies to reduce greenhouse gas emissions;
    - the IPCC scenario for stabilising CO_2 concentrations at 550 ppm by the year 2150;
    - the IPCC scenario for stabilising CO_2 concentrations at 450 ppm by the year 2090.
- Differences between 12 climate model simulations of regional climate change.

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

Temperature projections

NSW is likely to experience greatest warming west and north of the highlands, and least in southern and coastal areas. Most warming is expected to occur in spring and summer, and least in winter. Figure S2 and Table S1 show that by the year 2030, the SRES scenarios give an annual-average warming of 0.2 to 1.6°C in coastal and southern regions, relative to 1990, 0.2 to 1.8°C in the central-west, and 0.3 to 2.1°C in the north. By 2070, the warming increases to 0.7 to 4.8°C in coastal and southern regions, 0.7 to 5.6°C in the central-west, and 0.9 to 6.4°C in the north. If CO_2 concentrations are stabilised at 550 ppm by the year 2150, the upper limit of warming is reduced by 23% by 2030 and 38% by 2070. If CO_2 concentrations are stabilised at 450 ppm by the year 2090, the upper limit of warming is reduced by 25% by 2030 and 48% by 2070.

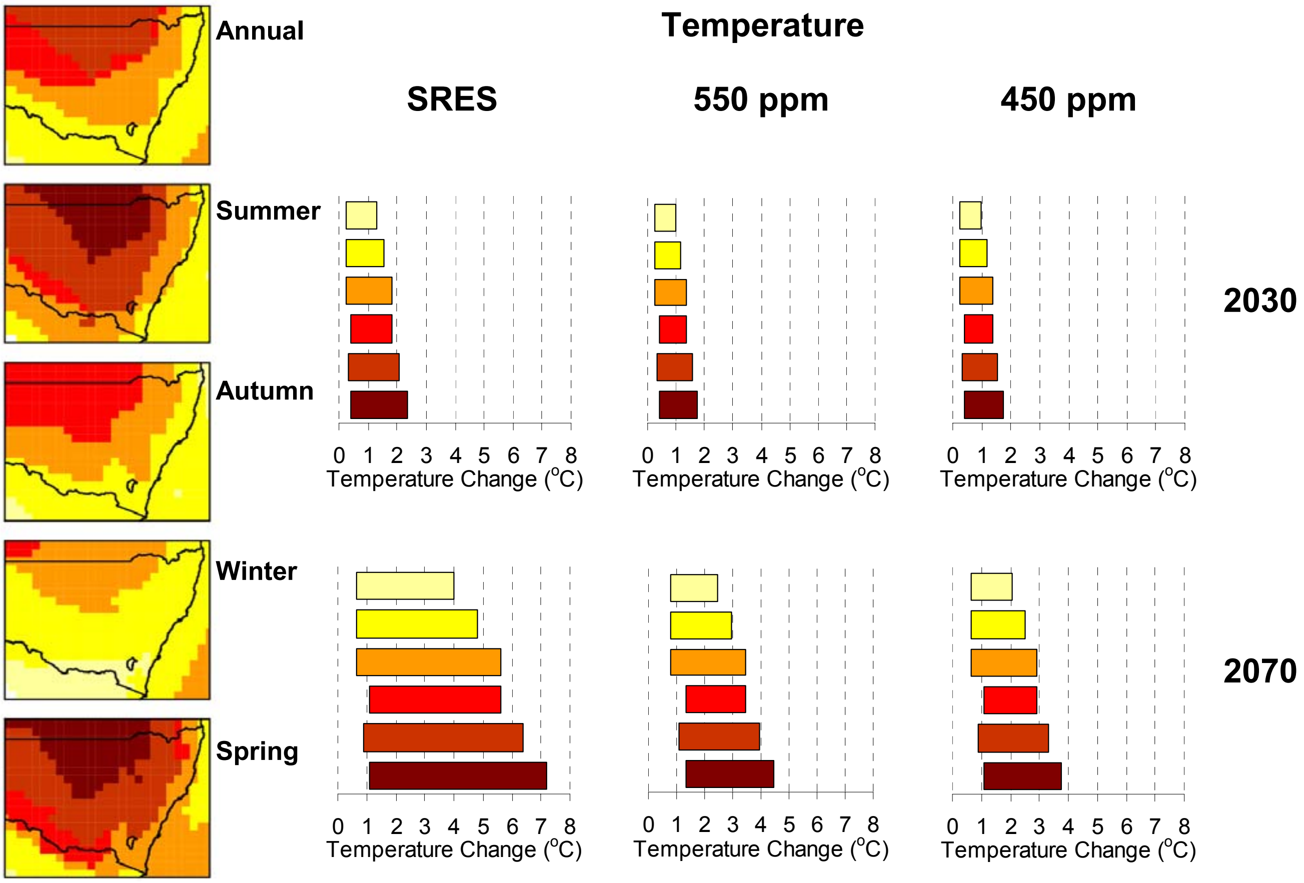

Figure S2. Projected change in average annual and seasonal temperature (°C) for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios exclude explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

Table S1. Projected change in annual average temperature (°C) for the years 2030 and 2070 relative to 1990.

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

Rainfall projections

There is a general tendency for decreasing annual-average rainfall (Figure S3). This is mainly confined to winter and spring. In autumn, the direction of rainfall change is uncertain over most of the State, with a tendency for decreases in the north and increases in the far west. Summer rainfall changes are uncertain over much of southern and western NSW, with a tendency for increases along the coast and in the north-east, and a tendency for decreases in the north-west.

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

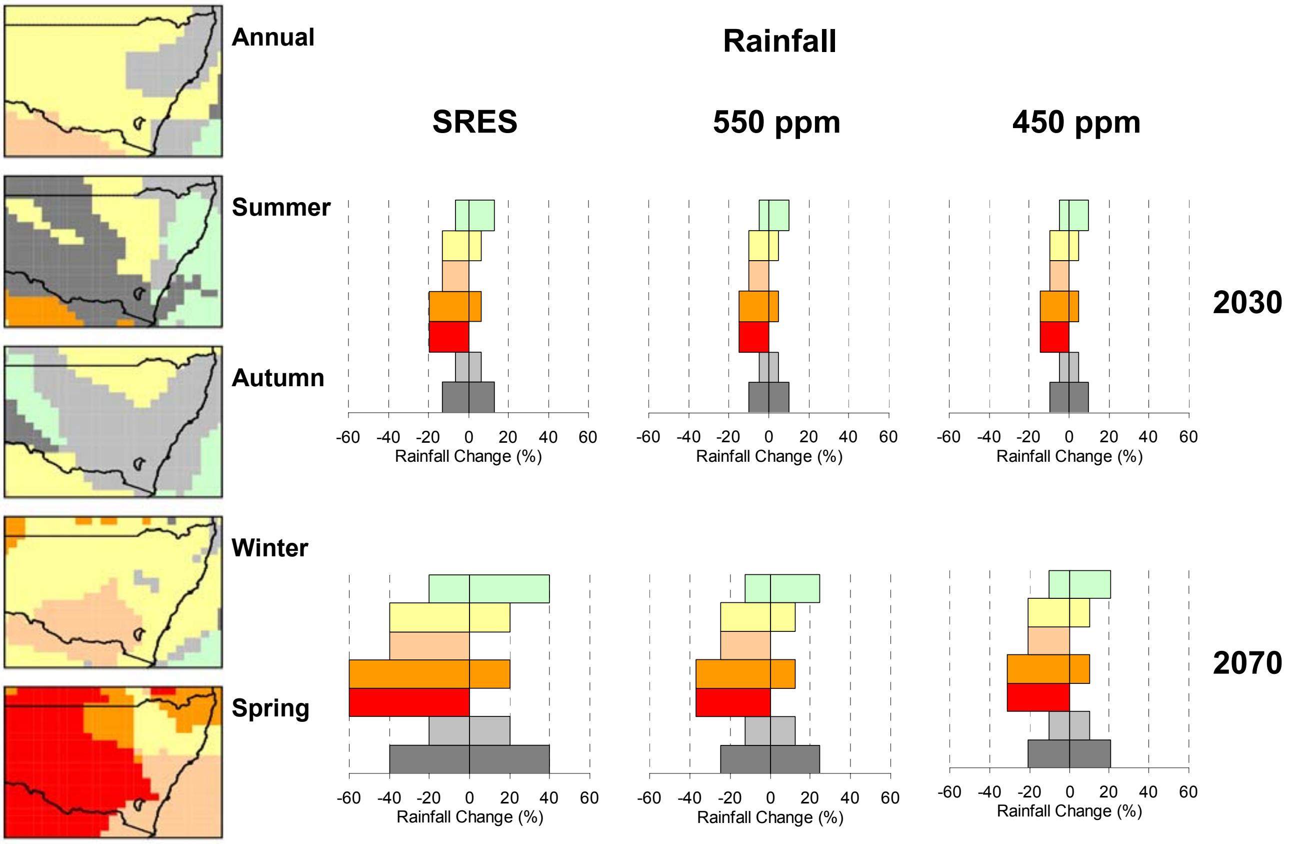

Figure S3. Ranges of change in average rainfall (%) for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

Atmospheric moisture balance projections

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

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

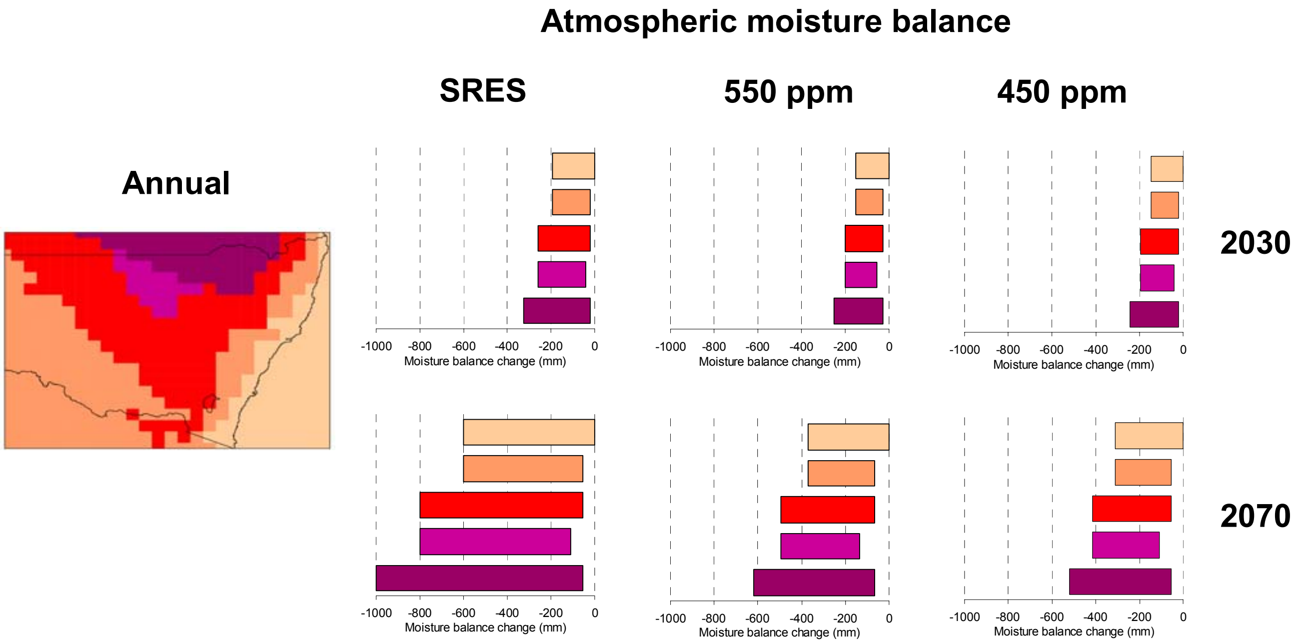

Figure S4: Patterns of change in annual average atmospheric moisture balance (mm) for the years 2030 and 2070, relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

Potential impacts

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

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1. Introduction

Substantial increases in greenhouse gas concentrations and global temperatures have occurred in the 20th century. Further global warming is likely during the course of the 21st century. It is thus appropriate to identify how the NSW climate has changed over the past century and how it may be affected by future climate change. This task requires analysis of high quality climate data collected by the Bureau of Meteorology, and analysis of climate-model estimates of future regional climate change. This report presents results from a study undertaken by CSIRO for the NSW Greenhouse Office.

The research activities undertaken for this study include:

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

This is the first part of a two-part assessment of climate change in NSW. The second part, to be completed in late 2004, will cover:

- Projected changes in climate variability and extremes for 2030 and 2070
  Many impact assessments will need information about extreme heat, frosts, floods, droughts, windstorms and storm tides. This will involve more detailed analysis of a smaller set of models for which this information is available. Projections will be generated for changes in
    a. extreme daily temperature;
    b. extreme daily rainfall;
    c. drought indicators;
    d. extremes of mean sea-level pressure and winds;
    e. the frequency, intensity and movement of mid-latitude circulation systems associated with extreme weather (e.g. cold fronts and east coast lows);
    f. Storm tides due to sea level rise and extreme weather (qualitative assessment).
- Summary of risk assessment approaches
  The summary will discuss assessment of current and future climate risks, including basic concepts of risk (impact x likelihood), vulnerability, the coping range and dealing with uncertainty.
- Recommendations for future research
  Gaps in knowledge and priorities for future research will be identified.

The following information comes from CSIRO research undertaken specifically for this project, supplemented by material published in high quality, peer-reviewed literature. Emphasis is placed upon the conclusions of reports published in 2001 by the Intergovernmental Panel on Climate Change (IPCC) and research published in scientific journals since 2001. The IPCC reports (IPCC, 2001a, b, c, d) involved 455 Convening / Lead Authors, 838 Contributing Authors, 70 Review Editors and comments from 1160 experts and governments. CSIRO contributed the services of two Convening Lead Authors, six Lead Authors, 11 Contributing Authors and two Reviewer Editors. The findings of the IPCC are accepted by CSIRO because they are based upon a rigorous and balanced assessment of the science, including uncertainties and gaps in knowledge. Scientific papers published since 2001 have generally confirmed and strengthened many of the IPCC conclusions.

2. Global climate change observations

2.1 Evidence for climate change

Climate change during the 20th century should be viewed in the context of millennial climate variability. Over millions of years, the Earth has experienced cold and warm periods, known as ice ages and interglacial periods. These natural climate changes are due to cyclic variations in the Earth's orbit that affect the amount of sunlight received at the surface. The Earth has three orbital variations. They occur in cycles of 19,000-23,000 years, 40,000-41,000 years and 96,000 years (Bryant, 1997). Before one million years ago, glacial cycles occurred every 41,000 years due to variations in the tilt of the Earth's axis of rotation (EPICA, 2004). However, during the past half million years, the dominant cycle has been about 100,000 years, mainly due to variations in the shape of the Earth's elliptical orbit. Over the past 740,000 years, glacial phases reached similar degrees of cooling, but the last 430,000 years had more pronounced warmth during the interglacial phases. The Earth has experienced interglacial conditions for the past 11,000 years – the Holocene warm period. Ice ages have been up to 10°C cooler than present.

During the past four transitions from glacial to interglacial periods from about 400,000 years ago, changes to the Earth's orbit initiated the warming. The changes were amplified by possibly 2 to 3°C by increases in greenhouse gases and then by reduced surface reflectance as northern hemisphere ice sheets melted several thousand years later (Petit *et al.*, 1999; Shackleton, 2000). Changes in temperature and CO_2 over the past 420,000 years are shown in Figure 1. The present CO_2 concentration of about 375 ppm is now higher than at any time in the past 740,000 years (EPICA, 2004).

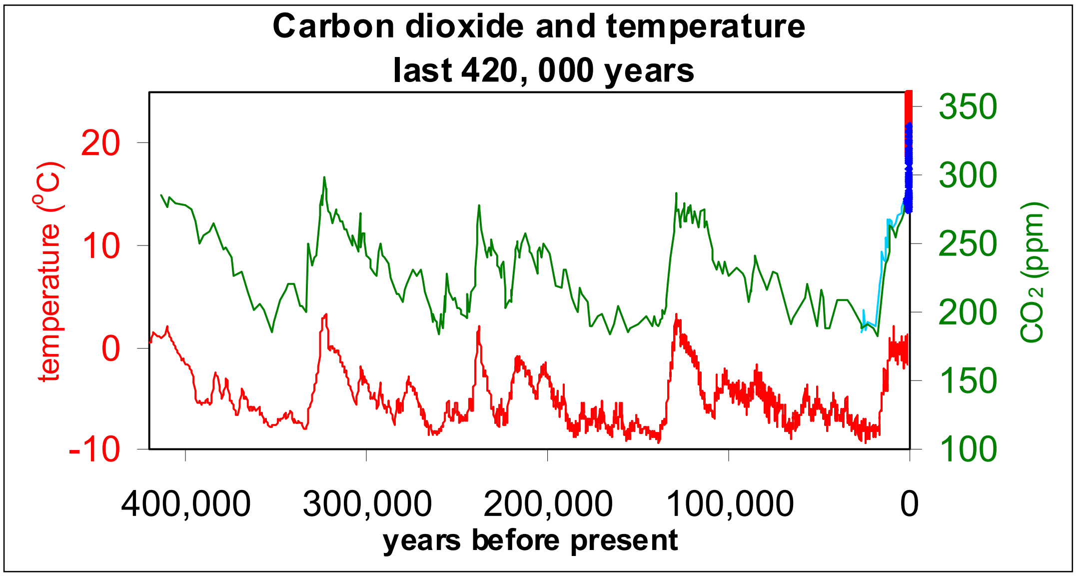


Figure 1: Changes in temperature (red) and carbon dioxide concentrations (green) over the past 420,000 years, derived from bubbles of air trapped in polar ice. Carbon dioxide (CO_2) symbols in blue and red are measurements made in recent decades. From Petit *et al.* (1999).

Figure 2 shows atmospheric concentrations of CO_2 over the past 10,000 years. This illustrates the rapid increase in CO_2 concentrations, which is largely a consequence of burning fossil fuels and clearing land following the Industrial Revolution. Since 1750, the CO_2 concentration has risen 31%. The rate of increase is possibly higher than at any time in the past 20,000 years. Concentrations of another greenhouse gas, methane, have increased 151% since 1750, but the level has stabilised since 1999 (Dlugokencky *et al.*, 2003). This appears to be due to the fixing of leaky gas pipes and uncapped oil wells, and the decline in oil and gas extraction in the Soviet Union. Whether methane stabilisation can be sustained is uncertain since more methane may be released as tundra thaws in the northern hemisphere (Stokstad, 2004). There is also a possibility of abrupt releases of methane from gas hydrates – ice-like deposits beneath the ocean floor that most commonly contain methane – if intermediate depths in the world's oceans warm. Gas hydrate deposits are stabilised by rising sea level, so the risk of an abrupt release of methane depends on the rate of oceanic warming against the rate of sea level rise (Benfield Hazard Research Centre, 2004).. Other greenhouse gases have increased, e.g. nitrous oxide has risen 17% and ozone in the lower atmosphere has grown 36%.

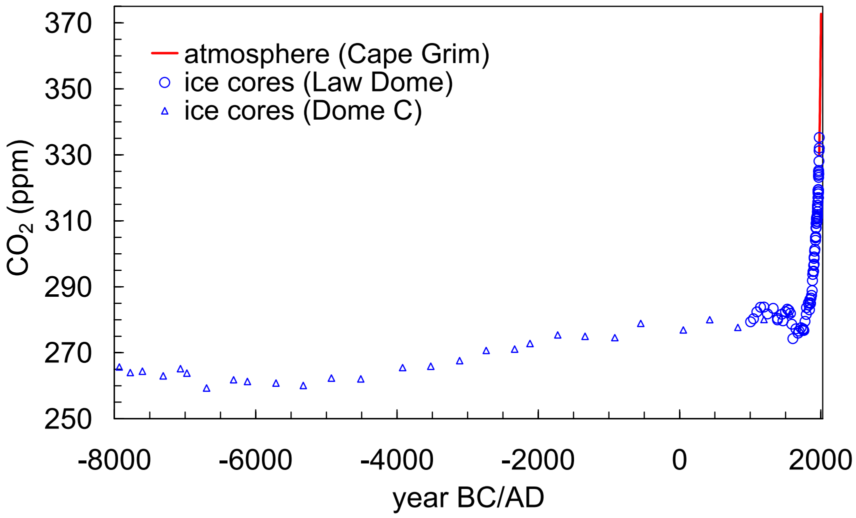


Figure 2. Global CO_2 concentrations from Antarctic ice core data (triangles: Dome C (Flückiger *et al.,* 2002); circles: Law Dome (Etheridge *et al.*, 1996)) and direct observations (red line) from the Cape Grim Baseline Atmospheric Program in north-west Tasmania (http://cdiac.ornl.gov).

Over the past 11,000 years, global-average temperature has varied 1-2°C (Bryant, 1997). Over the past 2,000 years, fluctuations of 1.0-1.5°C have occurred with dramatic repercussions. For example, northern Europe was cold until the 7th century, after which temperatures warmed to a peak, known as the Medieval Warm Period (900-1300 AD) when Vikings colonised Greenland and Iceland. Temperatures decreased dramatically after 1250 AD, and then again after 1600 AD, leading to the Little Ice Age. The Viking colony in Greenland was abandoned in 1369 AD, and the last Eskimo colony survived until about 1500 AD. The Little Ice Age ended around the year 1900. Figure 3 is a record of northern hemisphere temperatures based on proxy records (from ice-cores, tree-rings, lake sediments, coral-rings) over the past 1800 years combined with direct measurements for the past 140 years. The late 20th century warming in the northern hemisphere seems unprecedented in the past 1800 years (Mann and Jones, 2003). The validity of the record over the past 600 years was questioned by McIntyre and McKitrick (2003). Some corrections were made by Mann *et al* (2004) who concluded that none of the errors affected previously published results.

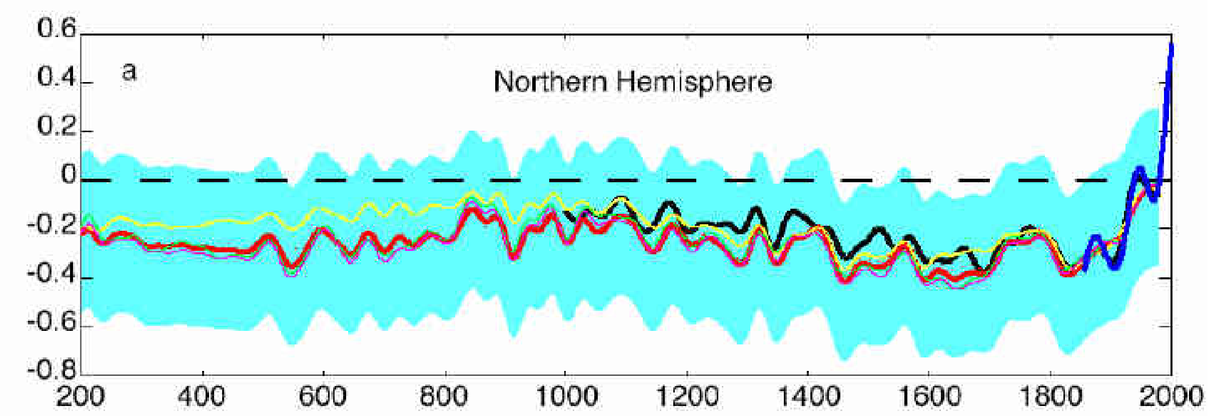


Figure 3. Northern Hemisphere temperature anomalies over the past 1800 years. The light blue shading indicates the 95% confidence intervals. The red, yellow, and purple lines are based on different areal and / or hemispheric correlation weighting. The thick black line is a composite of shorter reconstructions for the past 1000 years. The thick blue line shows smoothed observational records. Source: Mann and Jones (2003).

Thermometer records show that the global average surface temperature has risen by about 0.6°C since 1900 (Figure 4), with the warmest year being 1998, followed by 2002 and 2003 (WMO, 2003). There has been an increase in heatwaves, fewer frosts, warming of the lower atmosphere and oceans, retreat of glaciers and sea-ice, a rise in sea-level of 10-20 cm and increased heavy rainfall in many regions. Many species of plants and animals have changed their location or the timing of their seasonal responses in ways that provide further evidence of global warming.

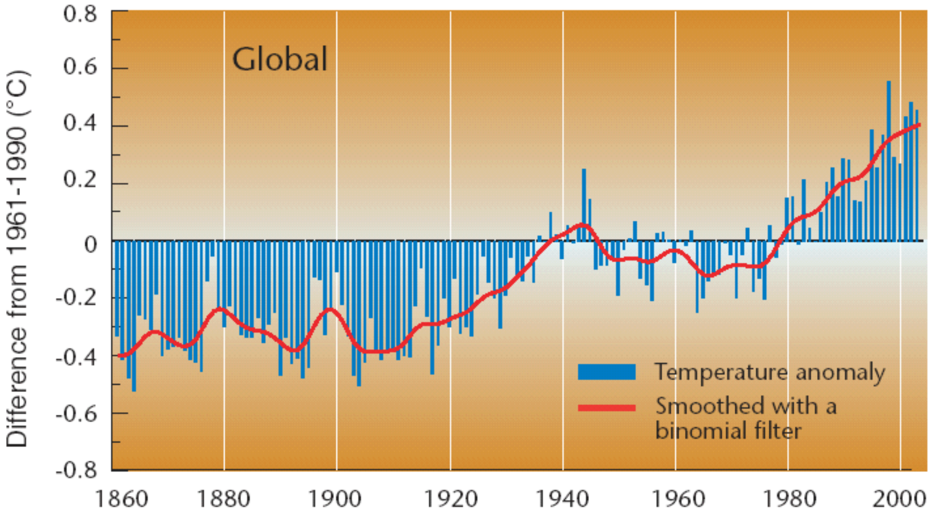


Figure 4. Global-average temperature anomalies from 1860 to 2003, relative to the average for 1961-1990. From WMO (2003).

2.2 Likely causes of climate change

The 20th century warming occurred in two major phases, from 1910-1945 and since 1976. Computer models of the climate systems have been used to estimate the relative contributions of various factors such as changes in solar radiation, aerosols from volcanic eruptions, increased greenhouse gas and aerosol emissions, stratospheric ozone depletion, and internal climate variability from events like El Niño. Most studies agree that global warming in the early 20th century can be explained by a combination of natural and human-induced factors (IPCC, 2001a). These studies also show that most of the warming in the last 50 years has been due to human activities that have increased greenhouse gas concentrations. The IPCC (2001a) concluded that, considering the 20th century as a whole, it is extremely unlikely that global warming can be explained by natural variations alone. A recent study by Meehl *et al.* (2003) found that "the early century warming was caused mostly by solar and volcanic forcing, and the late century warming mostly by the increase of greenhouse gases (partially offset by aerosol cooling)". This is shown in Figure 5.

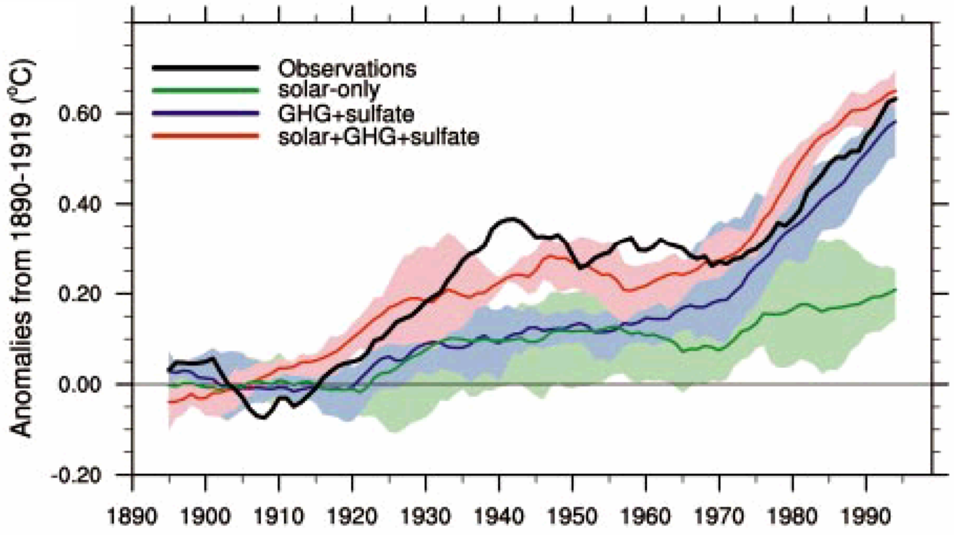


Figure 5. Global annual mean surface temperature anomalies (11-year running mean) relative to 1890-1919 for observations (black) and for climate model simulations driven by variations in solar radiation (green), greenhouse gases (GHG) and sulfate aerosols (blue), and all three factors (red). The shading indicates the range of uncertainty from an ensemble of four climate model simulations. From Meehl *et al.* (2003).

Despite the wide range of indicators of global warming, attention has been focused on a 23-year period from 1979-2001, when early studies with satellite data showed little or no warming in the lower atmosphere, whereas thermometer data showed that surface temperatures had increased. However, this disparity has now been mostly resolved. Santer *et al* (2003) found that apparent inconsistencies between satellite and surface results may be an artefact of satellite data uncertainties. Various studies (Vinnikov and Grody, 2003; Mears *et al.,* 2003, Fu *et al*., 2004) found good agreement between the satellite and surface data from 1978-2002, when necessary corrections were made to the satellite data. The longer record of temperatures from weather balloons shows that since 1958 the lower atmosphere has warmed by about 0.1^{o}C per decade, a similar rate to the surface warming.

The key findings of the IPCC (2001a, b) regarding past climate change are:

- An increasing body of observations gives a collective picture of a warming world and other changes in the climate system;
- Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that affect the climate system;
- There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities;
- Recent climate changes have already affected many physical and biological systems;
- Some human systems have been affected by recent increases in floods and droughts.

3. Observed climate change in New South Wales

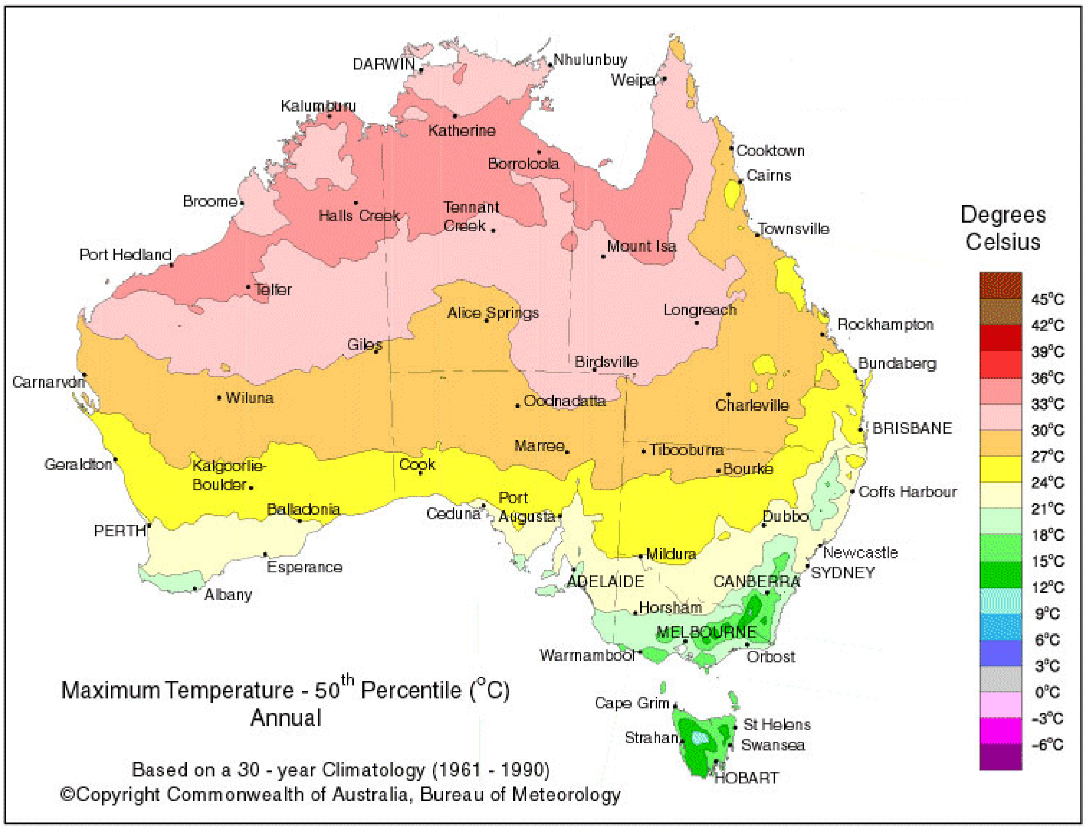
3.1 Introduction

Observational data reveal that the climate of NSW has changed considerably since 1950. Where appropriate, the analyses of long-term temperature variations presented here are based on homogeneous datasets consisting of climate records corrected for artificial discontinuities associated with changes such as location, instrumentation and exposure (Torok and Nicholls 1996; Trewin 2001; Della-Marta *et al.* 2004). Such discontinuities can be as large as natural variations and consequently must be removed before investigating the true long-term trends. In addition, only those temperature records considered free from the influence of urban warming are used. Rainfall data used are high-quality records selected for being largely free from missing data and other data quality problems (Lavery *et al.* 1992; 1997) and a grided dataset based on all quality checked observations (Jones and Weymouth 1997).

3.2 New South Wales climate

The climate of NSW is generally mild and temperate. However, extremely high daytime temperatures occur in the west during summer and extremely cold overnight temperatures occur in the tablelands and dry western slopes of NSW during winter. The Great Dividing Range has a major impact on the climate of the state, creating four distinct climate zones; the coastal strip, the high country, the western slopes and the flatter country to the west.

Annual maximum temperatures in NSW (Figure 6) are coldest in the high country where the median is less than 15°C in southern parts. The highest maximum temperatures in the state are recorded in the northwest where annual median values are more than 27°C. For overnight minimum temperatures (Figure 7) annual median values in NSW range from less than 6°C in the southern high-country to greater than 12°C in inland northern NSW. Minimum temperatures along the coastal strip are moderated by the warm waters of the Tasman Sea, resulting in a tongue of milder temperatures extending down the coast.



Maximum Temperature - 50th Percentile (°C)
Annual

Based on a 30 - year Climatology (1961 - 1990)
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Figure 6. Median annual maximum temperature. Based on 1961-1990 data.

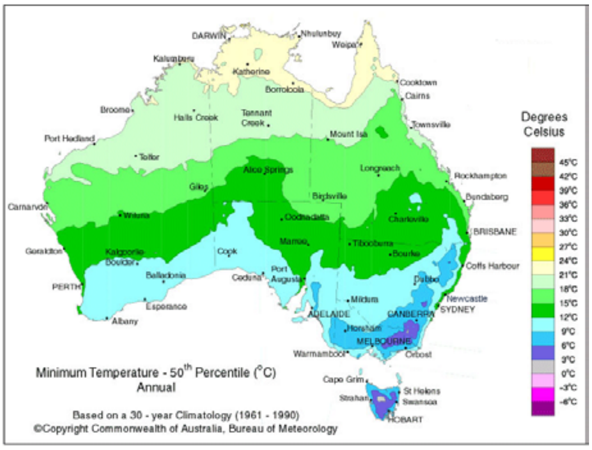


Figure 7. Median annual minimum temperature. Based on 1961-1990 data.

The highest annual rainfall in NSW (Figure 8) is recorded in parts of the north coast with annual 10th percentile, median and 90th percentile values greater than 800mm, 1200mm, and 2000mm respectively. These values generally decrease toward the west, with the annual 10th percentile, median and 90th percentile rainfall values dropping below 100mm, 200mm and 400mm in the far northwest. Median and extreme values increase in the southern high-country, with significant precipitation falling as snow during winter.

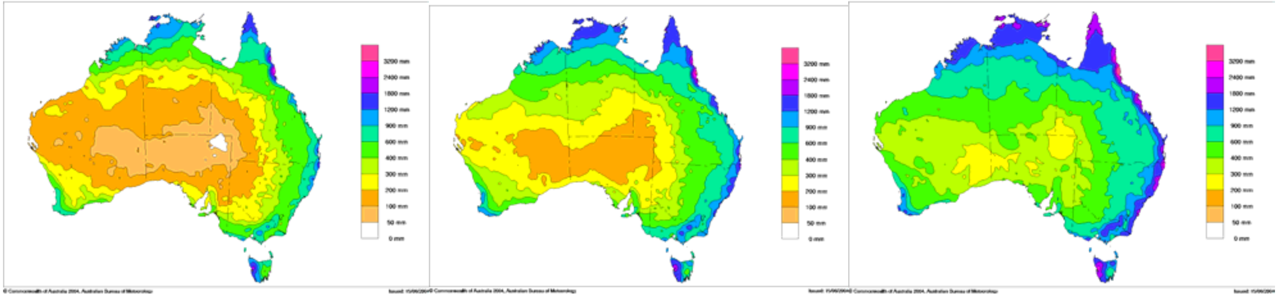

(a) **(b)** **(c)**

Figure 8. (a) 10th percentile (b) median and (c) 90th percentile annual rainfall. Based on 1961-1990 data.

There are several weather patterns that make important contributions to the overall rainfall patterns of NSW. These include northwest cloudbands, which bring about 20% of northern NSW rainfall and 10% of southern rainfall, winter frontal systems which particularly affect southern NSW, and interactions between these systems. Other significant rain-bearing systems include the remnants of Tropical Cyclones, troughs in easterly flow, "cut-off" and east coast low pressure systems, as well as easterly stream flow affecting coastal regions. A wide range of weather hazards are experienced in NSW, such as heatwaves, frosts, hail, lightning, tornadoes, severe winds, fire, floods, and dust-storms.

Robust relationships exist between Australian temperatures and rainfall, and the Southern Oscillation Index (SOI) – a measure of the strength of the El Niño-Southern Oscillation (ENSO). Along with most of eastern Australia, the strength of the relationship between SOI and NSW rainfall (as measured by correlation) peaks during winter and spring (Figure 9c). Consequently, if the SOI is strongly positive during these seasons NSW rainfall tends to be above average, and below average if the SOI is strongly negative. Correlations between seasonal SOI and NSW maximum temperatures are mostly negative, meaning that when the SOI is high (typically wet), maximum temperatures tend to be low. Jones and Trewin (2000) show this is due to wet seasons having greater cloud amount, and hence less incoming solar energy, and also greater surface moisture available for evaporative cooling. The relationship between SOI and minimum temperatures tends to be less consistent than for maximum temperatures. In NSW these correlations are mixed, apart from during autumn and winter when positive correlations dominate i.e., high SOI typically means greater than average cloud cover which tends to keep overnight temperatures higher.

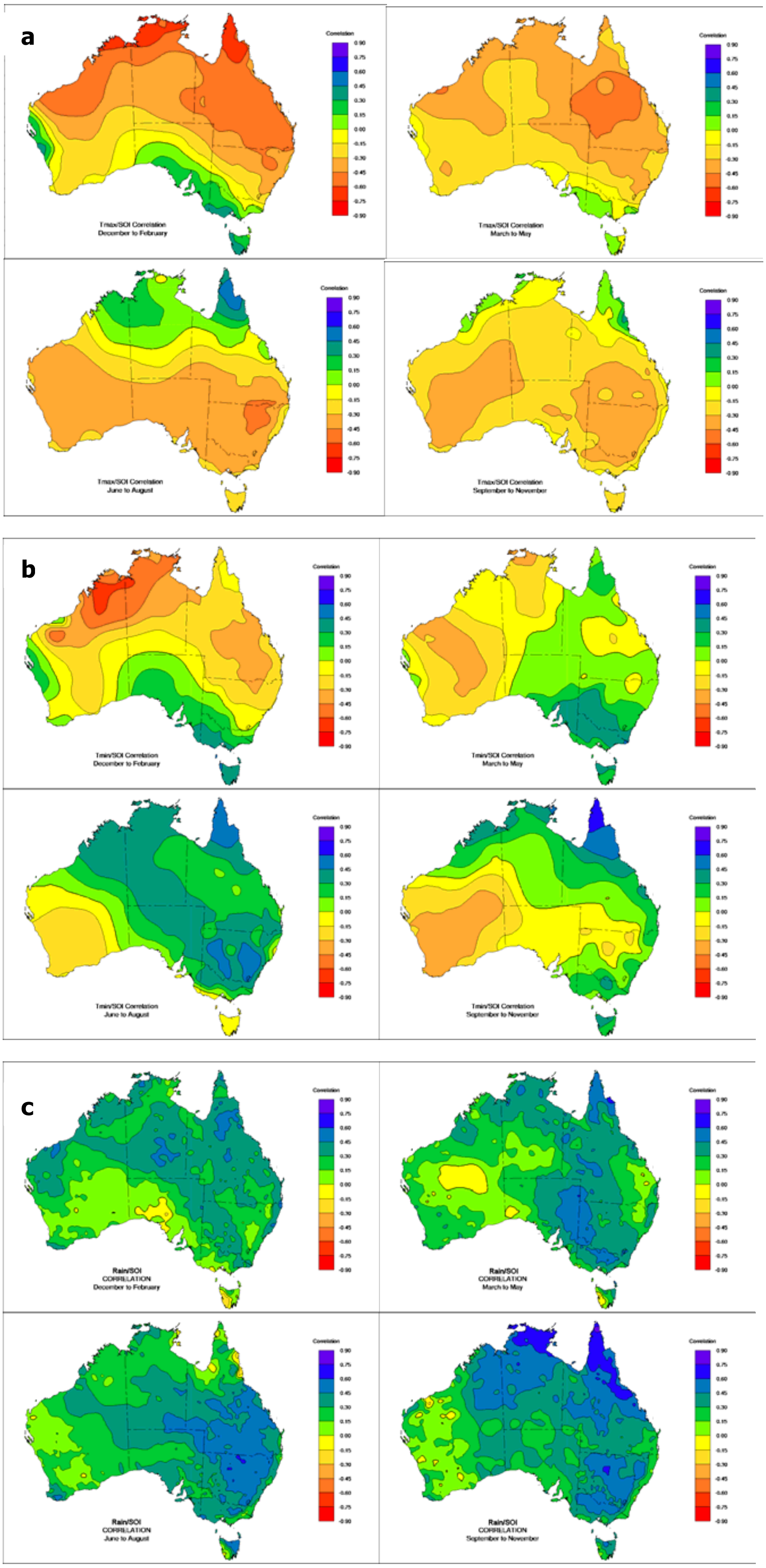


Figure 9. Maps of correlation between seasonal mean SOI and Australian (a) maximum temperature, (b) minimum temperature and (c) rainfall. Based on 1950-2003 data.

3.3 Climate trends

3.3.1 Trend maps

Maps of trends in maximum and minimum temperatures across Australia indicate that temperatures have widely increased since 1950. However, the magnitude and sign of these trends varies throughout the seasons. While annual mean maximum temperature trends since 1950 (Figure 10a) are mostly positive throughout Australia, strong contrasts are evident in summer maximum temperature trends (Figure 10b), with increases in the eastern states and South Australia, and cooling trends in Western Australia and the Northern Territory. These cooling trends are associated with large increases in rainfall. Autumn maximum temperature trends (Figure 10c) are similar to those for summer, with a large belt of cooling evident through the western half of the country. Winter and spring maximum temperatures (Figs. 10d-e) have generally increased since 1950, with the strongest trends recorded in central parts.

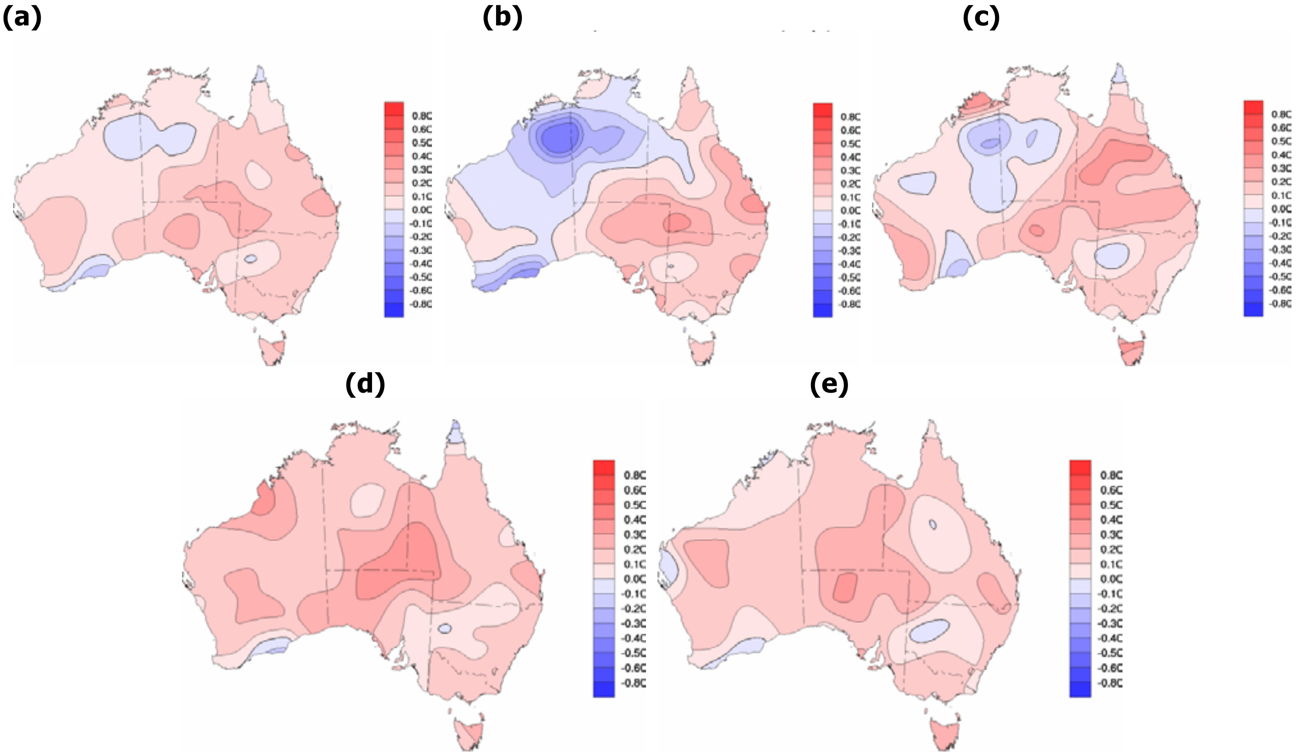


Figure 10. Maps of Australian (a) annual, (b) summer, (c) autumn, (d) winter and (e) spring maximum temperature trends from 1950-2003.

Over the post-1950 period, the vast majority of the country shows increased annual mean minimum temperatures (Figure 11a), with particularly strong trends in northern NSW and Queensland. Unlike maximum temperatures, summer minimum temperatures (Figure 11b) have warmed through the majority of the country, with only a few isolated areas of cooling. Since 1950, autumn and winter minimum temperatures (Figure 11c-d) have mainly warmed although scattered areas of cooling exist, predominantly in northern parts and extending into eastern Western Australia. Post-1950 trends in spring minimum temperatures (Figure 11e) show a strong pattern of increase through almost all the country.

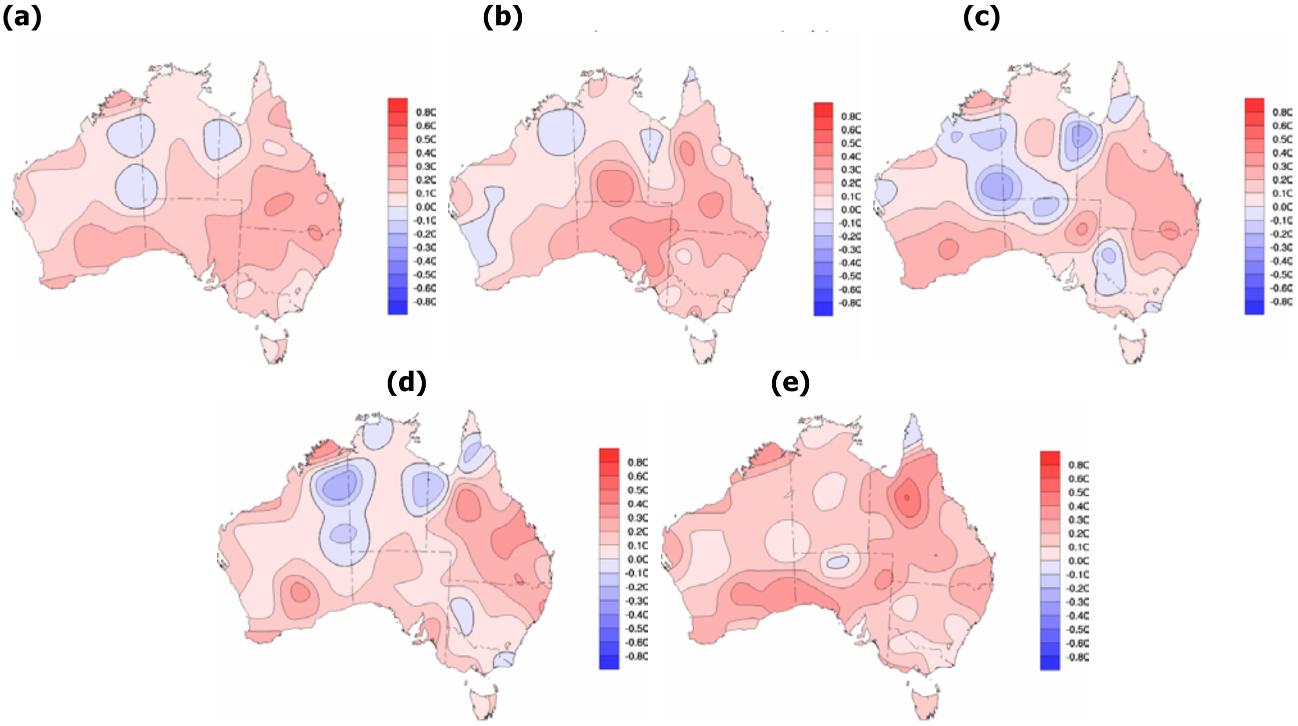


Figure 11. Maps of Australian (a) annual, (b) summer, (c) autumn, (d) winter and (e) spring minimum temperature trends from 1950-2003.

Strong contrasts in rainfall trends are evident throughout the country and seasons since 1950. Along with much of the eastern Australian seaboard, strong decreases in annual rainfall (Figure 12a) have occurred in eastern NSW. Increases in the western two-thirds of Australia are strongest in the northwest. For the post-1950 period, changes in summer rainfall (Figure 12b) are qualitatively similar to those for annual rainfall, with decline evident in eastern New South Wales and Queensland. Autumn rainfall (Figure 12c) shows eastern Australia mainly recording declines and the west generally showing an increase. Trends for winter rainfall (Figure 12d) are mostly weak and mixed, apart from coastal New South Wales which shows a strong decline. Spring rainfall changes (Figure 12e) are relatively weak with most of southeast Australia showing a decline. Since rainfall is highly variable, the period over which it is examined strongly influences trend values. The post-1950 decline in annual rainfall in eastern Australia is largely due to some very wet years during the early and mid-1950s and some very dry El Niño years in recent decades. A map of post-1900 trends in annual total rainfall (not shown) reveals modest increases over most of New South Wales (Collins and Della-Marta 2002).

3.3.2 Timeseries of means and percentage area of extremes

Using only the high-quality, non-urban observation sites, mean annual and seasonal maximum and minimum temperature timeseries for NSW (Figure 13) clearly show a strong rise since 1950, despite large variability in some seasons. Trends calculated over 1950 to 2003 are 0.15°C/decade for the NSW annual mean maximum temperature and 0.19°C/decade for the NSW annual mean minimum temperature. These trends are equivalent to a southward shift of the contours in Figures 6 and 7 by 100-200km.

Extreme climate events have the greatest impacts on society and will drive the social, economic and environmental adjustments flowing from climate change. Consequently, changes in climate extremes need to be studied along with changes in mean. Following the method of Collins and Della-Marta (2002), analyses of the percentage area of NSW recording extreme hot (within decile 10 or the highest 10 percent of historical values) or cold (within decile 1 or the lowest 10 percent of historical values) mean annual temperatures are shown in Figure 13, along with the corresponding mean temperature series. These are generally consistent with the long-term trends and interannual variability of the means i.e., when the mean is higher than average a greater proportion of the state tends to record extreme hot temperatures and a smaller proportion of the state records extreme low temperatures, and vice versa for low mean temperatures.

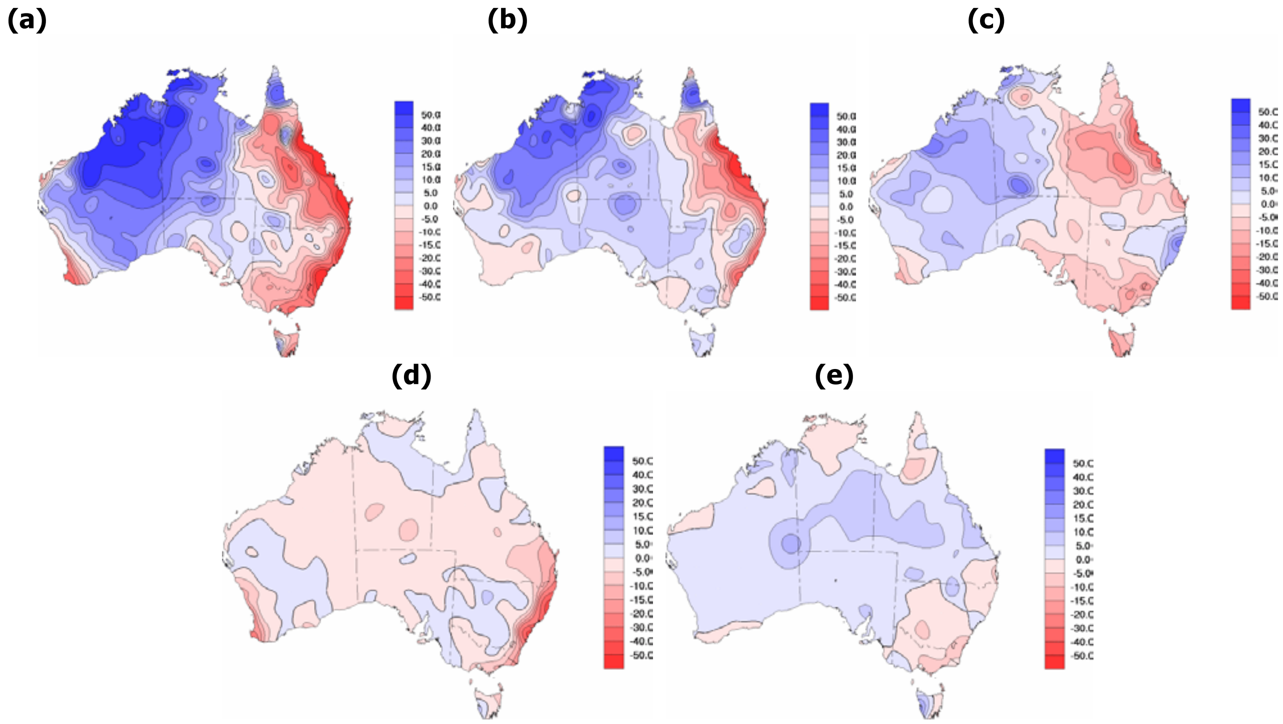


Figure 12. Maps of Australian (a) annual, (b) summer, (c) autumn, (d) winter and (e) spring rainfall trends from 1950-2003.

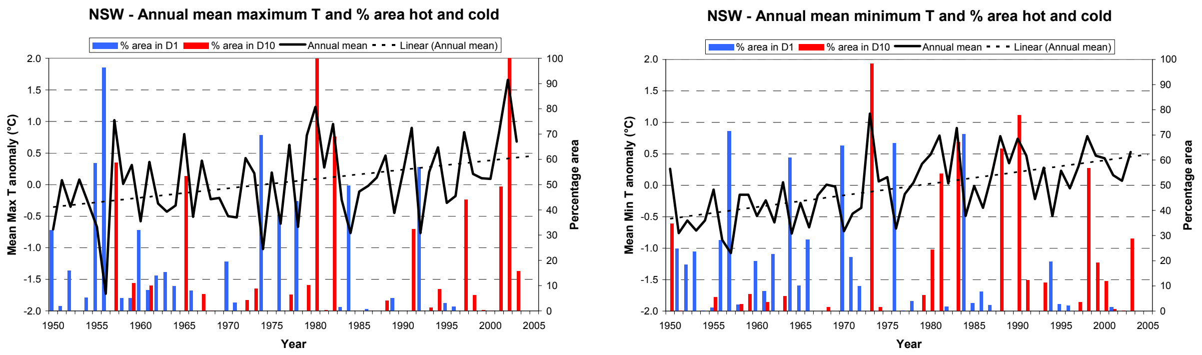


Figure 13. Timeseries of New South Wales mean annual maximum and minimum temperature anomalies and percentage area in top (hot - red) and bottom (cold - blue) deciles from 1950-2003. Temperature anomalies are with respect to 1961-1990 normal.

Since 1950 there is a tendency for years and seasons in more recent decades to record a higher proportion of NSW with extreme hot maximum and minimum temperatures. Recent winter and summer seasons have been particularly warm, recording large proportions of the state with extreme high maxima. During the 2002 drought all of the state recorded annual mean maximum temperatures within the highest decile.

The annual total rainfall averaged over all of NSW for each year since 1950 (Figure 14) shows a decrease of 14.3mm/decade, dominated by high year-to-year variability. Each of the seasons also shows a decline, with summer and autumn displaying the greatest variability. However, since 1900 the annual mean NSW rainfall (not shown) actually shows an increase of 10.6mm/decade. This difference highlights the dominance of interannual and inter-decadal rainfall variability, so that linear trends are highly dependent on the period of analysis. As for temperatures, year-to-year changes in mean rainfall are associated with intuitive changes in percentage areas reporting extreme rainfall; when the rainfall is high (e.g. in the mid-1970s) a large proportion of the state records decile 10 rainfall and a small proportion records decile 1 rainfall, and vice versa for low rainfall. Many El Niño years (such as 1965, 1982, 1994 and 2002) were associated with very low rainfall. The highest recorded proportion of the state with extreme low annual rainfall is 76% in 2002.

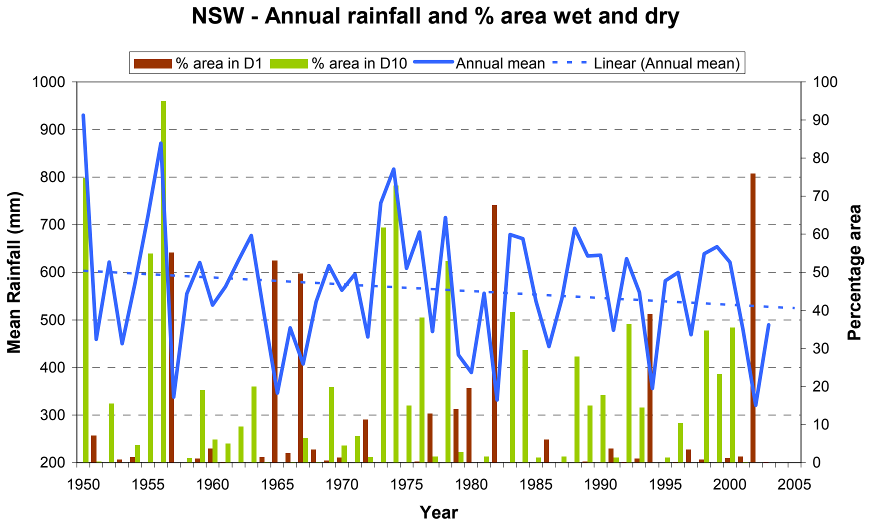


Figure 14. Timeseries of New South Wales annual mean rainfall and percentage area in top (wet – green) and bottom (dry – brown) deciles from 1950-2003.

3.3.3 Drought

Figure 15 shows annual mean temperature anomalies and rainfall totals averaged over NSW since 1950. During the 2002 drought, record low annual rainfall was recorded, accompanied by the highest mean maximum temperatures on record, but close to average mean minimum temperatures. Temperature increases in NSW mean that there is a tendency for more recent dry periods to be accompanied by warmer temperatures than in the past (Nicholls 2003). This suggests that the impact of the 2002 drought would have been exacerbated by temperature rises resulting in increased evaporation and water demand (Nicholls 2004).

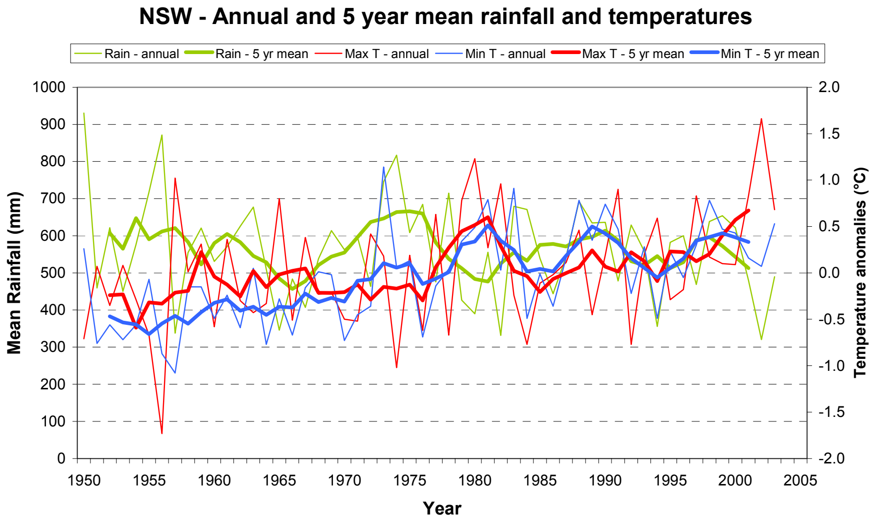


Figure 15. Timeseries of NSW annual and 5 year mean maximum and minimum temperature anomalies, and total rainfall, 1950-2003. Temperature anomalies are with respect to 1961-1990 normal.

A spatial analysis of the rainfall measured over April 2002 to January 2003 (the period of greatest rainfall deficiency) compared with the same period throughout the historical record (Figure 16a) shows that most of the eastern third of mainland Australia recorded rainfall within decile 1. Much of inland Queensland and pockets of northern and southern coastal NSW reported lowest on record rainfall for the 10 months to January 2003. Maximum temperature anomalies for the 10 month period (Figure 16b) are mostly large and positive throughout the drought affected area, whereas anomalies for mean minimum temperatures are more mixed (Figure 16c), reflecting the low cloudiness.

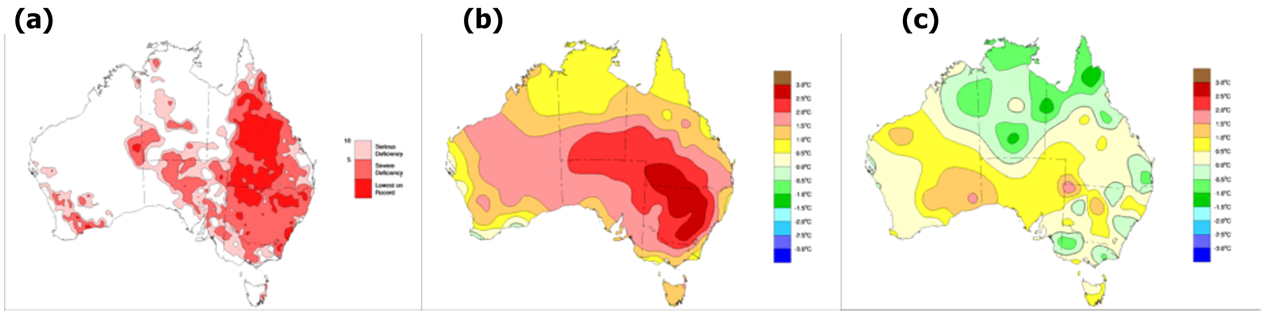


Figure 16. Map of (a) rainfall deficiencies, (b) maximum temperature anomalies and (c) minimum temperature anomalies associated with the April 2002-January 2003 drought.

3.3.4 Timeseries of daily extremes

Analyses of extreme daily temperature indices defined by Collins *et al.* (2000) are updated here using high-quality daily temperature records located in NSW. Due to a lack of digitised data these are confined to the 1957 to 2003 period. Shifts in the frequency of daily extreme temperature events (Figure 17) tend to follow shifts in NSW mean temperatures. Whilst there are regional variations, the NSW mean frequency of extreme hot events (e.g., hot days and nights) has generally increased since the mid-1950s, and the frequency of extreme cold events (e.g., cold days and nights) has decreased. Over 1957 to 2003, the NSW average shows an increasing trend in hot days (35^{o}C or more) of 0.10 days per year, an increasing trend in hot nights (20^{o}C or more) of 0.26 nights per year, a decreasing trend in cold days (15^{o}C or less) of 0.22 days per year and a decreasing trend in cold nights (5^{o}C or less) of 0.29 nights per year. The reduction in cold nights is consistent with a decline in the number of frost days (0^{o}C or less) of 0.14 days per year and a decline in frost season length (number of days between first and last frost) of 0.39 days per year (Figure 17c).

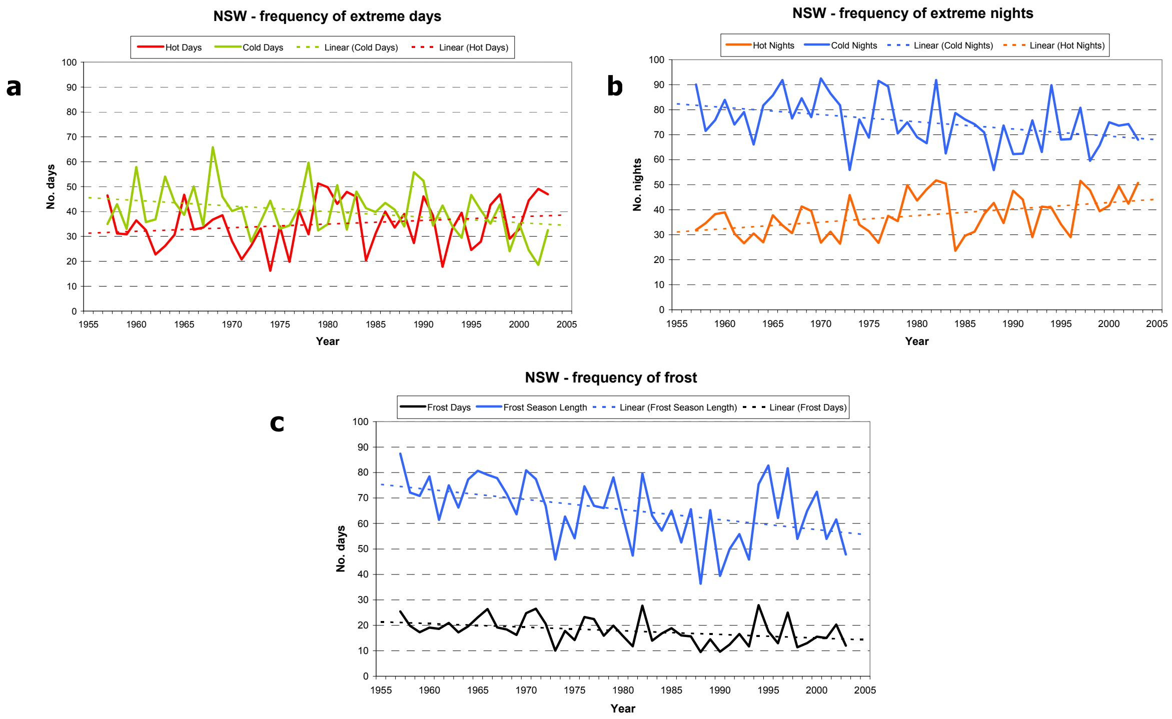


Figure 17. Average number of (a) hot (maximum temperature 35°C or more) and cold (maximum temperature 15°C or less) days per year, (b) hot (minimum temperature 20°C or more) and cold (minimum temperature 5°C or less) nights per year at "high-quality" NSW observation sites from 1957-2003, and (c) average number of frost days (minimum temperature 0°C or less) per year and frost season length (number of days between first and last frost days).

Using the technique of Manton *et al.* (2001), decreases in the annual frequency of extreme daily rainfall events (number of daily totals above the 1961-1990 mean 95th and 99th percentile levels) at high-quality rainfall sites in NSW (Figure. 18) are consistent with the overall decline in the state's annual mean rainfall since 1950. Decreases are generally stronger at coastal locations. Similar decreases are evident in the intensity of extreme rainfall (average of daily totals above or equal to the 95th/99th percentile levels), with the strongest trends located at coastal sites (Figure 19). The NSW annual mean frequency (Figure 20a) and intensity (Figure 20b) for these locations clearly show declines, despite the spatial variability expected from rainfall-derived indicators.

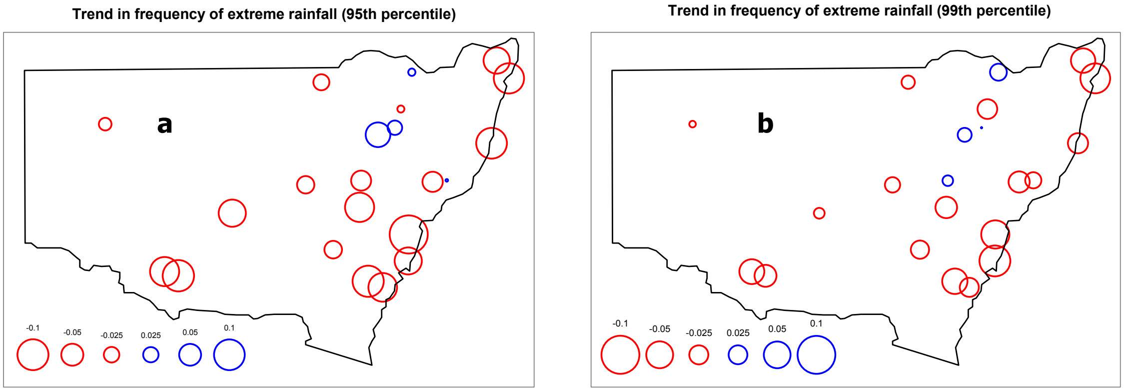


Figure 18. Map of trends in annual frequency (days/year) of extreme daily rainfall (number of daily totals above the 1961-1990 mean (a) 95th and (b) 99th percentile levels) from 1950-2003.

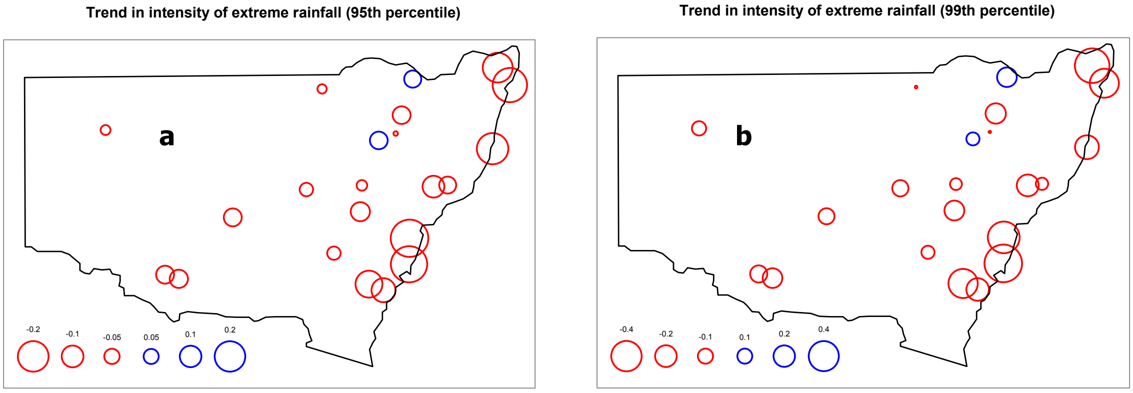


Figure 19. Map of trends in intensity (mm/year) of extreme rainfall (average of daily totals above or equal to the (a) 95th and (b) 99th percentile levels) from 1950-2003.

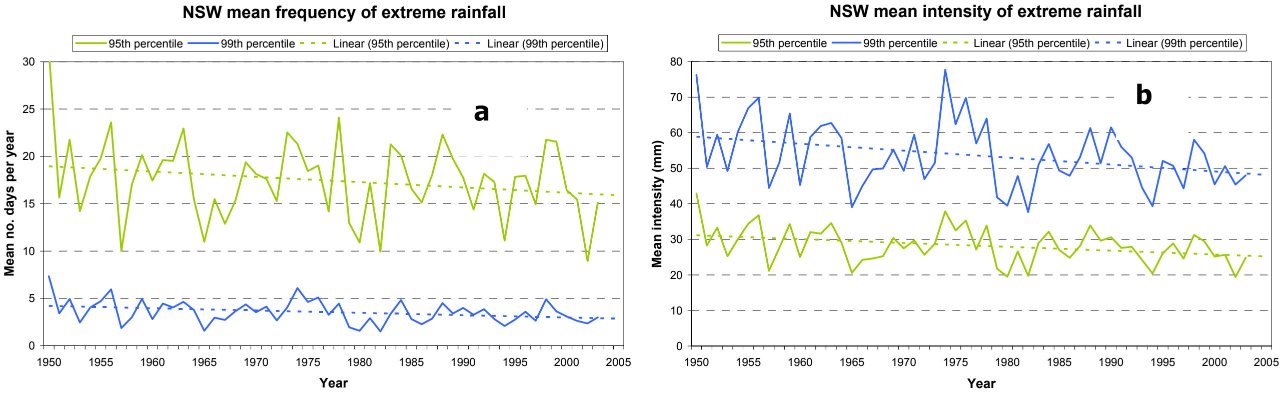


Figure 20. Timeseries of mean NSW (a) annual frequency of extreme daily rainfall above 95th and 99th percentile levels and (b) intensity of extreme rainfall (mm) above or equal to 95th and 99th percentile levels, from 1950-2003.

3.4 Causes of NSW climate change

Nicholls *et al.* (2004) examined the relationship between NSW mean maximum temperature and rainfall since 1910. Because the rise in mean maximum temperatures since 1950 has occurred largely independently of rainfall changes, Nicholls *et al.* (2004) argue that some mechanism other than rainfall changes is responsible. Karoly (2001) and Stott (2003) have attributed late 20th century warming over Australia to anthropogenic causes, being chiefly the enhanced greenhouse effect. While it is possible that natural variability such as ENSO and other human-related impacts such as land-use change may have contributed, the most obvious explanation for warming in NSW since 1950 is the enhanced greenhouse effect.

Due to the high variability of NSW rainfall, and the numerous influences on it, it is difficult to attribute rainfall changes to any particular cause. Recent research (Karoly, 2003) suggests rainfall changes could be due to some combination of natural and anthropogenic factors, such as decreasing stratospheric ozone and the enhanced greenhouse effect. Changes in NSW rainfall are also dependent on how ENSO responds to the enhanced greenhouse effect. Simulations show little change or a small increase in amplitude of El Niño events with enhanced greenhouse warming (IPCC 2001a). However, the confidence in this finding is low due to limitations in the ability of the models to accurately simulate the ENSO cycle.

3.5 Sea-level changes

Church *et al.* (2004) found a rise in mean relative sea-level (including land movement) around Australia of about 1.2mm/year over the period 1920 to 2000 (Figure 21). This is less than the global average due to a trend toward more frequent and intense El Niño events (which lower sea-levels in the Australian region) since the mid-1970s. One of the longest instrumental sea-level records in Australia is from Fort Denison, Sydney. By comparing pre- and post-1950 data, Church *et al.* (2004) found that the frequency of extreme sea-level events reaching 2.1 or 2.2 m in Sydney has doubled or tripled, respectively, since 1950. The analysis also suggests that the increase in frequency is due to both the increase in mean sea-level and an increase in interannual variability.

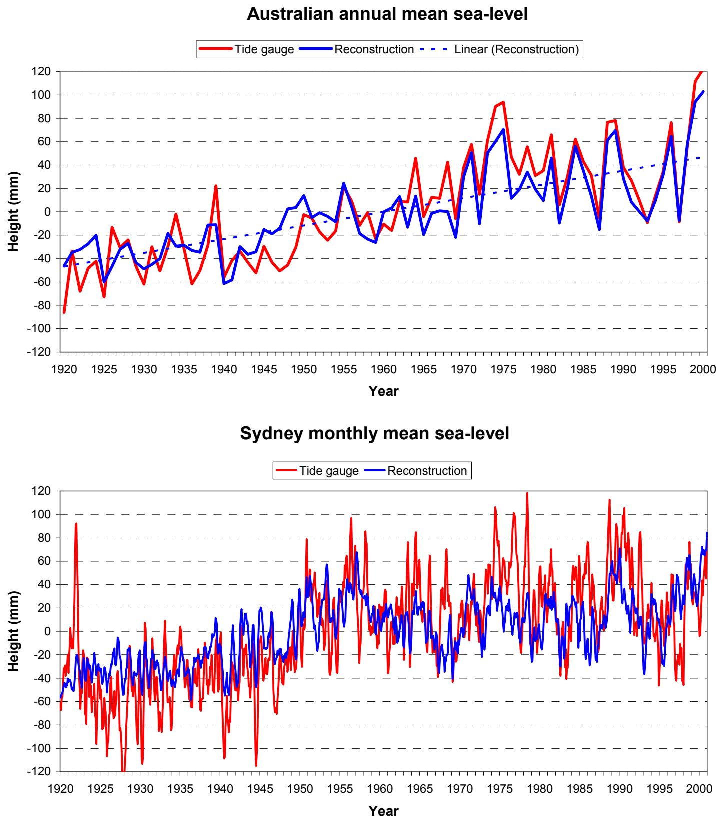


Figure 21. Observed (using coastal tide gauges) (red) and reconstructed (blue) timeseries of Sydney monthly mean sea-level and Australian annual mean sea-level from 1920-2000 (sourced from Church *et al.*, 2004). Reconstructions are made using satellite altimetry.

4. Future climate change

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

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

4.1 SRES emission scenarios

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

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

Figure 22 shows the SRES (2000) anthropogenic (human-induced) emission scenarios for carbon dioxide, methane, nitrous oxide and sulphur dioxide. Carbon cycle models are used to convert emissions into well-mixed atmospheric concentrations, allowing for uptake of emissions by the land and ocean, land and ocean climate feedbacks, and chemical reactions in the atmosphere. By the year 2100, carbon cycle models give estimates of atmospheric CO_2 concentrations ranging from 540 to 970 ppm (an increase of 44 to 159% relative to 375 ppm at present) (Figure 23; IPCC, 2001a). Methane concentrations are projected to change by -11 to +112% and nitrous oxide concentrations may rise 12 to 46%. Concentrations of tropospheric ozone, hydrofluorocarbons and perfluorocarbons are also projected to increase. The SRES (2000) scenarios include the possibility of increases or decreases in anthropogenic aerosols (e.g. black carbon, sulphate aerosols, biomass, aerosols and organic carbon aerosols) depending on the extent of fossil fuels use.

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

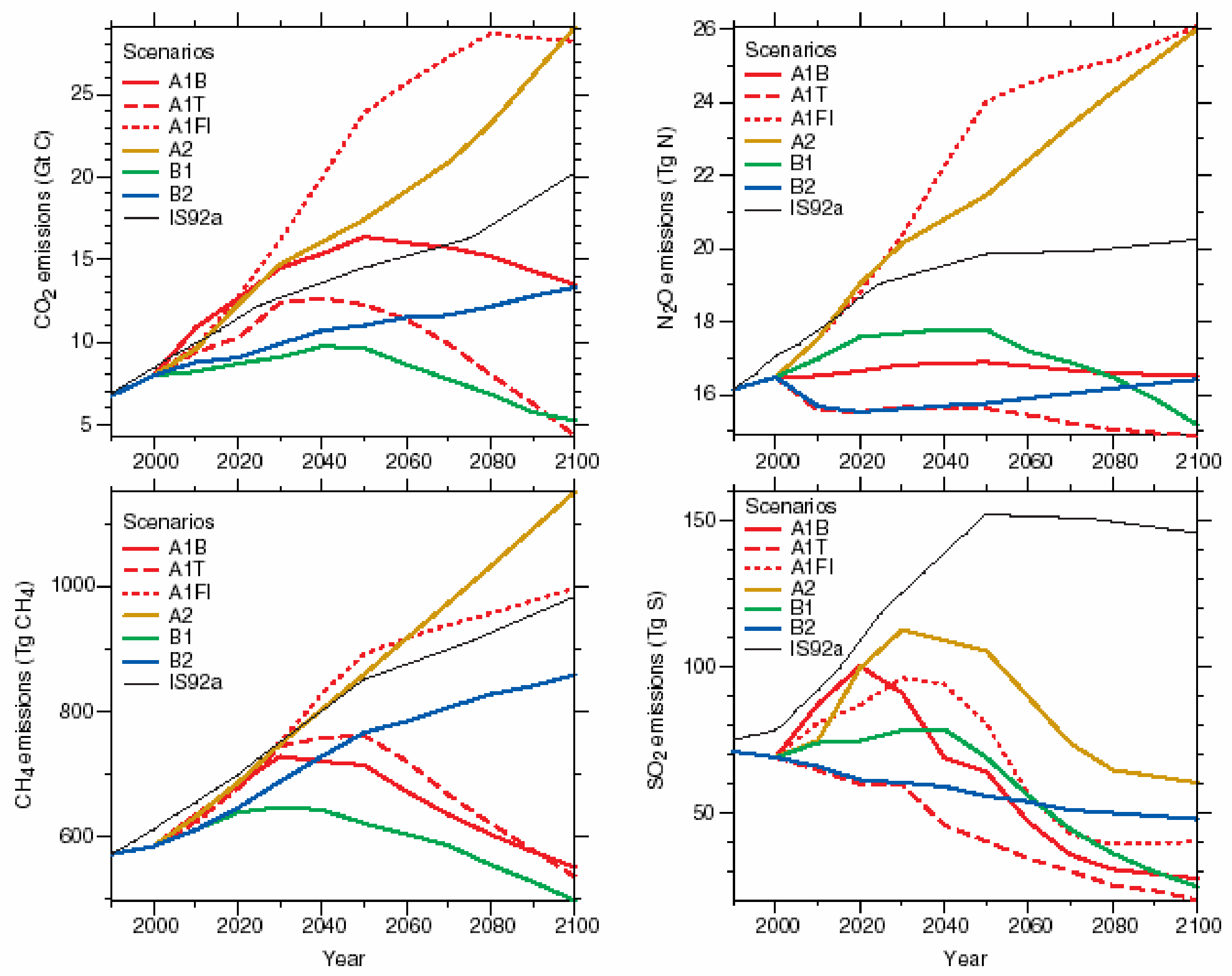


Figure 22. Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulphur dioxide (SO_2) for six SRES scenarios. The IS92a scenario is also shown (from the IPCC Second Assessment Report in 1996). Source (IPCC, 2001a).

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

Climate models need massive computing resources to perform a simulation with just one emission scenario. Each simulation has a unique climate sensitivity and pattern of climate change. Comparing and synthesising results from different models is a big job. Much simpler climate models have been developed to allow exploration of the sensitivity of climate to a wide range of inputs and assumptions. These simple models can be run on a desktop computer. They provide information about global-average warming and sea-level rise for various emission scenarios and other parameters. The simple models rely on the more-complex climate models for climate sensitivity, rates of ocean heat uptake and patterns of climate change. The SRES results for global-average warming and sea-level rise are shown in Figure 24.

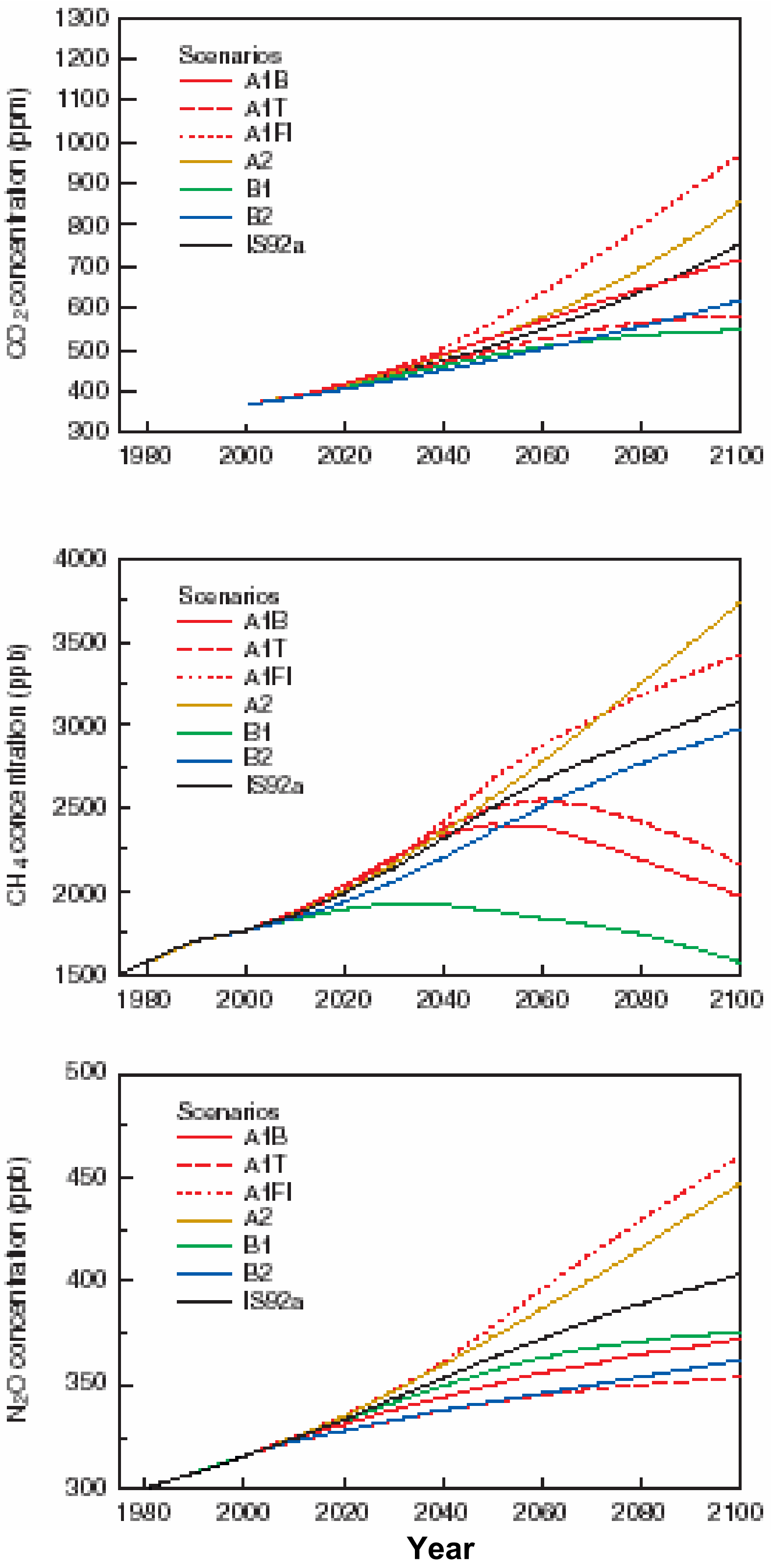


Figure 23. Atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) resulting from the six SRES scenarios. The IS92a scenario is also shown (from the IPCC Second Assessment Report in 1996). Source (IPCC, 2001a).

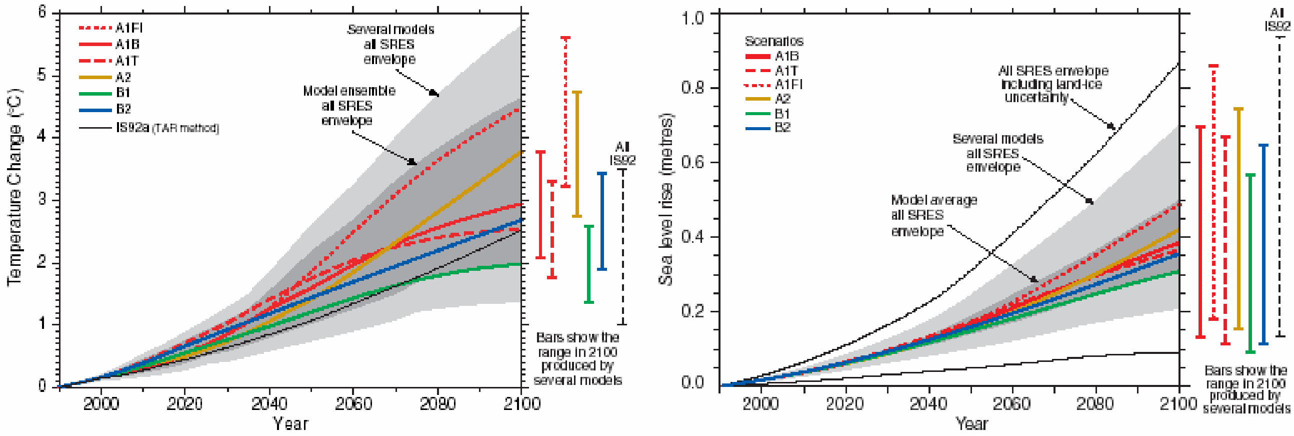


Figure 24. Projected changes in global-average temperature and sea level resulting from the six SRES scenarios, based on a simple climate model tuned to a number of complex climate models with a range of climate sensitivities. The IS92a scenario is also shown (from the IPCC Second Assessment Report in 1996). Source (IPCC, 2001a).

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

4.2 Emission reduction scenarios

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

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

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

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

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

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

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

One way of slowing global warming is to stabilise greenhouse gas concentrations. A range of CO_2 stabilisation scenarios were considered by the IPCC (2001a). Figure 25 shows the time paths of CO_2 emissions that would lead to stabilisation of CO_2 concentrations at 450, 550, 650, 750 and 1000 ppm sometime between the year 2090 and 2300. Lower CO_2 concentration targets would require an earlier reversal of emissions growth and earlier decreases to levels below current emissions. The shaded area shows the range of uncertainty in estimating CO_2 emissions corresponding to each concentration scenario, as represented in carbon cycle models. Also shown for comparison are CO_2 emissions for the A1B, A2, and B1 SRES scenarios. In all cases except the 1000 ppm scenario, stabilising CO_2 concentrations at a higher level than present (375 ppm) would require a reduction from the current level of 8 GtC (million tonnes of carbon) per year to around 3 GtC per year within the next 100 to 300 years, i.e. at least a 60% reduction in global emissions relative to present. For example, the path to stabilising at 550 ppm by 2150 would require emissions to peak at 40% above present (11.2 GtC) by the year 2025, then drop to 20% above present (9.5 GtC) by the year 2050, falling to 35% below present (5.2 GtC) by the year 2100. Alternatively, the path to stabilising at 450 ppm by the year 2090 would require emissions to peak at 20% above present (9.5 GtC) by the year 2010, then decrease to 38% below present (5.0 GtC) by the year 2050, and 70% below present (2.3 GtC) by the year 2100.

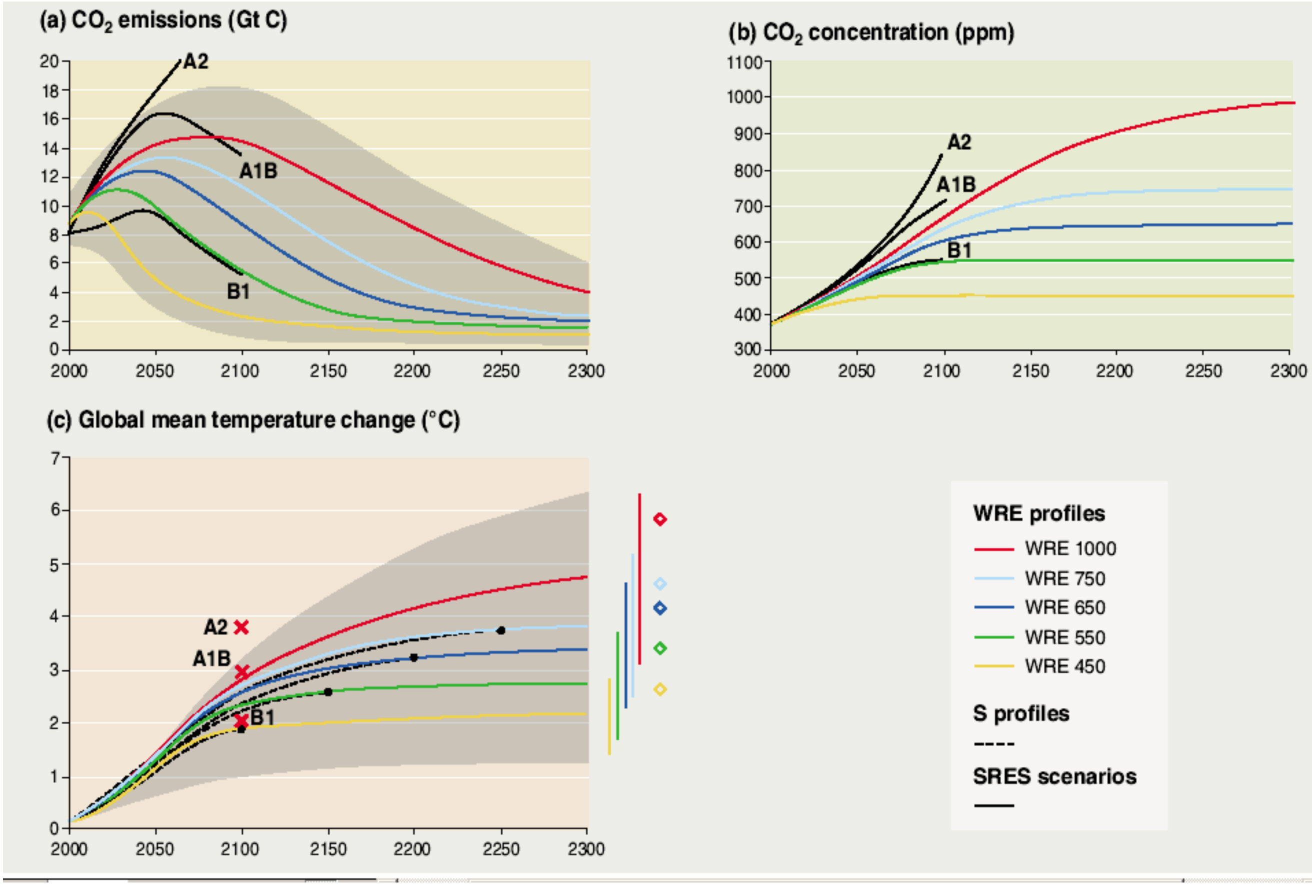


Figure 25. (a) Time paths of CO_2 emissions that would lead to (b) stabilization of the concentration of CO_2 in the atmosphere at 450, 550, 650, 750, and 1000 ppm. The shaded area shows the range of uncertainty in estimating CO_2 emissions corresponding to each concentration scenario. CO_2 emissions for the A1B, A2, and B1 SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. (c) The corresponding global warming includes coloured bars on the right-hand side showing the range at the year 2300 and the diamonds show the equilibrium (very long-term) warming. Red crosses show warmings in the year 2100 for the A1B, A2, and B1 scenarios and the dashed lines show warmings for the S profiles, an alternate set of CO_2 stabilization profiles (not shown in panels (a) or (b)). From IPCC (2001d).

In the IPCC (2001a) warming projections for CO_2 stabilisation, it is assumed that emissions of gases other than CO_2 follow the mid-range A1B scenario until 2100 and are constant thereafter. The global warming slows as growth in CO_2 concentration slows, and warming continues after the time at which the CO_2 concentration is stabilized (indicated by black spots in Figure 25c) but at a much weaker rate. For the 550 ppm stabilisation path, the warming by 2100 is reduced to between 1.5 and 2.9ºC, compared with 1.4 to 5.8ºC without emission reductions (O'Neill and Oppenheimer, 2002). For the 450 ppm stabilisation path, the warming by 2100 is reduced to between 1.2 and 2.3ºC.

Hansen (2004) proposed two "alternative" emission reduction scenarios. The first stabilises CO_2 at 475 ppm by 2100 and gives a global warming peaking at 1ºC in the period 2125-2150. The second stabilises CO_2 at 560 ppm by 2100 and gives a warming peaking at 2ºC by 2125-2150. While the CO_2 concentration targets are almost the same as the IPCC (2001a) targets described above, the resultant global warming value are slightly lower. This is because the time paths for Hansen's (2004) CO_2 and non-CO_2 gases emissions differ from those of the IPCC (2001a). Figure 26 shows that emission reductions clearly have a major impact on the upper limits of the SRES unmitigated global warming, but a minor effect on the lower limits.

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

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

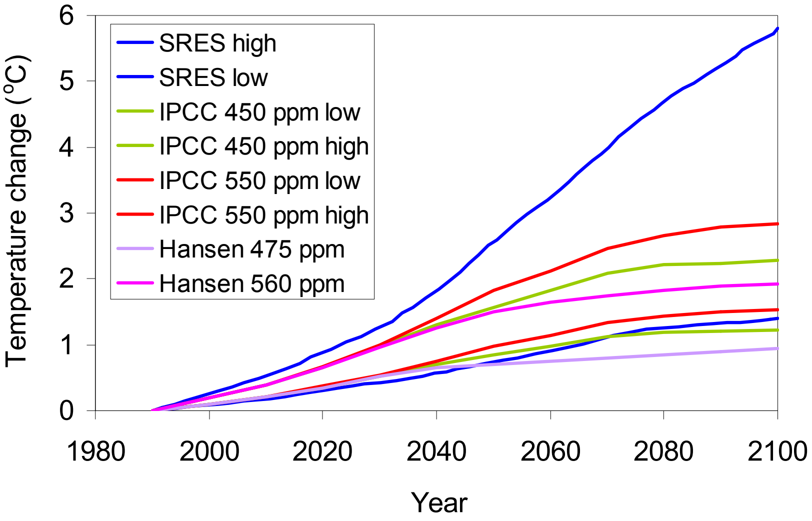


Figure 26. Comparison of projected global warming based on various assumptions about greenhouse gas emissions: SRES, IPCC scenarios for CO_2 stabilisation at 550 and 450 ppm, and Hansen's "alternative" scenarios for CO_2 stabilisation at 560 and 475 ppm.

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

The Kyoto Protocol is focussed on the period 2008-2012, with the aim of reducing CO_2 emissions from developed countries by 5%. Ratification of the Kyoto Protocol requires a "double trigger" (UNFCCC, 2002). The first trigger is ratification by 55 governments - a requirement that was met in 2002. The second trigger is that the ratifying governments must include developed countries representing at least 55% of that group's 1990 CO_2 emissions. As of 26 November 2003, 120 ratifying governments accounted for 44.2% of 1990 CO_2 emissions (UNFCCC, 2003). Russia's 17.4% would be essential for pushing the tally over the required 55% threshold. The six top emitters, responsible for about 70% of global greenhouse gas emissions, are the US, the EU, China, Russia, Japan and India. Only two of these countries, the EU and Japan, have agreed to ratify the Kyoto Protocol, although Russia has indicated that it may soon ratify. Developing countries were not required to sign. Further commitments would be needed so that developed countries reduce emissions substantially after 2012, and so that emissions from developing countries do not grow as much as expected. Various approaches are being considered (WBGU, 2003).

4.3 Climate model performance over New South Wales

The IPCC (2001a) concluded that confidence in the ability of models to project future climate has increased. This is because (i) our understanding of the physical and biogeochemical processes that govern the climate system has improved, (ii) recent models provide satisfactory simulations of current climate without the need for non-physical adjustments of heat and water fluxes at the ocean-atmosphere interface used in earlier models, (iii) simulations of 20th century climate change reproduce the observed large-scale changes in surface temperature, and (iv) there have been improvements in some aspects of the simulation of the El Niño Southern Oscillation, monsoons and the North Atlantic Oscillation, as well as selected periods of past climate. However, there are still particular uncertainties associated with clouds and their interaction with radiation and aerosols.

Most global climate models have grid points spaced about 300-500 km apart over the globe. Due to their coarse resolution, these models only provide broad-scale projections of climate change, whereas policy-relevant projections and impact assessments often require more detail. Regional climate models (RCMs) include enhanced components for the atmosphere and land surface, using a relatively fine grid (e.g. points 50-125 km apart) over a limited area (e.g. the Australian region). An RCM is driven outside the region of interest by input from a global climate model, so the results of an RCM depend on the global model in which it is embedded. RCMs give a much better representation of coastal and mountain effects and local variations in climate. CSIRO uses both global and regional models in development of regional climate change projections. A prerequisite for inclusion of a model in the projections is that it adequately simulates current climate conditions. An assessment was made of the ability of 19 groups of climate simulations (Table 1) to reproduce current patterns of temperature, rainfall and mean sea-level pressure over NSW.

Statistical methods have been used to verify the performance of each model in simulating the current average climate (verification of climate variability and trends was not undertaken). Observed and simulated patterns for 1961-1990 were compared by calculating (i) the pattern correlation coefficient which measures pattern similarity, and (ii) the root mean square (RMS) error which measures the magnitude of differences. A pattern correlation coefficient of 1.0 indicates a perfect match between observed and simulated spatial patterns and an RMS error of 0.0 indicates a perfect match between observed and simulated magnitudes. A region bounded by longitudes 141-154ºE and latitudes 28-37.5ºS was used to test ability of each model to simulate seasonal temperature, rainfall and mean sea-level pressure over NSW.

Figure 27 shows a sample result for summer temperature. The better performing models have results closer to the top left hand corner of the diagram. For temperature, most models achieve pattern correlations better than 0.8 and RMS errors less than 3°C. The exceptions for summer are the large RMS errors for NCAR CGM, DKRZ ECHAM3 and CSIRO CC50, and the poor pattern correlations for CCSR1 and CCSR2. Rainfall is more variable than temperature, so it is more difficult to simulate accurately. Most models achieve rainfall pattern correlations better than 0.6 and RMS errors less than 2 mm per day. For mean sea-level pressure, the pattern correlation coefficient for most models is above 0.8, and the RMS error is less than 2 hPa.

Table 1: Climate model simulations analysed in this report. See http://ipcc-ddc.cru.uea.ac.uk.

Centre	Model	Emission scenarios post-1990 (historical forcing prior to 1990)	Years	Horizontal resolution (km)	Temporal resolution available
CSIRO, Australia	CSIRO Mark2.1	IS92a,	1881–2100	~400	daily
CSIRO, Australia	CSIRO Mark2.2	SRES A1, A2,B1, B2	1881–2100	~400	daily
CSIRO, Australia	CSIRO DAR125	RCM in Mark2 with IS92a	1961-2100	125	daily
CSIRO, Australia	CSIRO CC50	Linked to Mark2 with SRES A2	1961-2100	50 over Aus	daily
CSIRO, Australia	CSIRO Mark3	SRES A2	1961-2100	~200	daily
Canadian CC	CCM1	1% increase in CO_2 p.a.	1900–2100	~400	monthly
Canadian CC	CCM2.1	IS92a	1961-2100	~400	monthly
Canadian CC	CCM2.2	SRES A2, B2	1961-2100	~400	monthly
DKRZ, Germany	DKRZ ECHAM3	IS92a	1880-2085	~600	monthly
DKRZ, Germany	DKRZ ECHAM4	SRES A2, B2	1860–2099	~300	monthly
GFDL, USA	GFDL1	1% increase in CO_2 p.a.	1958–2057	~500	monthly
GFDL, USA	GFDL2	SRES A2, B2	1958–2057	~500	monthly
Hadley Centre, UK	HadCM2	1% increase in CO_2 p.a.	1861–2100	~400	monthly
Hadley Centre, UK	HadCM3.1	IS92a	1861-2099	~400	monthly
Hadley Centre, UK	HadCM3.2	SRES A2, B2	1861-2099	~400	monthly
NCAR, USA	NCAR CGM	IS92a	1900-2035	~500	monthly
NCAR, USA	NCAR PCM	IS92a	1961-2098	~300	monthly
CCSR, Japan	CCSR1	IS92a	1890-2099	~600	monthly
CCSR, Japan	CCSR2	SRES A1, A2, B1, B2	1890-2100	~600	monthly

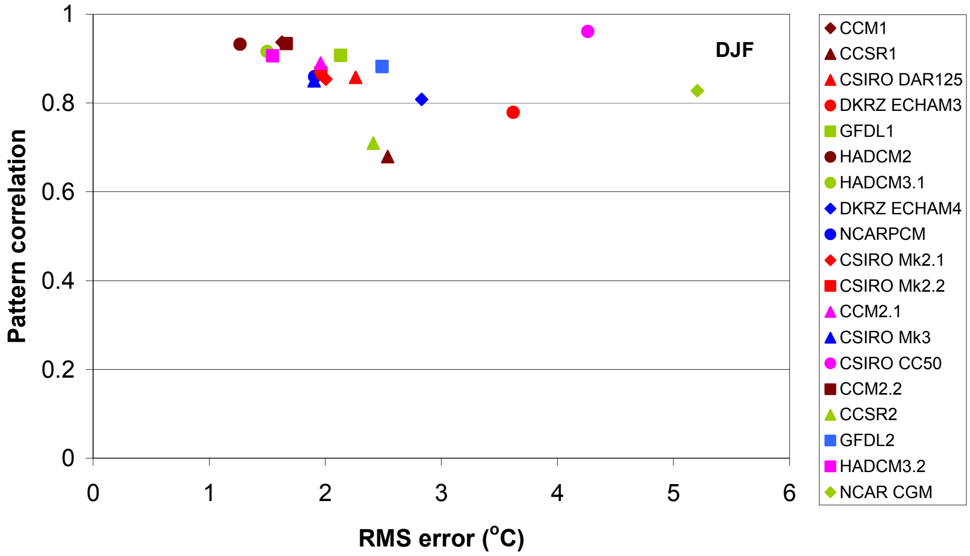


Figure 27. Pattern correlation and RMS error for observed versus model temperature in summer (Dec-Jan-Feb) for the 19 models in Table 1 over NSW. The better performing models have results closer to the top left hand corner of the diagram. This type of analysis was performed for other seasons, and for rainfall and atmospheric pressure.

These statistics suggest that most models capture the average climatic features reasonably well. However, some models perform better than others. To compare the overall performance of each model, a simple demerit point system based on thresholds was used. Models were assigned a point if they had an RMS error greater than 2.0, or a pattern correlation below 0.8 for pressure and below 0.6 for temperature and rainfall. Therefore a maximum of 24 demerit points could be accrued by a model (2 performance measures x 4 seasons x 3 climate variables). On this basis, the worst performers were the CCSR simulations with points ranging from 15 to 16, the GFDL simulations with scores of 10 and 11, ECHAM3 with 10 and NCAR GCM with 9. All remaining models had scores of 8 or less with the best performers being HADCM2, CSIRO DAR125, HADCM3.1, HADCM3.2 and CSIRO CC50 with 1 to 3 points.

The performance results revealed that all models did well in capturing the observed rainfall patterns, but there were some deficiencies in the simulation of pressure and temperature. In particular, the CCSR models, GFDL1, GFDL2 and ECHAM3 contained large biases in pressure in all seasons. Large RMS errors in temperature were evident in the CCSR models, ECHAM3, GFDL1, CSIRO Mark2.1 and NCARCGM. All of these models, except CSIRO Mark2.1, had at least 9 demerit points, so it seemed appropriate to use this as a cut-off. On this basis, 14 of the 19 simulations were considered suitable for climate change projections. The CCM2.1 and CCM2.2 patterns of change were averaged since the individual patterns were similar. Likewise, HADCM3.1 and HADCM3.2 patterns of change were averaged. CSIRO Mark2.2 and CSIRO Mark2.2 were not averaged since there were significant differences in the model features and climate change patterns. Hence, 12 simulations were used to create climate change projections for NSW.

4.4 Climate change projections for New South Wales

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

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

Results from the simulations were expressed as a change per degree of global warming, then converted to a map of change in 2030 or 2070 using IPCC global warming values (Figure 26).

Temperature projections

NSW is likely to experience greatest warming west and north of the highlands, and least in southern and coastal areas. Most warming is expected to occur in spring and summer, and least in winter. By the year 2030, the SRES scenarios give an annual-average warming of 0.2 to 1.6°C in coastal and southern regions, relative to 1990, 0.2 to 1.8°C in the central-west, and 0.3 to 2.1°C in the north (Figure 28 and Table 2).

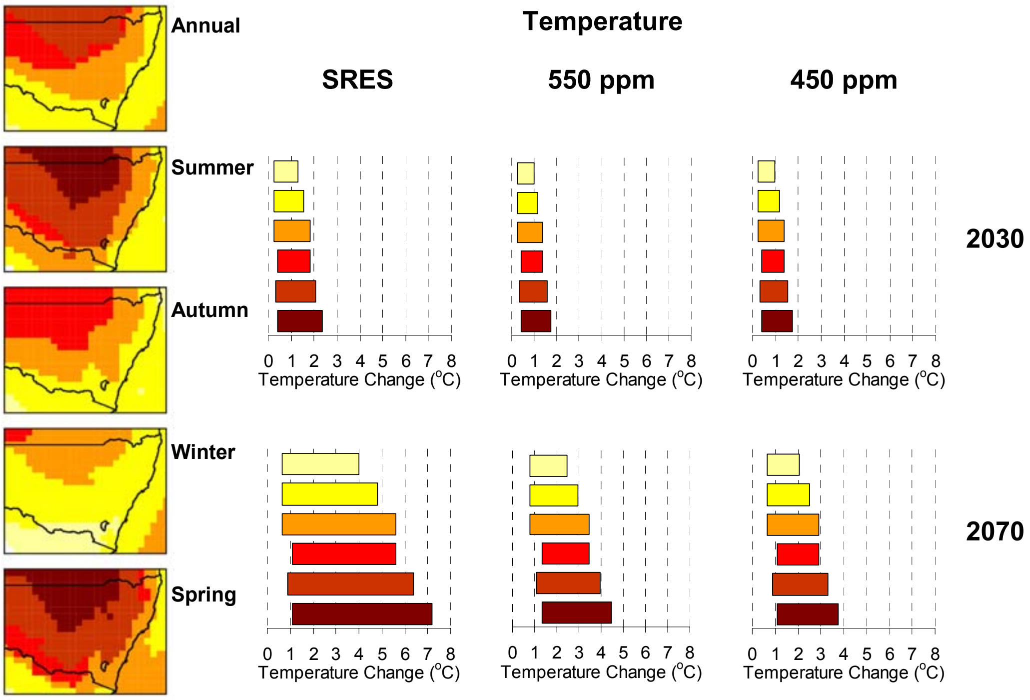


Figure 28. Ranges of change in average temperature (°C) for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

Table 2. Ranges of change in annual average temperature (°C) for the years 2030 and 2070 relative to 1990. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range of warming is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

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

By 2070, the warming increases to 0.7 to 4.8°C in coastal and southern regions, 0.7 to 5.6°C in the central-west, and 0.9 to 6.4°C in the north. If CO_2 concentrations are stabilised at 550 ppm by the year 2150, the upper limit of warming is reduced by 23% by 2030 and 38% by 2070. If CO_2 concentrations are stabilised at 450 ppm by the year 2090, the upper limit of warming is reduced by 25% by 2030 and 48% by 2070.

Rainfall projections

The models indicate a general tendency for decreasing annual-average rainfall over NSW (Figure 29). This is mainly confined to winter and spring. In autumn, the direction of rainfall change is uncertain over most of the State, with a tendency for decreases in the north and increases in the far west. Summer rainfall changes are uncertain over much of southern and western NSW, with a tendency for increases along the coast and in the north-east, and a tendency for decreases in the north-west.

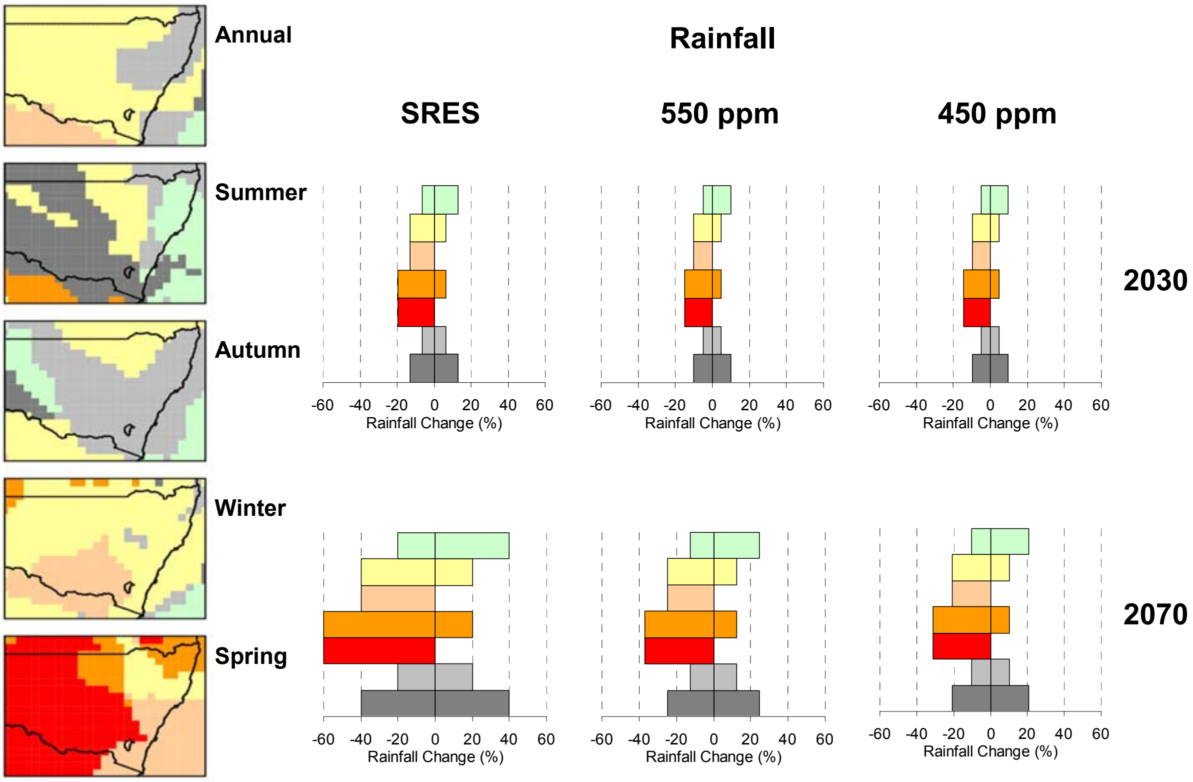


Figure 29. Ranges of change in average rainfall (%) for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

The magnitude of rainfall change depends on the scenario. By the year 2030, the SRES scenarios give changes of -13% to +7% in winter, in the north-west in summer and in the north in autumn, relative to 1990; -20% to +7% in spring; -7% to 13% along the coast and north-east in summer and in the far west in autumn. By 2070, these ranges of change triple, e.g. -13% to +7% becomes -40% to +20%. If CO_2 concentrations are stabilised at 550 ppm by the year 2150, the limits of the SRES rainfall changes are reduced by 23% by 2030 (e.g. -13% to +7% becomes -10% to +5%) and 38% by 2070 (e.g. -40% to +20% becomes -25% to +12%). If CO_2 concentrations are stabilised at 450 ppm by the year 2090, the limits of the SRES rainfall changes are reduced by 25% by 2030 and by 48% by 2070.

In some regions, the ranges of uncertainty indicate that rainfall could increase or decrease. While the potential decreases are larger than the potential increases, it would be helpful to know how many models agree on a decrease or increase in various regions, and the magnitude of the average change in rainfall. Figure 30 shows that most of the 12 models agree on a decrease in annual rainfall. Figure 31 shows that when patterns of annual rainfall change (per degree of global warming) are averaged across all 12 models, the whole of NSW shows decreased rainfall. Therefore, the ranges of uncertainty in Figure 29 are underpinned by a tendency decreased annual-average rainfall.

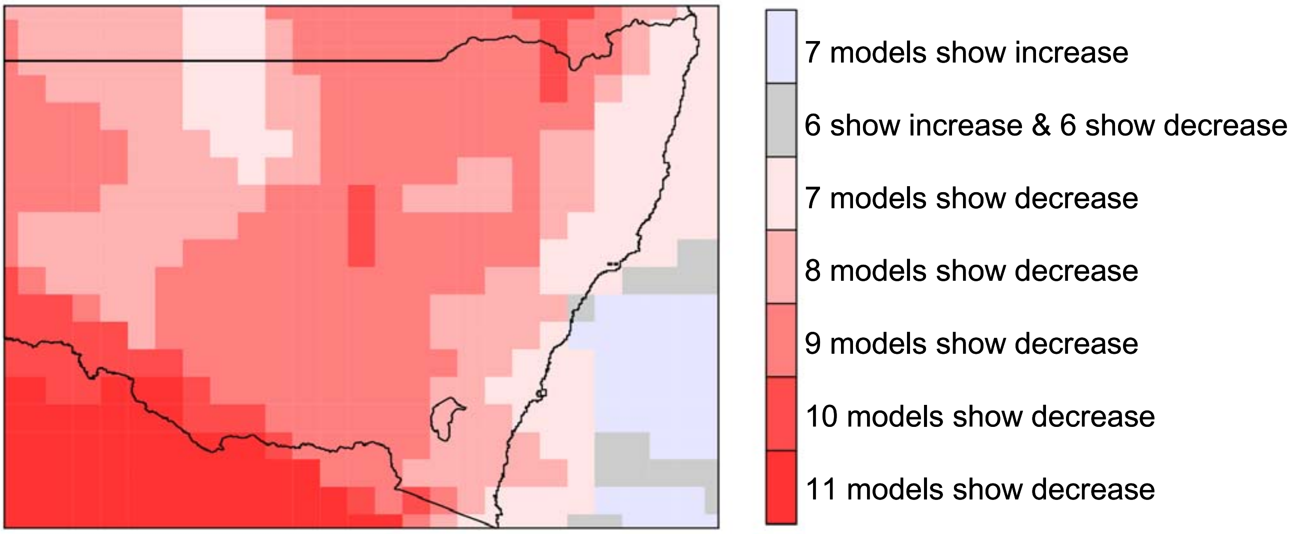


Figure 30. Number of climate models showing an increase or decrease in rainfall at each gridcell over NSW under enhanced greenhouse conditions.

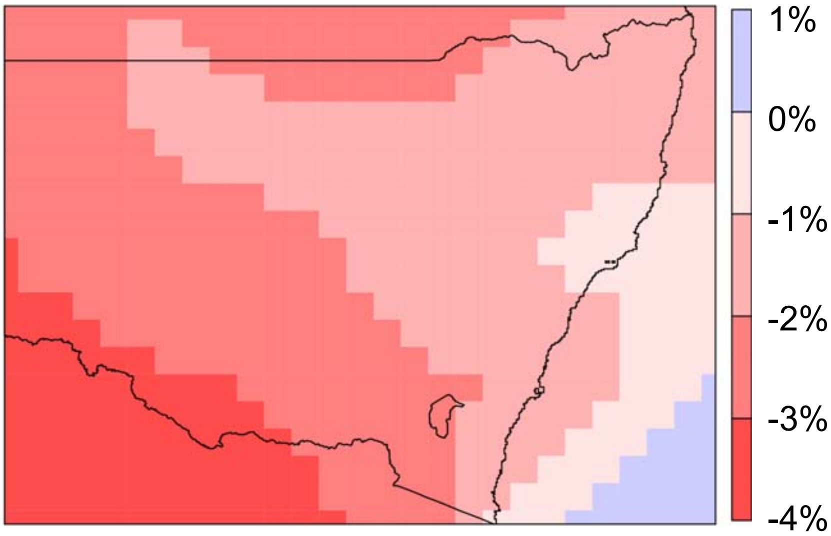


Figure 31. Change in rainfall (%) per degree of global warming, averaged over 12 models.

Evaporation and moisture balance projections

Atmospheric moisture balance is the difference between rainfall (supply) and potential evaporation (demand). Potential evaporation is the potential of the local air to evaporate available water from open water or soil, and transpire water from plants. A detailed description of different measures of evaporation is given in Appendix A. Climate change simulations show that increasing greenhouse gas emissions and higher temperatures are likely to be associated with increased potential evaporation. Changes in potential evaporation were calculated from seven simulations for which relevant monthly data were available, i.e. CCM1, CCM2.2, CSIRO DAR125, CSIRO CC50, CSIRO Mark2, CSIRO Mark3 and HadCM3.2.

Figure 32 shows that annual-average potential evaporation increases across NSW, with largest increases west of the highlands. The percentage changes are largest in winter and least in summer because baseline potential evaporation rates are low in winter and high in summer. By the year 2030, the SRES scenarios give annual-average increases of 1.5 to 13% west of the highlands and 1 to 8% along the coast, relative to 1990. By 2070, the increase is 4 to 40% west of the highlands and 2 to 24% along the coast. If CO_2 concentrations are stabilised at 550 ppm by the year 2150, the upper limits of the SRES potential evaporation changes are reduced by 23% by 2030 and 38% by 2070. If CO_2 concentrations are stabilised at 450 ppm by the year 2090, the upper limits of the SRES potential evaporation changes are reduced by 25% by 2030 and by 48% by 2070.

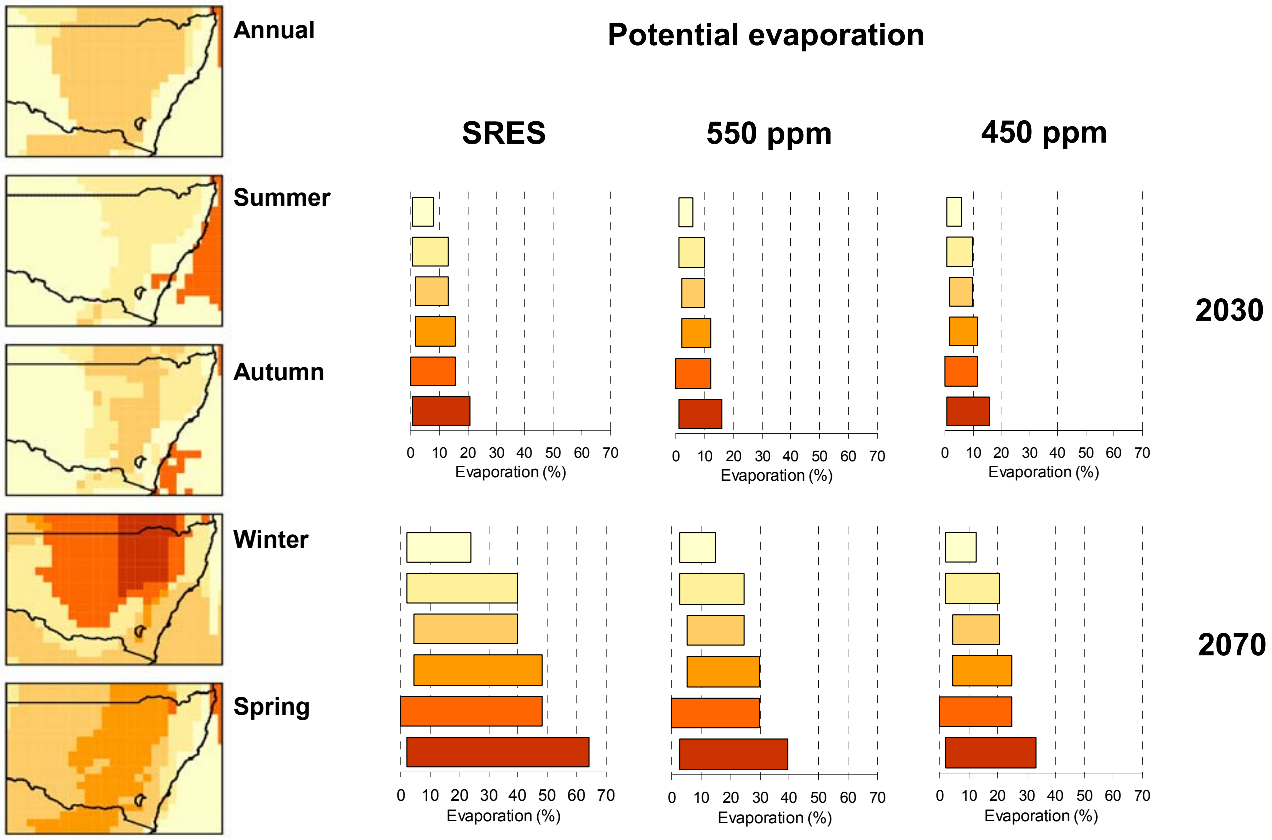


Figure 32. Ranges of change in point potential evaporation (%) for the years 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

Atmospheric moisture balance is a measure that integrates changes in both potential evaporation and rainfall. It is broadly indicative of how much moisture is in the environment. However, it cannot be used to infer quantitative changes in runoff or in other hydrological impacts. Using projections of point potential evaporation and rainfall, the change in the atmospheric moisture balance was calculated. Over NSW, average decreases in annual moisture balance are largest in the north and smallest along the coast. By 2030, annual average decreases range from 0 to 195 mm along the coast and 20 to 325 mm in the north, relative to 1990.

By 2070, the coastal decreases are 0 to 600 mm and the northern decreases are 55 to 1000 mm (Figure 33). If CO_2 concentrations are stabilised at 550 ppm by the year 2150, the lower limits of the SRES potential evaporation changes are reduced by 23% by 2030 and 38% by 2070. If CO_2 concentrations are stabilised at 450 ppm by the year 2090, the lower limits of the SRES potential evaporation changes are reduced by 25% by 2030 and by 48% by 2070.

These projected decreases in atmospheric balance are obviously very important and are being addressed further in ongoing research. This work includes an examination of why Australian pan evaporation has shown an apparent decrease in the observational record, rather than the increase that might have been expected due to higher temperatures.

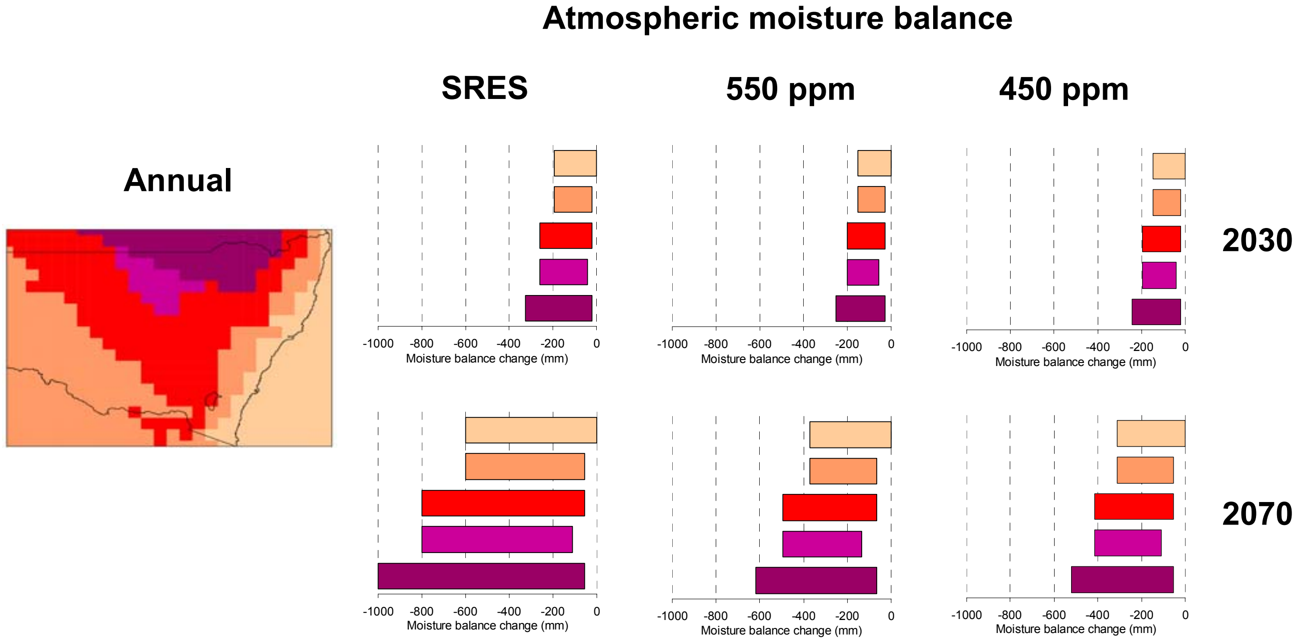


Figure 33. Pattern of change in annual-average atmospheric moisture balance (rainfall minus potential evaporation, mm) in 2030 and 2070, relative to 1990. The IPCC SRES scenarios do not include explicit actions to reduce greenhouse gas emissions. The reduction in the range is also shown for the IPCC's 550 ppm and 450 ppm CO_2 stabilisation scenarios.

5. Potential impacts and adaptation

The scope of this report does not extend to an assessment of potential impacts in New South Wales. However, there are some general comments that can be made about global and Australian impacts.

Many of the potential impacts of climate change cannot be expressed in monetary amounts. Even when attempts have been made to express costs in economic terms, for example by attaching a monetary value to human life, they have been subjectively value-laden and politically controversial. Few economic assessments have included the effects of changes in extreme weather events, loss of biodiversity, pests, disease or intergenerational equity issues.

Instead of attempting to express all costs in monetary terms, the IPCC (2001d) summarised the effects in terms of estimated ranges of unmitigated warmings up to the year 2100, and qualitative estimates of impacts in terms of five major categories or "reasons for concern". These categories were based on an assessment of hundreds of climate change impact studies from around the world.

1. *Risks to unique and threatened systems*: Natural systems are vulnerable to climate change, and more systems will be damaged irreversibly as global warming increases.
2. *Risks from extreme climate events*: Changes in extreme events are likely to be a major cause of impacts on ecosystems, crops, and society. In recent decades, exposure to these risks has increased partly due to demographic change and partly due to climate change.
3. *Distribution of impacts*: Adverse impacts are likely to be greater and occur earlier in tropical developing countries than in mid- and high-latitude developed countries. As warming increases with time even the more developed countries will experience adverse effects, but the poorer countries will remain more seriously affected.
4. *Aggregate impacts:* These are poorly quantified and multiple measures are needed because many impacts cannot be expressed in monetary terms. The consensus is that net global market impacts may be small (positive or negative, 1 or 2% of GDP) for small global warmings (less than 2 or 3°C), but will become increasingly negative for greater warmings.
5. *Risks from future large-scale abrupt changes*: There is an unquantified potential for large-scale and possibly irreversible changes in Earth systems resulting in impacts at regional and global scales. Examples include (i) slowing or stopping of the Gulf Stream and heat transport to western Europe, with possible regional effects elsewhere, including North America, and (ii) disintegration of the West Antarctic Ice Sheet and melting of Greenland ice leading to "rapid" global sea-level rises of several metres over coming centuries.

One of the biggest issues is water (Pittock, 2003). Annual-mean stream flow is expected to increase in high latitudes and south-east Asia, and decrease in central Asia, the Mediterranean, southern Africa and Australia (IPCC, 2001b). For other areas, there is no strong consistency in projections of stream flow. Water quality is likely to be degraded by higher water temperatures (e.g. toxic algal blooms), flood magnitudes and frequency are liable to increase, and low-flow events are likely to be more extreme. About 1.7 billion people live in countries that are water-stressed (using more than 20% of their renewable water supply), and this number is expected to increase to 5 billion by 2025. Demand for water is generally increasing as a result of population growth and economic development, but is falling in some countries. Climate change challenges current water resource management practices by adding uncertainty. Integrated catchment management will enhance the potential for adaptation. Adaptive capacity is unevenly distributed over the globe, so introducing integrated catchment management may be challenging in some countries.

Non-climatic changes may have a greater impact on water resources than global warming. The issue of global warming compared with other pressures on water supply is put in perspective by the UN World Water Development Report (UN 2003):

> *By the middle of this century, at worst 7 billion people in 60 countries will be faced with water scarcity, at best 2 billion in 48 countries, depending on factors like population growth and policy-making. Climate change will account for an estimated 20% of this increase in global water scarcity … Water quality will worsen with rising pollution levels and water temperatures.*

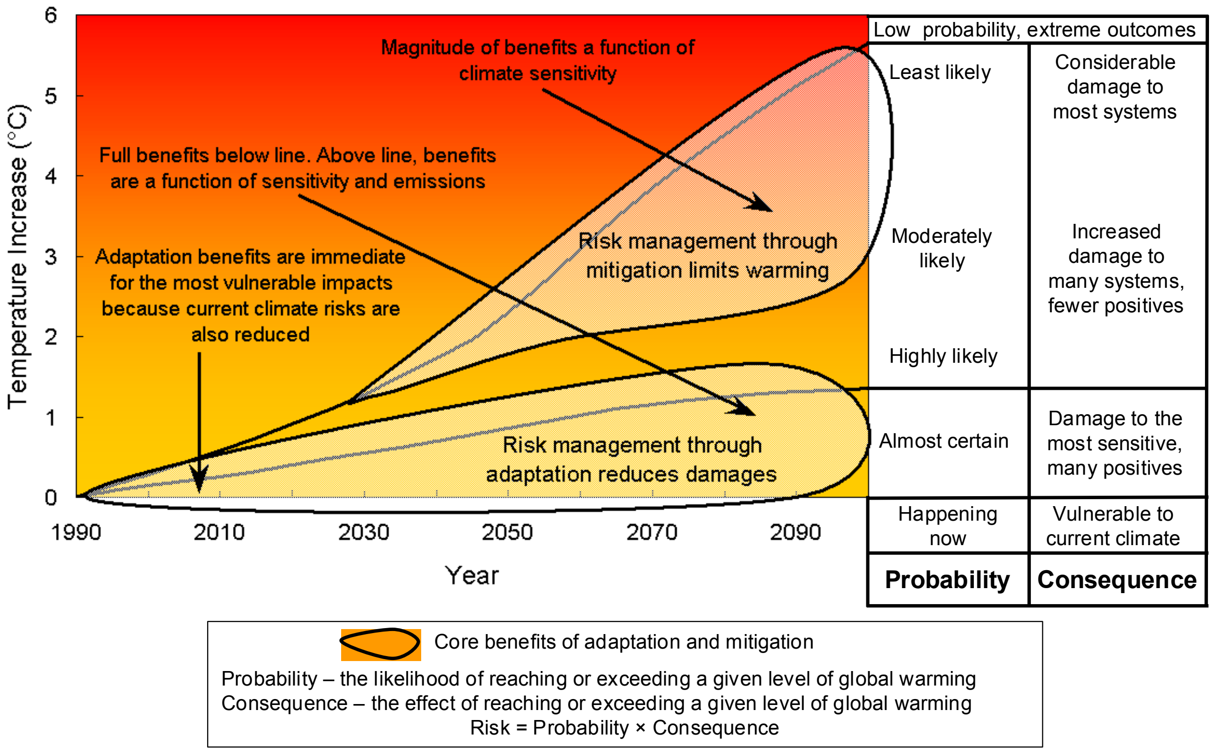
The best source of information on climate change impacts for Australia is "Climate change: an Australian guide to the science and impacts" by Pittock (2003), released by the Australian Greenhouse Office in December 2003. The guide contains substantial material on potential impacts NSW. Extracting and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

There are two basic ways of responding to the potential impacts of climate change:

1. Slow the rate of climate change and sea-level rise by reducing net greenhouse gas emissions
2. Plan adaptation strategies to reduce the risks and capitalise on any benefits.

Significant attention and effort has focussed on reducing net greenhouse gas emissions. As outlined in Chapter 3, large reductions in net emissions will be needed over the 21st century to eventually stabilise greenhouse gas concentrations and slow global warming in the 22nd century, so the return on the investment is not immediate. The complementary strategy of adaptation to climate change has a faster return on investment because it helps to deal with the impacts of current climate variability as well as ongoing climate change (Figure 34). Most Australian impact assessments have been presented in qualitative terms, or in quantitative terms that have a wide range of uncertainty, with little or no socio-economic perspectives.

Realistic climate change impact assessments should include the benefits of various adaptation options, which provide a means of increasing gains and reducing losses. Adaptation options might include improving water-use efficiency and effective trading mechanisms for water; more appropriate land-use policies; provision of climate information and seasonal forecasts to land managers to help them cope with climate variability and change; improved crop cultivars; revised engineering standards and zoning for infrastructure development; and improved bio-security and health services. Such measures often will have other benefits, but they will also have costs and limitations. Systematic exploration of adaptation options, and the need for appropriate foresight where this involves investment, would require more attention to the understanding, interests and motivation of many stakeholders.



Probability	Consequence
Low probability, extreme outcomes	
Least likely	Considerable damage to most systems
Moderately likely	Increased damage to many systems, fewer positives
Highly likely	
Almost certain	Damage to the most sensitive, many positives
Happening now	Vulnerable to current climate

Probability – the likelihood of reaching or exceeding a given level of global warming
Consequence – the effect of reaching or exceeding a given level of global warming
Risk = Probability × Consequence

Figure 34: Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on six greenhouse gas emission 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 based on the conclusions of IPCC (2001 b). Risk is a function of probability and consequence. From Jones (2003).

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Appendix A: Evaporation

Evaporation can be divided into potential and actual evaporation. More strictly, the term evapotranspiration should be used, which refers to the combination of evaporation from non-vegetated surfaces and transpiration from plants. Potential evaporation is the potential of the local air to evaporate available water from open water or soil, and transpire water from plants. Actual evaporation is the resulting water evaporated, which depends on the amount of energy absorbed by a plant, water or soil surface, the water available to be evaporated and the capacity of the airmass to remove that water. There are three different types of potential evaporation commonly in use.

1. *Pan evaporation* is routinely measured by meteorological agencies as the evaporation from a 1.2 m diameter pan, whose depth of water is about 0.5 m. Pan evaporation is used to represent potential evaporation but its measurement is highly error prone. When assessing surface moisture balance, hydrologists often prefer to calculate potential evaporation from models using climatic variables such as temperature, humidity, solar radiation or sunshine hours, and sometimes wind speed.
2. *Point potential evaporation* is most similar to pan evaporation and measures evaporation at a point.
3. *Areal potential evaporation* takes into account the ability of evaporation over large areas to modify the passing airmass, so it is less than point potential evaporation or pan evaporation. Areal potential evaporation takes place over areas larger than about 10 hectares (e.g. lakes, forests, large paddocks).

Potential and actual evaporation can be related through the principle of complementarity (Hobbins *et al.*, 2004). When water evaporates from the surface, it moistens and cools the air above. The principle of complementarity also shows that point potential and actual evaporation added together will equal twice the areal evaporation (Figure A1). The higher rainfall (or moisture at the surface) becomes, the higher actual evaporation will be and the lower potential evaporation will be. Therefore, pan evaporation measures the evaporation of water at a point and will always be much higher than lake evaporation or areal potential evaporation as measured over a larger area.

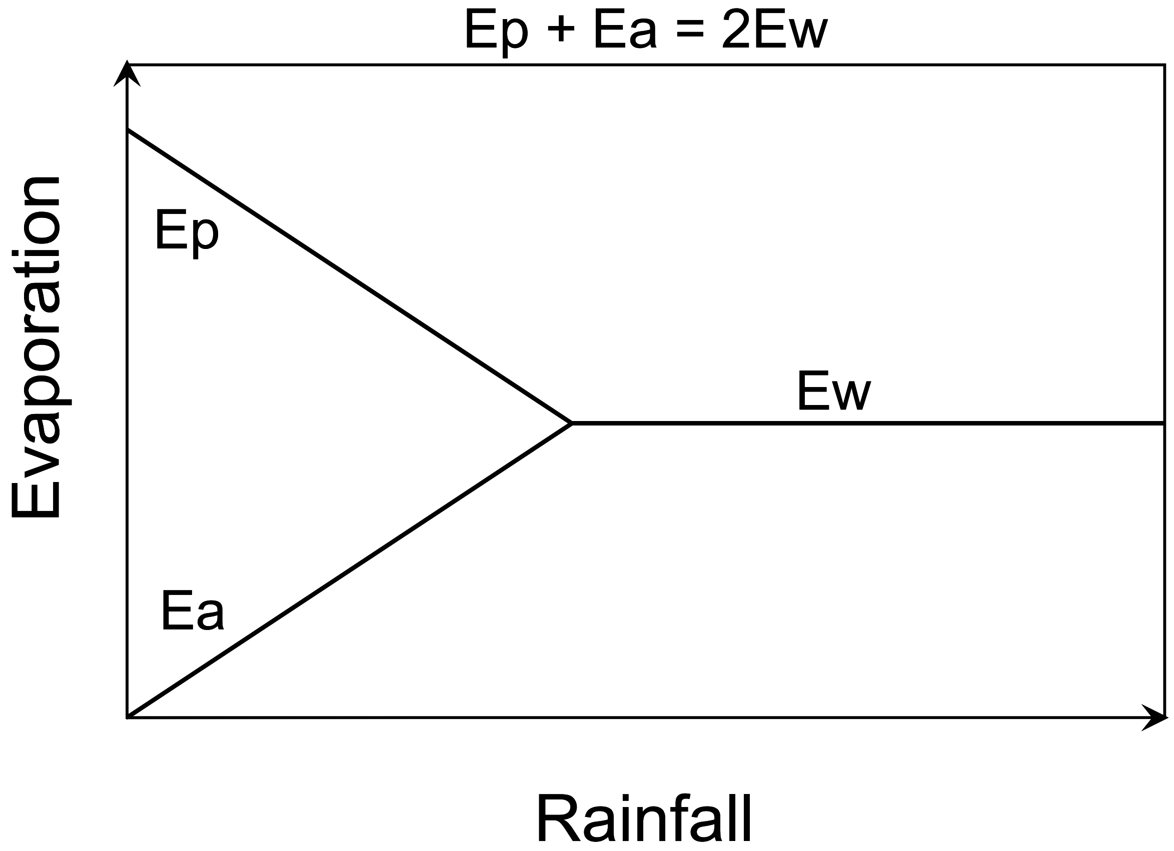

Figure A1. Schematic diagram of the principle of complementarity. Ep is point potential evaporation, Ea is actual evaporation and Ew is areal potential evaporation.

If actual evaporation increases because there is more water available (e.g. there is an upward trend in rainfall), potential evaporation is reduced. This produces the so-called "evaporation paradox", where an increase in rainfall and actual evaporation can lead to a decrease in potential evaporation due to the moistening and cooling of the atmosphere. Figure A2 shows this in regard to the principle of complementarity. If rainfall increases from R to R´, then actual evaporation increases from Ea to Ea´ and point potential evaporation decreases from Ep to Ep´.

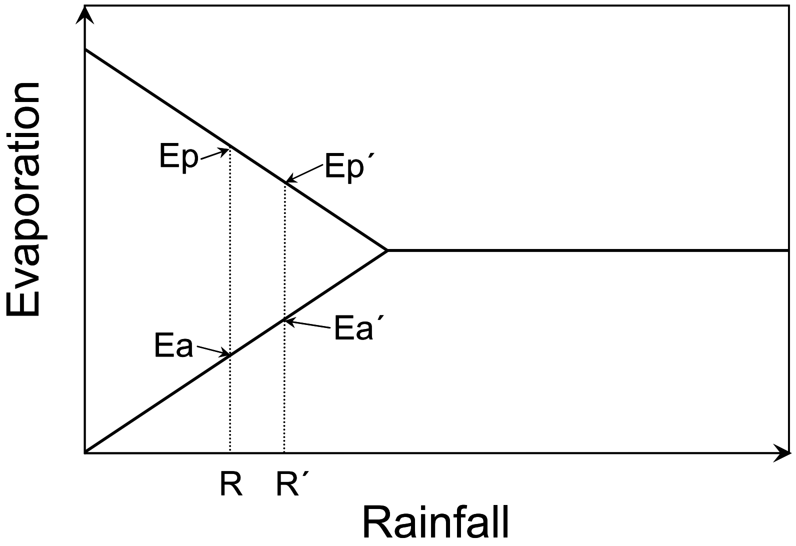

Figure A2. Schematic diagram showing the "evaporation paradox" where an increase in rainfall, and therefore actual evaporation, can lead to a decrease in point potential evaporation.

Roderick and Farquhar (2002) examined records of observed pan evaporation over recent decades. Some areas of the northern hemisphere showed a decrease in pan evaporation that may be due to a decline in sunlight from increase cloud or aerosols. Analysis of pan evaporation data at 61 Australian sites from 1975-2002 (Roderick and Farquhar, 2004) revealed significant decreases at 23 sites, no change at 33 sites and an increase at 5 sites. The Australian average trend was a decrease of about 4 mm per year. It is likely that the northern hemisphere results are due at least in part to the evaporation paradox, where increases in rainfall have led to the reduction of pan evaporation acting in a similar manner to point potential evaporation (e.g. Hobbins *et al.*, 2004). However, there has been no such increase in Australian average rainfall in recent years that could be used to offer a similar explanation. Roderick and Farquhar (2004) suggested three possible explanations - a decrease in net solar radiation, wind or vapour pressure deficit. They believe that the observed decrease in diurnal temperature range (difference between day and night temperature: Collins *et al.*, 2000) implies that vapour pressure deficit has remained constant, so suggest changes in radiation and/or wind. However, initial checks on the quality of the pan data suggests that no firm conclusions can be made without first implementing comprehensive quality controls.

The evapotranspiration volume of the Climatic Atlas of Australia (Bureau of Meteorology, 2001) provides maps for average total monthly point potential, areal potential and actual evaporation from 1961–1990, calculated using Morton's (1983) complementary relationship areal evaporation method. This uses average temperature, relative humidity and downward solar radiation as inputs. CSIRO produced estimates of point potential evaporation from a number of climate models using the same method as used by the CRC for Catchment Hydrology in the atlas (Bureau of Meteorology, 2001). These estimates validated reasonably well against observations.

One point of debate is whether the observed decrease in pan/potential evaporation will continue in future. Figure A3 shows that warmer and wetter conditions could lead to an increase in actual evaporation and an uncertain change in potential evaporation (possibly an increase from Ep to Ep'), assuming no change in wind speed. It also shows that warmer and drier conditions could increase potential evaporation and decrease actual evaporation, assuming no change in wind speed. In enhanced greenhouse simulations, point potential and areal potential evaporation increased in almost all months and regions in the models for which we had available data, increasing on a seasonal basis over Australia in all models.

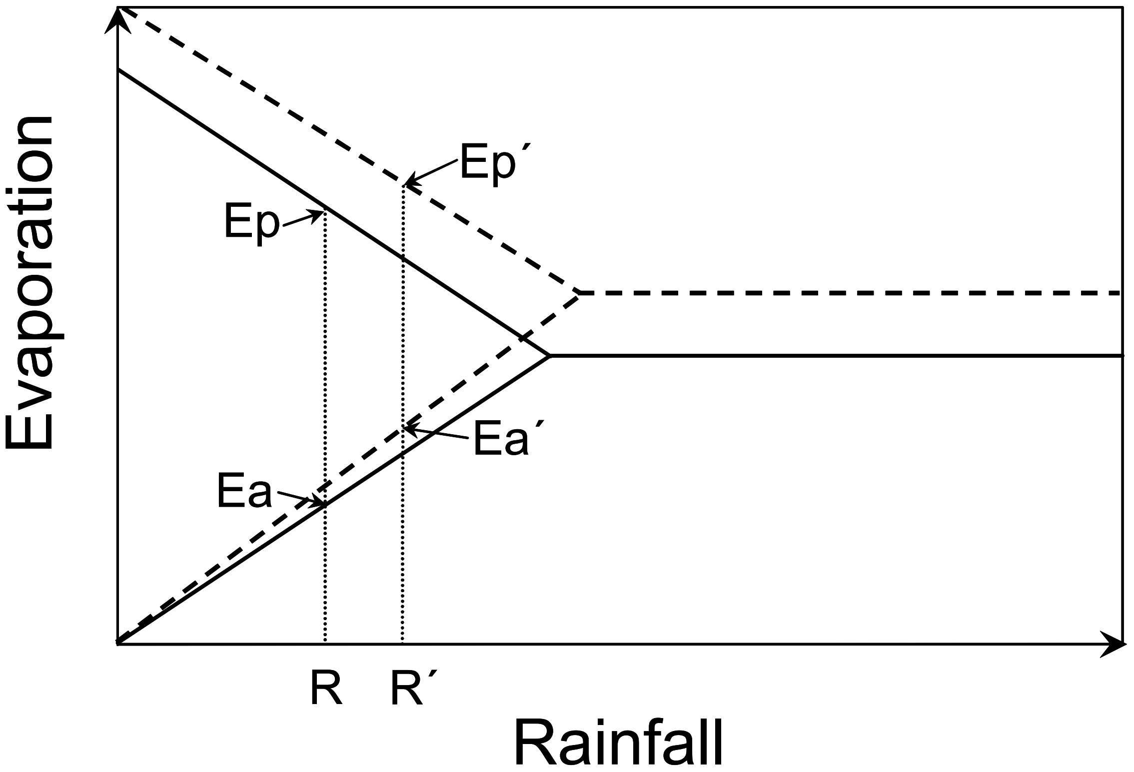

Figure A3. Schematic diagram showing how the relationship between rainfall, potential evaporation and actual evaporation may change under warmer conditions (dashed line), assuming no change in wind speed. If rainfall increases from R to R´, then actual evaporation may increase from Ea to Ea´ and point potential evaporation may increase from Ep to Ep´.