Climate Change in the Northern Territory

Consultancy report for the Northern Territory
Department of Infrastructure, Planning and Environment

by

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EXECUTIVE SUMMARY

This report presents results of a project undertaken by CSIRO for the Northern Territory Department of Infrastructure, Planning and Environment to assess observed and projected climate change over the Territory, as well as potential impacts and knowledge gaps. This assessment draws upon the latest findings of the Intergovernmental Panel on Climate Change (IPCC) published in 2001, as well as more recent information about regionally-specific changes in temperature, rainfall, potential evaporation, tropical cyclones and storm surges.

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 9-88 cm;
- Projected changes in climate extremes could have major consequences;
- Delaying and reducing damages would require slowing global warming, which in turn would require reductions in greenhouse-gas emissions;
- Since global warming cannot be avoided completely, adaptation will be necessary to complement efforts to reduce net greenhouse gas emissions.

The last two points deserve further emphasis. Some amount of global warming is inevitable in future. Therefore, strategies enabling adaptation to changes in climate will play an important part in reducing the damages and increasing the opportunities associated with impacts. Damages can also be reduced by slowing global warming and sea-level rise. This can be achieved by stabilising greenhouse gas concentrations. For example, to limit global warming to between 1.2 and 2.3°C by the year 2100, carbon dioxide concentrations would need to be stabilised at 450 parts per million (the current level being 373 ppm). Doing so would require a 70% reduction in global carbon dioxide emissions over the next 100 years. The reduction in emissions does not translate to an immediate reduction in concentrations because carbon dioxide has an atmospheric lifetime of 50-200 years.

Observed climate trends in the Northern Territory

Over the period spanning 1910 to 2000, Australia's average temperature increased by 0.76ºC, with the minimum temperature increasing by 0.96ºC and maximum temperature by 0.56ºC. Most of this increase has occurred since 1950, so the average warming has been about 0.14°C per decade. The frequency of extremely warm days and nights has increased while that of extremely cool days and nights has decreased. Since 1950, the Territory's average annual maximum temperature has increased by about 0.12ºC per decade, and the minimum has increased 0.17ºC per decade, with greater warming in May-Oct than Nov-Apr.

The Northern Territory has become wetter. From 1900-2002, the Territory-average rainfall rose 14.2 mm per decade during Nov-Apr and 2.5 mm per decade during May-Oct. However, since 1950, Territory-average rainfall has risen 35.7 mm per decade during Nov-Apr and fallen 0.4 mm per decade in May-Oct. This was mainly due to extremely wet conditions in the mid-1970s and 1999-2000. Since 1910, the intensity of heavy daily rainfall events has risen 10%, (mainly due to increases after 1970 during March to August).

Climate model representation of Northern Territory climate

The complexity of processes in the climate system means we cannot simply extrapolate past trends to forecast future conditions. Climate 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, sea ice, land surface, aerosols, carbon cycle, vegetation and atmospheric chemistry. Before the models can be used for climate change projections, an assessment of their ability to reproduce the current climate is needed. A comparison of observed and simulated patterns of temperature, rainfall and mean sea level pressure over the Territory indicated that eight of the 12 models available had acceptable performance. These models were driven by unabated greenhouse gas emissions scenarios for the 21st century. Model output provides information about projected climate change. Northern Territory projections have been made for the years 2030 (mid-term) and 2070 (long-term).

Changes in average temperature and rainfall

Projections of climate change for the Territory are presented as a range rather than a single value. The range includes key uncertainties such as the IPCC range of future greenhouse gas emission scenarios, the IPCC range of global warming, and model-to-model differences in the regional patterns of climate change. Temperature and rainfall projections for 2030 and 2070 are shown in Figure S1.

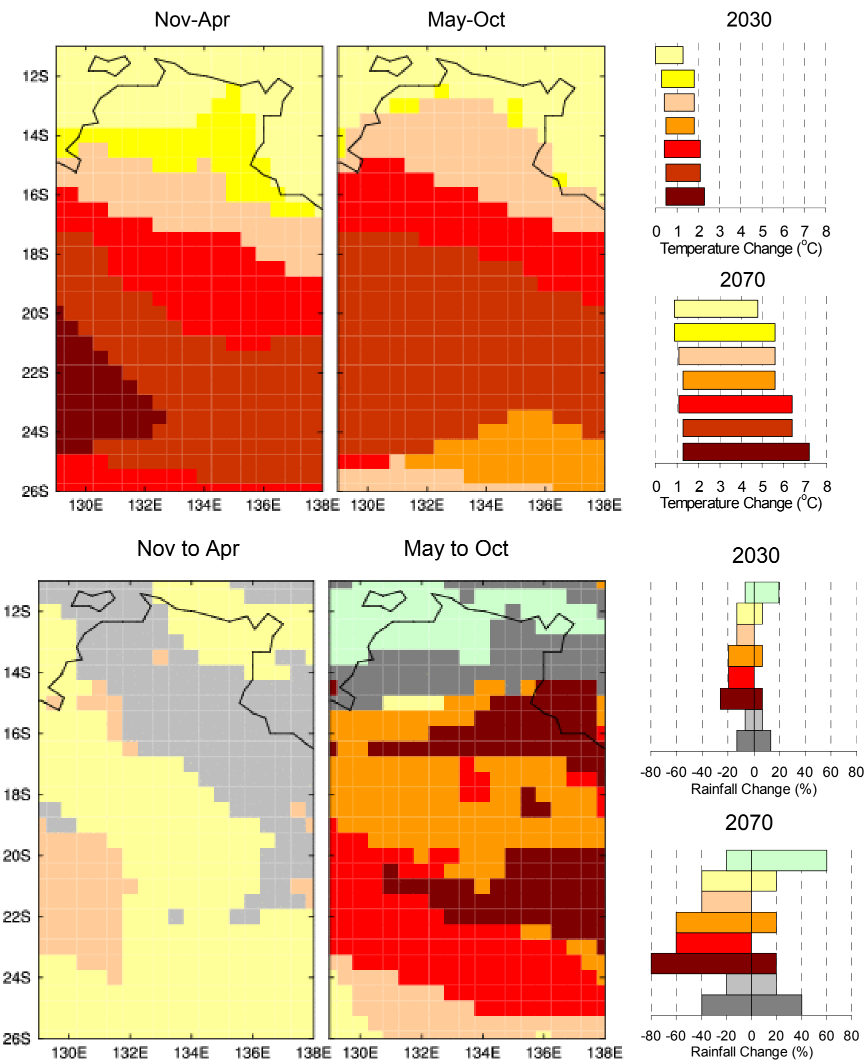


Figure S1: Ranges of change in average temperature (°C) and rainfall (%) for around 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps.

The Northern Territory is expected to warm 0.2 to 2.2°C by 2030, and 0.8 to 7.2°C by 2070, relative to 1990. Least warming is expected over the Top End and most warming in the south-west, especially in November to April. Wet-season rainfall (Nov-Apr) is likely to decrease over most of the Territory (-16 to +8% by 2030, and -40% to +20% by 2070), with little change in a 400-km-wide strip running from Darwin to Camooweal (±8% by 2030 and ±20% by 2070). Dry-season rainfall (May-Oct) is also likely to decrease (-20% to +8% by 2030, -60% to +20% by 2070), except near Darwin which is more likely to become wetter (-8% to +20% by 2030, -20% to +60% by 2070). Detailed analysis of simulated monthly-average rainfall near Darwin indicates that little change in the timing and magnitude of monsoon rainfall is likely in future. A similar analysis for Alice Springs shows drier conditions in future, especially from July to October, and a small decline in November and December suggesting a slight delay to the start of its wet-season.

Potential evaporation is the maximum evaporation possible from a particular surface under known environmental conditions. Climate change will increase potential evaporation. The difference between rainfall and potential evaporation is called the atmospheric moisture balance, i.e. the net amount of moisture available from the atmosphere. The Territory currently has a moisture deficit of 800-1600 mm in May-Oct because there is more potential evaporation than rainfall. In Nov-Apr, the deficit ranges from 1600 mm in the south to less than 400 mm over most of the Top End, but there is a moisture surplus of up to 400 mm from Darwin to Jabiru. Available atmospheric moisture is likely to decrease (Figure S2). In Nov-Apr, the moisture balance south of Daly Waters is expected to decline 30-130 mm by 2030 and 90-400 mm by 2070, with smaller decreases in the north (mostly 10-80 mm by 2030 and 50-240 mm by 2070). In May-Oct, moisture balance is expected to decline 20-100 mm by 2030 and 70-320 mm by 2070, with smaller decreases in the far south and Top End (10-80 mm by 2030 and 50-240 mm by 2070). The effect on river flow and soil moisture would need to be assessed using a detailed hydrological model.

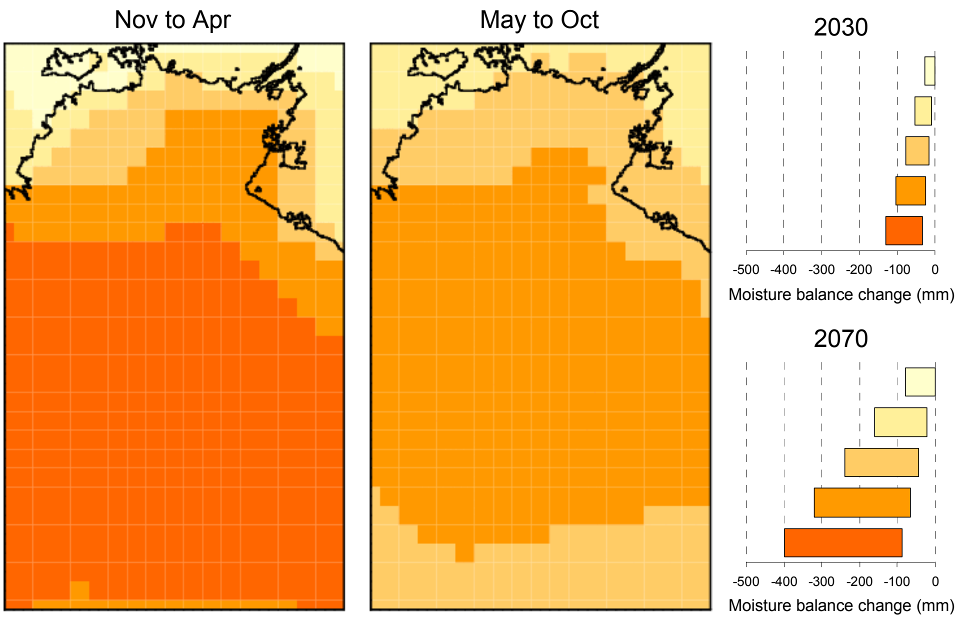


Figure S2: Patterns of change in moisture balance (mm) for November to April and May to October in 2030 and 2070, relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps.

Changes in extreme temperature

Changes in average temperature will affect changes in extremes. The average warming of 0.76°C in Australia since 1950 has already been associated with an increase in hot days and hot nights and a decrease in cold days and cold nights. The continued growth in the intensity and frequency of hot days is likely to increase fire risk, energy demand for air-conditioning, and heat stress to humans, animals and crops. Transport infrastructure may be affected by more frequent buckling of railway lines and melting of road tar.

The current number of days over 35°C and 40°C was computed at 11 sites using data from the Bureau of Meteorology: Darwin, Goulburn Island, Elcho Island, Oenpelli, Larrimah, Brunette Downs, Jervois, Tennant Creek, Rabbit Flat, Curtin Springs and Alice Springs. For example, Darwin currently averages almost 11 days over 35°C and no days over 40°C, Alice Springs currently averages 90 days over 35°C and 17 days over 40°C, and Rabbit Flat currently averages 155 days over 35°C and 51 days over 40°C.

By 2030, the average number of days over 35°C at coastal sites is expected to rise by 1-51 days. Inland, the likely increase is generally 5-30 days in the south, 5-40 days in the north and 5-70 days in the centre. By 2030, the absence of days over 40°C is likely to remain at coastal sites, but the average number of days over 40°C is expected to rise by 3-29 days in the south, up to 10 days at Oenpelli, 3-35 days at Larrimah and 5-45 days in the centre.

By 2070, the range of uncertainty in average warming is much larger, leading to an even greater range of uncertainty in extreme temperature impacts. The expected increase in days over 35°C is 13-300 days at coastal sites, 16-104 days in the south, 30-200 days in the north, and 26-130 days in the centre. The likely increase in days over 40°C is up to 9 days at coastal sites, 16-95 days in the south, 5-109 days at Oenpelli, 12-157 days at Larrimah and 19-152 days in the centre.

Hot spells of three to five days over 35°C were also calculated. At coastal sites, the present average is only one hot spell per year. Inland, the present average is 23-30 in the south, 31-42 in the north and 36-46 in the centre. By 2030, the number of hot spells is expected to grow by 1-10 on the coast and in the south, 2-22 in the north, and 2-17 in the centre. By 2070, the expected increase is 2-97 on the coast, 5-33 in the south, 9-68 in the north and 8-44 in the centre.

Extremely hot spells of three to five consecutive days over 40°C sometimes occur inland. The present average number of extremely hot spells is 3-8 in the south, 0-2 in the north and 4-12 in the centre. By 2030, up to 2 more extremely hot spells could occur on average at Oenpelli, up to 9 at Larrimah, 1-8 in the south and 1-14 in the centre. By 2070, the increase is expected to reach up to 29 at Oenpelli, 4-27 in the south and 3-47 in the centre and at Larrimah. The absence of extremely hot spells near the coast is expected to remain until at least 2070.

Tropical cyclones and storm surges

In the Northern Territory region, on average, there are 2.0 cyclones per year during strong La Niñas versus 1.8 during strong El Niño years. This is not a statistically significant difference because the sample size (number of cyclones) is small in this subset of the Australian region. There has been a decrease in cyclone incidence in the Australian and Northern Territory regions since 1967. More cyclones crossed land regions in the Territory during the period 1967-1981 (average of 2.5 per year) than during 1982-1996 (average of 1.7 per year). This difference is probably related to the larger number of El Niños that occurred in the latter period. Despite the decrease in total cyclone numbers, there has been a significant increase in average cyclone intensities (i.e. maximum wind speeds) in the Australian region since 1967.

The intensity of tropical cyclones is likely to continue to increase due to greenhouse warming, but changes in cyclone frequency are uncertain. The combination of sea level rise, stronger wind speeds and more intense rainfall may lead to more significant coastal impacts due to tropical cyclones.

Tropical cyclones, in addition to producing devastating winds and rainfall, also generate adverse oceanic conditions including storm surges and extreme waves. Storm surges can produce severe coastal flooding and bring sea waves further inland, which enables the destructive effects of breaking waves to erode the coastline and damage or destroy infrastructure. When riverine flooding occurs, storm surges can worsen the upstream flooding by slowing the drainage of rivers and streams. The coastline and islands of the Northern Territory are prone to storm surges due to the relatively shallow coastal waters across northern Australia. For example a storm surge of 6.6 m above normal tide level, occurred at Groot Eylandt in 1923. The storm surge caused by Cyclone Tracy was 1.6 m, although (fortunately) it did not coincide with high tide. A high tide with such a strong cyclone would have been far more disastrous.

There have been no studies to date that address the potential effects of cyclone intensity increases on storm surges in the Northern Territory. However, a study undertaken for Cairns found that the 1-in-100 year storm surge event under current climate conditions became a 1-in-55 year event when projected changes in cyclone intensity were incorporated. Storm surges will also be exacerbated by sea-level rise, which is estimated to be 5-15 cm by 2030 and 10-50 cm by 2070. In Cairns, the effect of stronger cyclones and a sea level rise of 25 cm by the year 2050 reduced the simulated return period to 1-in-40 years. This result implies an increase in storm surge height for a given return period in future.

Potential impacts and adaptation

The IPCC derived five "reasons for concern" based on an assessment of hundreds of climate change impact studies from around the world. They are:

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 global sea-level rises of several metres over coming centuries.

Some of the overseas impacts may indirectly affect Australia, for example, through changes in commodity prices and international trade. This has not been quantified for Australia. The best source of information on climate change impacts for Australia is the guide released by the Australian Greenhouse Office in December 2003. While the guide contains substantial material on impacts for most of Australia, there is limited information for the Northern Territory, reflecting a paucity of research on impacts for the region. Sector-based issues were summarized (Table S1) with a view to identifying priority areas for future research:

Risk assessment

Adaptation to climate change will involve significant changes in behaviour. Therefore, the assessment of climate change risks in the future needs to incorporate our understanding of current climate risks. This is the underlying principal of a "bottom up" approach to impact and adaptation studies. The biophysical and socio-economic aspects of risk under current climate are analysed and incorporated into an assessment of how climate and other drivers of change may alter future risks. This approach requires significant stakeholder input and benefits from the development of close collaborative links between stakeholders and climate scientists. There are still instances where traditional "top-down" impact studies are required. These include areas where basic deficiencies exist in our understanding of the impacts of present climate conditions on systems or activities. Long-term observations of natural systems are needed to monitor change and to record system behaviour across a range of climate variability.

Integration between natural resource sectors is also very important in the long term. For agriculture, there are cross-cutting issues related to loss of water supply and salinity. Biodiversity is vulnerable to land-use change and the impacts of altered nutrients, pests, plants and animals. Some coastal areas are vulnerable to sea-level rise and land subsidence. The largest challenges are for collaboration across different disciplines, and integrating the various biophysical, economic and social sciences.

Table S1: Sector-based issues affected by climate change

Sector	Key Issues
Water resources	Although the adaptive capacity of water management is high owing to large interannual climate variability, projected reductions in water supply and changes in water quality due to climate change need to be assessed.
Agriculture, livestock and fisheries	This sector is generally well adapted to climate variability but further work is needed on how climate change and higher levels of carbon dioxide may affect production systems so that adaptation strategies can be planned. Higher temperatures are likely to cause heat stress in many plants, and some horticultural crops (e.g. mangos and grapes) may experience inadequate winter chilling, leading to lighter yields. Enhanced plant growth and water-use efficiency resulting from higher carbon dioxide may provide initial benefits that offset any negative impacts from climate change. Distributions of pests and diseases may change. Impacts on fisheries are poorly understood.
Biodiversity	Mangroves and wetlands are highly vulnerable to sea-level rise. Monitoring key ecosystems and understanding of the relationships between biota and climate change at the species and community level are generally poor and need improvement. Many plant and animal species, and ecosystems (e.g. monsoon rainforests, sandstone heathlands), are fire-sensitive, so changes in fire regime are likely to have substantial impacts on such species. Changes in extreme temperatures, dry season length and severity will have major implications for some species.
Settlements and infrastructure	The increased risk of exposure to extreme weather events and sea-level rise has strong implications for many coastal settlements in the Territory, the insurance industry, primary industries, transport, tourism, health and the energy sector.
Health	There is likely to be more heat stress, more flood-related injuries, more diarrhoeal admissions to hospitals, and greater risk for Dengue fever, but little change in malaria transmission provided existing bio-security measures are maintained. The adverse health impacts of climate change will be greater in lower income populations, especially the elderly, sick and those without access to good housing including air conditioning and adequate fresh water supply.

Recommendations for further research

Priority research areas include:

- Improved monitoring of key environmental indicators and better access to information;
- Improved simulations of important climate processes in the Australian tropics including the El Niño Southern Oscillation;
- Improved projections of changes in average temperature, rainfall and moisture balance by using a broader set of the latest climate models from around the world;
- Development of projections for more climate variables, and where possible, providing probabilities for threshold exceedance;
- Development of extreme event projections using very fine resolution models, especially for extreme rainfall, floods, tropical cyclones, extreme winds, storm surges and fire.

With this information, studies could be undertaken to assess risks and adaptation options for vulnerable sectors such as water resources, agriculture, livestock, fisheries, insurance, tourism, energy, infrastructure planning, tropical wetlands, infectious diseases, pests and health. Cost-benefit analyses should be integrated across regions or sectors, including non-climate factors.

CSIRO's Climate Impacts and Adaptation Working Group has the capacity to address many of these issues, in collaboration with Territory agencies and other partners. Development of detailed research proposals is not within the scope of this study. A stakeholder workshop is recommended in which such issues can be discussed.

Table of Contents

1. Introduction

Substantial increases in greenhouse gas concentrations and global temperatures have occurred in the 20th century. Further global warming is inevitable during the course of the 21st century, despite international efforts to reduce greenhouse gas emissions. It is thus appropriate to identify how the Northern Territory's 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 Northern Territory Government.

The research activities undertaken for this study include:

- An assessment of changes in temperature and rainfall in the Territory over the past 100 years;
- A test of how well climate models perform over the Territory, and selection of the most reliable models for climate change projections;
- Projections of mean temperature, rainfall, potential evaporation and moisture balance;
- Projections of extreme daily temperature and hot spells;
- A summary of current knowledge about past and future tropical cyclone and storm surge behaviour over the Territory;
- A summary of current knowledge about potential impacts;
- A summary of gaps in knowledge needing further research.

2. Global climate change

The following summary of global climate change draws upon 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. CSIRO accepts the findings of the IPCC because they are based upon a rigorous and balanced assessment of the science, including uncertainties and gaps in knowledge. Subsequent scientific papers have confirmed and strengthened many of the IPCC conclusions.

2.1 Evidence for climate change

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

Figure 1 shows atmospheric concentrations of a major greenhouse gas, carbon dioxide (CO_2), over the past thousand years based on ice-core data (bubbles of air trapped in polar ice) combined with direct measurements for recent decades. This illustrates the rapid increase in CO_2 concentrations, which is largely a consequence of burning fossil fuels and clearing land since the Industrial Revolution. The CO_2 concentration has risen from a background level of around 280 parts per million (ppm) to its current level of around 370 ppm and is now higher than at any time over the past 420,000 years (Figure 2). The rate of increase of CO_2 is also higher than at any time in at least the past 20,000 years. Concentrations of another greenhouse gas, methane, have stabilised since 1999. 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. The response to these mitigating actions has been rapid because methane, the main component in natural gas, remains in the atmosphere for only eight to twelve years before it breaks down. In contrast, carbon has an atmospheric "lifetime" of 50 to 200 years (IPCC, 1990).

Also shown in Figure 1 is a record of northern hemisphere temperatures based on proxy records (from ice-cores, tree-rings, lake sediments, coral-rings) combined with direct measurements for the past 140 years. The late 20th century warming in the northern hemisphere is unusual relative to temperature variations over the past 1000 years (Mann *et al.,* 1999) and indeed over the past 1800 years (Mann and Jones, 2003).

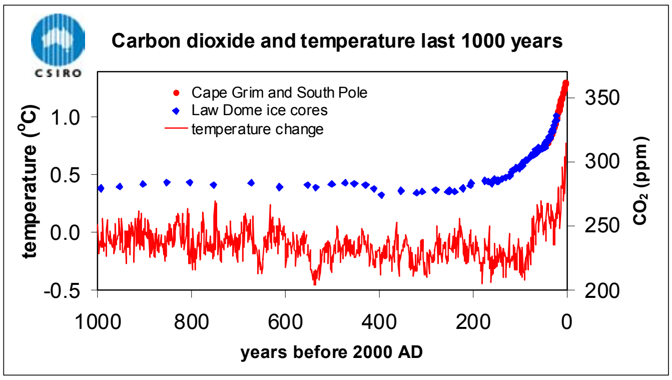


Figure 1: Global CO_2 concentrations (direct observations and ice core data) and Northern Hemisphere temperature anomaly (direct observations and proxy data - mainly tree-rings). Sources: Mann *et al.* (1999) and Etheridge *et al.* (1996).

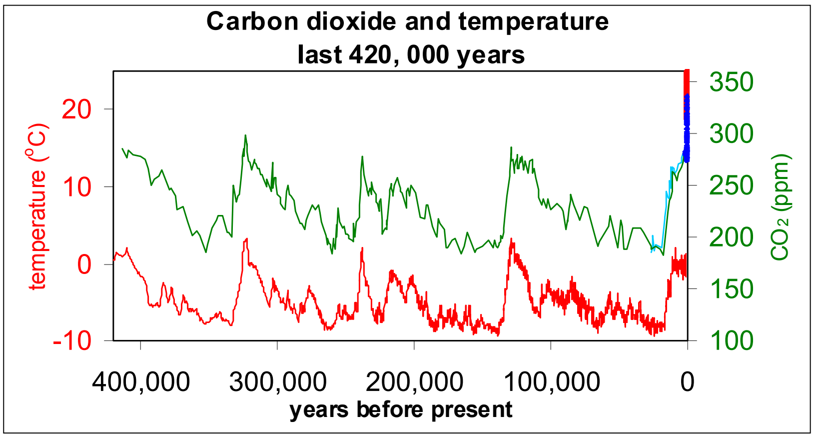


Figure 2: Changes in temperature (red) and carbon dioxide concentrations (green) over the past 420,000 years, derived from bubbles of air trapped in polar ice. Carbon dioxide (CO_2) symbols in blue and red are measurements made in recent decades. From Petit *et al.* (1999).

Evidence for global warming is multi-faceted. The global average surface temperature has risen by about 0.6°C since 1900 (Figure 3), 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 deep oceans, retreat of glaciers and sea-ice, a rise in sea-level of 10-20 cm and increased heavy rainfall in many regions. Some critics worry that this warming may simply reflect urbanisation - the so-called heat island effect. However, warming is also found in rural, small-island and sea-surface temperature records, none of which would have urban heat island effects. 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.

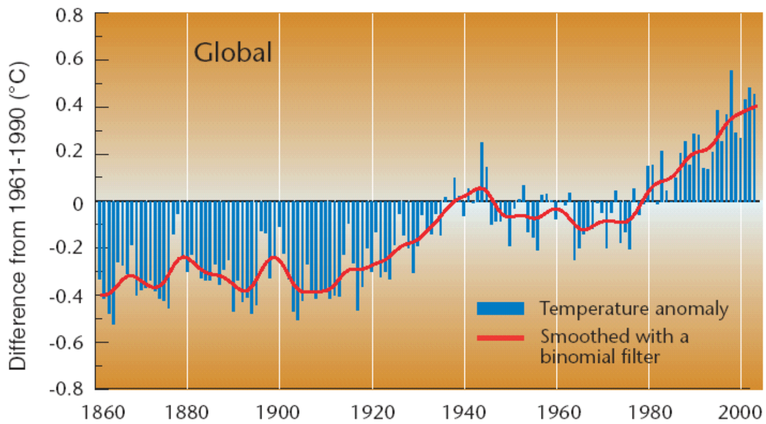


Figure 3: Global-average temperature anomalies from 1860 to 2003, relative to the average for 1961-1990. From WMO (2003).

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 radiation from the sun, dust from volcanic eruptions, increased greenhouse gases, increased levels of smog and smoke particles, 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 4.

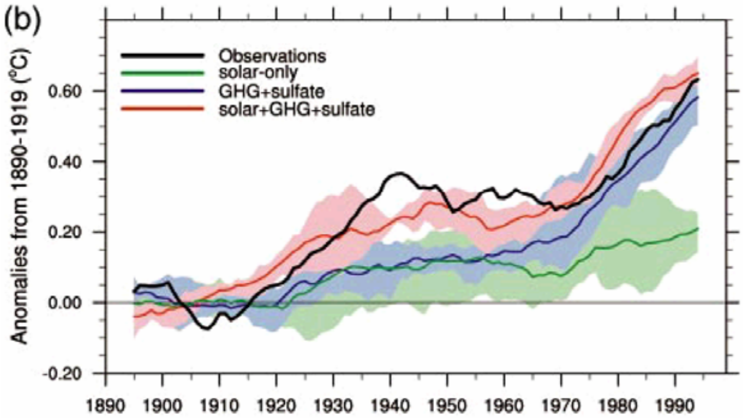


Figure 4: Global annual mean surface temperature anomalies (11-year running mean) relative to 1890-1919 for observations (black), solar-forcing only (green), greenhouse gas (GHG) plus sulfate aerosol forcing (blue), and all three forcings (red). The shading indicates the range of uncertainty from an ensemble of four climate model simulations. From Meehl *et al.* (2003).

Despite the wide range of indicators of global warming, critics often focus 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. Vinnikov and Grody (2003) and Mears *et al* (2003) 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°C per decade, a similar rate to the surface warming.

2.3 Future climate change

With regard to future climate change, key findings of the IPCC (2001a, b) are that:

- Confidence in the ability of models to project future climates has increased
- Atmospheric composition will continue to change throughout the 21st century
- Global average temperature and sea level are projected to rise
- There will be more hot days, fewer cold days, and more intense precipitation and tropical cyclones
- Natural systems are vulnerable to climate change and some will be irreversibly damaged
- Many human systems are sensitive to climate change. The vulnerability of these systems is defined by their capacity to adapt.

The IPCC provided a range of projected global average warming and sea-level rise, based upon a set of future emission scenarios of greenhouse gases and sulphate aerosols, which were used in climate models run on super-computers. The Terms of Reference for the scenarios required that they allow for a broad range of plausible future technology-population-economy pathways without 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 (SRES, 2000). Of course, greenhouse gas emissions can be affected by non-climate change policies designed for a wide range of other purposes. This influence is broadly included in the scenarios. Therefore, these scenarios represent a "business as usual" vision of the future, providing a baseline against which the need for, and effectiveness of, emission reductions can be compared. (A separate set of emission reduction scenarios, designed to stabilise carbon dioxide concentrations, was also considered by the IPCC, and these are described later in this chapter).

Castles and Henderson (2003) claimed that the IPCC warming projections were based on greenhouse gas emissions that are too high because market exchange rates (MER) were used rather than purchasing power parity (PPP) in calculating future economic growth. The claims have been reviewed and refuted by international experts (Nakicenovic *et al.*, 2003; IPCC, 2003). In any case, long-term emission projections are based on many independent driving forces, not just economic growth. Manne and Richels (2003) compared emissions calculated using PPP and MER and found a minor effect on global warming (5.5% less warming by the year 2100 for the MER-based emissions). Therefore the IPCC range of emission scenarios remains valid.

Representative CO_2 emissions for six of the 40 emission scenarios are shown in Figure 5a and the associated atmospheric concentrations in Figure 5b. Changes in the concentrations of other greenhouse gases and sulfate aerosols were also estimated, but are not shown. Each scenario was considered by the IPCC to be equally plausible, but probabilities were not assigned. Note that even for scenarios such as B1 that show a reversal in the rate of emissions around 2040, CO_2 concentrations will still increase throughout this century from about 370 ppm in the year 2000 to 550 ppm by 2100. Scenarios such as A1FI lead to concentrations exceeding 950 ppm by 2100. These estimates were based on carbon cycle models which show that about 50% of the emitted CO_2 remains in the atmosphere, where it has a "lifetime" of 50 to 200 years (the remaining 50% is absorbed by the terrestrial biosphere and oceans) (IPCC, 1990).

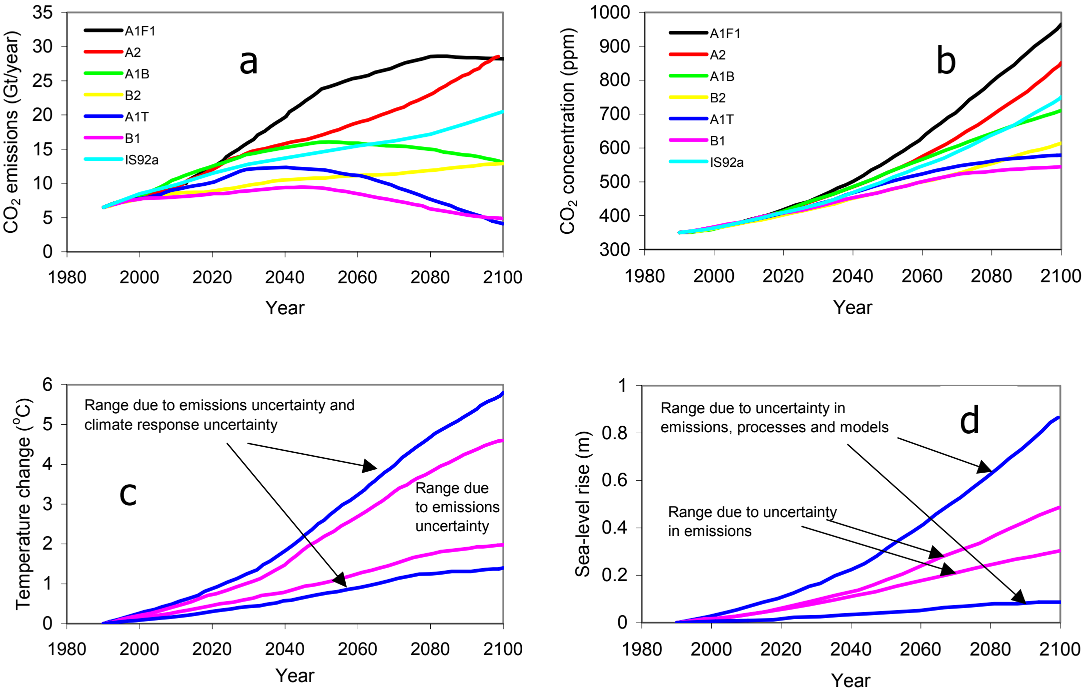


Figure 5: (a) Six emission scenarios for CO_2, plus the IS92a mid-case scenario used by the IPCC in 1996, (b) corresponding atmospheric concentrations, (c) global-average warming relative to 1990 and (d) global average sea-level rise relative to 1990. From IPCC (2001a).

These scenarios were fed into climate models which simulate the behaviour of the atmosphere, land, oceans and ice caps. Global average warming ranges from 0.4 to 1.3ºC by the year 2030 and 1.4 to 5.8ºC by the year 2100, relative to 1990, which is a warming rate of 0.1 to 0.5ºC per decade (Figure 5c). The observed warming rate since the 1970s has been 0.15ºC per decade. About half of the warming range stems from uncertainty about future emissions (uncertainty in human behaviour) and about half stems from variations in model sensitivity (scientific uncertainty). Associated with this warming is a rise in sea-level of 3 to 17 cm by 2030 and 9 to 88 cm by 2100, or 0.8 to 8.0 cm per decade (Figure 5d). The observed global-average sea-level rise over the 20th century has been 1 to 2 cm per decade. Australian stations, after correction for geological effects and data quality, indicated a sea level rise of 1.2 to 1.6 cm per decade (Lambeck, 2001).

The IPCC noted that various gaps in knowledge remain. There is a need for improved:

- observations of climate and biophysical indicators of climate impacts;
- understanding of how climate change may affect extreme events;
- understanding of unresolved processes and feedbacks, both physical and biogeochemical;
- projections of emissions of greenhouse gases and aerosols, their associated climatic effects;
- regional climate change projections;
- understanding of vulnerability of natural and human systems to climate change;
- Further exploration of regional and sector-specific potentials for technological and social innovation options to reduce net greenhouse gas emissions (defined as mitigation by the IPCC);
- Development of methodologies for estimating and comparing socio-economic costs and benefits of mitigation, adaptation and residual impacts.

2.4 Responding to climate change

The projections in Figure 5 do not include measures to reduce net greenhouse gas emissions. Given that the impacts of unabated global warming may be harmful in some regions, there is a need to consider ways in which the risks may be mitigated. 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."

Article 3 of the Convention refers to the precautionary principle, which states that "*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 scenarios were considered by the IPCC (2001a). Figure 6 shows the time paths of CO_2 emissions that would lead to stabilisation of the concentration of CO_2 in the atmosphere at 450, 550, 650, 750, and 1000 ppm sometime between the year 2090 and 2300. Lower CO_2 concentration levels 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 scenarios, which exclude greenhouse gas emission reductions. In all cases except the 1000 ppm scenario, stabilising CO_2 concentrations at a higher level than present (370 ppm) would require a reduction from the current level of 8 Gt (million tonnes) per year to around 3 Gt per year within the next 100 to 300 years, i.e. at least a 60% reduction in global emissions. The path to 450 ppm by the year 2090 would require emission reductions of about 40% by the year 2050 and about 70% by the year 2100. The path to 550 ppm by 2150 would require a 20% reduction in emissions by 2050 and a 35% reduction by 2100.

In the warming projections, 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 6c) but at a much weaker rate. For the 550 ppm stabilisation path, the warming by 2100 is reduced to 1.5 to 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 1.2 to 2.3ºC. 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% limit. 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 sign the Kyoto Protocol. Developing countries were not required to sign. Further commitments are needed so that developed countries reduce emissions substantially after 2012, and so that emissions from developing countries do not grow as much as expected. At least 11 approaches are being considered, one of which is extending the Kyoto Protocol (ECOFYS, 2003). Greenhouse gas abatement strategies are not included in the climate change projections given in subsequent chapters of this report. The projections will be based on the unabated greenhouse gas emission scenarios shown in Figure 5.

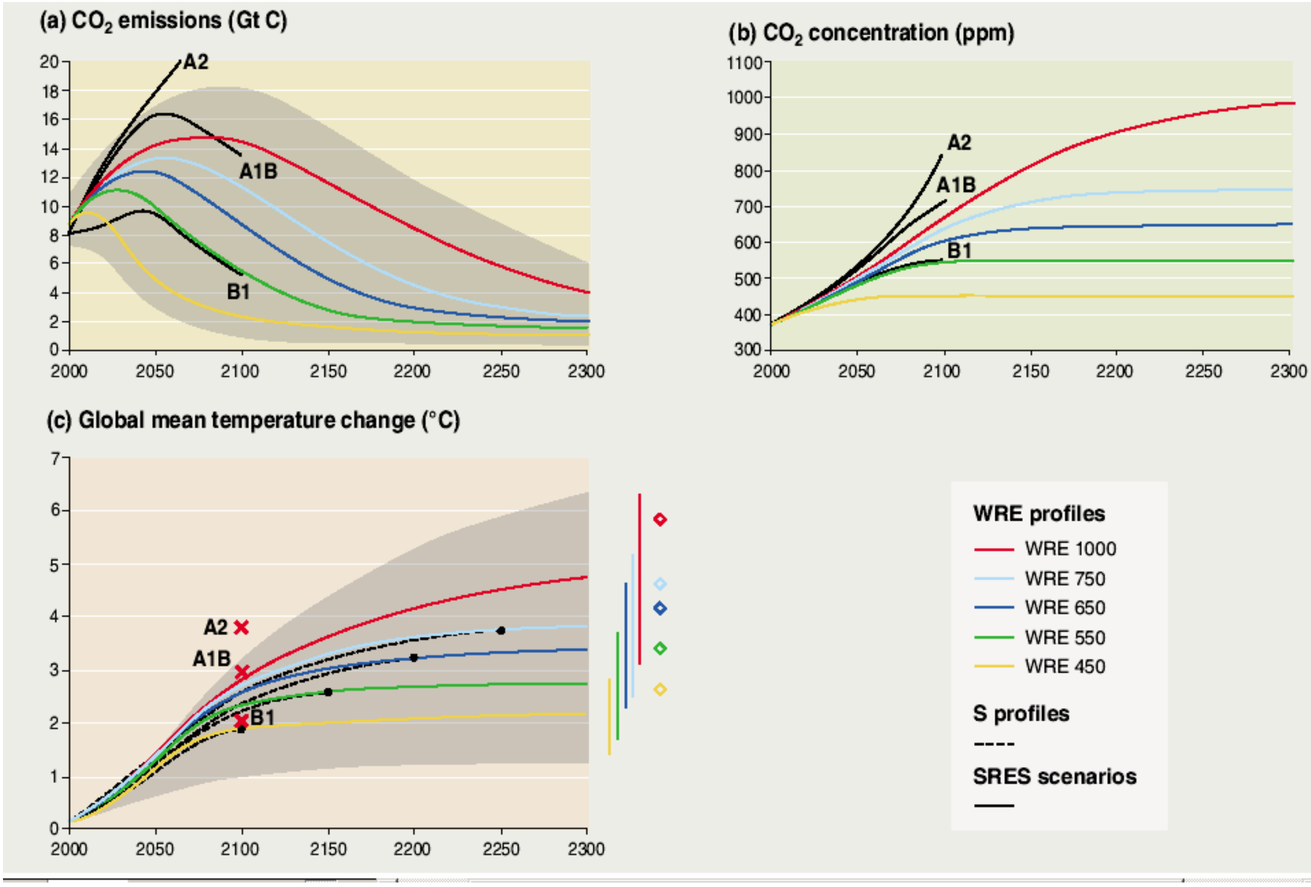


Figure 6: (a) Time paths of CO_2 emissions that would lead to (b) stabilization of the concentration of CO_2 in the atmosphere at 450, 550, 650, 750, and 1000 ppm sometime between the year 2100 and 2300. The shaded area shows the range of uncertainty in estimating CO_2 emissions corresponding to each concentration scenario. Also shown for comparison are CO_2 emissions for the A1B, A2, and B1 scenarios, which do not include greenhouse gas emission reductions. (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).

3. Observed regional trends

3.1 Average climate

The Northern Territory has a distinct wet season (Nov-Apr) and dry season (May-Oct). The wet season is strongly influenced by the summer monsoon, especially in the north where there are thunderstorms and occasional cyclones. The behaviour of the monsoon and the frequency of cyclones are affected by the El Niño Southern Oscillation (ENSO), which is an east-west see-saw in pressure across the tropical Pacific Ocean. The El Niño phase tends to suppress monsoon and cyclone activity over the Territory, while the La Niña phase tends to enhance this activity. The strongest correlations between rainfall and the Southern Oscillation Index over the Northern Territory occur in Sep-Nov, with moderate correlations in Dec-Feb and poor correlations from Mar-Aug (Sturman and Tapper, 1996). From May-Oct, most of the Territory is very dry, except in the south which receives 10-20 mm of rain per month from cold fronts and north-west cloud bands (Figure 7). The wet season is warmer and more humid than the dry season. Maximum temperatures (Figure 8) are higher in the south than the north during the most of the wet season, but the converse applies in the dry season. Minimum temperatures are higher in the north than the south throughout the year (Figure 9).

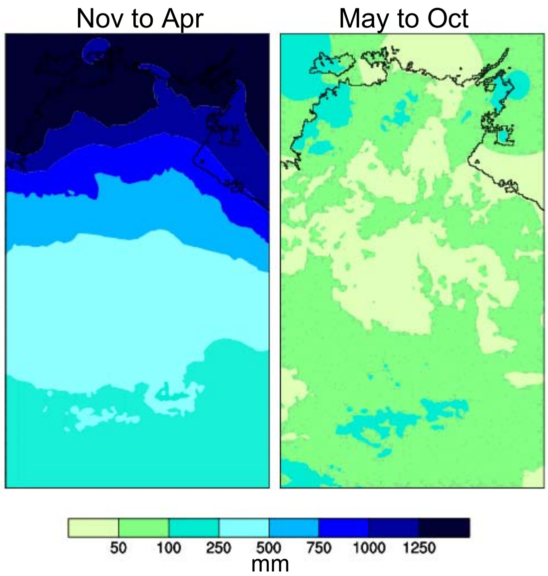


Figure 7: Rainfall (mm) averaged over Nov-Apr and May-Oct from 1961-1990, based on grided data from the Bureau of Meteorology.

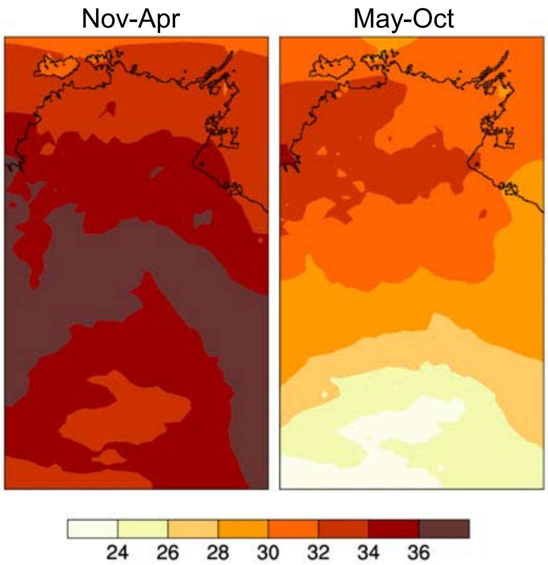


Figure 8: Maximum temperature (°C) averaged over Nov-Apr and May-Oct from 1961-1990, based on grided data from the Bureau of Meteorology.

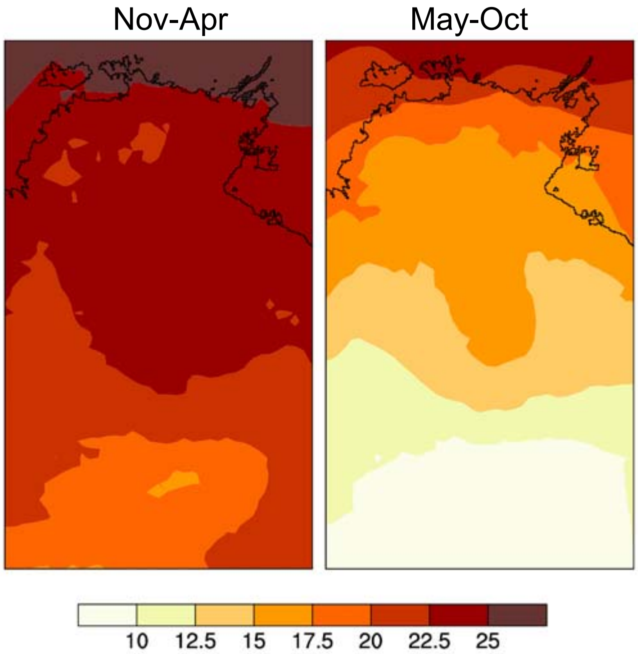


Figure 9: Minimum temperature (^{o}C) averaged over Nov-Apr and May-Oct from 1961-1990, based on grided data from the Bureau of Meteorology.

Evaporation is an important part of the water cycle. It depends not only on the availability of water but also on the availability of energy to change water to vapour, the existence of a vapour concentration gradient, and a turbulent atmosphere to carry the vapour away (Oke, 1987). Potential evaporation is the maximum evaporation possible from a particular surface under given environmental conditions. Over the Territory, potential evaporation from Nov-Apr ranges from 1200 mm in the north to more than 1800 mm in the south (Figure 10), with smaller rates in the south during May-Oct (less than 1200 mm). The difference between rainfall and potential evaporation is called the atmospheric moisture balance, i.e. the net amount of moisture available from the atmosphere. In May-Oct, the Territory has a moisture deficit of 800-1600 mm. In Nov-Apr, the deficit ranges from 1600 mm in the south to less than 400 mm over most of the Top End, but there is a moisture surplus of up to 400 mm from Darwin to Jabiru.

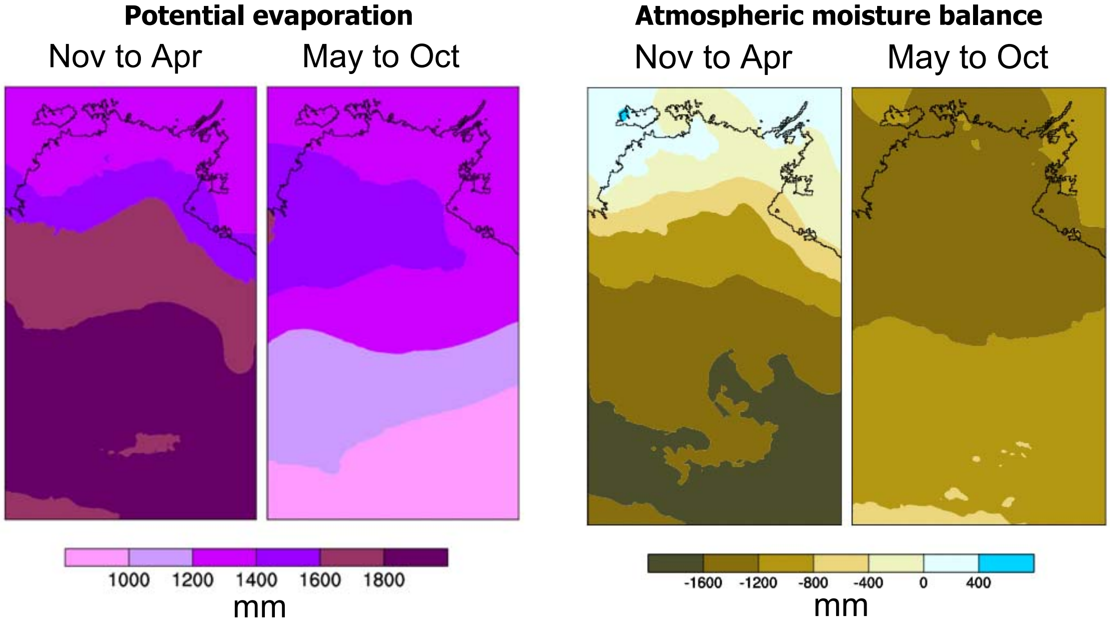


Figure 10: Potential evaporation (mm) and atmospheric moisture balance (rainfall minus potential evaporation, mm) averaged over Nov-Apr and May-Oct from 1961-1990, based on grided data from the Bureau of Meteorology.

3.2 Climate variability

Temperature

Analysis of temperature trends in the Australian region for 1910 to 2000 shows that the continental average temperature has increased by 0.76ºC (Collins *et al.*, 2000). Most of this warming occurred during the second half of the 20th century (Figure 11), at a slightly faster rate than the global average. The all-Australian annual mean temperature for 2003 was 0.62°C above the 1961-90 average, making it Australia's sixth warmest year on record since 1910 (BOM, 2004).

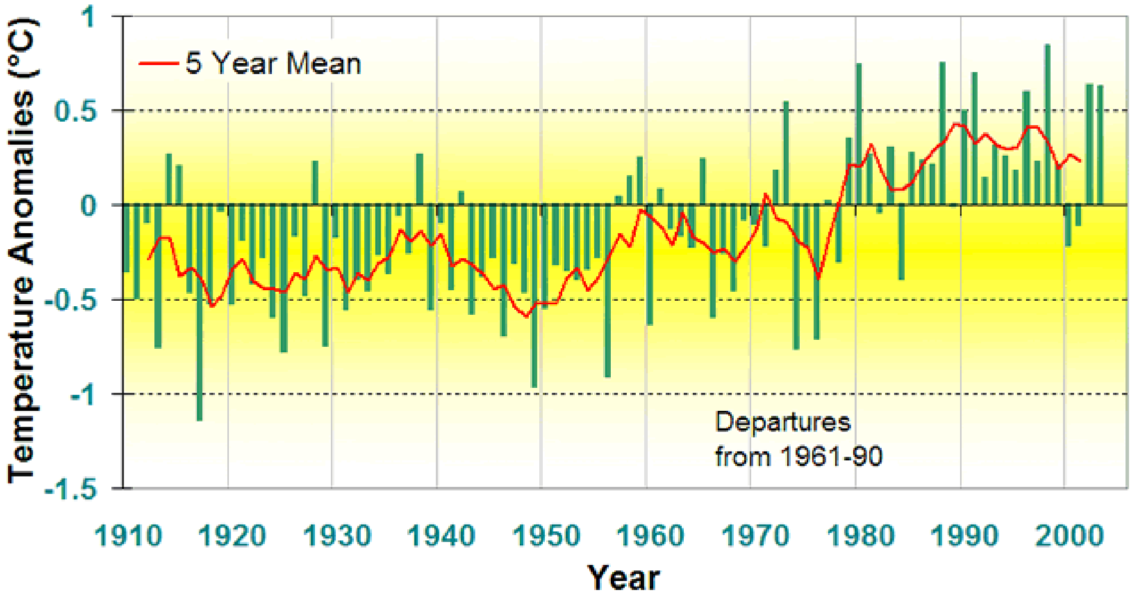


Figure 11: Average Australian annual mean temperature anomalies from 1910-2003, relative to the 1961-1990 average. Source: Bureau of Meteorology.

For the period 1950 to 2002, Australian average surface temperature has increased by 0.17ºC per decade. Minimum temperatures have increased at a faster rate (0.21ºC per decade) than maximum temperatures (0.13ºC per decade). The greatest warming has occurred in southern and eastern Australia, with least warming and some cooling in the northwest (Figure 12). The frequency of extremely warm days and nights has increased while that of extremely cool days and nights has decreased during the last five decades (Collins *et al.,* 2000).

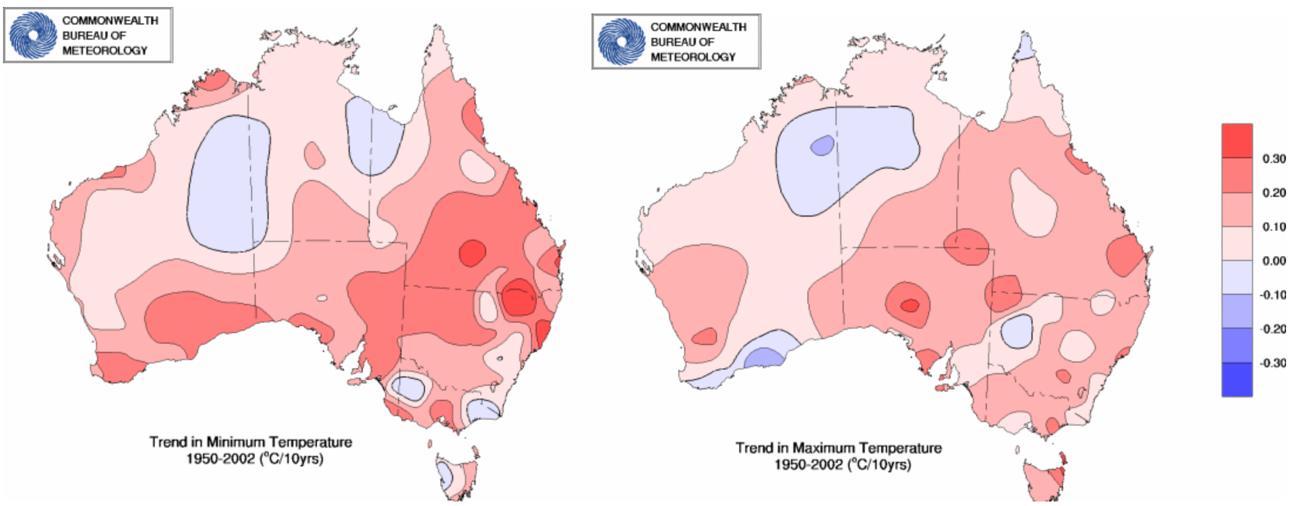


Figure 12: Trends in Australian annual-average maximum and minimum temperature from 1950–2002. Source: Bureau of Meteorology.

While most of the Northern Territory has warmed, some parts have cooled slightly. During November to April, maximum temperatures have risen by 0-0.2^{o}C per decade except for a cooling of 0-0.1^{o}C per decade in the central west, while minimum temperatures have increased risen 0.1-0.2^{o}C per decade throughout most of the Territory (Figure 13). During May to October, maximum and minimum temperatures have risen by 0.1-0.2^{o}C per decade in most of the west and 0.2-0.4^{o}C in most of the east. When temperatures are averaged over the whole of the Territory, the year-to-year variability can be seen (Figure 14). Territory-average annual maximum temperatures have increased by 0.12^{o}C per decade, due to a rise of 0.03^{o}C per decade in Nov-Apr and 0.20^{o}C per decade in May-Oct. Territory-average annual minimum temperatures have increased by 0.17^{o}C per decade, due to a rise of 0.14^{o}C per decade in Nov-Apr and 0.21^{o}C per decade in May-Oct.

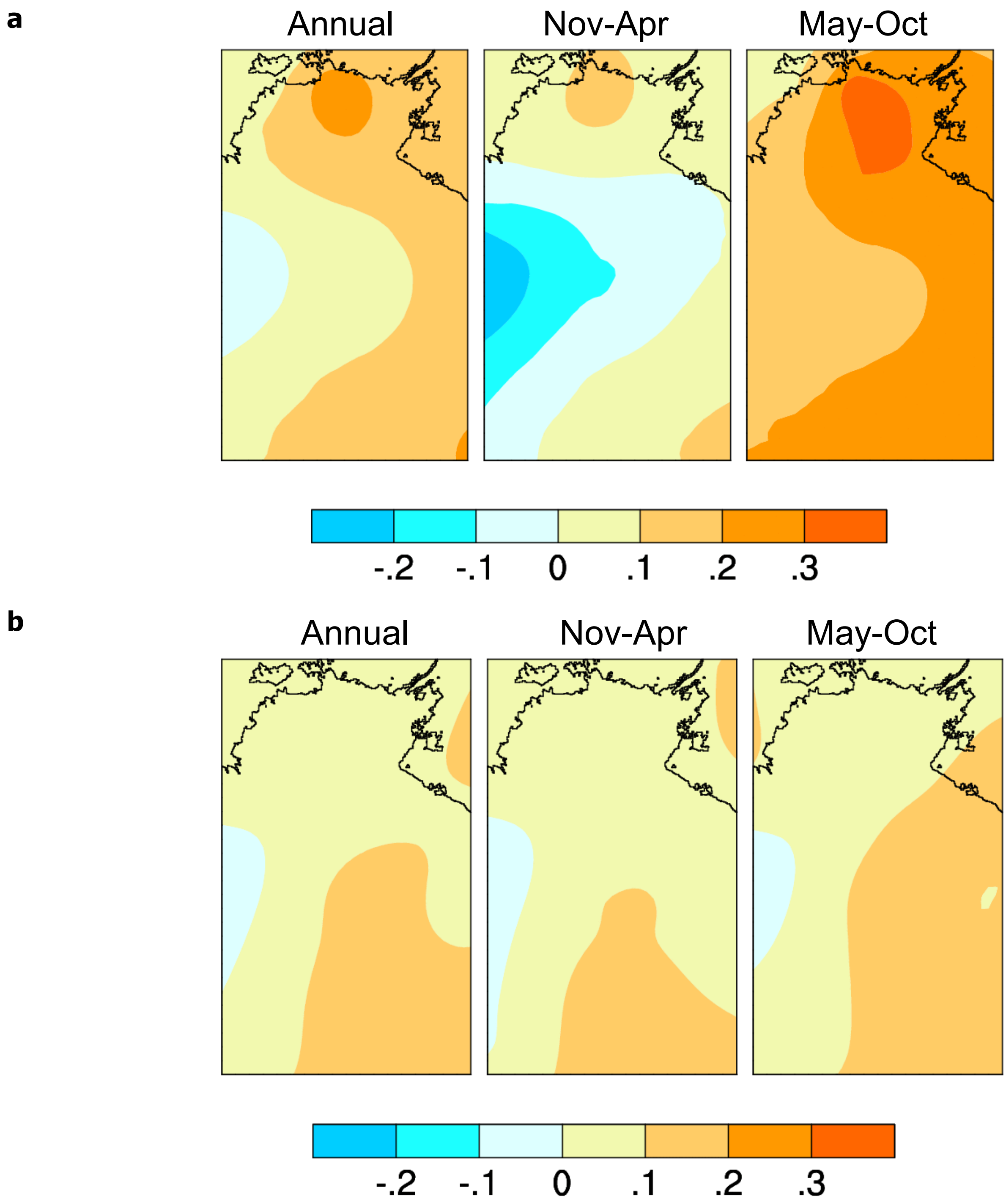


Figure 13: Annual, Nov-Apr and May-Oct trends in (a) maximum and (b) minimum temperature (^{o}C per decade) from 1950-2002.

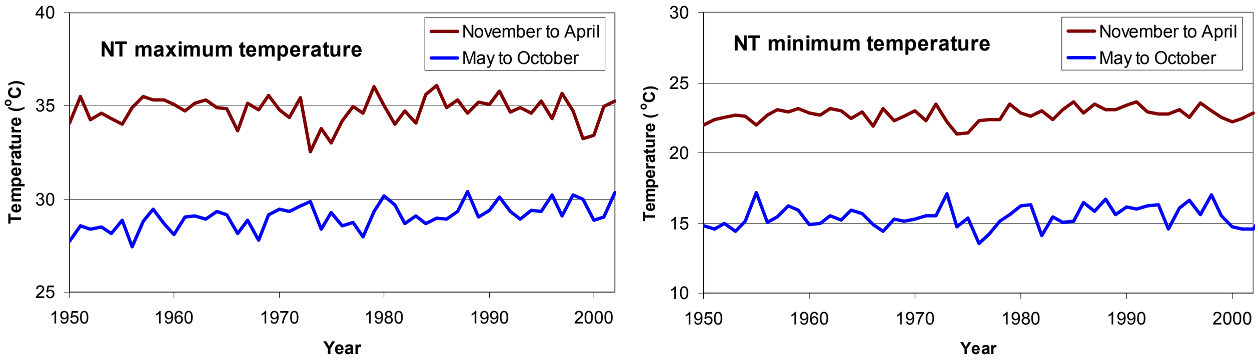


Figure 14: Time series of NT-average changes in May-Oct and Nov-Apr maximum and minimum temperature from 1950-2002.

Rainfall

Australian-average annual total rainfall records from 1900-2003 show a weak increasing trend, mainly due to some very wet years in the mid-1970s, late 1990s and 2000 (Figure 15). The pattern of rainfall trends since 1950 shows increases over most of the western two-thirds of continent, and decreases in the east and south-west (Figure 16). The Northern Territory has become wetter since 1950, due to widespread increases during November to April, and patchy increases during May to October (Figure 17). When rainfall is averaged over the whole of the Territory (Figure 18), the year-to-year variability shows the extremely dry years of 1901, 1904-05, 1951, 1960, 1969, 1989 and 1991, and the very wet years of 1903, 1920, 1973-75 and 1999-2000. The dry periods tend to be El Niño years, while the wet periods tend to be La Niña years. Over the period 1900-2002, the Territory-average rainfall rose 14.2 mm per decade during Nov-Apr and 2.5 mm per decade in May-Oct. However, since 1950, Territory-average rainfall has risen 35.7 mm per decade during Nov-Apr and fallen 0.4 mm per decade in May-Oct.

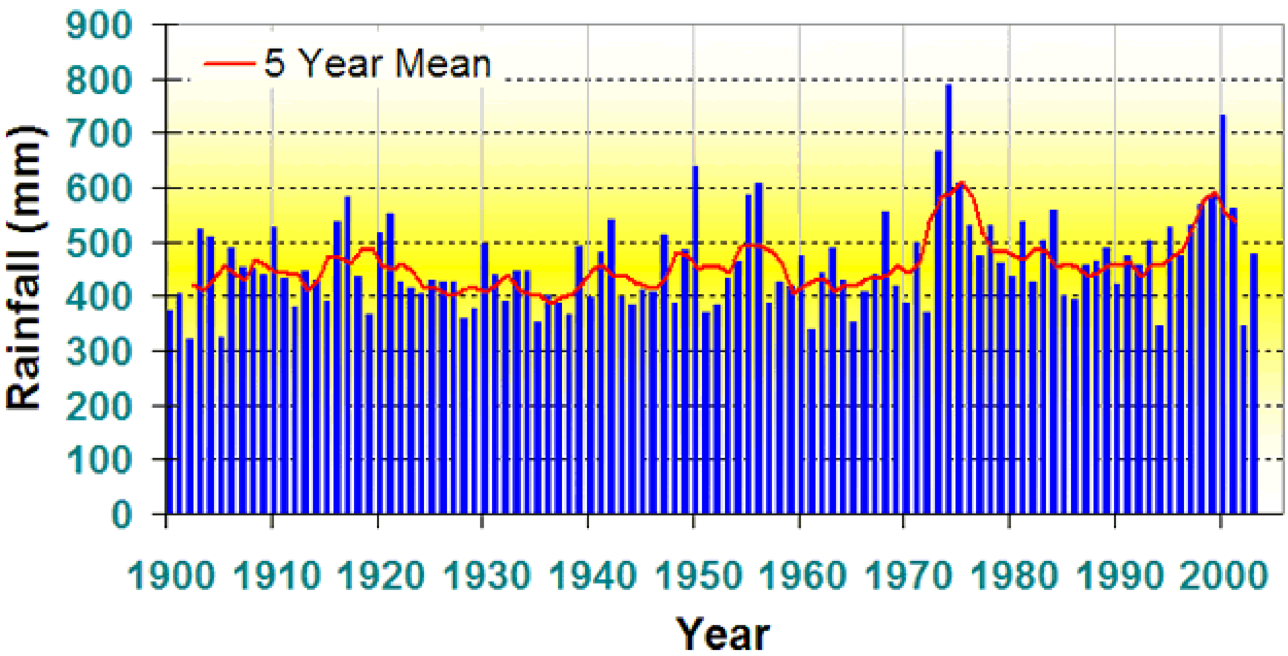


Figure 15: Australian-average annual total rainfall from 1900-2003. Source: Bureau of Meteorology.

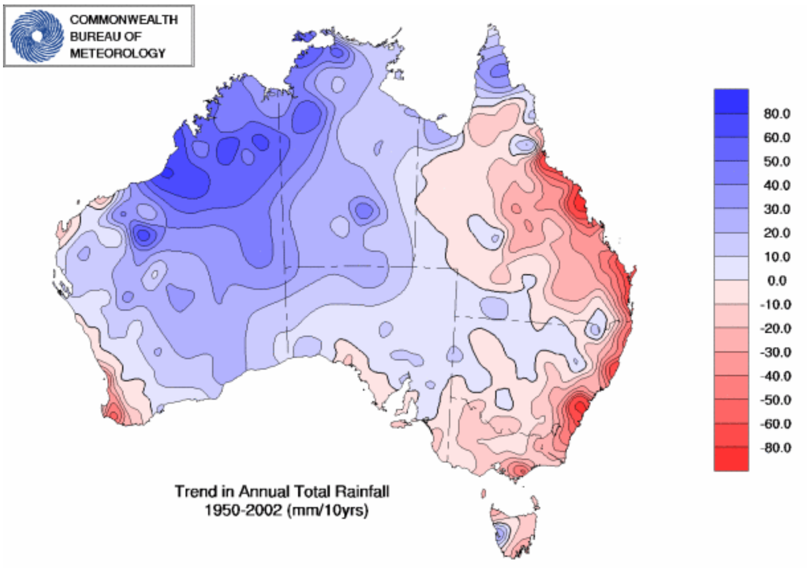


Figure 16: Annual rainfall trends in Australia for 1950-2002. Trend units are mm per decade. Source: Bureau of Meteorology

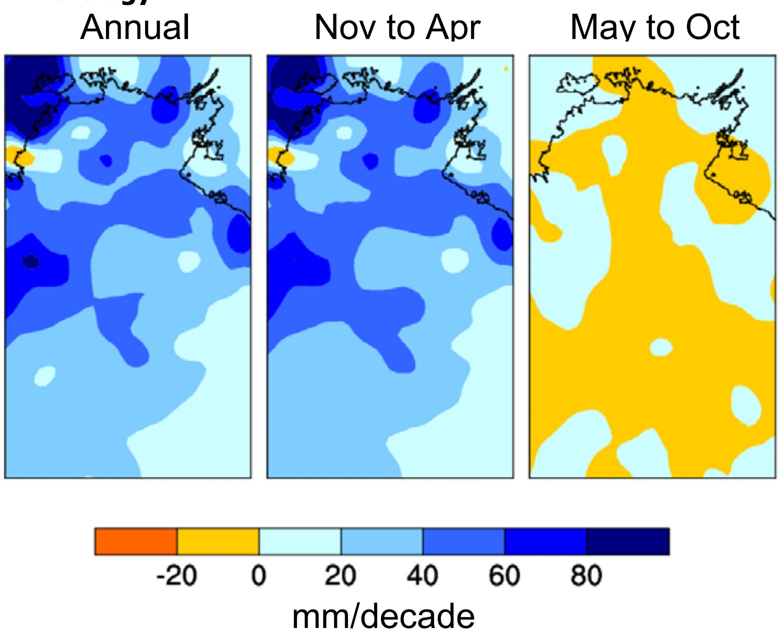


Figure 17: Annual, May-Oct and Nov-Apr rainfall trends (mm per decade) from 1950-2002.

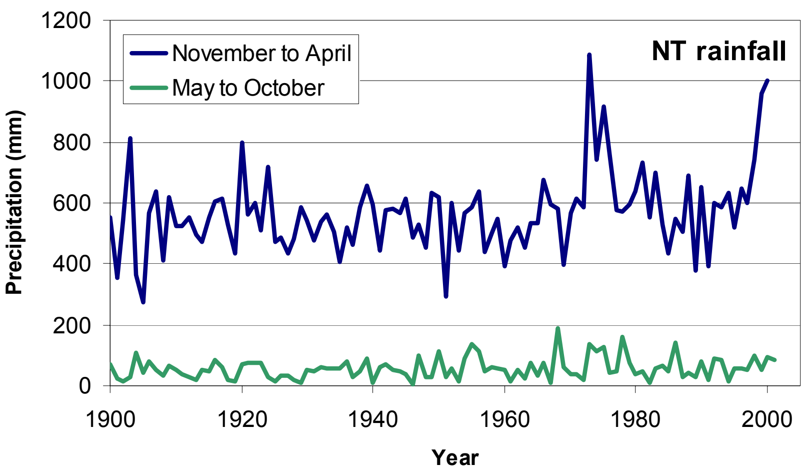


Figure 18: All-NT-average rainfall in May-Oct and Nov-Apr from 1900-2002.

Extreme daily rainfall has increased in many parts of the world, including Australia, over the 20th century (Groisman et al., 2000). An analysis of daily data in Australia from 1910-1995 (Hennessy et al., 1999) showed widespread increases in the intensity of the heaviest 1% of daily rainfall events (4th heaviest event each year, or heaviest event in a 3-month season) (Figure 19). In the Northern Territory, annual heavy rainfall has increased 10% due to increases of 20-30% in autumn and winter (Mar-Aug), a small decrease in spring (Sep-Nov) and little change in summer (Dec-Jan). Figure 20 shows the year to year variability in heavy rainfall, averaged over the Northern Territory, from 1910-1995. Most of the increase has occurred since 1970. Suppiah and Hennessy (1996) investigated trends in heavy daily rainfall during September to April from 1910-1989 at 53 tropical Australian sites. Most (46) of these sites had increasing trends in the 90th percentile rainfall intensity (heaviest 10% of events each year). This included all 14 sites in the Northern Territory, with statistically significant trends at Darwin, Waterloo, Brunette Downs and Tempe Downs. Significant correlations exist between the Southern Oscillation Index and heavy rainfall intensity between June and February, with stronger correlations in the post 1950 period. To test whether heavy rainfall trends are largely due to trends in ENSO, the ENSO influence was removed and trends in heavy rainfall were recomputed. This resulted in fewer and weaker positive trends in the tropics, but the significant increases remained at Darwin, Waterloo, Brunette Downs and Tempe Downs. Suppiah and Hennessy (1996) concluded that the increases in heavy rainfall are not solely due to ENSO variability.

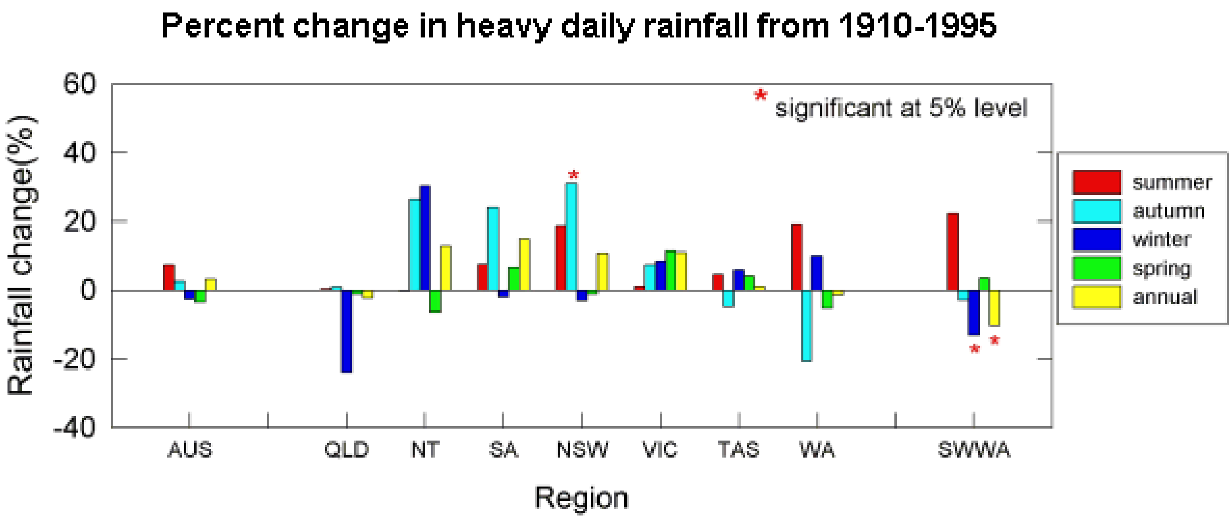


Figure 19: Changes in the magnitude of the heaviest 1% of daily rainfall events in various Australian regions and seasons from 1910-1995.

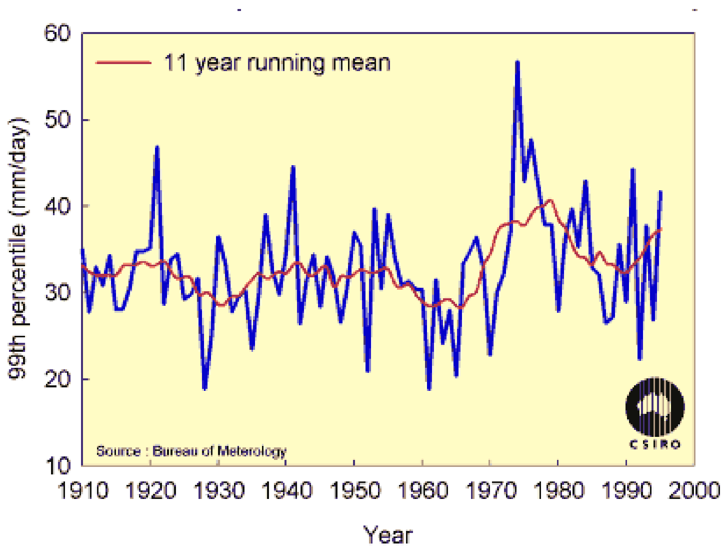


Figure 20: The magnitude of the heaviest 1% of daily rainfall events each year averaged over the Northern Territory from 1910-1995, with an 11-year running mean.

4. Simulating current regional climate

The complexity of processes in the climate system means we cannot simply extrapolate past trends to forecast future conditions. Climate models are the best tools we have for forecasting weather and climate. The most common application is in daily weather forecasting for specific cities or regions. Models are also used for three to 12 month climate forecasts for regions like Australia, which can assist agribusiness and other industries plan for the months ahead. Another application is projecting the effect of human activities on climate over the coming decades, and explaining the causes of climate change over past decades.

A climate model is a simplified mathematical representation of the Earth's climate system. The key components are the atmosphere, ocean, polar-ice and land surface. Meteorological variables such as temperature, rainfall, mean sea-level pressure and winds are typically computed in 30-minute time-steps over a three-dimensional grid of points across the globe for a number of decades. When driven with observed energy inputs from solar variability, volcanic eruptions, greenhouse gases, aerosols and ozone depletion, the models reproduce most observed climatic patterns well. When driven by projected changes in some of these energy inputs over the 21st century and beyond, the models simulate detailed patterns of climate change.

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. Current limitations on computer power restrict spatial resolution, so most models have grid points spaced about 300 km apart over the globe, 10-20 layers in the atmosphere and 20-30 layers in the ocean.

Due to their coarse resolution, global climate 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 at its boundaries by input from a global climate model, so the results of an RCM will depend on the global model in which it is embedded. Regional climate models 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 12 climate models (Table 1) to simulate current patterns of temperature, rainfall and mean sea-level pressure over the Northern Territory.

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	Mark2	IS92a, SRES A2, SRES B2	1881–2100	~400	daily
CSIRO, Australia	DAR125 (RCM)	Nested in Mark2 with IS92a	1961-2100	125	daily
CSIRO, Australia	CC50	Linked to Mark2 with SRES A2	1961-2100	50 over Aus	daily
CSIRO, Australia	Mark3	SRES A2	1961-2100	~200	daily
Canadian CC	CCM1	1% increase in CO_2 p.a.	1900–2100	~400	monthly
Canadian CC	CCM2	IS92a	1961-2100	~400	monthly
DKRZ, Germany	ECHAM3/LSG	IS92a	1880-2085	~600	monthly
GFDL, USA	GFDL	1% increase in CO_2 p.a.	1958–2057	~500	monthly
Hadley Centre, UK	HadCM2	1% increase in CO_2 p.a.	1861–2100	~400	monthly
Hadley Centre, UK	HadCM3	IS92a	1861-2099	~400	monthly
DKRZ, Germany	ECHAM4/OPYC3	IS92a	1860–2099	~300	monthly
NCAR, USA	NCAR	IS92a	1960-2099	~500	monthly

4.1 Average patterns of pressure, temperature and precipitation

Statistical methods have been employed to verify the performance of each model in simulating the current climate. 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 120-145ºE and latitudes 5-30ºS was used to test ability of each model to simulate mean sea-level pressure over and around the Northern Territory. In Figure 21, the better performing models have results closer to the top left hand corner of each diagram. The correlation coefficient of most models is above 0.8, indicating that the models simulate the observed pattern of mean sea level pressure over a large area reasonably well. The RMS error is less than 2 hPa for most models, but there are larger errors in some models, particularly in GFDL and ECHAM3.

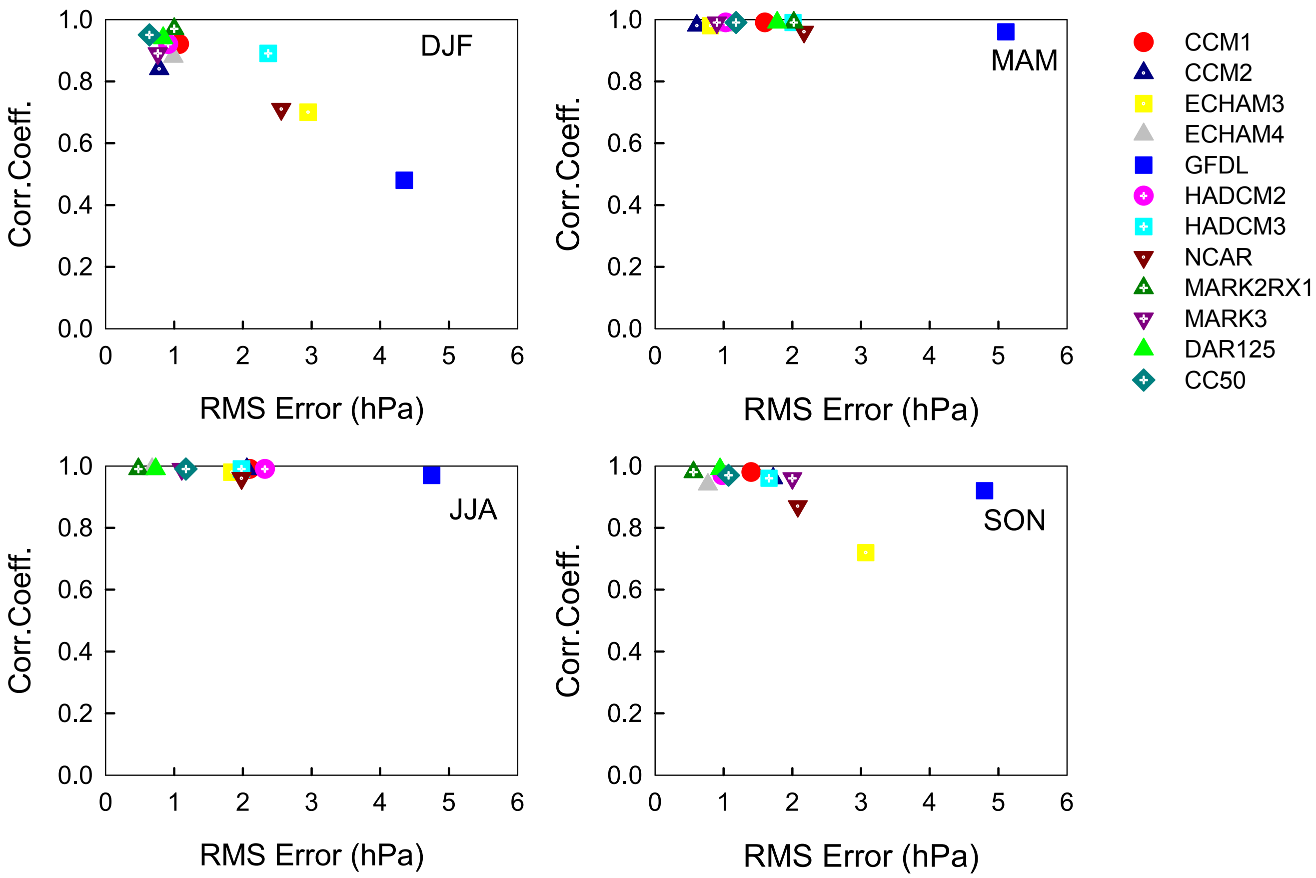


Figure 21: Pattern correlation and RMS error for observed versus model mean sea level pressure in each season (DJF is Dec-Feb, MAM is Mar-May, JJA is Jun-Aug, SON is Sep-Nov) for the models listed in Table 1, over the region defined by latitudes 5-30°S and longitudes 120-145°E.

Figure 22 shows the pattern correlation and RMS error for seasonal-average temperature and rainfall for each model over the Northern Territory (longitudes 129-138ºE and latitudes 10-26ºS). For temperature, most models achieve pattern correlations better than 0.8 and RMS errors less than 3°C. Notable exceptions are the large RMS errors for NCAR, ECHAM3, ECHAM4 and CCM2. The lower pattern correlations in summer are not surprising or worrying because there is little spatial variation in observed temperatures in this season. 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. Some pattern correlations are weak in winter because the observed rainfall pattern is weak, so this is not a concern. The poor correlations in autumn and spring are more troubling since this means the models are not adequately capturing the observed rainfall gradient from north to south. Large RMS errors in summer rainfall are generated by GFDL, DAR125, NCAR, CCM1 and ECHAM3.

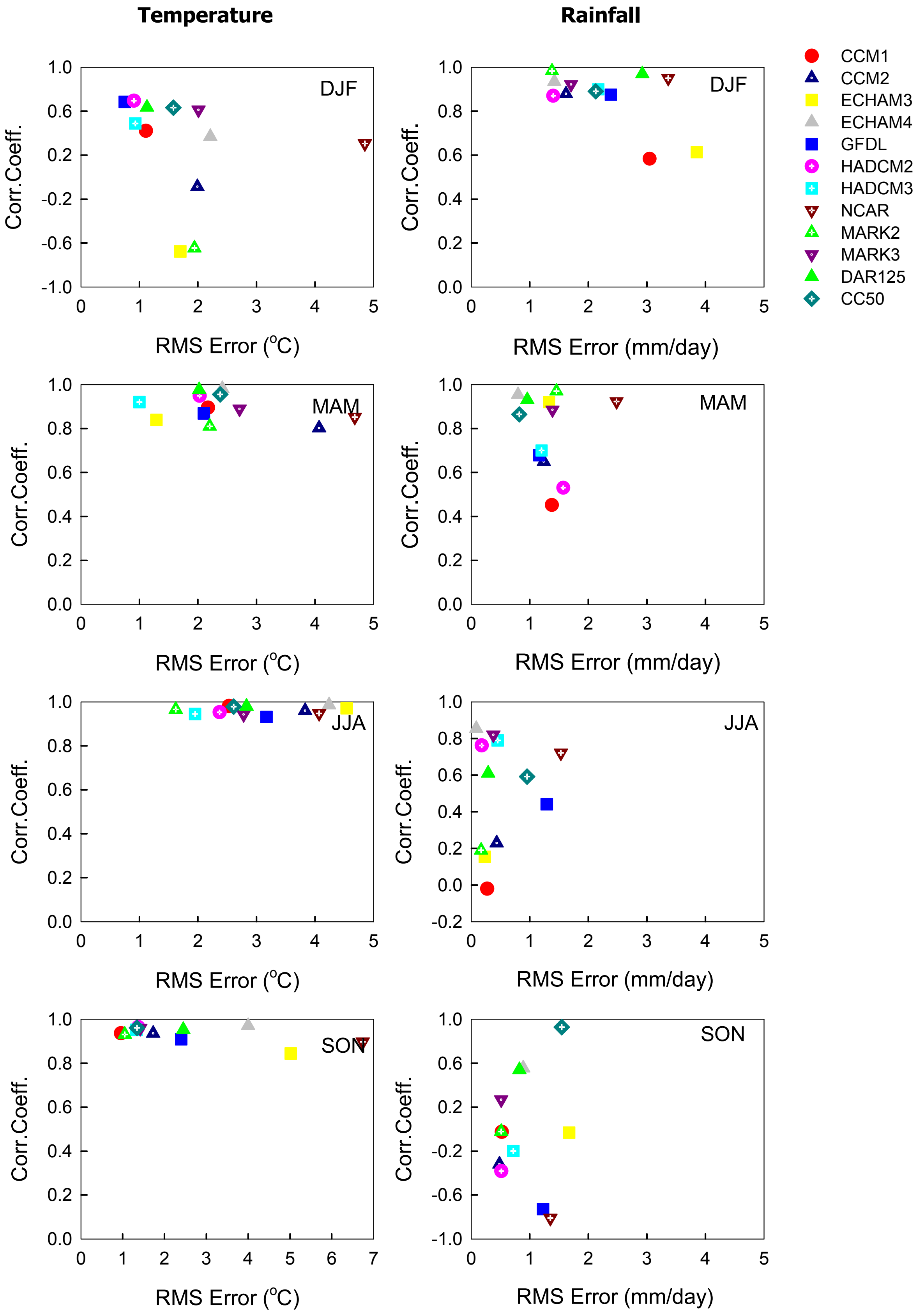


Figure 22: Pattern correlation and RMS error for observed versus model temperature (left column) and rainfall (right column) in each season (DJF is Dec-Feb, MAM is Mar-May, JJA is Jun-Aug, SON is Sep-Nov) for the models in Table 1 over the Northern Territory (longitudes 129-138°E and latitudes 10-26°S).

These statistics suggest that most models capture the average climatic features reasonably well. However, some models clearly perform better than others. To compare the overall performance of each model, a simple demerit point system based on thresholds was devised. Models were assigned a point if they had an RMS error greater than 2.0 for pressure and rainfall and greater than 3.0 for temperature, or a pattern correlation below 0.8 for MSLP and 0.6 for temperature and rainfall. An arbitrary limit of five demerit points was defined as unsatisfactory performance. Using this system, the best performing models are CC50, DAR125, Mark2, Mark3, HADCM2 and ECHAM4 with scores between zero and two. The poorest performing models are NCAR, ECHAM3 and GFDL with scores of ten, six and six respectively.

The CCM1 and CCM2 models had marginal temperature and rainfall performance, with four demerit points each, especially during the monsoon months. A further test of model performance was deemed necessary. Given the importance of the timing and amount of monsoon rainfall, the observed monthly-average rainfall over the Top End (12-15°S, 129-136°E) was compared with that simulated by each model (Figure 23). Most models adequately capture the annual cycle of rainfall, with a peak of around 270 mm in January and February, and less than 40 mm per month from May to October. DAR125 and CC50 significantly overestimate monsoon rainfall, while GFDL and CCM1 are too dry during the monsoon. A demerit point was allocated to a model for each month in which the error exceeded 40% of the observed value between November and April. The best performers were HadCM3 and ECHAM4 with no demerit points. The poorest performers were CCM1, GFDL and HadCM2 with six, four and four points respectively. While adding these demerit points to those from the previous analysis involves some double-counting of precipitation demerits, the importance of monsoon rainfall justifies this additional emphasis. The six best performing models are subsequently CC50, ECHAM4, Mark3, HadCM3, Mark2 and DAR125 with scores between two and four. Another two acceptable models are CCM2 and HadCM2. The four least acceptable models are ECHAM3, CCM1, GFDL, and NCAR with scores of eight, ten, ten and twelve respectively. These four models were excluded from the projections in Chapters 5 and 6.

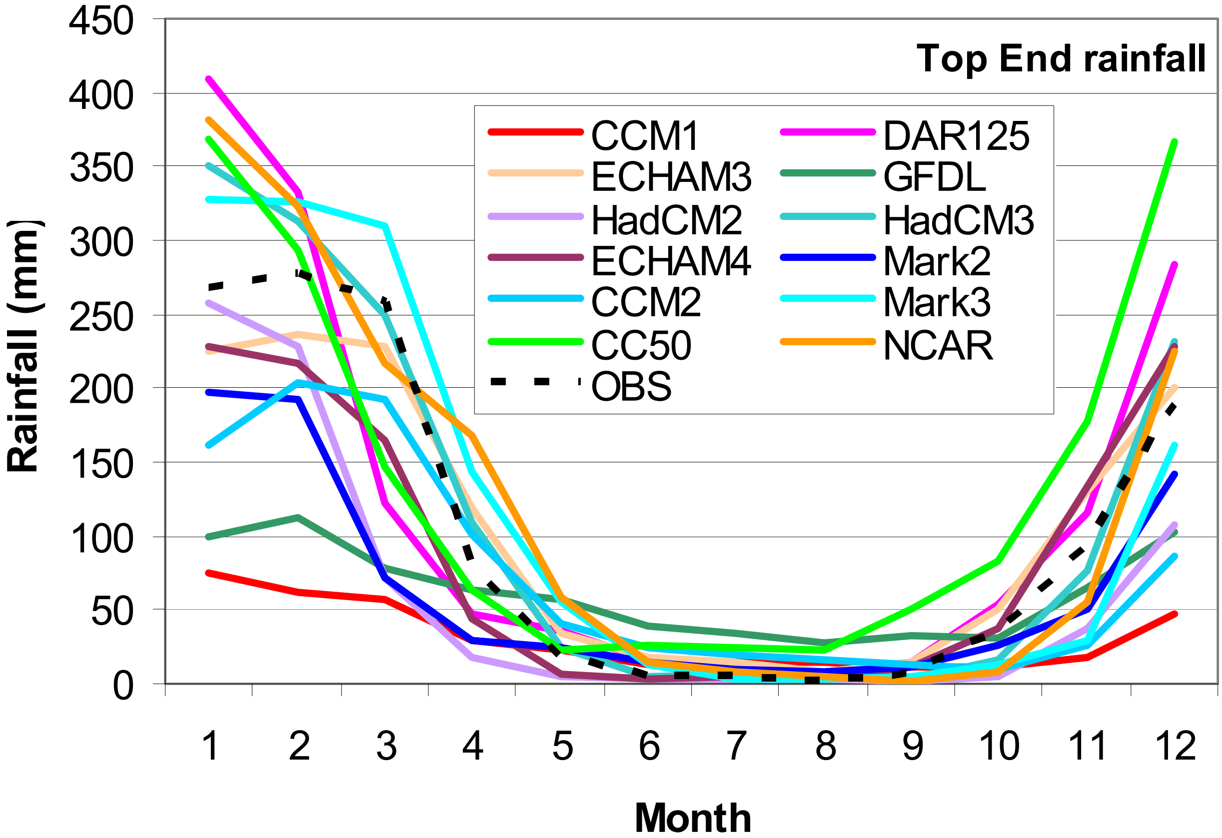


Figure 23: Observed (OBS: Bureau of Meteorology) versus simulated monthly-average rainfall over the Top End (12-15°S, 129-136°E) for the models listed in Table 1, based on the period 1961-1990. Months run from 1 (January) to 12 (December).

5. Projected climate change for 2030 and 2070

Under enhanced greenhouse conditions, climate models generally simulate a global-average warming of 0.4 to 1.3°C by 2030, and 1.1 to 4.0°C by 2070 (IPCC, 2001a). Greater warming occurs over land and near the poles. Global-average rainfall increases. Figure 24 shows results from ten models analysed in an earlier CSIRO study (all models in Table 1 except DAR125 and CC50). Most models (at least eight out of ten) simulate rainfall increases in mid to high latitudes and near the equator, and rainfall decreases in the subtropics.

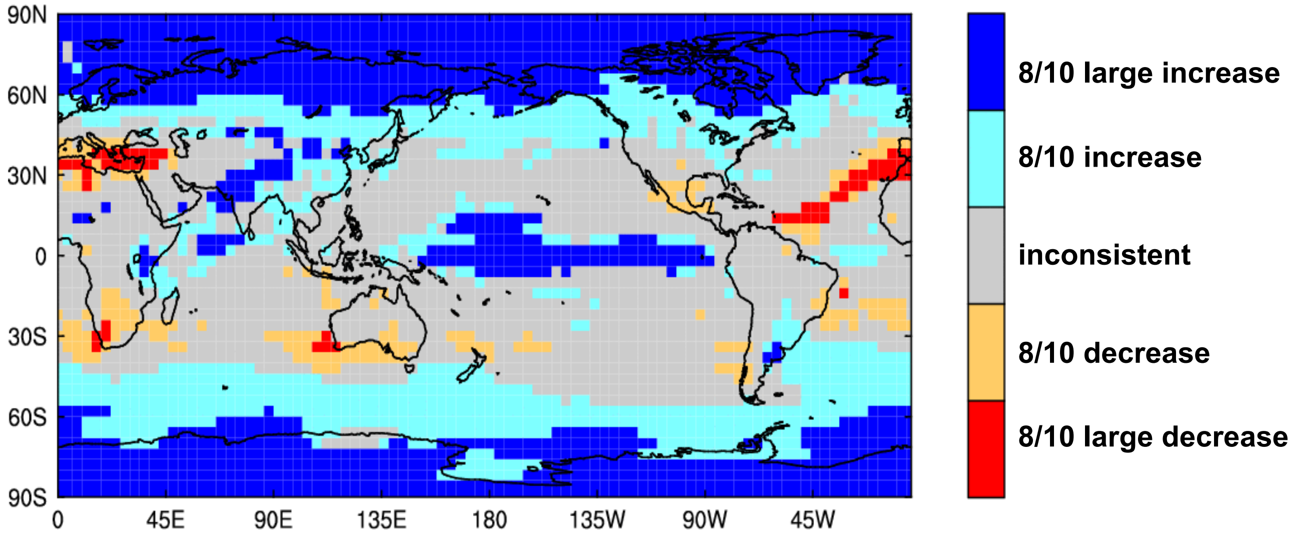


Figure 24: Inter-model consistency in direction of simulated annual rainfall change in ten global climate models (see Table 1). Coloured regions show where at least 8 out of 10 models agree on the direction of rainfall change. Large changes occur where the average change across the models is greater than 5% per degree of global warming.

Some of the patterns of simulated rainfall change can be explained by examining simulated changes in mean sea-level pressure. There is broad agreement amongst the models on a pattern of increased pressure over latitudes 35-55°S in the southern hemisphere (Figure 25). The reason for this pattern is not well understood, but there is evidence that the increased pressure is related to the delayed surface warming in southern high latitudes due to the downward transport of heat by the ocean (Whetton et al. 1996). The band of increased pressure extends slightly further north in winter and the decreased pressure over the continent is stronger in summer. This would weaken the westerly winds across southern Australia and would be expected to reduce rainfall over southern Australia, particularly in winter and spring.

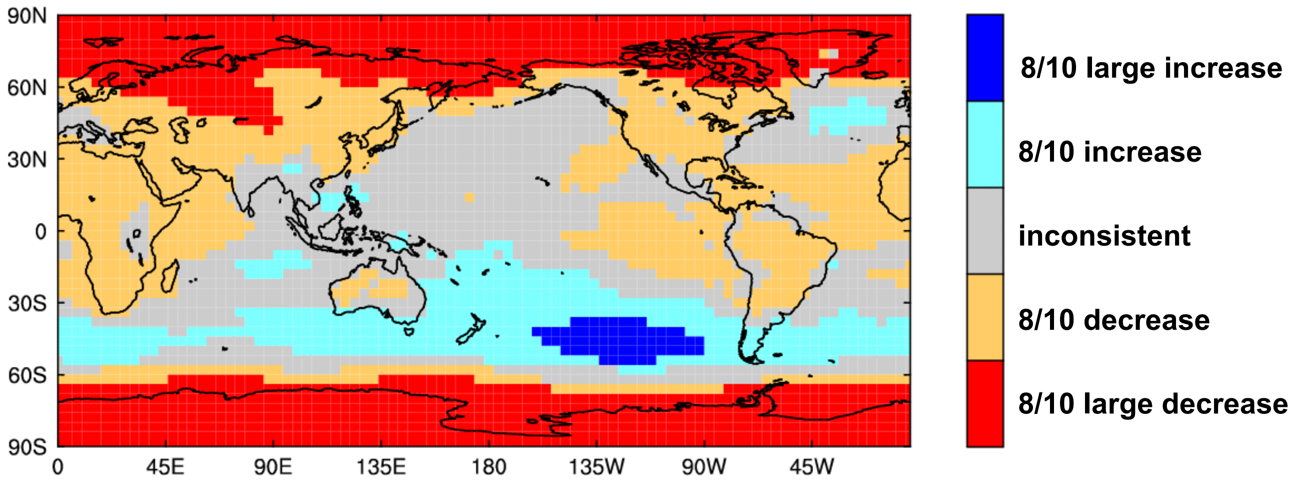


Figure 25: Inter-model consistency in direction of simulated annual pressure change in ten global climate models (see Table 1).

There is also some agreement amongst models on decreased pressure over central and northern Australia. This would be expected to increase rainfall, particularly in summer when this feature is more evident. However, Figure 25 also shows a tendency for pressure to decrease over the eastern tropical Pacific and increase in the western tropical Pacific. This pattern may be viewed as the atmospheric response to an El Niño-like warming pattern simulated by most models in the Pacific (Cai and Whetton, 2000). The IPCC (2001a) stated that climate models indicate little change or a small increase in El Niño intensity over the next 100 years, but this is tempered by shortcomings in how well El Niño is simulated in climate models. If the average climate becomes more like El Niño, rainfall reductions would be expected in northern and eastern Australia. Therefore the net effect of pressure changes on northern and central Australian rainfall is unclear.

It was beyond the scope of this report to analyse the underlying causes of simulated changes in Northern Territory temperature and rainfall, e.g. changes in mean sea-level pressure, sea-surface temperature or ocean circulation. This could be undertaken in a subsequent study since climate models include most of the relevant processes driving changes in temperature and rainfall. Our projections are presented as a range rather than a central estimate. The range incorporates quantifiable uncertainties associated with the range of unabated future emission scenarios for greenhouse gases and sulfate aerosols, the range of global warming from the IPCC (2001a) and model to model differences in the patterns of climate change over the Northern Territory. This method is described in more detail by Whetton (2001).

Based on the analysis in section 4, the eight most reliable models for projecting climate change over the Northern Territory are HadCM2, HadCM3, ECHAM4, CCM2, MARK2, MARK3, DAR125 and CC50. Projections were computed for 2030 and 2070 for:

- Patterns of change in average temperature, rainfall and moisture balance (rainfall minus potential evaporation) for May to October and November to April;
- Site-specific changes in extreme daily temperatures;
- Changes in monthly-average rainfall over Darwin and Alice Springs.

5.1 Projected changes in average temperature and rainfall

Patterns of change in average temperature are presented in Figure 26 as colour-coded maps for the wet season (November to April) and dry season (May to October) by 2030 and 2070, relative to 1990. These years illustrate changes in average climate that may be expected in over time horizons of relevance to different environmental, regional and sectoral planning issues. Superimposed on these average changes will be natural variability from year to year. The conditions in any individual year cannot be predicted beyond about nine months in advance. By 2030, the average warming over the Territory is about 0.2-2.2°C with least warming over the Top End and most warming in the south-west, especially in November to April. By 2070, the warming ranges from 0.8 to 7.2°C, with 0.8-5.6°C over the Top End and 1.1-6.4°C over most of the southern half of the Territory.

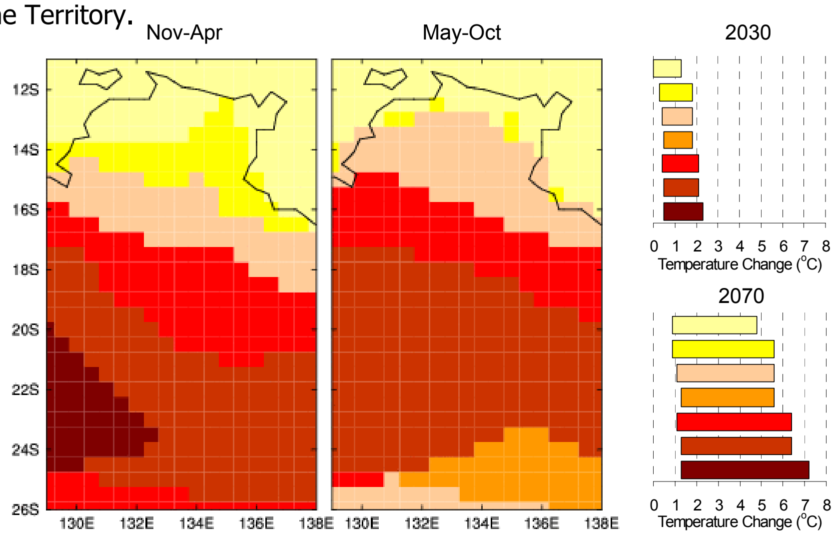


Figure 26: Average November to April and May to October changes in temperature (°C) for 2030 and 2070, relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps.

Figure 27 shows changes in rainfall. Most of the Territory tends to become drier in both the wet season and dry season. During November to April, by 2030, the changes are mostly in the range –16% to +8%, but there is a 400-km-wide band from Darwin to Camooweal where there considerable inconsistency between models on small rainfall changes ranging from -8% to +8%. By 2070, the changes range from -40% to +20%, with changes of -20% to +20% in the uncertain region. During May to October, by 2030, the changes are mostly in the range -20% to +8%, except near Darwin where the range is -8% to +20%. Since this is the "dry season", the hydrological importance of these changes is probably low. By 2070, the ranges are -60% to +20% over most of the region and -20% to +60% near Darwin. These large ranges of uncertainty may appear daunting, but when rainfall changes are combined with changes in potential evaporation, a more robust picture of moisture availability emerges.

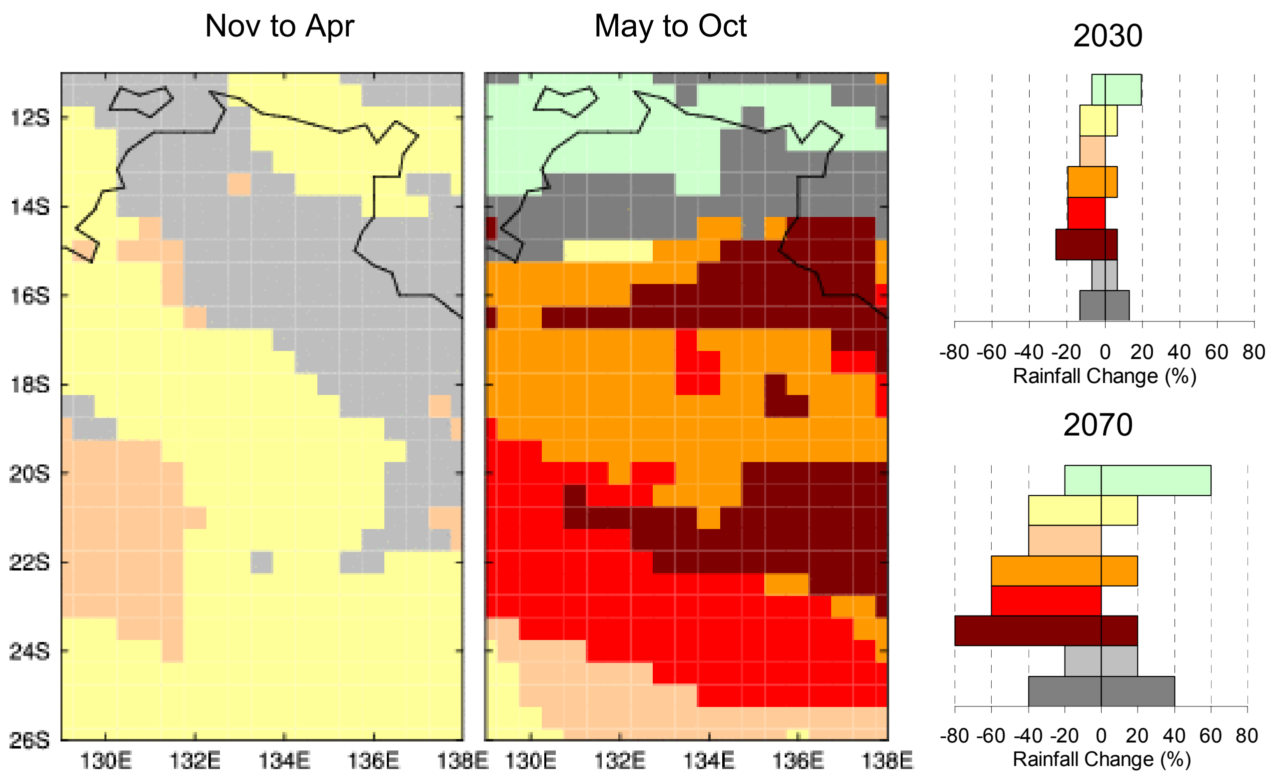


Figure 27: Average November to April and May to October changes in rainfall (%) for 2030 and 2070, relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps.

5.2 Projected changes in evaporation and moisture balance

Potential evaporation is the maximum evaporation possible from a particular surface under known environmental conditions. The potential cannot be realised in the absence of moisture. Higher temperatures will increase potential evaporation. The combined effect of regional changes in rainfall and increased potential evaporation would lead to changes in atmospheric moisture balance, i.e. the net amount of moisture available from the atmosphere. The change in atmospheric moisture balance was derived by subtracting the changes in potential evaporation from changes in rainfall. Potential evaporation data were available for only five of the eight acceptable models.

Projected changes in potential evaporation and moisture balance are shown in Figure 28. Potential evaporation generally increases 2-5% by 2030 and 4-20% by 2070, with smaller increases in the north and larger increases in the central-west in Nov-Apr and in the south in May-Oct. When changes in rainfall are combined with increases in potential evaporation, there is a net reduction in moisture available from the atmosphere, i.e. the region become drier. In Nov-April, moisture balance south of Daly Waters declines 30-130 mm by 2030 and 90-400 mm by 2070, with smaller decreases in the north where the decrease is mostly

10-80 mm by 2030 and 50-240 mm by 2070. In May-Oct, moisture balance declines 20-100 mm by 2030 and 70-320 mm by 2070, with smaller decreases in the far south and Top End (10-80 mm by 2030 and 50-240 mm by 2070). The impact on river flow and soil moisture could be assessed using a detailed hydrological model. These changes should be compared with the current average moisture balance values shown in Figure 10. In May-Oct, the Territory has a moisture deficit of 800-1600 mm. In Nov-Apr, the deficit ranges from 1600 mm in the south to less than 400 mm over the Top End, with a moisture surplus of up to 400 mm from Darwin to Jabiru.

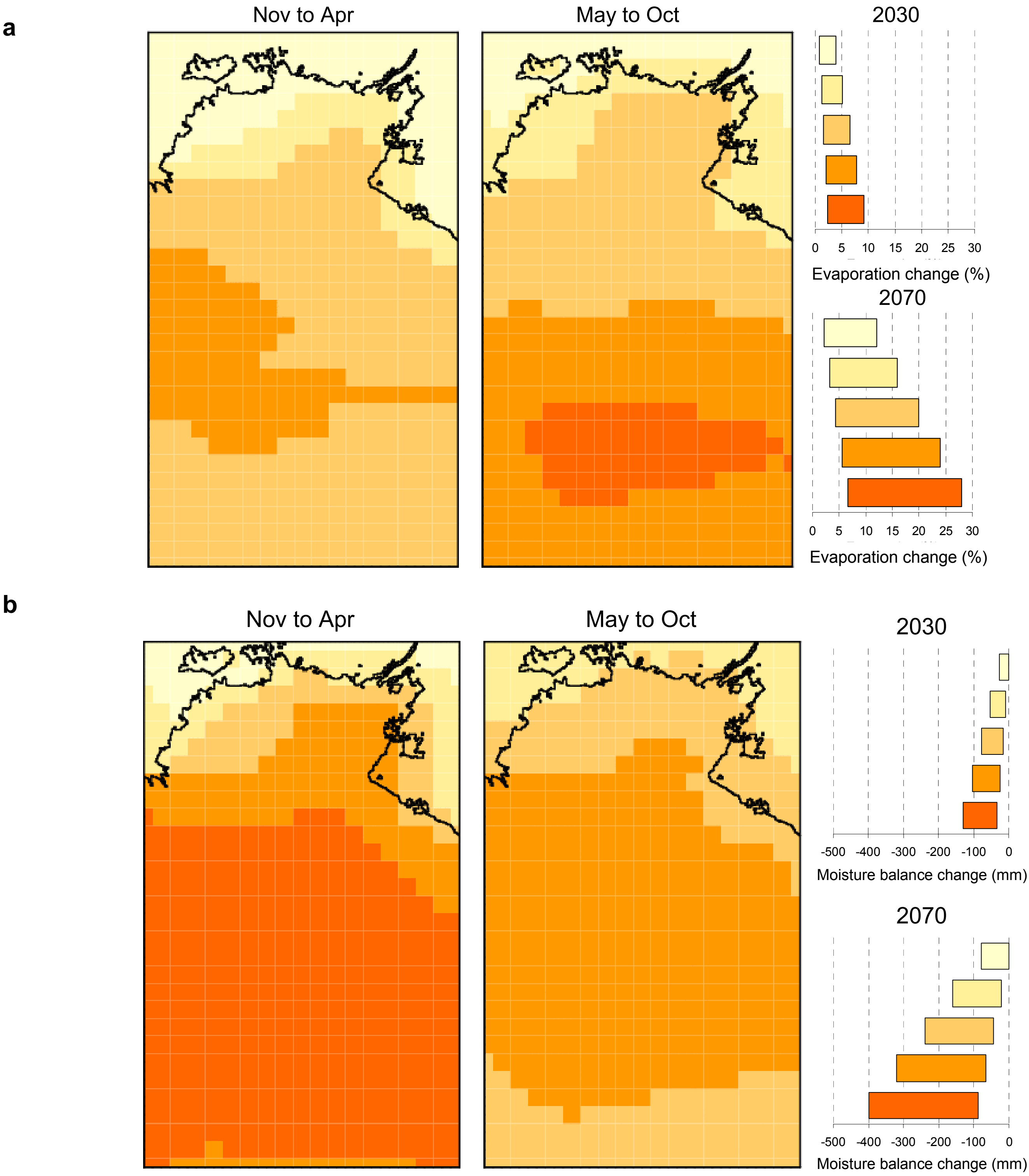


Figure 28: Patterns of change in (a) potential evaporation (%) and (b) moisture balance (mm) for November to April and May to October in 2030 and 2070, relative to 1990.

6. Projected changes in extreme temperature

Changes in average temperature will be felt through changes in extremes. The average warming of about 0.8°C in Australia since 1950 has been associated with an increase in hot days over 35°C by 0.16 days per year, an increase in hot nights over 20°C by 0.26 nights per year, a decrease in cold days below 15°C by 0.12 days per year and a decrease in cold nights below 5°C by 0.24 nights per year (Collins *et al.,* (2000). While individual heatwaves cannot be attributed to changing climate, it is reasonable to expect that such events will occur more frequently, start earlier or end later than has tended to occur historically.

6.1 Extreme temperature projections for the Northern Territory

An increase in hot days and hot spells is likely to increase fire risk, energy demand for air-conditioning, and heat stress to humans, animals and crops. Transport infrastructure is also likely to be affected with greater frequency of buckling of railway lines and melting of road tar.

This chapter focuses on projections of extremes in temperature at selected sites, based on daily data quality and availability from the Bureau of Meteorology. For the 30-year period 1971-2000, the following 11 sites were chosen since they had less than 10% missing days: Darwin, Goulburn Island, Elcho Island, Oenpelli, Larrimah, Brunette Downs, Jervois, Tennant Creek, Rabbit Flat, Curtin Springs and Alice Springs. For example, Darwin currently averages almost 11 days over 35°C and no days over 40°C, Alice Springs averages 90 days over 35°C and 17 days over 40°C, and Rabbit Flat averages 155 days over 35°C and 51 days over 40°C.

Extreme temperature projections were computed by adding the range of mean warming for 2030 or 2070 (Figure 26) to the observed daily data, then computing the modified number of days exceeding 35°C or 40°C. This method assumes no change in daily temperature variability about the mean, which is consistent with results from climate change simulations over Australia (Whetton *et al.*, 2002).

Changes in the annual number of days over 35°C are shown in Table 2. The first three sites are coastal with very low temperature variability. This makes them highly sensitive to small changes in average temperature. By 2030, the average number of days over 35°C at coastal sites is expected to rise by 1-51 days. Inland, the increase is generally 5-30 days in the south, 5-40 days in the north and 5-70 days in the centre. By 2070, the range of uncertainty in average warming is much larger, leading to an even greater range of uncertainty in extreme temperature impacts. The increase in days over 35°C is 13-300 days at coastal sites, 16-104 days in the south, 30-200 days in the north, and 26-130 days in the centre.

Hot spells of three to five days over 35°C were also calculated (note that five consecutive days above the threshold has been counted as a single hot spell while six days has been counted as two hot spells). At coastal sites, the present average is only one hot spell per year. Inland, the present average is 23-30 in the south, 31-42 in the north and 36-46 in the centre. By 2030, the increase in hot spells is generally 1-10 on the coast and in the south, 2-22 in the north, and 2-17 in the centre. By 2070, the increase is 2-97 on the coast, 5-33 in the south, 9-68 in the north and 8-44 in the centre.

Table 2: The average number of days or 3-5-day spells above 35°C per year for selected sites.

Site	Days over 35°C			3-5-day spells over 35°C		
	Present	2030	2070	Present	2030	2070
Darwin	10.5	11.7-61.7	33.6-316.1	0.7	0.9-10.4	4.2-97.9
Goulburn Island	7.7	8.5-43.4	20.7-221.2	0.7	0.8-5.9	3.0-62.8
Elcho Island	11.8	12.5-47.1	30.3-273.7	1.1	1.2-8.4	4.8-81.3
Oenpelli	123.8	128.2-196.3	167.6-320.6	31.1	33.2-53.6	44.3-99.3
Larrimah	146.9	153.5-213.8	175.7-315.1	41.5	43.3-63.0	50.5-99.8
Brunette Downs	153.2	159.8-204.8	181.2-283.4	44.3	46.1-61.0	53.0-88.3
Tennant Creek	126.7	132.8-174.2	152.2-258.8	35.8	37.5-51.3	44.0-80.5
Rabbit Flat	154.6	161.9-194.2	177.2-263.0	45.6	47.9-58.7	53.1-83.0
Jervois	112.7	116.4-143.6	129.2-204.8	29.5	30.7-39.6	34.6-59.5
Curtin Springs	102.3	106.7-133.5	118.7-192.1	25.9	27.4-36.1	31.1-56.0
Alice Springs	90.0	95.9-125.2	109.6-193.6	23.1	24.9-33.8	28.9-56.7

Changes in the annual number of days over 40°C are shown in Table 3. By 2030, the absence of days over 40°C remains at coastal sites. However, the average rises by 3-29 days in the south, up to 10 days at Oenpelli, 3-35 days at Larrimah and 5-45 days in the centre. By 2070, the increase in days over 40°C is up to 9 days at coastal sites, 16-95 days in the south, 5-109 days at Oenpelli, 12-157 days at Larrimah and 19-152 days in the centre.

Extremely hot spells of three to five days over 40°C were also calculated. At coastal sites, the absence of such events remains until at least 2070. Inland, the present average is 3-8 in the south, 0-2 in the north and 4-12 in the centre. By 2030, up to 2 more extremely hot spells could occur on average at Oenpelli, up to 9 at Larrimah, 1-8 in the south and 1-14 in the centre. By 2070, the increase is up to 29 at Oenpelli, 4-27 in the south and 3-47 in the centre and at Larrimah.

Table 3: The average number of days or 3-5-day spells above 40°C per year for selected sites.

Site	Days over 40°C			3-5-day spells over 40°C		
	Present	2030	2070	Present	2030	2070
Darwin	0	0	0-7.9	0	0	0-0.5
Goulburn Island	0	0	0-5.0	0	0	0-0.4
Elcho Island	0	0	0-8.6	0	0	0-0.6
Oenpelli	1.6	1.7-11.1	5.9-110.9	0.1	0.1-1.6	0.6-28.7
Larrimah	12.0	14.6-46.9	24.3-169.3	1.9	2.4-11.1	5.1-48.5
Brunette Downs	36.0	41.0-81.2	59.4-187.7	7.8	9.3-21.0	14.3-55.2
Tennant Creek	19.5	24.1-60.6	38.5-158.4	3.6	4.7-14.4	8.2-45.9
Rabbit Flat	50.7	57.8-93.4	75.0-179.4	11.7	14.1-25.7	19.7-54.0
Jervois	36.5	40.5-65.5	52.1-130.4	7.6	8.8-15.5	11.7-35.0
Curtin Springs	28.2	31.5-56.8	43.2-119.8	5.2	6.0-12.7	9.0-31.6
Alice Springs	16.9	20.9-43.2	30.9-111.5	2.6	3.6-9.5	6.1-29.3

7. Monthly-average rainfall changes near Darwin and Alice Springs

Given the importance of the timing and magnitude of monsoon rainfall in the Northern Territory, simulated changes in monthly-average rainfall were analysed for the Darwin and Alice Springs regions. Figure 29 shows the annual cycle of rainfall for a 200 km x 200 km region covering Darwin and Mary River, for the eight model simulations for "present" (1961-1990), and two 15-year periods centred on 2030 and 2070. The observed average (1961-1990) rainfall is also shown for comparison. While dry-season rainfall is well simulated by all models, wet-season rainfall is more challenging. There is not an obvious "best" model, so all are treated equally. In 2030 and 2070, some models generate wetter conditions while others indicate drier conditions.

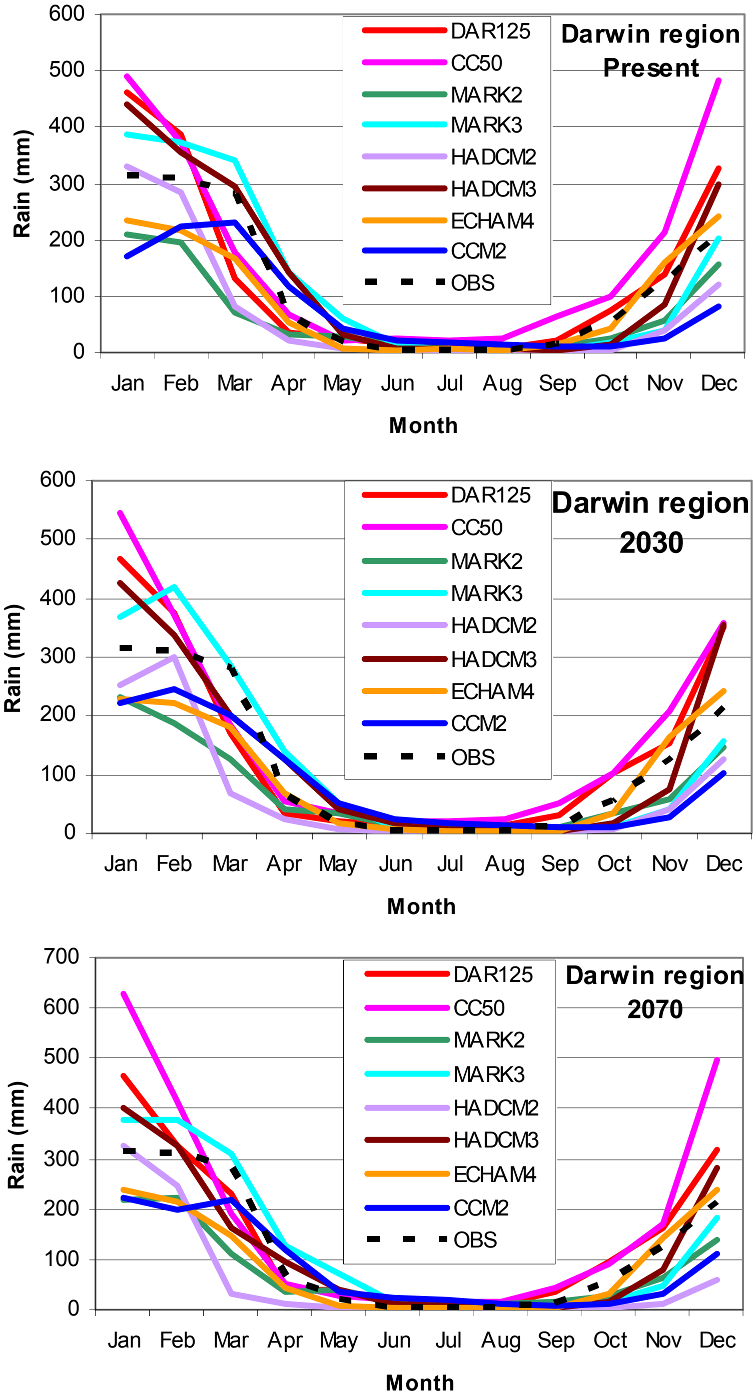


Figure 29: Observed (1961-1990) versus simulated monthly-average rainfall over the Darwin region (12-14°S, 130-132°E) for present, 2030 and 2070.

To simplify the information in Figure 29, the monthly results from each of the eight models has been averaged (Figure 30). This indicates, firstly, that the 8-model-average gives a good simulation of observed rainfall in February and from April to November, but slightly overestimates December and January rain and slightly underestimates March rain. Secondly, comparison of simulations for the three 15-year periods suggests little change in the timing and magnitude of average monthly rainfall in future.

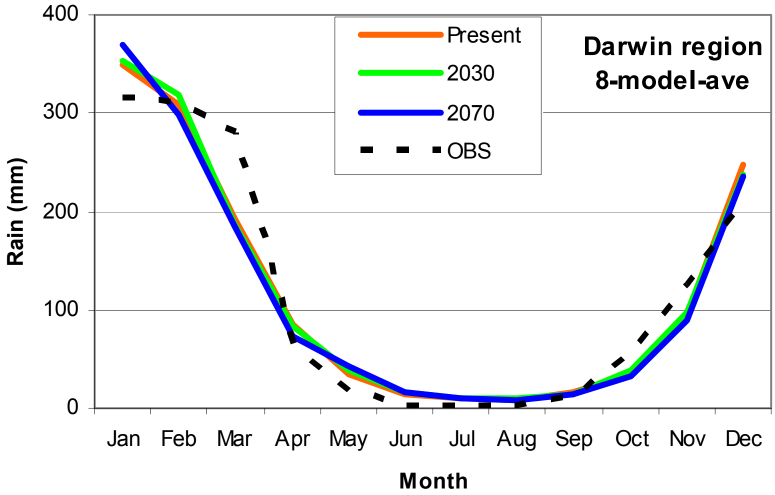


Figure 30: Observed (1961-1990) and simulated monthly-average rainfall over the Darwin region (12-14°S, 130-132°E) averaged over 8 models for present, 2030 and 2070.

A similar analysis was done for a 200 x 200 km region centred on Alice Springs where the wet season is clearly less intense than in Darwin. Figure 31 shows the eight model simulations for present conditions (1961-1990). Again, there is not an obvious "best" model, so all are treated equally. There is a tendency for most models to overestimate rainfall slightly (by 5 to 20 mm per month), as seen in the 8-model-average results (Figure 32). Diagnosing the cause would require analysis of regional pressure data. In 2030 and 2070, most models simulate drier conditions, especially from July to October. The magnitude of wet-season (Nov-Apr) rainfall shows little change in future, although there is a small decline in November and December suggesting a slight delay to the start of the wet-season.

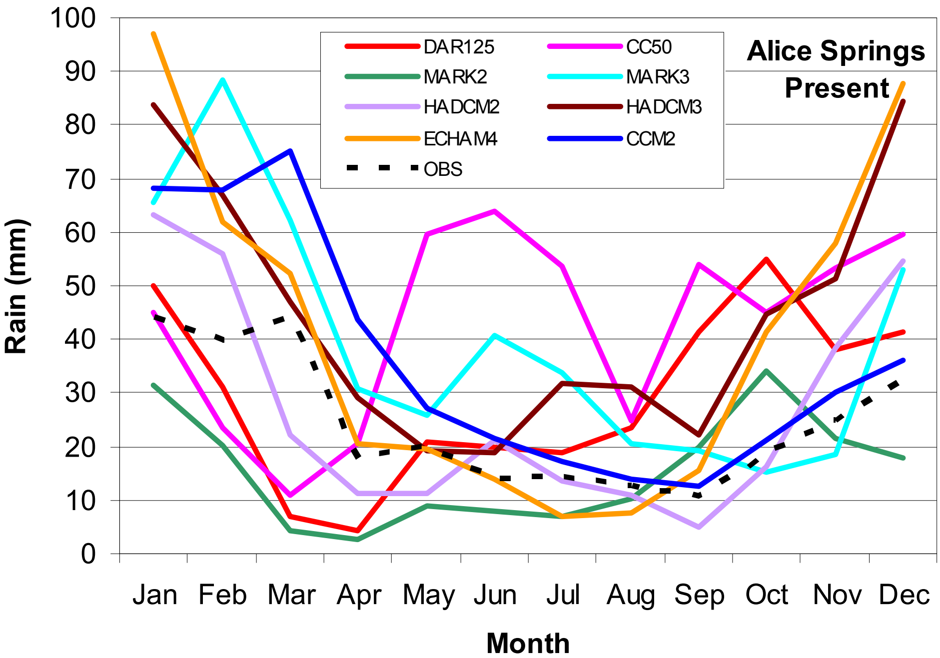


Figure 31: Observed versus simulated monthly-average rainfall over the Alice Springs region (23-25°S, 130-132°E) for present conditions (1961-90).

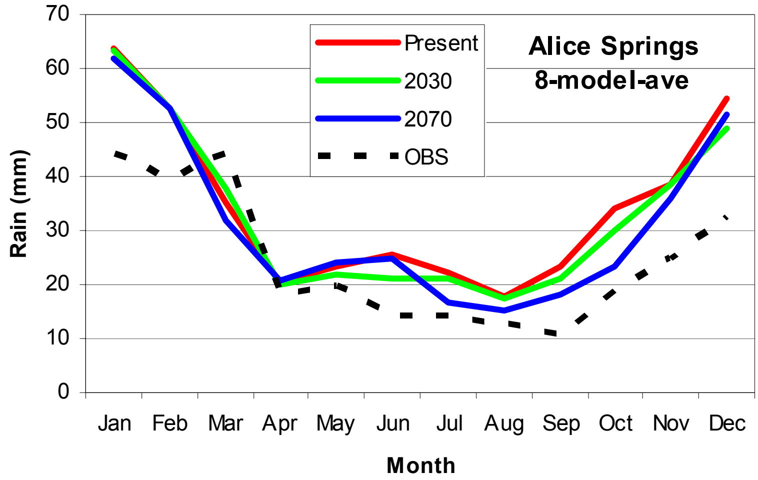


Figure 32: Observed (1961-1990) and simulated monthly-average rainfall over the Alice Springs region (23-25°S, 130-132°E) averaged over 8 models for present, 2030 and 2070.

8. Tropical cyclones and storm surges

This section provides a review of existing information about historical and future changes in tropical cyclones and storm surges.

8.1 Tropical cyclones

A summary of historical trends in cyclone paths, numbers and intensities in the Australian region will be presented, as well as possible future changes in cyclone characteristics. In addition, some results will be shown specifically for the Northern Territory.

The Northern Territory region was defined as spanning the longitudes 129°E – 138°E. The cyclone season was defined by the year in which each season begins (i.e. the 1967 cyclone season lasted from 1 July 1967 to 30 June 1968). Tropical cyclone data were from the Bureau of Meteorology. Storms were classified as "cyclones" if they had central pressures of less than 1000 hPa.

Current trends in cyclone numbers and tracks

Figure 33 shows tracks of cyclones in the Australian region for the cyclone seasons 1967-2000. Cyclones are most frequent off the east coast of Queensland near the latitude of Cairns, in the Gulf of Carpentaria, and off the Western Australian coast north of Carnarvon. They occur less frequently in the Arafura Sea.

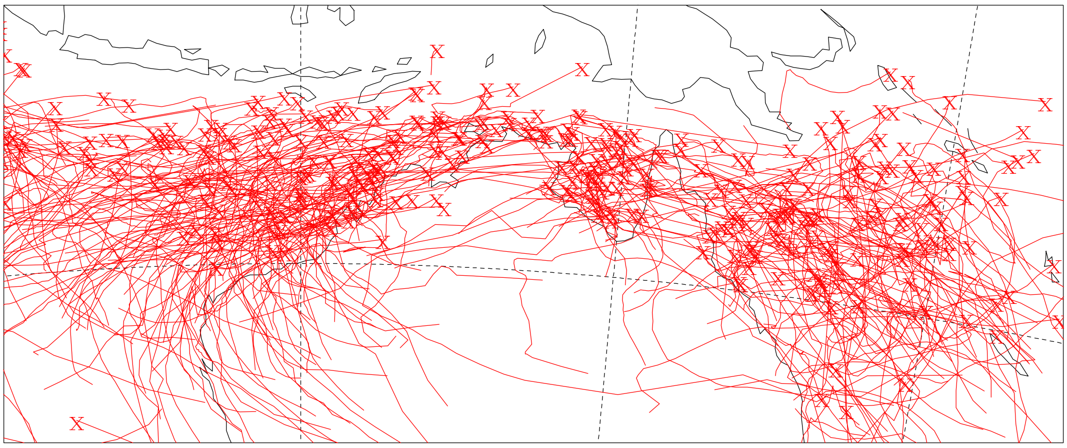


Figure 33: Tracks of every fifth cyclone in the Australian region, 1967-2000 cyclone seasons.

Trends in tropical cyclones are difficult to detect because of the high year-to-year and decade-to-decade variations in their numbers in the Australian region. This has been widely documented by many authors (Nicholls, 1979, 1984, 1985, 1992; Basher and Zheng, 1995). Also, because tropical cyclones are rare events, the observational record to date in the Australian region (about forty years of reliable data since the advent of satellite tracking) is too short to establish the actual incidence of tropical cyclones at every location. Attempts have been made to infer the true tropical cyclone incidence from debris fields left by past cyclones (e.g. Nott and Hayne 2001), but it remains to be seen whether these techniques will give reliable results.

Nicholls *et al.* (1998) showed that there has been a slight downward trend in tropical cyclone numbers in the Australian region (Figure 34). However, this decline is much less pronounced for storms west of longitude 138°E (the Northern Territory's eastern border). The decline is partly attributed to an improved discrimination between tropical cyclones and other low pressure systems, leading to a sudden drop in the number of weak cyclones in the mid-1980s. If weak cyclones are excluded from the analysis, the trend is more gradual and mainly follows the downward trend in the Southern Oscillation Index, i.e. there have been more El Niños since the mid-1970s. The number of intense cyclones (with minimum pressure less than 970 hPa) has increased. This does not appear to be attributable to improved discrimination between cyclones or trends in the Southern Oscillation Index (Nicholls *et al.*, 1998)

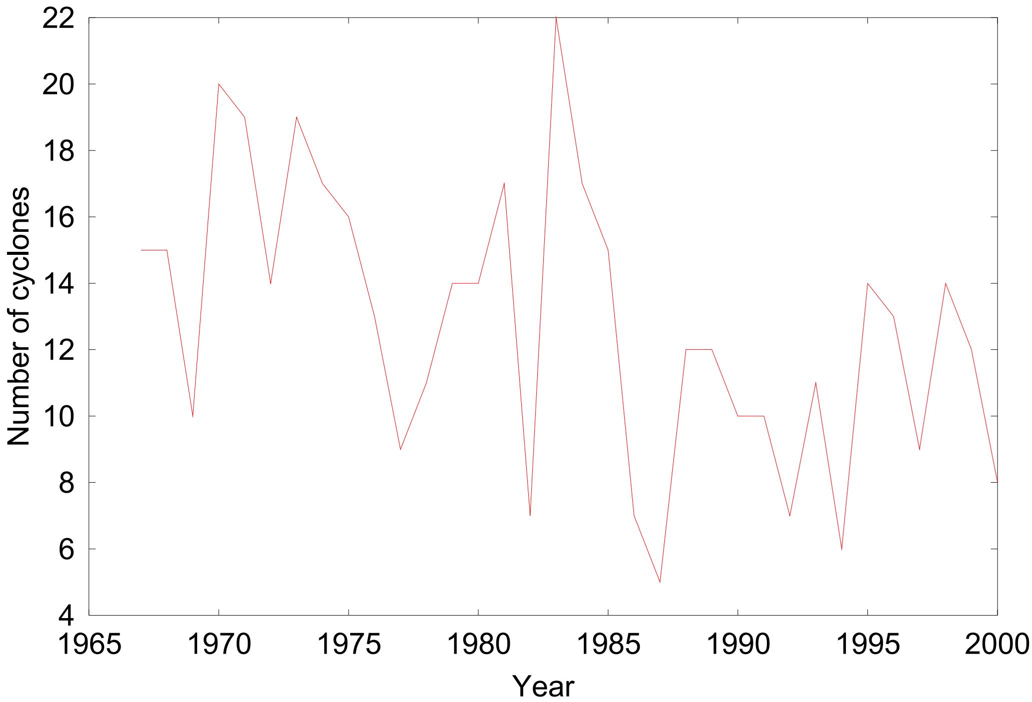
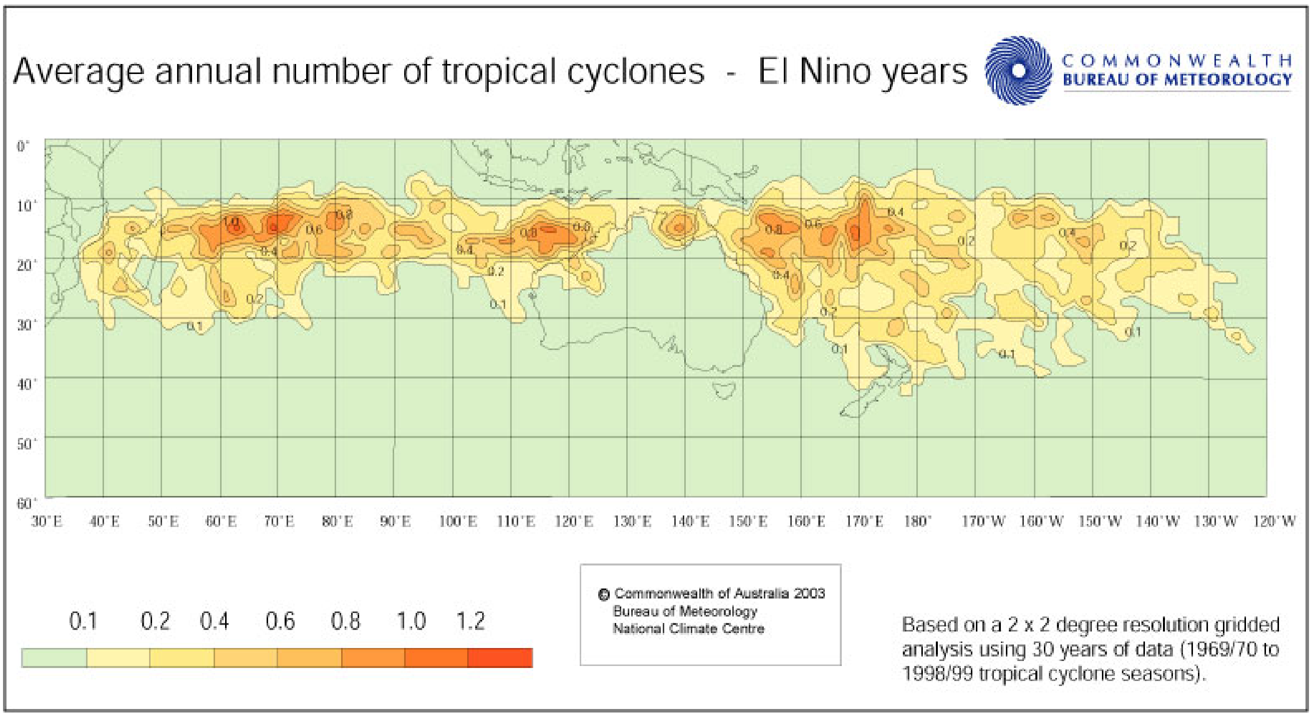


Figure 34: Cyclone numbers in the Australian region, 1967-2000 cyclone seasons.

The El Niño-Southern Oscillation (ENSO) phenomenon has a large impact on cyclone incidence. The Southern Oscillation Index (SOI) is a common measure of ENSO behaviour. Figure 35 shows a comparison between cyclone tracks for strong La Niña conditions (SOI greater than 10) and strong El Niño conditions (SOI less than -10). There is clearly a larger number of cyclones close to the Australian coastline during La Niñas. Over the entire Australian formation region, correlations between cyclone formation and the SOI are strong: for the period 1967-2000, the correlation is 0.61, which is highly significant. West of longitude 138^{o}E, the correlation is still strong, at 0.54.

In the Northern Territory region, on average, there are 2.0 cyclones per year during strong La Niñas versus 1.8 during strong El Niño years. This is not a statistically significant difference because the sample size (number of cyclones) is small in this subset of the Australian region. Likewise, there is no significant correlation between cyclone numbers in this region and the SOI, but again this may be due to the fact that it is a small region with insufficient cyclones for good statistics.

There has been a decrease in tropical cyclone incidence in the Australian and Northern Territory regions. More cyclones crossed land regions in the Territory during the period 1967-1981 (average of 2.5 per year) than during 1982-1996 (average of 1.7 per year). This difference is statistically significant at the 95% confidence level and is probably related to the larger number of El Niños that occurred in the latter period. Inter-decadal variations in tropical cyclone numbers were also found off the east coast of Queensland by Grant and Walsh (2001).



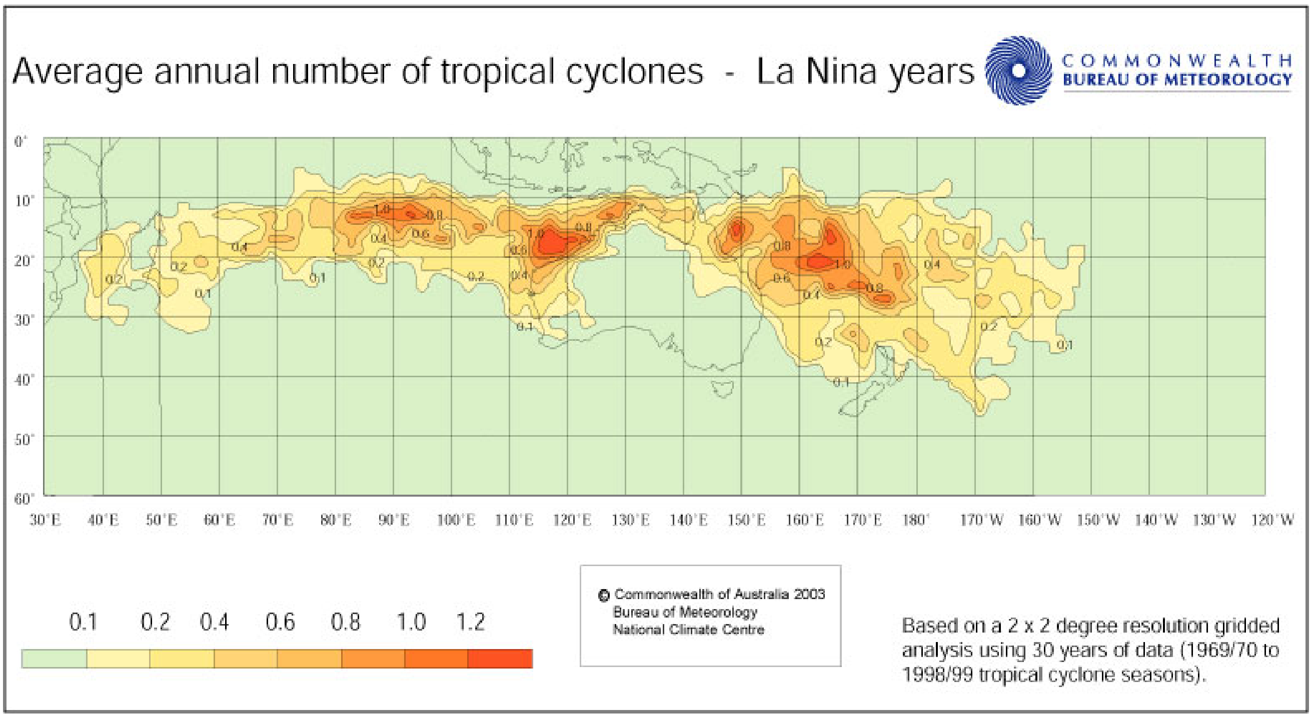


Figure 35: Average occurrence of tropical cyclones in the Australia region (top) El Niño years; (bottom) La Niña years. Source: Bureau of Meteorology.

Cyclone intensities

There have been significant increases in average intensities (i.e. maximum wind speeds) of tropical cyclones in the Australian region since 1967. Figure 36 shows the trend in average cyclone intensity per season over this period, with a clear decrease in average central pressures during this time indicating an increase in cyclone intensities. Reasons for this are not clear. It is premature to ascribe this result to a climate change without considerably more investigation.

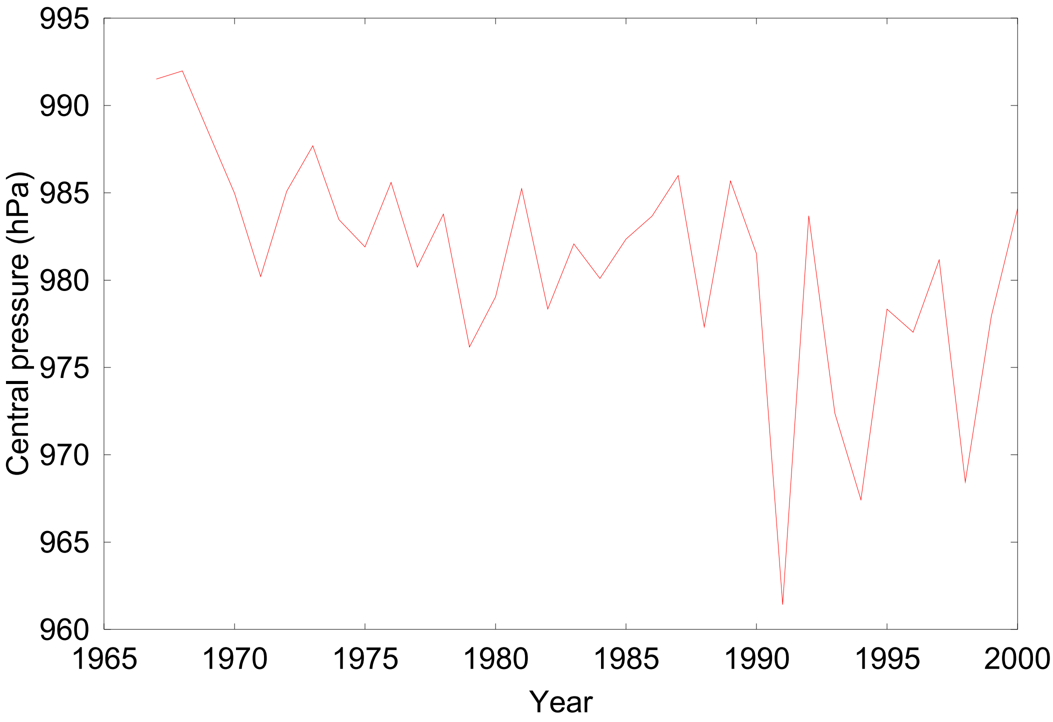


Figure 36: Average cyclone central pressure per cyclone season in the Australian region, 1967-2000. Decreasing values indicates more intense cyclones.

Future trends in cyclone numbers and tracks

Future trends in tropical cyclone numbers and tracks are unclear. The main difficulty is that despite many years of work, it is still uncertain whether ENSO will change in a warmer world. Opinions on this topic differ considerably (Tsonis *et al.*, 2003; Karl and Trenberth, 2003). A number of climate model simulations indicate a change to a more "El Niño-like" climate in a warmer world (Giorgi *et al.*, 2001), but this is not a firm conclusion. Since ENSO has a strong effect on tropical cyclone numbers in the Australian region, this creates considerable uncertainty about future predictions.

Future trends in cyclone intensities

There is more convincing evidence of future increases in cyclone intensities (Giorgi *et al.* 2001; Walsh 2004). The main physical argument is that with projected increases in sea surface temperatures, more energy is available for tropical cyclones and thus maximum storm intensities increase. Both theoretical techniques and model simulations support this view. However, climate models of tropical cyclones to date have been run with horizontal resolutions no finer than 18 km, which is relatively coarse compared with the actual processes taking place in tropical cyclones. Other model experiments suggest that resolutions finer than 5 km are needed to fully capture the important processes for intensity changes in tropical cyclones.

Another important effect of global warming on tropical cyclones is a possible increase in maximum rainfall amounts. Both Knutson and Tuleya (1999) and Walsh and Ryan (2000) simulate increases in tropical cyclone rainfall rates of about 25% by the late 21st century. Extreme winds (defined as the top 1% of wind speeds) in the DAR125 model have been examined over two 40-year periods centred on 1980 and 2030. Figure 37 shows the difference in extreme wind-speeds between the two intervals and indicates that extreme winds increase across much of tropical northern Australia during December to February. This is probably due to the occurrence of more intense cyclones in the model during the 40 years centred on 2030.

The combination of sea level rise, stronger wind speeds and more intense rainfall may lead to more significant coastal impacts due to tropical cyclones. It is unlikely that these impacts would be noticeable before about 2050, as the current interannual variability will remain larger than the climate change effect until then. After 2050, impacts should start to become more apparent (Walsh 2004).

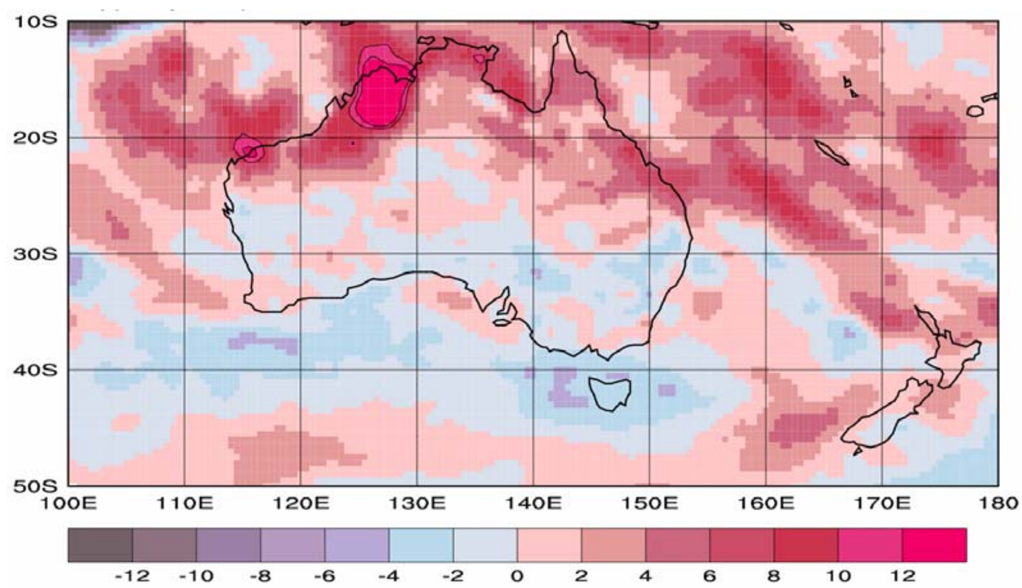


Figure 37: Percent changes in December-February extreme wind speeds (top 1% each summer) between the period 1961-2000 and 2010-2050 from the DAR125 climate model.

8.2 Storm surges

Tropical cyclones, in addition to producing devastating winds and rainfall, also generate adverse oceanic conditions including storm surges and extreme waves. A storm surge is a temporary elevation in sea level lasting from several hours to a day brought about by the intense onshore winds and falling atmospheric pressure of a tropical cyclone as it approaches or crosses the coast. Storm surges can produce severe coastal flooding and bring sea waves further inland, which enables the destructive effects of breaking waves to erode the coastline and damage or destroy infrastructure. Where riverine flooding occurs, storm surges can worsen the upstream flooding by slowing the drainage of rivers and streams.

The severity of a storm surge depends on a number of factors. The first set of factors relates to the characteristics of the tropical cyclone and include:

- Intensity (usually measured by the minimum central pressure or the maximum wind speed attained);
- Size (distance from the cyclone centre to the radius of maximum winds);
- Translation speed (horizontal movement of cyclone);
- Proximity and direction of movement relative to the coast.

Other factors influencing storm surges include the depth of the adjacent ocean, the shape of the coastline and the presence of offshore islands. Wide continental shelves amplify storm surges by slowing the ocean currents thereby increasing water depth. Storm surges can also be increased in bays and inlets where ocean currents become channelled towards the shore.

In addition to the increase in sea level due to storm surge, the increased frequency of breaking waves also can contribute to a temporary net increase in sea level known as wave setup. This is distinct from wave run-up which is the maximum inland penetration of sea water that occurs as a wave breaks. All these effects are worsened when the storm surge coincides with high tide. Figure 37 illustrates the various contributions to sea levels at the coast.

The coastline and islands of the Northern Territory are prone to storm surges due to the relatively shallow coastal waters across northern Australia. For example, a storm surge of 6.6 m above normal tide level, occurred at Groote Eylandt in 1923 (NTLIS, 2004). The storm surge caused by Cyclone Tracy was 1.6 m, although (fortunately) it did not coincide with high tide. Approximately two cyclones occur per year in the Gulf of Carpentaria while about one cyclone per year occurs in the Arafura or Timor Seas.

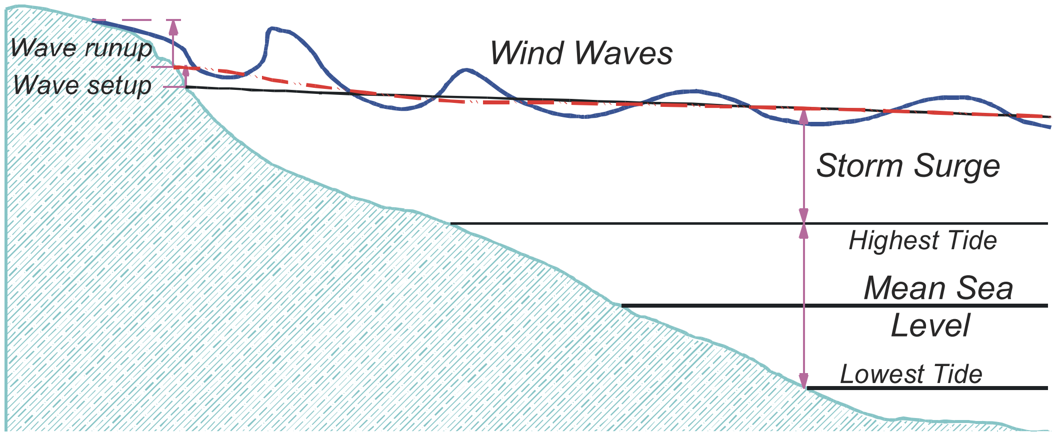


Figure 38: Contributions to sea level due to tides, storm surge and wind-generated waves.

Storm surge return periods provide information on the average time between storm surges of a given magnitude. Return period analysis for storm surges usually requires sophisticated statistical techniques combined with hydrodynamic modelling. This is because cyclones and their associated surges at a given location are sufficiently rare that there are insufficient measurements (e.g. tide gauge records) to provide a reliable estimation of their frequency and magnitude. A study by VIPAC Ltd (1994) utilised wave models, hydrodynamic models to represent tides and currents, and statistical representation of historical cyclone behaviour to determine storm surge return periods near Darwin. It did not consider climate change impacts on cyclones or sea-level rise. Table 4 indicates that the 1-in-100 year surge height is 4.2-5.5 m, the 1-in-1,000 year surge is 4.8-6.7 m, and the 1-in-10,000 year surge is 5.4-7.9 m. These results are relative to mean sea-level, and include the astronomical tidal range of about 4 metres (above and below mean sea-level). Therefore, according to Table 4, the 1-in-100 year storm surge adds 0.2-1.5 metres to the highest astronomical tide, the 1-in-1000 year surge adds 0.8-2.7 metres, and the 1-in-10,000 year surge adds 1.4-3.9 metres.

There have been no studies to date that address the potential effects of cyclone intensity increases on storm surges in the Northern Territory. However, one such study has been undertaken for Cairns (McInnes *et al.*, 2003). In that study, it was found that the 1-in-100 year storm tide event under current climate conditions became a 1-in-55 year event when projected cyclone intensity changes in the Coral Sea were incorporated. The intensity changes were based upon climate model results of Walsh and Ryan (2000).

Global-average sea level is projected to increase by 5-15 cm by 2030, 10-50 cm by 2070 and 9-88 cm by the year 2100 (IPCC, 2001a). Applying a mid-range sea-level rise estimate of about 25 cm by the year 2050 to the Cairns region reduced the return period to 1-in-40 years. The area of Cairns inundated by the top 5% of storm surge events more than doubled. Because of the site-specific nature of storm surges, the Cairns results cannot be extrapolated to other regions. However, the likely increase in cyclone intensity and sea-level would be expected to increase storm surge heights affecting the Northern Territory.

A recent reconstruction of global sea-level from 1950 to 2000 (Church *et al.*, in press) indicates that Darwin sea-level has risen 0.8 mm per year relative to land-based tide gauges. When allowance is made for the fact that the land at Darwin is rising by 0.4 mm per year (due to rebound from the last ice-age), then the absolute sea-level rise is 1.2 mm per year. Darwin is in a region with less than the global-average rate of rise, when corrections for land movement are included. The lower rise at Darwin compared with the global average is a result of more frequent, persistent and intense El Niño events in the last two decades.

The most recent sea level data for Darwin up to about 2002 (Church, personal communication) gives a rise of 1.5 mm per year relative to land-based tide gauges (over about 1959 to 2002) because the latest data show a rapid rate of rise. This contrasts with the value of -0.02 mm per year from an earlier study by the National Tidal Facility (Mitchell *et al.*, 2000) which was over a shorter period, ending in 1997 with a low sea level during an El Niño event. This stresses the need to always use the longest records available to minimise the effect of interannual variability.

Table 4: Storm tide heights (m) for return periods (RP) of 100, 1,000 and 10,000 years relative to mean sea level at various Darwin locations (VIPAC Ltd., 1994). The highest astronomical tide is about 4 metres every 18.6 years.

STORM TIDE PREDICTIONS (Cyclone Storm Surge plus Wave Set-Up plus Astronomical Tide)			
Location	**Storm tide height (m)**		
	100-year RP	**1,000-year RP**	**10,000-year RP**
Point Blaze	5.0	6.0	7.1
Fog Bay	5.1	6.3	7.5
Native Point	5.2	6.4	7.6
Bynoe Harbour	5.3	6.6	7.8
Masson Point	5.5	6.7	7.9
Charles Point	4.6	5.6	6.6
West Point	5.1	6.4	7.5
West Arm	5.1	6.4	7.6
Channel Island	5.1	6.4	7.7
Wickham Point	5.1	6.4	7.7
East Arm PORT	4.9	6.0	7.0
Darwin South SEAWALL	5.0	6.2	7.4
Fannie Bay	5.2	6.4	7.6
Casuarina Beach	5.3	6.6	7.8
Lee Point	4.5	5.5	6.5
Shoal Bay	5.1	6.3	7.5
Gunn Point	4.5	5.3	6.2
Point Stephens	4.2	4.8	5.4

9. Potential impacts and adaptation

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.*

9.1 Summary of Northern Territory climate change

Based on the results described in Chapters 7 and 8, average temperatures over the Northern Territory are projected to increase by 0.2 to 2.2°C by 2030, and 0.8 to 7.2°C by 2070, relative to 1990. Least warming is expected over the Top End and most warming in the south-west, especially in November to April. There would be associated increases in potential evaporation and heatwaves, and fewer frosts in the south during winter. Wet-season rainfall (Nov-Apr) is expected to decrease over most of the Territory (-16 to +8% by 2030, -40% to +20% by 2070), with little change in a 400-km-wide strip running from Darwin to Camooweal (±8% by 2030 and ±20% by 2070). Dry-season rainfall (May-Oct) is likely to decrease also (-20% to +8% by 2030, -60% to +20% by 2070), except near Darwin which has a tendency for wetter condition (-8% to +20% by 2030, -20% to +60% by 2070). When rainfall changes are combined with increases in potential evaporation, a general decrease in available atmospheric moisture is projected. In Nov-Apr, the moisture balance south of Daly Waters declines 30-130 mm by 2030 and 90-400 mm by 2070, with smaller decreases in the north (mostly 10-80 mm by 2030 and 50-240 mm by 2070). In May-Oct, moisture balance declines 20-100 mm by 2030 and 70-320 mm by 2070, with smaller decreases in the far south and Top End (10-80 mm by 2030 and 50-240 mm by 2070). Droughts are likely to become more frequent and more severe where moisture balance declines.

Since most climate impacts are due to extreme weather events, future changes in extreme events need to be considered. By 2030, the average number of days over 35°C at coastal sites is expected to rise by 1-51 days. Inland, the increase is likely to be 5-30 days in the south, 5-40 days in the north and 5-70 days in the centre. The intensity of tropical cyclones is likely to increase. This, combined with a sea-level rise 5-15 cm by 2030 and 10-50 cm by 2070, would increase coastal inundation due to storm surges. The frequency of heavy rainfall and inland flooding may also increase.

9.2 Potential impacts and adaptation for the Northern Territory

The best source of information on climate change impacts for Australia is the guide by Pittock (2003), released by the Australian Greenhouse Office in December 2003. While the guide contains substantial material on impacts for most of Australia, there is limited information for the Northern Territory, reflecting a paucity of research on impacts for this region. One of the main recommendations of this report is the need to address these information gaps.

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 2, 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 39). Most Australian climate change impact assessments on natural or human systems 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.

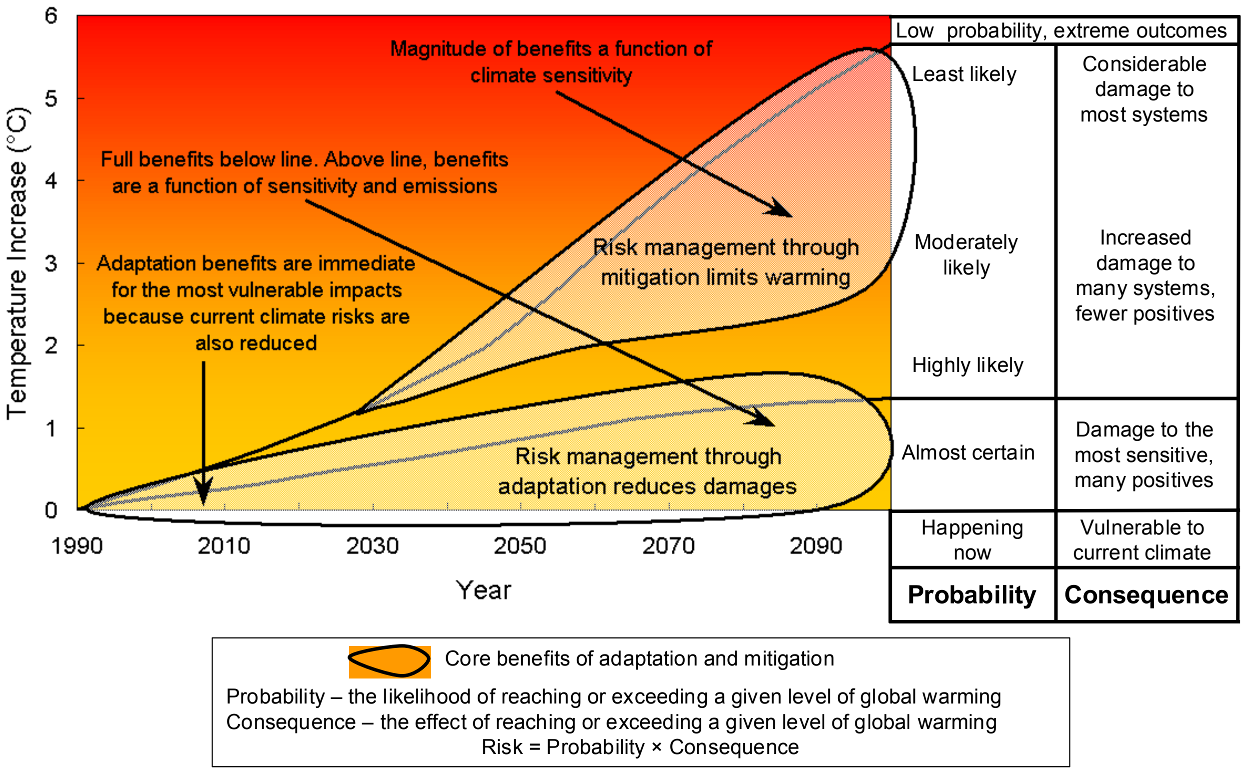


Figure 39: Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on six greenhouse gas emission scenarios with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold exceedance as a function 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 Pittock *et al.* (2003).

The following summary of impacts and adaptation is drawn from Pittock (2003). In addition to Territory-specific assessments, information for other regions is presented where it is considered relevant to the Territory. The following sectors will be addressed:

- Water resources;
- Ecosystems;
- Agriculture, livestock and fisheries;
- Settlements and industry;
- Human health.

Water resources

Increased evaporation and decreased rainfall in many areas would adversely affect water supply, agriculture, and the survival and reproduction of key species. Water quality may also be affected due to increased soil erosion following drought, lower flows and higher water temperatures, leading to more eutrophication and algal blooms. The climate of 2002-2003 highlighted the impacts of an unusually hot drought including a 30% reduction in 2002-2003 agricultural output equivalent to 1% of GDP, flow-on effects to rest of the economy which lowered GDP a further 0.6%, loss of 70,000 jobs, a federal government drought relief package totalling $728 million over three years for farmers and businesses affected in rural regions, widespread bushfires, large dust storms, low dam levels and water restrictions (Adams et al., 2003). Water resource managers and users will be increasingly vulnerable if droughts become more frequent or more intense in future. This is more likely in the southern two-thirds of the Northern Territory in Nov-Apr where the moisture balance deficit is already large (Figure 10), and is projected to decrease most (Figure 28). In some areas, water resources are already stressed and highly vulnerable, with intense competition for water between agriculture, power generation, urban areas and environmental flows.

Ecosystems

Many Australian species have evolved to cope with large year-to-year variability, but not to long-term change in the average climate. Australian ecosystems are therefore vulnerable to climatic change, as well as to other threats including invasion by exotic animals and plants introduced by human activity. This vulnerability has been exacerbated by fragmentation of ecosystems through land-use changes. A warming of 1°C would threaten the survival of species currently living near the upper limit of their temperature range. Species that have restricted climatic niches and are unable to migrate because of fragmentation of the landscape, soil differences, or topography could become endangered or extinct. Other ecosystems that are particularly threatened by climate change include coral reefs and freshwater wetlands in the coastal zone and inland. In some cases, natural adaptation processes may be very accommodating, whereas in others adaptation may be very limited, particularly in landscapes fragmented by human activities. Thomas *et al.* (2004) studied the effect of global warming on 1003 species in six regions, including Australia, by 2050. They found that 15-35% of species would be committed to extinction. Most of the Australian species considered were in Queensland.

Hughes (2004) reviewed climate change impacts on Australian ecosystems. Significant impacts were found for most vegetation types that have been modelled to date, although the benefits of carbon dioxide fertilisation have rarely been included in models. Limited information is available about the impacts of climate change on ecosystems in the Northern Territory. The Tropical Savannas CRC is quantifying carbon stocks and carbon cycling in northern Australian tropical savannas, with a view to determining how these are influenced by climate change, grazing, fire and tree clearing. The CRC is also studying water and carbon exchange in tropical savannas, but there is no link to climate change at this stage. Changes in temperature and rainfall regimes may also change fruiting and flowering phenology. This may affect habitat suitability for consumer animals (e.g. parrots, honeyeaters, bats, rodents, ants).

Fire is a major factor driving ecology in northern and central Australia, with a range of fire-sensitive species and environments. Climate change is likely to alter existing fire regimes, through changes in the amount and extent of rainfall patterns, changes in fuel load (growth, curing rates and composition of grasses), changes in wind regimes, and possible changes in ignition patterns (i.e. lightning).

The Commonwealth Government's Biological Diversity Advisory Committee commissioned a workshop of scientists and policy makers to examine the impacts of climate change on Australian biodiversity (Howden et al, 2003a). The workshop concluded that climate change is already having an impact on biodiversity, the impacts will increase dramatically within decades, and there are many options for mitigation. Priorities for action included:

1. Understanding and managing for climate variability
2. Immediate preservation of components of biodiversity that are sensitive to climate change
3. Facilitating long-term adaptation
4. Monitoring research, and policy development
5. Mitigating climate change and reducing other pressures on biodiversity.

The report noted:

- Dramatic expansion of some tidal creek systems in the Northern Territory has occurred since 1940. In the Lower Mary River system, two creeks have extended more than 4 km inland, invading freshwater wetlands. Rates of extension of saltwater ecosystems inland have exceeded 0.5 km/yr. Over 17,000 ha of freshwater wetlands have been adversely affected and a further 35-40% of the plains is immediately threatened. The report states "multiple causes are likely, but include sea-level rise".
- Low relief in these wetlands means that even small rises in sea level could result in large areas being affected by saltwater intrusion, leading to an expansion of the estuarine wetland system at the expense of the present-day freshwater wetlands.

Specific threats to wetlands from climate change and sea-level rise have been studied as part of a national vulnerability assessment (Waterman, 1996). The best example is provided for Kakadu National Park. World Heritage and Ramsar Convention-recognised freshwater wetlands in this park could become saline, given current projections of sea-level rise and climate change (Bayliss *et al.*, 1997; Eliot *et al.*, 1999). Coastal wetlands are nursery areas for many commercially important fish (e.g. barramundi), prawns and mudcrabs, so wetland survival is also important for the fishing industry. Changes in vegetation and animal populations in

Kakadu would have cultural, social and economic consequences for the Aboriginal and non-Aboriginal people living in or visiting the area (Finlayson, 2003). The responses that may be necessary are:

1. Systematic examination of perceptions and values with respect to management of the region
2. Responsibility and accountability for increased natural hazards, e.g. tropical cyclones
3. Broader and transparent governance structures and processes
4. Balance between economic imperatives and ecological conditions
5. Improved access to existing information
6. Environmental investigation, including research and monitoring.

Australia has the third-largest mangrove area in the world, covering an area of 8,195 km^2, of which 36% is in the Northern Territory (Zann, 1995). Mangroves are valued for the habitat they provide for a diversity of marine organisms including commercial species such as fish and mud crabs, their ability to stabilise and trap sediments, and their protection of inland areas from storm surges and flooding (Ellison, 2003). A rise in temperature and carbon dioxide would increase mangrove productivity and expand ranges into higher latitudes. However, the more dominant response is likely to be the retreat of mangroves due to sea-level rise. Monitoring of Australian mangroves is needed to allow early detection of climate change impacts.

There are also a number of water-dependent systems other than mangroves and floodplains, e.g. spring-fed rainforests and riparian areas. Any change in rainfall patterns would affect such distinctive environments.

Agriculture, livestock and fisheries

Rural industries in the Northern Territory comprise cattle and other livestock (including buffalo, poultry, pigs, crocodiles and camels), horticulture (fruit, vegetables, nursery and cut flowers) and crops (field crops, hay and seed) (DBIRD, 2003). Fisheries comprise wildstock harvesting, aquaculture and recreational fishing. The value of rural and fisheries industries was $309.8 million in 2002. Cattle was worth $184 million, fisheries $101 million, horticulture $85.7 million, other livestock $13.5 million and field crops $6.6 million. Forestry is developing, with a major *Acacia mangium* plantation (for pulp) on the Tiwi islands.

Agriculture is sensitive to changes in climate, water availability, carbon dioxide fertilisation, pests and diseases. Agricultural activities are vulnerable to projected regional reductions in rainfall, and are especially threatened by general warming that will increase evaporation and water demand. Drought frequency and severity, and consequent stresses on agriculture, are likely to increase in many agricultural regions in Australia. Higher temperatures are likely to cause heat stress in many plants, and some horticultural crops (e.g. mangos and grapes) may experience inadequate winter chilling, leading to lighter yields. Enhanced plant growth and water-use efficiency resulting from higher carbon dioxide may provide initial benefits that offset any negative impacts from climate change, although the balance is expected to become negative with warmings in excess of 2-4°C and associated reductions in atmospheric moisture. Thus by the mid to late 21st century, the net effects on agriculture of changes in carbon dioxide and climate are likely to be negative.

According to the review by Hughes (2004), the interaction between elevated carbon dioxide and water supply will be especially critical for grasslands and rangelands where about 90% of the variance in primary production can be accounted for by annual precipitation (Campbell *et al.,* 1997). Howden *et al.* (1999a) found that an average 10% reduction in rainfall could counter the beneficial effect of a doubled carbon dioxide concentration. A 20% reduction in rainfall at doubled CO_2 concentrations is likely to reduce pasture productivity by about 15% and live-weight gain in cattle by 12% and substantially increase variability in stocking rates. Simulations by Howden *et al.* (1999b, c) for native pastures showed that the beneficial effects of doubling CO_2 are stronger in dry years, but that nitrogen limitations may reduce the potential benefits.

Heat stress in beef cattle will increase further with greenhouse-induced global warming. Howden and Turnpenny (1997) suggest a need for further selection for cattle lines with greater thermoregulatory control, but they point out that this could be difficult because it may not be consistent with high production potential (Finch *et al.*, 1982, 1984). The vulnerability of the Australian beef industry to impacts of the cattle tick (*Boophilus microplus*) under various climate change scenarios was investigated by White *et al.* (2004). They considered impacts on European, zebu and cross-bred cattle having different levels of resistance to cattle ticks. In the absence of adaptation measures, projected losses in live-weight gain ranged from 7,800 tonnes per year by 2030 to 21,600 tonnes per year by 2100, compared to present estimated losses of 6,600 tonnes per year. The principal adaptation options available to the beef industry are to switch to more resistant breeds, or to increase the frequency of tick control treatment. Switching to optimal breeds greatly reduced the losses due to ticks, even taking them below the present loss rate overall.

In Australia, plant diseases cause significant losses in yield and quality of primary production in both natural and managed systems, with significant economic penalties (Chakraborty *et al.*, 1998). Impacts of climate change will be felt in altered geographical distributions of crop losses due to changes in the physiology of host-pathogen interaction. Changes will occur in the type, amount and relative importance of pathogens and diseases. Uncertainties about the exact location-specific nature of the climatic changes, and about specific host-pathogen behaviour, limit the ability to predict specific and overall impacts (Chakraborty *et al.*, 1998). Other key uncertainties concern reliable indicators of over-wintering success in most species, and how climate may affect interactions between species. Both experimental and modelling approaches are available for impact assessment research.

A summary of the key priorities for climate change adaptation strategies for the main Australian agricultural sectors is presented in Table 5. Mid-latitude regions with adequate water supplies have many options available for adaptation to climate change, in terms of crop types and animal production systems drawn from other climatic zones. However, in the tropics, temperatures will increasingly move outside past bounds, so the productivity of available systems is likely to decline unless genetic modifications can provide new alternatives.

Table 5: A summary of priorities for climate change adaptation strategies for the main Australian agriculture sectors (based on Howden *et al.*, 2003b, with additions from Pittock, 2003).

Cropping

- Develop further risk amelioration approaches (e.g. zero tillage and other minimum disturbance techniques, retaining residue, extending fallows, row spacing, planting density, staggering planting times, erosion control infrastructure) and controlled traffic approaches – even all-weather traffic
- Research and revise soil fertility management (fertiliser application, type and timing, increase legume phase in rotations) on an ongoing basis
- Alter planting schedules to be more opportunistic depending on environmental condition (e.g. soil moisture), climate (e.g. frost risk) and markets
- Further develop warning systems for likelihood of very hot days, drought and high erosion potential
- Select varieties with appropriate thermal time and vernalisation requirements, heat shock resistance, drought tolerance, high protein levels, resistance to new pest and diseases and perhaps varieties that set flowers in hot/windy conditions

Livestock industries – grazing and intensive

- Research and promote greater use of strategic resting of paddocks
- Develop regionally safe carrying capacities i.e. constant conservative stocking rate
- Modify timing of mating based on seasonal conditions
- Develop water use efficiency strategies to manage potentially lower irrigation water availabilities
- Research intensive livestock management in tropical environments particularly dealing with heat stress
- Further selection for cattle lines with greater thermoregulatory control

Horticulture

- Change varieties so they are suited for future conditions and re-assess industry location
- Research on altering management to change bud burst, canopy density, etc., in fruit trees
- Undertake risk assessment to assess sustainability in more marginal areas (e.g. chilling requirements)

Water resources

- Increase monitoring of water use in terms of production and climate rather than area
- Develop probabilistic forecasts of likely water allocation changes
- Develop tools that enhance crop choice (maximise efficiency and profit per unit water)
- Build climate change into integrated catchment management, relevant strategic policies and new infrastructure
- Incorporate climate change into long-term water sharing agreements

Pests, pathogens and parasites

- Systematically map vulnerability of plants and animals to endemic and exotic pests, pathogens and parasites
- Select animal breeds and plant varieties resistant to pests, pathogens and parasites already in Australia
- Strengthen quarantine measures within Australia and at ports of entry

Distributions of about 3,200 species of marine fish broadly mapped by CSIRO show that while many of the species reside in tropical waters less than 4% of tropical species are endemic with well known distributions, compared to 40% of temperate species. Thus, impacts of climate change are expected to be greater on temperate endemics relative to tropical species. However, while tropical species may be wider ranging, they tend to rely on habitats that are rare, e.g. coral reefs and mangrove habitats.

Australian ocean fisheries are influenced by the extent and location of nutrient upwellings governed by prevailing winds and currents. In addition, ENSO influences recruitment of some fish species and the incidence of toxic algal blooms, but the effect of climate change on ENSO is uncertain. Marine aquaculture may be vulnerable as warming coastal waters may adversely affect production. The variability of some fish and prawn species recruitment and catches are correlated with rainfall and river flow in tropical Australia (Platten, 1996; Vance *et al.*, 1985 and 1996), probably due to runoff-driven export of juveniles from estuary nursery beds. Therefore, projected rainfall changes over the Top End may affect some species. There is insufficient knowledge about the impacts of climate change on regional ocean currents and about physical-biological linkages to enable confident predictions of changes in fisheries productivity.

Settlements and industry

The most vulnerable settlements and industries in Australia are those that are subject to flooding, landslides, fires, tropical cyclones and other severe storms. In Australia, around 87% of economic losses due to natural disasters are caused by weather-related events (Table 6) (BTE, 2001). From 1967 to 1999, these losses averaged $942 million per year (in 1999 Australian dollars), mostly due to floods, severe storms and cyclones. The high average cost of cyclones in the Northern Territory includes significant damage associated with Cyclone Tracy in 1974. Consequent revisions to building codes since 1974 have probably reduced the average cost of cyclone damage, along with the decline in cyclone numbers crossing the Northern Territory (see Chapter 8). While only 7% of economic losses came from bushfires, they were the most hazardous type of disaster in terms of deaths and injuries. The estimated cost of deaths and injuries from natural disasters averaged $41 million per year.

Table 6: Average annual cost of Australian natural disasters by State and Territory for the period 1967-1999 (excluding death and injury costs) in 1999 Australian million dollars (BTE, 2001).

State/Terr.	Flood	Severe storms	Cyclones	Earthquakes	Bushfires	Landslides	Total
NSW	128.4	195.8	0.5	141.2	16.8	1.2	484.1
QLD	111.7	37.3	89.9	0	0.4	0	239.2
NT	8.1	0	134.2	0.3	0	0	142.6
VIC	38.5	22.8	0	0	32.4	0	93.6
WA	2.6	11.1	41.6	3.0	4.5	0	62.7
SA	18.1	16.2	0	0	11.9	0	46.2
TAS	6.7	1.1	0	0	11.2	0	18.9
ACT	0	0.1	0	0	0	0	0.1
Total	**314.0**	**284.4**	**266.6**	**144.5**	**77.2**	**1.2**	**1087.4**
% total	28.9	26.2	24.5	13.3	7.1	0.1	100.0

From 1967-1999, there has been a significant increase in the number of disaster events (mainly floods and extreme storms), which may be due to two factors: better reporting of events in more recent times, and increasing population in coastal areas prone to storms (BTE, 2001). A third factor may be climate change (Coleman, 2003). Thus, projected increases in tropical cyclone intensity, storm tides and possible changes in their frequency, along with sea-level rise, would have major impacts. Increased frequency of extreme daily rainfall and fire would increase damages to settlements and infrastructure. The increased risk of exposure to extreme events has strong implications for the insurance industry, with increased premiums possible for clients, insurers and re-insurers, or reduced coverage. This may adversely affect some property values.

Adaptation to natural variability in these cases usually takes the form of planning zones, early warning systems, evacuation plans, emergency services, insurance or engineering standards for buildings and infrastructure. Many of these settlements and structures are designed to last 20-100 years — a timeframe in which climate change may have significant influence. This means that planning zones and design standards should allow for a changing climate.

For the Australian coastline, a guide has been developed to allow for sea-level rise and climate change (May *et al.*, 1998), as well as good practice and coastal engineering guidelines (Institution of Engineers, 1998; RAPI, 1998). Local governments in some parts of Australia are also identifying measures they could implement to adapt to climate change, but such action has not been well documented. For example, stakeholders in the Cairns Great Barrier Reef region are becoming involved in a study to identify climate sensitivities and possible actions to deal with the impacts of climate change (Crimp *et al.*, 2003). CSIRO (2002) published a brochure on climate change and coastal communities that reviews relevant climate change projections and discusses likely impacts and uncertainties.

The rate and nature of degradation of infrastructure is directly related to climatic factors. Computer models have been developed to predict degradation as a function of location, materials, and design and construction factors (Cole *et al.*, 1999a, b, c, d and 2000). Given that such structures are deigned to last at least 50 years, placement, design and construction need to allow for climate change. Any increase in the rate of degradation as a result of climate change may promote additional failures when a severe event occurs. If the intensity or geographical spread of severe climate events changes, this effect may be compounded. Anticipation of future climate change likely to occur during the lifetime of new buildings and infrastructure may have great social and economic benefits, and therefore that climate change should be integrated into all future planning processes, whether public or private (PIA, 2002; Boyle, 2003).

A scoping study by Queensland Transport (1999) identified vulnerabilities for the Queensland transport infrastructure that will require adaptation. Some of these vulnerabilities will have parallels in the Northern Territory. Infrastructure assessed in the report included coastal highways and railways, port installations and operations (as a result of high winds, sea-level rise, and storm surges), inland railways and roads (washouts and high temperatures), and some airports in low-lying areas. Key climate variables considered were extreme rainfall, winds, temperatures, storm surge, flood frequency and severity, sea waves and sea level. Regional projections for each of these variables were created, with levels of confidence, for four regions of Queensland for 2030, 2070, and 2100. Overall, the potential effects of climate change were assessed as noticeable by 2030 and likely to pose significant risks to transport infrastructure by 2070, if no adaptation were undertaken. Setting new standards, in the form of new design criteria and conducting specific assessments in prioritized areas where infrastructure is vulnerable, was recommended for roads and rail under threat of flooding, as well as bridges, and ports. Detailed risk assessments for airports in low-lying coastal locations were also recommended. The buckling of railway lines and melting of road tar may also become more frequent with an increase in the number of hot days.

In tropical Australia, energy demand, essentially for air conditioning, is likely to increase in the warmer seasons (Lowe, 1988; Howden and Crimp 2001). This may require adaptation to reduce demand and / or greater peak generating capacity. However, this increase in demand will be partly offset in southern parts of the Territory by reduced winter demand for heating. The balance between these trends will differ between cities. The effect of higher temperatures is likely to be considerably greater on peak energy demand than on net demand, suggesting that there will be a need to install additional generating capacity over and above that needed to cater for underlying economic growth. A greater frequency of extreme events such as floods, fires and high winds may adversely affect the security and continuity of supply of electricity transmission and other communications systems.

Reduced runoff, higher riverine, estuarine and coastal aquifer salinity, and increased algal blooms would exacerbate water supply and water quality problems in some urban areas, and in a number of smaller inland communities. Some small communities with particular dependence on adversely affected agricultural and tourism industries may be threatened. In the Northern Territory, tourism may be adversely affected by the loss of some freshwater ecosystems in Kakadu due to sea-level rise. Longer and more intense heatwaves in central Australia may shorten the season suitable for outdoor tourism.

Internationally, there has been growing concern about climate change in the insurance and finance industries. The Insurance Australia Group (Coleman, 2003) believes that climate change threatens the insurance industry’s core business, so the industry needs to become proactive by, for example, driving public awareness programs that identify vulnerable areas, researching adaptation strategies to minimise risk, and lobbying governments to enforce building codes. Premium-based incentives can motivate stakeholders to more effectively minimize exposure to disasters (Leigh *et al.* 1998).

Human heath

Climate impacts on health can be direct or indirect. Direct effects include heat stress and the consequences of natural disasters. Indirect effects include disrupted agriculture or increased incidence of vector-borne diseases. Impacts will depend on location and many other factors including health services and the individual and societal capacity to take necessary precautions.

An assessment of Australian health risks posed by climate change (McMichael *et al.*, 2003) was published recently. The report focussed on the years 2020 and 2050. Key findings included:

- Heat-related deaths in people aged over 65 currently average 1100 per year, summed over ten major Australian cities. Including the effect of population growth and aging, the projected warming over the next 50 years may result in 3,000 to 5,000 extra heat-related deaths per year, in the absence of adaptive measures. In Darwin, the present annual number of heat-related deaths in people aged over 65 is only 2. This could increase to between 15 and 22 by 2020, and between 43 and 146 by 2050.
- Extreme rainfall events are expected to increase, leading to more flood-related injuries and deaths. For the baseline period 1970-2001, the Northern Territory had the highest national rate of flood-related deaths at 3.04 per million people, and the highest rate of flood-related injuries at 8.69 per million people. The relative risk of death and injury due to flooding was estimated to increase between 50 and 60% by 2020, with little further change by 2050 due to a drying tendency.
- The "malaria-receptive" zone may expand southward, but there is unlikely to be increased malaria infection provided existing bio-security measures are maintained.
- Suitable conditions for the transmission of dengue fever may extend southward. In the Northern Territory, the current southern limit is latitude 15^{o}S (e.g. Mataranka). The transmission zone could move to 15.5^{o}S (e.g. Birdum) by 2020, and to 16^{o}S (e.g. Daly Waters) by 2050.
- An increase in diarrhoeal disease is anticipated. An average of 624 diarrhoeal admissions is recorded among Aboriginal children at the Alice Springs hospital each year, with a peak between March and May. A warming of 0.5-1.0^{o}C by 2020 would lead to a 3-5% increase in diarrhoeal admissions, while a 1.0-3.5^{o}C warming by 2050 would lead to a 5-18% increase.
- Ross River virus (RRv) is widely distributed throughout Australia. It causes epidemic polyarthritis, which consists of arthritic symptoms that persist for several months or years and can be severe and debilitating. The disease is a significant public health issue in Australia, with 51,761 notifications from 1991 to 2002 (an average of some 4,500 cases per year). There is no treatment for the disease and, in the absence of a vaccine, prevention remains the sole public health strategy. Unlike some other vector-borne diseases, numerous mosquito species are believed to be capable of transmitting the virus, and many different hosts have been suggested. Rising temperatures and changing rainfall patterns are likely to have significant impacts on the transmission of RRv. Further research is required to quantify the risks.

The adverse health impacts of climate change will be greater in lower income populations, especially the elderly, sick and those without access to good housing including air conditioning and adequate fresh water supply. Numerous existing adaptations, such as quarantine and eradication of disease vectors, are available to deal with most changes. Some adaptations may require more energy production or higher water use (e.g. air conditioning), and vector controls may result in reduced population immunity to the disease carried.

Vulnerability

Vulnerability is a result of exposure to hazard and capacity to adapt. Thus, vulnerability will be greatly affected by future changes in demography, economic and institutional capacity, technology and the existence of other stresses. These stresses include invasion by exotic animal and plant species, degradation and fragmentation of natural ecosystems through agricultural and urban development, increased fire frequency and intensity, dryland salinisation, removal of forest cover, and competition for scarce water resources. Soil erosion from dust storms and water runoff may increase due to more severe droughts and loss of vegetative cover, coupled with higher winds and more intense rainfall events. While climate change is just one of many stresses, it may in some cases cause systems to exceed critical management thresholds. Several of these vulnerabilities are likely to interact with each other.

Without a more detailed assessment the key vulnerabilities for the Northern Territory appear to be:
- salt-water intrusion into Kakadu and other freshwater wetlands;
- agricultural commodities and international trade;
- droughts, floods and water supply;
- increased exposure to extreme events such as droughts, cyclones, storm surges and heatwaves;
- infectious diseases like Dengue Fever and Ross River virus.

9.3 Conclusions

Adaptation to climate change will involve significant changes in behaviour. Therefore, the assessment of climate change risks in the future needs to incorporate our understanding of current climate risks. This is the underlying principal of the "bottom up" approach to impact and adaptation studies. In this, the biophysical and socio-economic aspects of risk under current climate are analysed and incorporated into an assessment of how climate and other drivers of change may alter future risks (McInnes *et al.*, 2002).

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

Integration between natural resource sectors is also very important in the long term. For agriculture, the largest challenges are at the landscape rather than the enterprise scale. Agriculture is vulnerable to loss of water supply and salinity, biodiversity is vulnerable to land-use change and the impacts of altered nutrients and pest plant and animals, some areas of coast are vulnerable to increasing sea level and subsidence. The largest challenges are for collaboration across different disciplines, integrating the various biophysical disciplines, economics and social sciences. Priority research areas are identified in Chapter 10.

10. Gaps in knowledge and research priorities

10.1 Climate change projections

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

The climate projections for average temperature, rainfall, potential evaporation and moisture balance incorporate the ranges regional uncertainty simulated by eight climate model simulations, scaled for the years 2030 and 2070 using ranges of global warming uncertainty from the IPCC. Significant uncertainties remain in some of the regional projections, particularly for rainfall over the Top End. This is partly due to the limited number of models available that perform well over the region, and the wide range of uncertainty in global warming. The range of global warming is unlikely to be revised before the next IPCC Assessment in 2007. However, new model simulations are made available every 6-12 months by CSIRO and the IPCC Data Distribution Centre (DDC). Inclusion of a broader range of models that perform well over the Northern Territory may reduce the range of regional uncertainty. In addition, it may be possible to give greater weight to models that perform better in the region, rather than giving equal weight to each model. Probabilities could be assigned to selected threshold values for use in risk assessments.

There may be other climate variables that would be relevant to particular sectors, the analysis of which was beyond the scope of the present study. These could include climate change projections for relative humidity, wind, ocean temperature and sea level.

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

- Extreme rainfall and floods: Most climate models indicate that extreme rainfall will increase due to global warming, even in regions where mean rainfall decreases slightly. Analysis of extreme rainfall for Australia has been limited to a few CSIRO models for which daily rainfall data are available. A broader range of models could be used if a method was developed for estimating changes in extreme rainfall for a given change in average rainfall and global temperature, both of which are readily available for many models. This would enable the preparation of ranges of change in extreme rainfall similar to those provided in this report for average rainfall. Projections could then be developed for sectors where changes in both average and extreme rainfall are essential (e.g. water resources).
- El Nino Southern Oscillation: The IPCC (2001a) report concluded that there was no consensus on how ENSO would be influenced by global warming. This was based on a set of climate models that is now outdated, some of which had poor simulations of present ENSO behaviour. Given the importance of ENSO for Australian climate variability, including droughts, floods, fire and cyclones, an assessment of present and future ENSO behaviour should be undertaken using latest set of climate models available from the IPCC DDC. CSIRO's Mark3 model gives a fairly good simulation of ENSO, due to its enhanced north-south resolution in the Pacific, but some unresolved biases need further research.
- Tropical cyclones: Uncertainty remains about future changes in cyclone intensity, frequency and location. This is partly because most climate models have a relatively coarse grid (approx. 200 km) which inadequately reproduces ENSO and cyclone behaviour. Improved cyclone projections will require simulations using a fine resolution grid (less than 30 km) so that important features can be captured. CSIRO and collaborators have the capacity to undertake these simulations. Cyclone climate simulations in the Australian region have already been done at a resolution of 30 km using CSIRO's regional climate model embedded within the CSIRO Mark 2 global climate model (Walsh et al. 2004). Intensity simulations have been performed at a resolution of 18 km. For reliable cyclone intensity simulations, we need at least 5 km resolution. One option is to embed a fine resolution model over a small region of interest within the CSIRO Mark 3 global climate model. This will be attempted in 2004, but only at 30 km resolution.
- Extreme wind: As with cyclones, the generality of the model results for severe winds needs to be determined by analysing the results of addition models.

- Storm surges: Changes in the frequency and intensity of storm surges will affect coastal inundation. While this has not been assessed for the Northern Territory, CSIRO has quantified these impacts for Cairns. A similar study could be undertaken for specific coastal locations in the Territory.
- Fire: Warmer and drier conditions will increase the risk of fire, but this has not been quantified for the Northern Territory. CSIRO has the capacity to quantify changes in the risk of fire weather, which would complement the research being undertaken on fuel load and carbon exchange by the CRC for Tropical Savannas.

10.2 Risk assessments

As noted in Chapter 9, few climate change risk assessments have been undertaken for the Northern Territory. Given the potential for significant changes in climate, extreme events and sea level, there is a need to consider the vulnerability of various sectors. Building this knowledge underpins the development of adaptation strategies to reduce risks and increase benefits.

Water resources

One of the most robust conclusions of this report is the likely increase in temperature and reduction in moisture available from the atmosphere. These changes will have significant impacts on water supply, demand and quality. The magnitude of these impacts is unknown for the Northern Territory. High priority should be given to quantifying these impacts, and potential adaptation strategies, at the catchment level.

Ecosystems

On a national scale, Howden et al (2003a) identified a number of information gaps related to biodiversity:

- Monitoring indicator organisms;
- Documenting impacts that are already occurring;
- Understanding factors affecting distribution and abundance of species, likely migration rates and identification of migration barriers and refuges;
- Analyses of species, ecosystems and regions most vulnerable to climate change;
- Assessment of adaptation options;
- Analyses of present and future socio-economic costs of climate change impacts on biodiversity with or without adaptations;
- Understanding the factors determining resilience and adaptive capacity of ecosystems;
- Developing policy that is robust to the uncertainties and long response times of climate change impacts.

While some broad-scale biodiversity monitoring is established in the Territory, more attention should be directed at species and environments considered sensitive indicators of climate change. Finlayson and Eliot (2001) have proposed a coastal monitoring program for Northern Australia, especially the wetlands. The program involves formal consultation with relevant community groups and government agencies, identification of major processes and causes of ecological change, implementation of management prescriptions based on results of monitoring and an audit of management outcomes. However the assessment of tropical wetlands is bedevilled by a lack of information, with the exception of a few locations, and the absence of an integrated inventory, assessment and monitoring program (Finlayson, 2003).

Consideration of possible changes in the extent and/or abundance of weed and pest species is required. There is also a need to assess current climatic factors governing plant phenology and associated organisms, and how these may be affected by climate change. Further modelling of the present climatic envelope of a range of species and environments is needed, and modelling of climate change impacts (notably fire).

Agriculture, livestock and fisheries

Chapter 9 provided a summary of current knowledge about the impacts of climate change on Australian agriculture, livestock and fisheries. Few of these studies were specific to the Northern Territory. Most of the studies for tropical Australia have focussed on Queensland. Hence, there is a need for stakeholders to determine the most important issues for the Territory. Climate change impacts on major industries such as cattle, fisheries, mangos and table grapes are likely to be of key concern in the Northern Territory. These industries alone were valued at $371 million in 2002 (DBIRD, 2003).

Priority research issues for cattle include heat stress, pasture productivity, cattle tick and selection of optimal breeds. For mangos and grapes, the research issues include assessing the beneficial effects of higher levels of CO_2 versus the negative effects of higher temperatures and less rainfall.

Changes will occur in the type, amount and relative importance of pests and diseases. Uncertainties about the exact location-specific nature of the climatic changes, and about specific host-pathogen behaviour, limit the ability to predict specific and overall impacts (Chakraborty *et al.*, 1998). Other key uncertainties concern reliable indicators of over-wintering success in most species, and how climate may affect interactions between species. Both experimental and modelling approaches are available for impact assessment research. As the development and implementation of adaptation strategies generally take a long time, more research is urgently needed. For fisheries, there is insufficient knowledge about impacts of climate changes on regional ocean currents, estuaries, freshwater wetlands and physical-biological linkages to enable confident projections of impacts. Given the importance of fisheries in the Territory, this should be a priority research area.

Health

In view of the risk for increased transmission of Dengue Fever and Ross River virus in the Northern Territory, more research is required at the regional level into the ecology of these viruses, its hosts and vectors, and the impact of human activities (such as environmental modification, vector control and preventive education) on reducing the risk of infection. Modelling of the relationship between climatic factors and disease outbreaks would help in the prediction of future potential consequences of climate change.

Settlements and industry

The increased risk of exposure to extreme events has strong implications for many coastal settlements in the Territory, the insurance industry, primary industries, transport, tourism, health and the energy sector. In addition to improved projections for extreme events, research is required to scope the options for revised planning zones, early warning systems, evacuation plans, emergency services, insurance schemes, and energy and engineering standards for buildings and infrastructure.

Integrated assessments

Since climate change is only one of many issues affecting decision-making, other issues should be integrated into risk assessments, e.g. projected changes in demographics, land-use, technology and international trade. Integrated assessments will enable co-benefits and possible clashes of interest to be identified, and the overall least cost and most beneficial strategies chosen. This requires wide understanding of natural and human systems, and consultation with stakeholders so that the human element can be included and stakeholders can identify with strategies to be adopted. Given that uncertainties will always exist, assessments should be set in a risk management framework, where risk is the product of likelihood and consequence.

Costing

Comprehensive regional or cross-sectoral estimates of the costs and benefits of climate are not yet available. While there are likely to be winners and losers, it is almost certain that the costs of impacts and adaptations will increase with increasing global warming. Potential costs and benefits of impacts and adaptation need to be compared with costs and benefits of reducing net greenhouse gas emissions in any overall policy response.

A number of overseas cost-benefit studies have emphasised the likely dominance of the impacts of extreme events, the existence of critical thresholds, and the possibility of large-scale changes to the climate system that could have disastrous impacts. CSIRO has been involved in a few economic assessments for specific climate change impacts, e.g. water and agriculture in the Macquarie River Basin of NSW, and the spread of Queensland fruit-fly. In addition, CSIRO has allocated resources to strategic research on Socio-economic Integration, part of which is dealing with climate change. Therefore, the capacity to undertake cost-benefit analyses is being given high priority in CSIRO. Regional and sectoral analyses could be done for the Northern Territory.

The way forward

CSIRO's Climate Impacts and Adaptation Working Group has the capacity to address these issues, in collaboration with Territory agencies and other partners. Development of detailed research proposals is not within the scope of this study. A stakeholder workshop is recommended in which such issues can be discussed.

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