Australian Government
Australian Greenhouse Office

Climate Change:

An Australian Guide to the Science and Potential Impacts

Edited by Barrie Pittock

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Summary

This guide sets out the main facts and uncertainties regarding climate change, and helps provide Australians with policy-relevant, but not policy-prescriptive, advice and source material. It is largely based on, and consistent with, the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC TAR) published in 2001. However, this guide has been substantially updated with relevant summaries of the latest international and Australian observations, scientific developments, and studies regarding the impacts of, and adaptation to climate change in Australia.

While much progress in understanding the climate change issue has been made, uncertainties continue to exist about aspects of the climate change science, and regarding societal developments that will affect the extent of future climate change and societal vulnerability. Some impacts of climate change are now inevitable. However, more certainty and understanding is needed to guide decision-makers towards the most effective and cost-efficient means to adapt to climate changes in the near-term (next decade), and to avoid unacceptably large climate changes in the longer term (multi-decades to centuries) through emissions reductions measures.

The high probability of at least some global warming, given the inertia in the climate and socioeconomic systems, means that some adaptation will be necessary. This will be most efficient if the location- and activity-specific nature of the likely impacts is taken into account. Considerable uncertainties about location-specific impacts can be further reduced by targeted research, while case-by-case assessments of adaptation strategies will be needed for many particular sectors and locations.

Any emission reductions will progressively reduce the likelihood of impacts at the high end of the existing large range of emissions scenarios, and thus help to avoid the potentially most damaging climate change possibilities. Thus, in order to establish minimum objectives for emissions reductions, attention needs to be given to the more extreme possibilities to which adaptation may not be possible. These will determine critical greenhouse gas concentration thresholds that must be avoided if the objective of the United Nations Framework Convention on Climate Change is to be achieved. Increased research is needed to quantify the probability and global and local consequences of these high impact scenarios.

Climate Change Science: The Global Perspective

The TAR concluded that global warming has taken place over the last century, and there is new and stronger evidence that most of the warming over the last 50 years is attributable to human activities. It is likely that the 1990s was the warmest decade in the last 1000 years, at least in the Northern Hemisphere. Other observations are consistent with this observed warming, including a rise in global average sea level and ocean heat content, and decreases in snow cover and ice extent both in mountain glaciers and Arctic sea ice. Recent evidence suggests that a predicted slow-down in the deep ocean circulation driven by variations in temperature and salinity may also be occurring.

The TAR reported that statistically significant associations between increases in regional temperatures and observed changes in physical and biological systems have been documented in freshwater, terrestrial, and marine environments on most continents. While overall levels of confidence in this conclusion are still debated, surface and satellite-based observations since the TAR support this conclusion.

Projected warmings in the 21st century are dependent on scenarios of future emissions of greenhouse gases and aerosols. Using the *Special Report on Emissions Scenarios* (SRES), global average warming projections range from 1.4 to 5.8 ºC by 2100 relative to 1990. These scenarios were regarded as 'plausible' by the IPCC, but not assigned any probabilities. While recent criticism of the technical basis of these scenarios is being considered by the IPCC, it is likely that future projections will lie in roughly the same range, with values near the middle of the range being more probable.

TAR projections of global average sea level rise by 2100 range from 9 to 88 cm, made up about half by thermal expansion of sea water, about one quarter from melting of glaciers, and a small positive contribution from Greenland ice melt and possibly a negative contribution from snow accumulation over Antarctica. However, the contribution from Antarctica is especially uncertain, with recent events on the Antarctic Peninsula raising the possibility of an earlier positive contribution from the West Antarctic Ice Sheet (WAIS).

The TAR stated that it is likely there will be higher maximum temperatures and heat indices over many land areas, and reduced frequency of low temperatures, including frosts. More intense precipitation events are likely over many mid- to high-latitude land areas. Increased summer continental drying and associated risk of drought are likely in mid-latitudes. Tropical cyclones are projected to become more intense with higher peak winds and rainfall intensities. Other patterns of climate variability, including the El Niño-Southern Oscillation (ENSO), may vary in intensity and frequency, with some climate models suggesting more El Niño-like average conditions, and others no change.

The TAR chapter on radiative forcing (Houghton *et al.*, 2001, Chapter 6) notes several possibly interacting anthropogenic causes for climate change, including increasing greenhouse gas concentrations, the direct and indirect effects of anthropogenic particulates, and stratospheric ozone depletion. Subsequent papers consider the effects on the atmospheric circulation of these various forcings, noting particularly that while aerosol radiative effects are largely confined to the Northern Hemisphere, effects may propagate into the Southern Hemisphere via atmospheric dynamics. They also find that increasing greenhouse gas concentrations and stratospheric ozone depletion may both be contributing to a strengthening of the polar vortex in both hemispheres, with a polewards movement of the mid-latitude westerly winds, and associated effects on regional climates.

Most coupled ocean-atmosphere models suggest a weakening of the convective overturning of the ocean in the North Atlantic and around Antarctica, which would affect ocean circulation and could have significant regional impacts on climate. Conditions setting up such changes may be initiated in the 21st century, but the effects may not become evident until centuries later. The same may be true for melting of the Greenland ice cap and disintegration of the WAIS, both of which could contribute several metres to mean sea level rise over coming centuries. Conditions may also be set for an eventual acceleration of the increase of greenhouse gases in the atmosphere due to the terrestrial biomass changing from a sink to a source of carbon dioxide, a slowing down of absorption of carbon dioxide into the oceans, and possible release of large quantities of methane from crystalline structures (hydrates) on the sea floor.

Some studies suggest that uncertainties about future discount rates mean that the cost of delayed but severe impacts merit greater consideration. Moreover, recent studies by several groups of economists suggest the possibility that such ‘catastrophic’ impacts, even if their occurrence is uncertain and some time into the future, may dominate any risk analysis of the impacts of climate change.

Time lags in the ocean-atmosphere system mean that climate change, and especially sea level rise, will continue long after stabilisation of greenhouse gas concentrations in the atmosphere. Time lags in socioeconomic systems, while they can be influenced by human decisions, will in general mean that adaptation to the impacts of climate change, and emissions mitigation strategies will take time to implement and would be more costly if they need to be taken rapidly. The longer adaptation and mitigation measures are delayed, the more rapidly they may have to be undertaken later.

Observed Changes in Australian Climate and Ecosystems

Australian average temperatures have risen by 0.7 ºC over the last century, and the warming trend appears to have emerged from the background of natural climate variability in the second half of the 20th century. Rainfall has increased over the last 50 years over north-western Australia, but decreased in the south-west of Western Australia, and in much of south-eastern Australia, especially in winter. The changes are consistent with an observed increase in mean sea level pressure over much of southern Australia in winter. Effects on runoff are potentially serious as evidenced by a 50% drop in water supply to the reservoirs supplying Perth since the 1970s and near-record low water levels in storages in much of south-eastern Australia in 2002–03 due to low rainfall and high temperatures in the south-east since 1996.

Attribution of the rainfall changes is under lively discussion within the scientific community. In the case of the south-west of Western Australia, a combination of natural variability and a trend due to the enhanced greenhouse effect is considered to be the likely cause, although recent papers suggest that stratospheric ozone depletion may also be causing a southward shift of the westerlies and associated rainfall systems. Northern Hemisphere aerosol effects may also have played a part via changes to atmospheric dynamics, but as aerosol lifetimes in the atmosphere are short and precursor sulfur emissions are being curtailed, this effect is probably of diminishing importance. If rainfall decreases are due to anthropogenic effects they may well continue, necessitating “informed adaptation” to a reduced water supply.

It is at least as difficult, with the current state of knowledge, to attribute changes in Australian ecosystems to climate change, as other local causes are possible in many cases. However, a number of observed changes in vegetation, wetlands, terrestrial vertebrates, marine birds and coral reefs are consistent with regional warming trends.

Scenarios for the Australian Region

The Australian region spans the tropics to mid-latitudes and has varied climates and ecosystems, including deserts, rangelands, rainforests, coral reefs and alpine areas. The climate is strongly influenced by the surrounding oceans. The ENSO phenomenon leads to alternations between floods and prolonged droughts, especially in eastern Australia. The region is therefore sensitive to the uncertain but possible change toward a more El Niño-like mean state suggested by the TAR.

Extreme events are a major source of current climate impacts, and changes in extreme events are expected to dominate impacts of climate change. Return periods for heavy rains, floods and storm surges of a given magnitude at particular locations would be reduced by possible increases in intensity of tropical cyclones, mid-latitude storms and heavy rain events. Changes in the location-specific frequency of tropical cyclones could cause either increases or decreases in return periods locally.

Based on the SRES scenarios used by the IPCC, and regional changes in climate simulated by nine climate models, annual average temperatures in Australia are projected to increase by 0.4 to 2.0 °C by 2030, and 1.0 to 6.0 °C by 2070, relative to 1990. There would be associated increases in potential evaporation and heatwaves, and fewer frosts. Warming is expected to be greater inland than near the coast. Projections for changes in annual rainfall suggest changes in the south-west lie in the range of –20% to +5% by 2030, and –60% to +10% by 2070, with changes of –10% to +5% by 2030 and –35% to +10% by 2070 in parts of south-eastern Australia. Projected changes in other parts of northern and eastern Australia show either that there could be an increase or decrease in rainfall at a given locality. When rainfall changes are combined with increases in potential evaporation, a general decrease in available soil moisture is projected across Australia, with droughts likely to become more severe. Most regions would experience an increase in the intensity of heavy rain events.

Before stabilisation of greenhouse gas concentrations at any level greater than the present, the north-south temperature gradient in mid-southern latitudes is expected to increase, strengthening the high-latitude westerlies in the Southern Hemisphere and the associated west-to-east gradient of rainfall across Tasmania in winter. Following stabilisation of greenhouse gas concentrations, these trends would be reversed.

Warming is likely to continue for centuries after stabilisation of greenhouse gas concentrations, but at a slower rate, while sea level would continue to rise almost unabated for many centuries.

The central estimates of the global average warming by 2100 in typical scenarios for the stabilisation of carbon dioxide at concentrations up to 1000 ppm (present concentration is about 370 ppm) lie in the bottom half of the range of warmings for the SRES range of scenarios. Stabilisation at any concentration between 450 and 1000 ppm would thus limit impacts and risks in Australia by 2100, although impacts would still be significant. The higher the stabilised carbon dioxide concentrations, the greater would be the impacts and risks, especially beyond 2100.

Water Supply and Hydrology

Climate variability is a major factor in the Australian economy, principally through the flow-on effects of ENSO-related major droughts on agriculture. Farmers will be increasingly vulnerable if interannual droughts occur more frequently or are more intense in the future. Less secure water supplies would accentuate competition between users and threaten allocations for environmental flows and future economic growth. Adelaide and Perth are the main cities with water supplies that are most vulnerable to climate change. Rising salinity in the Murray River is already of increasing concern for Adelaide. Any increase in flood frequency would adversely affect housing and other aspects of the built environment, such as industry and communication networks in low lying areas.

In some areas, water resources are already stressed and are highly vulnerable, with intense competition for water supply. This is especially so with respect to salinisation and competition for water between agriculture, power generation, urban areas and environmental flows. Increased evaporation and possible decreases of 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.

Evidence suggests that the observed warming trend in Australia has already contributed to an increased severity of drought through higher potential evaporation and water demand.

While there are many pressing problems regarding water supply, climate change is likely to add to them, making solutions more difficult. An integrated approach is needed to optimise results.

Ecosystems and Conservation

Australia had been isolated from the rest of the world for millions of years until relatively recent human settlement. Some species are found over quite limited ranges of average climate. These two factors leave many of the region's ecosystems vulnerable to climate change and to invasion by exotic animal and plant species introduced by human activity. This vulnerability has been exacerbated by fragmentation of ecosystems through land-use changes.

Warming of 1 °C would threaten the survival of species currently living near the upper limit of their temperature range, notably in some Australian alpine regions where some species are already near these limits, as well as in the south-west of Western Australia. Other 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.

Australia has one of the greatest concentrations of coral reefs in the world. Rising sea level by itself may not be deleterious. However, the combination of sea level rise with other induced stresses—notably, increasing atmospheric carbon dioxide (which leads to a decrease in calcification rates of corals); increasing sea temperatures, leading to coral bleaching; possibly increased riverine outflow events causing low salinity and high pollution; and damage from tropical cyclones—may place much of this resource at risk.

Projections for coral bleaching suggest that serious bleaching events will become more frequent, decreasing the chance of recovery and leading to increasing death of corals. Major bleaching events in 1997–98 and 2002 may be forerunners, with warming trends combining with El Niño events to produce sea surface temperatures above bleaching thresholds.

Agriculture and Forestry

A significant proportion of exports from Australia are agricultural and forestry products—production of which is sensitive to any changes in climate, water availability, carbon dioxide fertilisation, and pests and diseases. Returns from these commodities could be affected by a projected increase in agricultural production in mid- to high-latitude Northern Hemisphere countries and resulting impacts on commodity prices and world trade. Climate change will be only one factor affecting Australian agriculture, but it may exacerbate an already difficult situation, particularly in regard to the availability of water for irrigation.

Agricultural activities are particularly vulnerable to projected regional reductions in rainfall in the south-west and possibly other parts of southern Australia, and are especially threatened by general warming that will increase potential evaporation and water demand. Drought frequency and severity, and consequent stresses on agriculture, are likely to increase in many agricultural regions of Australia. This would be exacerbated by any tendency toward a more El Niño-like average state. Enhanced plant growth and water-use efficiency resulting from carbon dioxide increases 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 rainfall decreases. Thus by the mid to late 21st century net effects on agriculture are likely to be negative.

Fisheries

Australian fisheries are influenced by the extent and location of nutrient upwellings governed by prevailing winds and boundary currents. In addition, ENSO influences recruitment of some fish species and the incidence of toxic algal blooms. There is as yet insufficient knowledge about impacts of climate changes on regional ocean currents and about physical-biological linkages to enable confident predictions of changes in fisheries productivity. The increasing importance of marine aquaculture makes this industry of particular concern, as warming coastal waters may adversely affect production, especially of Atlantic salmon, which are near their high temperature limit in southern Tasmania.

Settlements, Industry, and Human Health

About 80% of Australia's population live within 50 km of the coast. Marked trends to greater population and investment in exposed coastal regions are increasing vulnerability to tropical cyclones and storm surges. Thus, projected increases in tropical cyclone intensity and possible changes in their location-specific frequency, along with sea level rise, would have major impacts—notably, increased storm-surge heights for a given return period. Increased frequency of high-intensity 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 in turn may adversely affect some property values.

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 (notably Perth and Adelaide) and in a number of smaller inland communities. Some small communities with particular dependence on adversely affected agricultural and tourism industries may be threatened.

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. Higher temperatures will also increase peak demand for electricity for air conditioning, requiring either adaptation to reduce demand or greater installed peak generating capacity.

Tourism would be adversely affected by the death of coral reefs and loss of some freshwater ecosystems, such as Kakadu. The ski industry and dependent communities will need to adapt to reduced natural snow cover.

There is high confidence that projected climate changes will enhance the spread of some disease vectors, thereby increasing the potential for disease outbreaks (e.g. Dengue fever and Ross River virus), despite existing bio-security and health services. Despite the likely spread of the malaria vector, there is unlikely to be increased malaria infection, provided existing bio-security measures are maintained.

Economically and socially disadvantaged groups of people in Australia, especially Aborigines and Torres Strait Islanders, are particularly vulnerable to additional stresses on health and living conditions induced by climate change.

External Issues

The impacts of climate change overseas may affect Australia through trade and commodity prices. Adverse effects on developing countries may increase the dislocation of populations in those countries due to economic and environmental problems, raising issues for Australia's aid program.

Vulnerability

Climate change will add to existing stresses on achievement of sustainable land use and conservation of terrestrial and aquatic biodiversity. 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, bushfires 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.

Settlements, industry and infrastructure will be vulnerable to adverse effects of extreme weather events, and particularly to increased heat stress on people and materials.

Major exacerbating problems include rapid population and infrastructure growth in vulnerable coastal areas, inappropriate use of water resources, behavioural barriers, economic disincentives and complex institutional arrangements.

Adaptation

Adaptation to climate change, as a means of maximising gains and minimising losses, is important for Australia, but is relatively little explored at the location-specific level and in a cost-benefit framework. Impacts assessments, to be realistic, must include at least some adaptation. Options 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 users to help them manage for 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 multiple stakeholders.

While Australians are experienced in dealing with climate variability, human-induced climate change is likely to take us outside the range of previous experience, and thus requires new strategies to cope with new situations that cross over previous management thresholds. This will apply especially in relation to the long-term sustainability of industries and resources.

Integrated Assessments

Since climate change is only one of many issues, decision-making needs to consider climate change in conjunction with other issues affecting the same decision strategies. Adaptation to, and mitigation of, climate change are both necessary complementary strategies, so it may be advantageous to consider both in any integrated assessment. Integrated assessments will enable co-benefits and possible clashes of interest to be identified, and the overall least cost and most beneficial strategies to be 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.

Any assessments must take into account uncertainty. This requires that assessments be set in a risk management framework, where risk is seen as the product of the probability of a climatic effect and the consequences of that effect.

Climate change, and our understanding of it, is evolving rapidly in the real world, and on the scientific, technological and policy fronts, so policies and decisions need to be decided on the basis of the best current information, but in the knowledge that they will need to be adjusted with time.

Costing

Comprehensive cross-sectoral estimates of net climate change impact costs for various greenhouse gas emission scenarios, as well as for different societal scenarios, are not yet available. Confidence remains very low in the previously reported estimate in the IPCC TAR for Australia and New Zealand of –1.2 to –3.8% of gross domestic product for an equivalent doubling of carbon dioxide concentrations. This out-of-date estimate did not account for many currently identified effects and adaptations. Costs due to impacts and costs of adaptations will increase with increasing global warming. They will increase even more rapidly as various critical thresholds are reached, such as changes from profit to loss in particular farming enterprises, or riverine and coastal flooding exceeding present planning limits. Potential costs and benefits of climate change need to be balanced against costs and benefits of mitigation in any overall policy response.

A number of overseas studies have emphasised the likely dominance in any realistic global cost-benefit analyses 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. The latter high-impact but low-probability and/or long-delayed impacts may dominate cost-benefit analyses due to their magnitude, and uncertainty about appropriate discount rates, which could be low or even negative if there are economic downturns or disasters.

Conclusion

Australia is vulnerable to changes in temperature and precipitation projected for the next 50 to 100 years, because it already has extensive arid and semi-arid areas, relatively high rainfall variability from year to year, and existing pressures on water supply in many areas. In addition, vulnerability arises due to high fire risk, Australian ecosystems sensitive to climate change, and invasion by exotic animal and plant species introduced by human activity. Australia also has a high concentration of population in coastal areas, an economy strongly dependent on world commodity prices, tourism dependent on the health of the Great Barrier Reef and other fragile ecosystems, and economically and socially disadvantaged groups of people. Impacts of climate change will be complex and to some degree uncertain, but increased foresight would enable us to optimise the future through planned adaptation and mitigation. Mitigation can reduce the ultimate extent of climate change and its impacts, but is a global problem requiring cooperative global solutions. Adaptation is essential to cope with unavoidable climate changes, and in this country is essentially a task to be performed by Australians for Australians in each local situation.

Further research is necessary to reduce the uncertainties, better establish probabilities, and identify the most cost-effective adaptation and mitigation options and strategies, which in most cases need to be location- and sector-specific.

1

Introduction

1. Introduction

1.1 A Brief History of Climate Change Concerns

Recent concern about climate change due to the enhanced greenhouse effect needs to be put in its scientific and social policy perspective. Earth's climate has varied with time ever since the planet formed some 5 billion years ago (Frakes, 1979) and, of course, local climate varies with location and topography. The concern now is about climatic changes comparable in magnitude to the difference between a glacial and an inter-glacial climate in the past (roughly 5 °C warming in global average temperature), but projected to occur in a mere 100 years, compared with several thousand years in the past, and at a time when there is an unprecedented human population dependent on the climate for food, water and life.

The climate system obtains its energy from the Sun, and so varies on daily and seasonal timescales, and also with the Earth's orbital variations and changes in solar output. Complex interactive processes between the atmosphere, oceans and biosphere, and within these sub-systems, amplify or suppress externally forced climate variations, generating internal variations on year-to-year, inter-decadal and century timescales.

During the 100,000-year glacial-interglacial cycles, the area covered by ice caps at high latitudes and in mountainous regions changed dramatically, with consequent fluctuations in sea level by tens to hundreds of metres. These fluctuations had dramatic effects on Australia, with small ice caps and glaciers in Tasmania and the Snowy Mountains disappearing at the end of the last glaciation between about 15,000 and 10,000 years ago. At the same time the sea level rose by some 150 m, cutting off Tasmania in the south and New Guinea in the north, and many inland rivers and lakes dried out. This greatly changed the lives of the thinly dispersed Aboriginal population, and the distribution of plants and animals (Mulvaney and Golson, 1971).

Such climatic variations are larger than those directly attributable to the variations in Earth's orbit around the Sun, and appear to have been amplified by variations in the concentration of greenhouse gases in the atmosphere, notably carbon dioxide and methane. Concentrations of these gases varied in close correlation with global temperature and sea level. Greenhouse gases are transparent to visible radiation, but absorb some of the outgoing heat (or infrared) radiation. Therefore, higher concentrations of these gases in the atmosphere lead to warming. Large quantities of carbon dioxide and methane are stored in sediments on the ocean floor and in vegetation, and these stores are strongly influenced by changes in climate and sea level.

Knowledge of these past changes, and speculation about future changes in climate and their impacts, greatly advanced during the 20th century, both at a global level and with particular reference to Australia.

As early as 1896, Svente Arrhenius pointed out that the burning of fossil fuels (oil, coal and natural gas) might cause an increase in atmospheric carbon dioxide, thereby warming the Earth. During the 1930s, Roger Revelle showed convincingly for the first time that atmospheric concentrations of carbon dioxide were increasing, and in the 1950s Carl-Gustav Rossby initiated systematic measurements of carbon dioxide in Europe. Revelle and Charles Keeling started such measurements in Hawaii and at the South Pole during the International Geophysical Year (1957–58), and careful assessments of future carbon dioxide (CO_2) increases were carried out by Revelle and Suess in 1957 and Bolin and Eriksson in 1959.

Carbon dioxide was first measured in Australia to study plant growth in 1971. Measurements were also made by CSIRO from air collected in flasks on Qantas flights to study global background concentrations (Garratt *et al.*, 1998). This led to the establishment of the Cape Grim background air pollution monitoring station in 1976, which quickly confirmed that carbon dioxide concentrations were rising over south-eastern Australia.

During the early 1970s there was speculation worldwide about the possible rapid onset of a new glaciation, inspired by and extrapolated from global cooling in the 1950s and 1960s and the fact that previous inter-glacials had lasted only some 10,000 to 15,000 years. The then observed cooling trend was in part blamed on increased particulate pollution of the atmosphere, but the US Federal Council for Science and Technology (FCST, 1974) concluded that in the longer term increases in carbon dioxide would win out over particles and lead to some warming. Prompted by the same concerns, a committee set up by the Australian Academy of Science in 1976 firmly rejected the fear of a new "ice age" on timescales of a century or so, although it said very little about the possibility of global warming (AAS, 1976).

This neglect of global warming was remedied in 1980 when the Australian Academy of Science sponsored a conference in Canberra on carbon dioxide and climate (Pearman, 1980). This included the first attempt to construct a scenario for climate change for Australia, based on four methods: numerical modelling (which was then quite primitive); comparison of ensembles of warm and cold years; paleoclimatic reconstructions of past warm epochs; and dynamical or empirical reasoning.

Continuing increases in greenhouse gas concentrations, coupled with a realisation that the effective lifetime of carbon dioxide in the atmosphere was much longer than that of particulates, making for a greater cumulative warming effect, led by the early 1980s to a growing scientific interest in assessing the likelihood and magnitude of global warming. This evidence was summarised in 1986 by the Scientific Committee on Problems of the Environment (SCOPE, 1986), a committee of the International Council of Scientific Unions (ICSU). The SCOPE report concluded that if the observed rate of carbon dioxide increase continued, it would reach double pre-industrial values toward the end of the 21st century, and that this would lead to global average warming in the range 1.5–5.5 °C, with associated global average sea level rise in the range 20–165 cm. The report went on to discuss possible impacts on agriculture, forests and ecosystems.
This detailed report closely followed on a public statement along similar lines made by a conference of scientists at Villach in Austria in October 1985, which was sponsored by ICSU along with the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP).

The latter two UN organisations set up the Intergovernmental Panel on Climate Change (IPCC) in 1988 with the task of reporting to the Second World Climate Conference in November 1990, and the United Nations General Assembly, on "the scientific information that is related to the various components of the climate change issue …" and "formulating realistic response strategies for the management of the climate change issue." It was envisaged by some that this might lead to international negotiations directed toward an agreement on a convention to eventually limit greenhouse gas emissions and to adapt to unavoidable climate changes. The IPCC established three Working Groups at that time (with some later changes), one on assessing available scientific information on climate change, a second on assessing the environmental and socioeconomic impacts, and the third to formulate response strategies. The IPCC has issued three major Assessment Reports, in 1990, 1996 and 2001 (Houghton *et al.*, 2001; McCarthy *et al.*, 2001; Metz *et al.*, 2001), and a special report on *The Regional Impacts of Climate Change* in 1998 (Watson *et al.*, 1998). There have been a number of other IPCC reports, including the *Special Report on Emission Scenarios* (SRES) in 2000 (Nakicenovic and Swart, 2000), which produced a wide range of plausible scenarios for future greenhouse gas and aerosol emissions up to the year 2100.

The projected global warming in the 21st century is comparable with past changes during the glacial-interglacial cycles, although likely faster, and to a warmer climate than past interglacials. A big difference is that now there are more than 6 billion people living on Earth, so that human exposure to risk is much greater than in the past, and natural ecosystems are more fragmented. Moreover, there are many other concurrent changes to, and stresses on, our environment and human systems, in addition to climate change, so the combined effects need to be considered.

The immediate problem in relation to climate change is how to cope with or minimise any adverse effects, and take advantage of any potential benefits, while seeking to minimise the magnitude of human-induced climate change. There are also delays and time-lags in the socioeconomic and climate systems, which mean that actions taken now may have repercussions in decades or centuries to come, and thus foresight is needed to take action now that will forestall adverse effects in the future.

In the longer run, what we learn and do in the coming decades about human-induced climate change may also help the world avoid otherwise dangerous natural climate changes in the more distant future.

This guide aims to point to the main facts and uncertainties regarding climate change, and to help provide Australians with policy-relevant, but not policy-prescriptive, advice and source material. It contains numerous citations in the text (in the form 'Authors/editors, year') to references listed at the end of the document. It is largely based on, and consistent with, the IPCC TAR, especially the Working Group I (WG I) report (Houghton *et al.*, 2001) on *The Scientific Basis* and Chapter 12 ('Australia and New Zealand') of the Working Group II (WG II) report (McCarthy *et al.*, 2001) *Impacts, Adaptation and Vulnerability*. However, the present guide has been substantially updated with relevant summaries of the latest international and Australian observations, scientific developments, and studies regarding impacts and adaptations in Australia.

1.2 The Australian Setting

The climate changes experienced by Australia in the 21st century will, of course, depend in part on our location and existing climate. Moreover, the nature of Australian society, ecosystems and industries will largely determine the impact climate change will have on us, and our ability to adapt to climate change.

Australia is a large, relatively flat continent reaching from the tropics to mid-latitudes, with relatively nutrient-poor soils, a very arid interior, and rainfall that varies substantially on seasonal, annual, and decadal time scales. Australian ecosystems contain a large proportion of endemic (solely Australian) species, reflecting their long evolutionary history and isolation from other landmasses. They have been subject to significant human influences, before and after European settlement some 200 years ago.

Australia's climate is strongly influenced by the surrounding oceans. Key climatic features include tropical cyclones and monsoons in northern Australia; migratory mid-latitude storm systems in the south; less well understood influences from the Indian Ocean; and the El Niño-Southern Oscillation (ENSO) phenomenon, which causes floods, prolonged droughts, and bushfire outbreaks, especially in eastern Australia. La Niña years typically have above-average rainfalls, while El Niño years have widespread drought. Major droughts typically cause declines in GDP of around 1%, with much larger regional impacts in affected areas.

The total land area is 7.7 million square km, and the population is approximately 20 million. Much of the country is very sparsely populated; most people (80%) live in a relatively small number of cities and towns within 50 km of the coast. Australia has a significant population of indigenous peoples who generally have a lower economic and health status than other Australians. Australia has a developed economy and is a member of the Organisation for Economic Cooperation and Development (OECD); unlike other OECD countries, however, its export trade is dominated by commodity-based industries of agriculture and mining, and it lies largely in the tropics and sub-tropics.

1.3 Socioeconomic Trends

Australia's population is growing at a rate of about 1.3% per year, approximately equally from natural increase and immigration. The population is progressively aging, in line with other OECD countries. The nation's health status is improving, but the health of indigenous people lags significantly. The main population centres are growing faster than rural areas. Tropical and sub-tropical coastal zones in Queensland and New South Wales are developing two to three times faster than the national average, for urban/suburban uses and for recreation and tourism.

Agricultural commodity prices have tended to fall, but yields per hectare have risen, and farm sizes and total volume of production have increased (ABARE, 1997; Wilson and Johnson, 1997). Average return on agricultural assets is low. Service industries are an increasing fraction of all industry, and there is a trend towards more intensive agriculture and forestry and diversification of rural land use, including specialty crops and tourism. There is increasing competition for water in areas of low rainfall where irrigation is essential to intensive cropping; urban demands are rising, and water is needed to maintain natural ecosystems (Hassall and Associates *et al.*, 1998). Tourism is a major growth industry that is increasing the pressure on natural attractions such as coastal zones and reefs.

Environmental concerns include air and water pollution from urban industries, land transport, and intensive farming and related processing; and soil erosion; rising water tables, and associated salinisation; and loss of species (largely due to habitat loss). Reduction in river flow, with associated salinisation of water supplies and algal blooms, is a major problem for riverine communities and ecosystems. Environmental management in Australia increasingly is based on the principle of sustainable management and an integrated approach to environmental impacts. A major trend to a "user pays" principle and to market-driven water rights, with caps on irrigation supplies, is causing significant changes in rural industry. However, there still are many instances, particularly in coastal management, where these principles are not applied.

1.4 Projecting the Future

1.4.1 The need for, and nature of, foresight

Foresight is variously defined as care or provision for the future, perception gained by looking forward, and the act or power of foreseeing. Prudent people use foresight to decide or plan their actions so as to optimise their future prospects. It is an everyday occurrence. Governments around the world have recognised that human societies, through their use of resources and waste products, are capable of changing the environment, including the climate. That is why the Intergovernmental Panel on Climate Change was formed – to provide foresight in relation to the possible human impacts on climate, with a view to helping societies make better decisions and formulate wiser policy options and decisions in relation to climate change.

As we shall see in the next section, foresight requires some estimate of future conditions, and in the case of climate change this includes projections of future emissions of greenhouse gases and particulates into the atmosphere, consequent concentrations of these pollutants in the atmosphere, and their climatic effects. Moreover, in order to understand how serious this might be, estimates are also needed of the consequences to society in terms of potential impacts on areas such as agriculture, health and infrastructure. This is complicated by the fact that impacts depend not just on the stresses applied, but also on the resilience and adaptability of society; and that requires an understanding of how changes in society will affect resilience and adaptability.

There are, as viewed from the present, many possible futures. How we foresee the future possibilities, and the conscious or unconscious choices we make that will influence development of society, will determine which of the possible futures will actually occur. The purpose, from a policy perspective, is not to predict which of the possible futures will occur, but rather to inform us so that we might choose which one we would prefer and attempt to bring that future to reality.

1.4.2 The nature and uses of predictions, scenarios and projections

There can be considerable confusion regarding the differences between ‘predictions’, ‘scenarios’ and ‘projections’. A prediction is a statement that something *will* happen in the future, based on known conditions at the time the prediction is made, and assumptions as to the physical or other processes that will lead to change. Because present conditions are often not known precisely, and the processes affecting the future are not perfectly understood, such predictions are seldom certain, and are often best expressed as probabilities. Daily weather forecasts are ‘predictions’ in this sense – they are predictions of what the weather will be like, but have uncertainties due to inexact observations and weather models. They are often expressed in probabilistic terms.

A scenario is a plausible description of some future state, with no statement of probability. It is used to enable people to explore the question ‘What if such and such were to happen?’. Scenarios are often used in literature to stretch the imagination, and increasingly in businesses and government to enable them to develop a range of strategies or contingency plans to cope with possible changes in business or other conditions. Scenarios are alternative pictures of how the future might unfold. They are used to assess consequences, and thus to provide some basis for policies that might influence future developments, or enable businesses or governments to cope with the new situation when it occurs.

Projections are sets of future conditions, or consequences, derived on the basis of explicit assumptions, such as scenarios. Even for a given scenario or set of assumptions, projections introduce further uncertainties due to the use of inexact rules or ‘models’ connecting the scenario conditions to the projected outcomes.

The plausibility of a scenario is a key issue in considering the results of projecting the future on the basis of such a scenario: if a scenario is not plausible it is not worth worrying about in setting policy, but if it is plausible we may need to take its possibility into account. Possibility has several elements. These are that the scenario is logically, physically, biologically, and historically possible (Bradbury, 1998).

As stated above, a plausible scenario is useful for asking 'What if …' questions, and thus for helping to make policy choices that may influence which of the 'what ifs' actually comes to pass. In the climate change context this means they are useful for influencing policy regarding the need to reduce greenhouse gas emissions. Even in this case, however, if reducing greenhouse gas emissions is costly, the urgency and extent of such reductions depends not just on the possibility of a scenario, but also on its probability. The probability of projections based on given scenarios is thus a legitimate issue.

Scenarios, without estimated probabilities, are also of some use in relating to adaptation policy in that they suggest what it is that we might need to adapt to, and thus help us to anticipate what sort of adaptations might be needed, and to identify the need for increased resilience and adaptive capacity (Lempert and Schlesinger, 2000; Barnett, 2001). However, in order to answer specific planning questions like 'How large should the spillway of a new dam at location x be in order to cope with the maximum possible flood at that location in 2070?' it is necessary to know more than that a given change in rainfall is possible. Rather, the probability of such a change needs to be known, since expensive engineering design needs to be based on cost-effective risk minimisation (for discussion on this point see e.g., Pittock *et al.*, 2001, and Schneider, 2002).

1.4.3 The IPCC SRES emissions scenarios

With the aim of providing policy-relevant advice on the consequences of human-induced climate change in the 21st century, the IPCC commissioned a range of scenarios of greenhouse gas and sulfate aerosol emissions up to the year 2100. These emission scenarios were developed by a panel of authors, with wide consultation, and an open process of review and comment by experts and governments, followed by subsequent revisions (Nakicenovic, 2000a and b). The scenarios were reported in the *Special Report on Emissions Scenarios* (SRES) (Nakicenovic and Swart, 2000). They were intended to feed into projections of climate change in the TAR in 2001, and to enable a discussion of the potential impacts, adaptations and vulnerability of sectors, regions and countries.

Future emissions are the product of complex interacting systems driven by population change, socioeconomic development, and technological change; all of which are highly uncertain, especially when extended as far as the year 2100. The 40 SRES scenarios were based on four different "storylines" of mutually consistent developments across different driving forces (see **Box 1**), and multiple modelling approaches, leading to a total of 35 scenarios containing data on all gases required to force climate models. Resulting accumulated emissions by 2100, expressed in units of thousands of millions of tonnes of carbon equivalent (GtC), range from a low of 770 GtC to approximately 2540 GtC. This range compares with the earlier (1992 and 1995) so-called IPCC IS92 range of 770 to 2140 GtC, so the upper end of the range is now greater than before (Houghton *et al.*, 2001). Corresponding projected carbon dioxide concentrations at 2100 are from 540 to 970 ppm (Houghton *et al.*, 2001, p.12).

The SRES scenarios include estimated emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulfur dioxide (SO_2). Generally, the SRES emission scenarios contain higher upper limits on carbon dioxide emissions, but lower emissions of sulfur dioxide than the IS92 scenarios. The former would increase the upper limits of global warming due to increased infrared absorption, but a large part of the increase in warming relative to earlier scenarios comes from the lower sulfur dioxide emissions, which lead to reduced regional cooling by sulfate aerosols in highly industrialised regions such as Europe, the United States and southern and eastern Asia.

These scenarios do not include explicit policy options to reduce greenhouse emissions, such as might be adopted under the United Nations Framework Convention on Climate Change (UNFCCC), although other socioeconomic and technological trends considered by the SRES lead in some cases to considerable reductions in greenhouse gas and/or sulfur emissions. These scenarios were characterised by the SRES as 'plausible', but no further estimates of probability were attached, and indeed estimates of probability would be difficult to derive with any confidence. They are clearly not predictions, and do not have equal probability of occurrence in the real world.

Box 1. The emissions scenarios of the Special Report on Emissions Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focusses on local and regional levels.

From: Houghton *et al.*, 2001, TS Box 4.

Some critics have argued that the scenarios are unrealistic. Their criticisms hinge on technical issues associated with estimating global and regional economic growth rates over the next century. While some, though not all, of the technical criticisms appear soundly based, it is not clear that they impact upon the IPCC's projections for temperature increases.
The climate models used to produce the projections of climate change that underlie the IPCC assessment are developed and validated separately from the emissions scenarios.
Any re-assessment of the range of emissions scenarios may affect the upper and/or lower bounds of the projected climate change over the next 100 years, but are most unlikely to alter the main conclusions that significant climate change is likely to occur with significant impacts.
The SRES emissions projections are drawn from, and consistent with, the published literature, including several recent US studies that use more sophisticated models than were available at the time the SRES scenarios were developed. This matter has been brought to the attention of the IPCC and papers on this subject will be considered in developing or interpreting scenarios for the Fourth Assessment Report.

In any case, due to their late publication, the SRES scenarios were not applied in any detailed studies of impacts globally or regionally in time for inclusion in the TAR. Rather, estimated impacts globally and regionally resulting from earlier and generally lower emissions scenarios were put in an interpretive framework in the TAR in which the possibility of larger emission scenarios was considered.

Unlike parts of the Northern Hemisphere, high regional concentrations of sulfate aerosols are not expected in the Australasian region under any accepted scenario, so any increase in warming resulting from reduced sulfate aerosols will be less over Australia than in some regions of the Northern Hemisphere. This should be reflected in regional patterns of warming per °C of global warming, although it may be nonlinear due to time-varying rates of decrease in sulfate emissions and some cross-equatorial influence on Australia from high regional sulfate emissions in Asia in the early decades of the 21st century.

1.4.4 Projections of Australian socioeconomic futures

An important consideration in estimating potential impacts of climate change is the future exposure of populations, human systems and ecosystems to climatically induced stresses, and the capacity of those so exposed to adapt to the stresses. So far this has been largely neglected, especially in Australia, with only the most general comments on likely changes in exposure, e.g., to sea level rise and storm surges in low-lying coastal zones where populations and investments are increasing more rapidly than the national average. Ideally, socioeconomic scenarios used to estimate future emissions of greenhouse gases should be used at the local or regional scale as the basis for consistent estimates of exposure and adaptive capacity. At a broad regional level such data are contained in the SRES scenarios, although it is complicated by the fact that different global socioeconomic scenarios may lead to similar magnitudes of climate change globally and regionally, but with different regional exposures and adaptive capacities. Moreover, the socioeconomic data have not been provided at the space scales appropriate to, for example, estimates of exposure and adaptability on the coast of Queensland.

However, some idea of future exposure and adaptive capacity could be based on various scenarios of Australian population growth and socioeconomic conditions contained in various foresighting studies already undertaken in Australia.

GBN Australia produced two closely related reports *Alternative Futures: Scenarios for Business in Australia to the Year 2015* (GBN Australia, 1999), and *Alternative Futures for*

Business in Australia to the Year 2015: Towards Strategies (GBN Australia, 2000). The project aimed "to identify alternative, plausible scenarios for the future of business in Australia and to explore strategies that maximise our ability to generate wealth and jobs, to integrate into global markets and to contribute to a rising standard of living for the Australian community as a whole". The reports explored four alternative scenarios styled "Sound the Retreat", "Brave Old World", "First Global Nation" and "Green is Gold", of which the last explicitly dealt with global environmental concerns.

The Business Council of Australia commissioned another study, from the Australian Academy of Technological Sciences and Engineering and SGS consultants, called "Population Futures" (AATSE, 2001). This study aimed to assess the environmental constraints to population growth in Australia, out to 2050, and to assess technological, behavioural, pricing and settlement planning interventions that might be used to manage population-related environmental issues. It found that only four environmental issues were strongly related to population, while a number of others were 'tenuously' related to population. However, its focus seems to be more on what impact an increased population might have on the environment, rather than on what influence environmental problems, such as the global problem of climate change, might have on the Australian population.

An ongoing study by the Resources Futures Program of CSIRO Sustainable Ecosystems (Foran and Poldy, 2002) seems to have a more integrated approach where feedbacks between the environment and population are possible. This study aims essentially at providing insight into options for Australia's population, technology, resources and environment to 2050. It looks at the consequences of low, medium and high population growth rates, resulting in 20 million, 25 million and 32 million people, respectively, by 2050. Consequences are explored for people, urban infrastructure, the natural environment, energy, water and a range of other issues. Amongst the conclusions (Foran and Poldy, 2002) was a need to recognise:

- that Australia's social, economic and physical systems are linked over very long time scales, and that short-term decisions have long-term consequences
- that there is inbuilt inertia in our institutional systems, requiring time for change to take effect.

These are themes reflected in the IPCC TAR Synthesis report.

Any realistic assessment of the overall impacts of climate change on Australian society and its environment, and of its capacity to adapt to climate change, will need to integrate such socioeconomic futures studies with climate change studies. They are all part of any interconnected future.

2

Climate Change Science

2 Climate Change Science

2.1 The Global Picture: Updated Conclusions from the IPCC Third Assessment Report

2.1.1 Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate

The atmospheric concentration of carbon dioxide (CO_2) has increased by 31% since 1750. The present carbon dioxide concentration has not been exceeded during the past 420,000 years and likely not during the past 20 million years. The current rate of increase is unprecedented during at least the past 20,000 years. About three-quarters of the anthropogenic emissions of carbon dioxide to the atmosphere during the past 20 years is due to fossil fuel burning. The rest is predominantly due to land-use change, especially deforestation.

The atmospheric concentration of methane (CH_4) has increased by 1060 ppb (151%) since 1750 and continues to increase. The present CH_4 concentration has not been exceeded during the past 420,000 years. Slightly more than half of current CH_4 emissions are anthropogenic (e.g., use of fossil fuels, cattle, rice agriculture and landfills). The atmospheric concentration of nitrous oxide (N_2O) has increased by 46 ppb (17%) since 1750 and continues to increase. The present N_2O concentration has not been exceeded during at least the past thousand years. Since 1995, the atmospheric concentrations of many of those halocarbon gases that are both ozone-depleting and greenhouse gases (e.g., $CFCl_3$ and CF_2Cl_2) are either increasing more slowly or decreasing; both in response to reduced emissions under the regulations of the Montreal Protocol and its Amendments. Their substitute compounds (e.g., CHF_2Cl and $CF3CH_2F$) and some other synthetic compounds (e.g., perfluorocarbons or PFCs) and

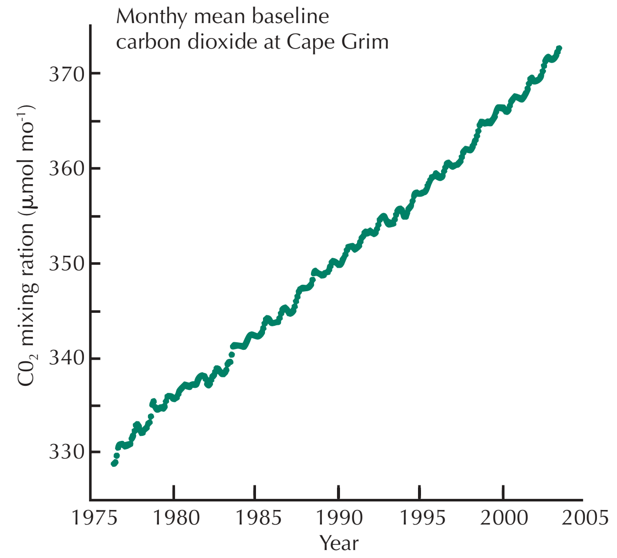


Figure 2.1.
Concentrations of carbon dioxide measured at Cape Grim, Tasmania. They lag behind those at Northern Hemisphere observatories by about one year, because most emissions occur in the Northern Hemisphere, and it takes about a year for them to mix into the Southern Hemisphere. Source: CSIRO Atmospheric Research.

sulfur hexafluoride (SF_6) are also greenhouse gases, and their concentrations are currently increasing.

Measurements of the concentration of carbon dioxide in the lower atmosphere, taken at the Cape Grim air pollution observatory in north-west Tasmania, are shown in **Figure 2.1**. Pre-industrial concentrations, measured from bubbles trapped in glacier ice, were about 280 ppm (parts per million).

2.1.2 Detection and attribution of observed climate change (Houghton *et al.,* 2001)

Observed climate change

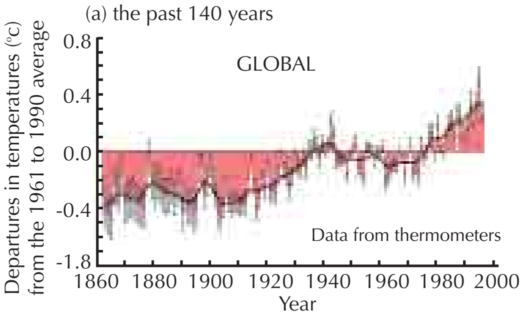
The TAR states that since the release of the Second Assessment Report (SAR) in 1995, additional data from new studies of current and palaeoclimates, improved analysis of data sets, more rigorous evaluation of their quality and comparisons among data from different sources have led to a greater understanding of climate change.

The global average surface temperature (the average of near surface air temperature over land, and sea surface temperature) has increased since 1861. Over the 20th century the increase has been 0.6 ± 0.2 °C. This value is about 0.15 °C larger than that estimated by the SAR for the period up to 1994, owing to the relatively high temperatures of the additional years (1995 to 2000) and improved methods of processing the data. These numbers take into account various adjustments, including those for urban heat island effects. The record shows a great deal of variability; for example, most of the warming occurred during the 20th century, during two periods, 1910 to 1945 and 1976 to 2000, and it is only in the late 1970s that the temperature starts to consistently exceed the 1961 to 1990 average (see **Figure 2.2a**).

Analyses of proxy data for the Northern Hemisphere indicate that the increase in temperature in the 20th century is likely to have been the largest of any century during the past 1000 years (see **Figure 2.2b**). It is also likely that, in the Northern Hemisphere, the 1990s was the warmest decade and 1998 the warmest year of the millenium. Because less data are available, less is known about annual averages prior to 1000 years before present and for conditions prevailing in most of the Southern Hemisphere prior to 1861.

Variations of the Earth's surface temperature for:

(a) the past 140 years



(b) the past 1,000 years

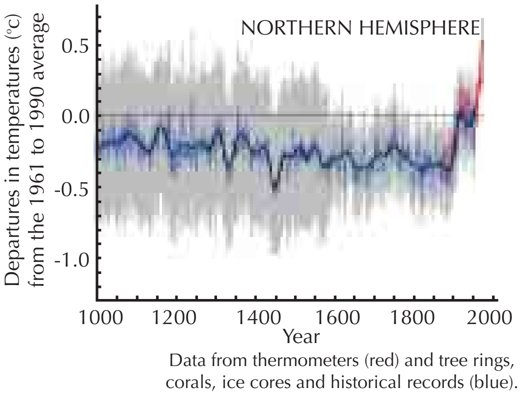


Figure 2.2.
Variations of the Earth's surface temperature for (a) the last 140 years (global) and (b) the past 1000 years (Northern Hemisphere). (Adapted with permission from Houghton *et al.*, 2001, **Figure 1** of Summary for Policymakers.)

The TAR also concluded that:

- Temperatures have risen during the past four decades in the lowest eight kilometres of the atmosphere.
- Snow cover and ice extent have decreased.
- Global average sea level has risen and ocean heat content has increased.

A recent paper by Soon and Baliunas (2003) claims, from a review of the literature on proxy climate data, that "Across the world, many records reveal that the 20th century is probably not the warmest nor a uniquely extreme climatic period of the last millennium." However, this is very misleading, since the paper does not compare estimates of global average temperatures at all, but merely non-synchronous qualitatively warm and cold 'anomalies' in each individual record. Curiously, the paper mentions "wetness or dryness" as an indicator of a warm period also. Essentially it claims evidence for the Medieval Warm Period in any relatively warm (or wet or dry) anomaly occurring locally in any 50-year period between 800 and 1300 AD (a period of 500 years). However, local anomalies can occur for many reasons, and often average out across larger regions. Virtually by definition, natural multi-decadal variability ensures that any local proxy record spanning a 500-year period must show at least one such 50-year long anomaly. The paper then compares the number of such qualitatively defined non-synchronous local anomalies over the earlier 500-year period with the number of local 50-year anomalies within the 20th century, which now only count if they are the warmest in the whole 1000-year long record. A comprehensive reply to the Soon and Baliunas (2003) paper has recently appeared (Mann *et al.*, 2003).

As the actual temperature record demonstrates (see **Figures 2.2a and b**), abnormal warming has only occurred globally since the late 1970s. It is therefore unlikely that any given 50-year average of a proxy temperature record at a single location in the 20th century will show this to be the warmest on record, especially as most of the long proxy records reviewed stopped in the early or mid-1990s. What is significant about the late 20th century is the global nature of the warming since the 1970s. Clearly, what is needed to detect abnormal warming due to a global phenomenon such as the enhanced greenhouse effect is evidence of a synchronous warming at many locations around the globe. Such global-scale synchronicity is lacking in the record for the so-called Medieval Warm Period, which seems to be confined largely to the North Atlantic region.

Attribution of observed climate change

Regarding attribution, the TAR states: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

Since the SAR, progress has been made in reducing uncertainty, particularly with respect to distinguishing and quantifying the magnitude of responses to different external influences. Although many of the sources of uncertainty identified in the SAR still remain to some degree, new evidence and improved understanding support the above conclusion.

- There is a longer and more closely scrutinised temperature record and new model estimates of variability. The warming over the past 100 years is very unlikely to be due to internal variability alone, as estimated by current models. Reconstructions of climate data for the past 1000 years also indicate that this warming was unusual and unlikely to be entirely natural.
- There are new estimates of the climate response to natural and anthropogenic forcing, and new detection techniques have been applied. Detection and attribution studies consistently find evidence for an anthropogenic signal in the climate record of the last 35 to 50 years.

- Simulations of the response to natural forcings alone (i.e., the response to variability in solar irradiance and volcanic eruptions) do not explain the warming in the second half of the 20th century. However, they indicate that natural forcings may have contributed to the observed warming in the first half of the 20th century.

- The warming over the last 50 years due to anthropogenic greenhouse gases can be identified despite uncertainties in forcing due to anthropogenic sulfate aerosol and natural factors (volcanoes and solar irradiance). The anthropogenic sulfate aerosol forcing, while uncertain, is negative over this period and therefore cannot explain the warming. Changes in natural forcing during most of this period are also estimated to be negative and are unlikely to explain the warming.

- Detection and attribution studies comparing model simulated changes with the observed record can now take into account uncertainty in the magnitude of modelled response to external forcing, in particular that due to uncertainty in climate sensitivity.

- Most of these studies find that, over the last 50 years, the estimated rate and magnitude of warming due to increasing concentrations of greenhouse gases alone are comparable with, or larger than, the observed warming. Furthermore, most model estimates that take into account both greenhouse gases and sulfate aerosols are consistent with observations over this period.

- The best agreement between model simulations and observations over the last 140 years has been found when all the above anthropogenic and natural forcing factors are combined. These results show that the forcings included are sufficient to explain the observed changes, but do not exclude the possibility that other forcings may also have contributed.

In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.

Furthermore, it is very likely that the 20th century warming has contributed significantly to the observed sea level rise of some 10 to 20 cm, through thermal expansion of sea water and widespread loss of land ice. Within present uncertainties, observations and models are both consistent, with a lack of significant acceleration of sea level rise during the 20th century (as expected due to inertia).

Several studies since the TAR support these conclusions. Hansen *et al.* (2002) used the GISS model to explore the effect on global temperature of various natural and anthropogenic forcings. They conclude that the observed global temperature change during the last 50 years is primarily the result of these forcings. They also note that the ocean temperatures lag behind these forcings, such that additional global warming of about 0.5 ºC is already “in the pipeline” due to the imbalance between incoming and outgoing radiation. Braganza *et al.* (2003) use some simple indices of global climate variability in observational and climate model data, and demonstrate that the correlation between these indices is consistent with forced climate variations during the twentieth century.

At a more regional scale, Gillett *et al.* (2003) detect a human influence on sea level pressure patterns (which they suggest is underestimated in the climate models), Zweirs and Zhang (2003) find a greenhouse and sulfate aerosol signal in regional patterns of temperature change over six spatial domains from global to individual continents, and Raisanen and Alexandersson (2003) find an anthropogenic explanation for a proportion of the temperature and rainfall changes over Sweden.

Climate model suggestions of a slowdown of the ocean thermo-haline circulation, in response to warming, increased rainfall and runoff at high latitudes and reduced sea ice formation (Stocker, 2000; Lockwood, 2001) are also supported by observations (Delworth and Dixon, 2000; Matear *et al.*, 2000; Kim *et al.*, 2001; Dickson *et al.*, 2002; Gille, 2002).

2.1.3 Detection of climate change impacts (McCarthy et al., 2001)

Observational evidence indicates that climate changes in the 20th century have already affected a diverse set of physical and biological systems. Examples of observed changes with linkages to climate include shrinkage of glaciers; thawing of permafrost; shifts in ice freeze and break-up dates on rivers and lakes; increases in rainfall and rainfall intensity in most mid- and high latitudes of the Northern Hemisphere; lengthening of growing seasons; and earlier flowering dates of trees, emergence of insects and egg-laying in birds. Statistically significant associations between changes in regional climate and observed changes in physical and biological systems have been documented in freshwater, terrestrial and marine environments on all continents except Australia (but see Hughes, 2003, and section 2.2.2 below).

This conclusion in the TAR is based on the investigation of possible links between observed changes in regional climate and biological or physical processes in ecosystems. The author team gathered more than 2500 articles on climate and one of the following entities: animals, plants, glaciers, sea ice and ice on lakes or streams. To determine if these entities have been influenced by changing climate, only studies meeting at least two of the following criteria were included:

- a trait of these entities (e.g., range boundary, melting date) shows a change over time
- the trait is correlated with changes in local temperature
- local temperature changed over time.

At least two of these three criteria had to exhibit a statistically significant correlation. Only temperature was considered because it is well established in the literature how it influences the entities examined and because temperature trends are more globally homogeneous than other locally varying climatic factors, such as precipitation changes. Selected studies also had to have examined at least 10 years of data; more than 90% had a time span of more than 20 years.

Several papers published since the TAR by some of the same authors and others (Hughes, 2000; Parmesan and Yohe, 2003; Root *et al.*, 2003; Walther *et al.*, 2002) further discuss this multitude of evidence. While there is some discussion about levels of confidence (Jensen, 2003), both Parmesan and Yohe (2003) and Root *et al.* (2003) find a “systematic trend” or “fingerprint” in changes in the distribution and behaviour of wild animals and plants. Parmesan and Yohe find an average range shift polewards due to global warming of 6.1 km per decade, and an advancement of spring events by an average of 2.3 days per decade. Root *et al.* (2003) point out that such trends, combined with other stresses such as habitat destruction, could lead to disruption of the connectedness of species within ecosystems, and to “numerous extirpations and possibly extinctions” of species.

Amongst the many other recent analyses supporting such observed trends are: Beaugrand *et al.*, 2002 (crustaceans in the North Atlantic); Stebbing *et al.*, 2002 (northward extension of range of southern fish species in the North Atlantic); Lucht *et al.*, 2002 (modelled and satellite observations of high northern latitude greening and spring budburst); Fitter and Fitter, 2002 (spring flowering of British plants); and Klanderud and Birks, 2003 (upwards movement of plant species in Norwegian mountains).
A study of breeding behaviour in a red squirrel population in the Yukon, Canada (Reale *et al.*, 2003) found that the timing of breeding has advanced by 18 days over the last 10 years (6 days per generation). This is attributed both to

changing behaviour within generations, and to selective breeding favouring early breeders.

While most of these observations are for Northern Hemisphere plants and animals, where long datasets are available, shorter data sets in Australia suggest similar shifts toward the south (bats, birds), upward in elevation (alpine mammals) or along changing rainfall contours (birds, semi-arid reptiles) according to a recent review by Hughes (2003) – see section 2.2.2.

Attribution of changes in crop production is complex, with climate change being only one factor along with changes in crop varieties, application of fertilisers, effects of pollutants such as ozone and nitrogen fallout, and direct effects of increasing carbon dioxide concentrations affecting water use efficiency and photosynthesis. Nevertheless, two papers claim to have detected yield trends due to climate change. Nicholls (1997) removed the long-term trends in Australian wheat yield and climate data to obtain a relationship between climate variability and yield. He then used this relationship, and the observed climatic trends to estimate the proportion of the yield increases that might be due to climate change. Over the period 1952 to 1992 he found that climate change accounted for some 30–50% of the yield increase. This was mainly due to increasing temperatures, including reduced frost frequency (Stone *et al.*, 1996), and may not hold for much greater warmings (see section 4.3.3). Lobell and Asner (2003) analysed data for yields of corn and soybeans in the midwestern United States for 1982–98, and corresponding local climate. They found a strong negative relationship between year-to-year yield data and temperature (a 17% decrease in yield per degree warming), and that local temperatures had in fact fallen over this period (contrary to global averages). Their study suggested that with an increasing temperature trend in the future, yields might fall. Both these studies are open to debate (e.g., Godden *et al.*, 1998), but they do suggest a detectable influence of temperature trends on crop yield in the real world.

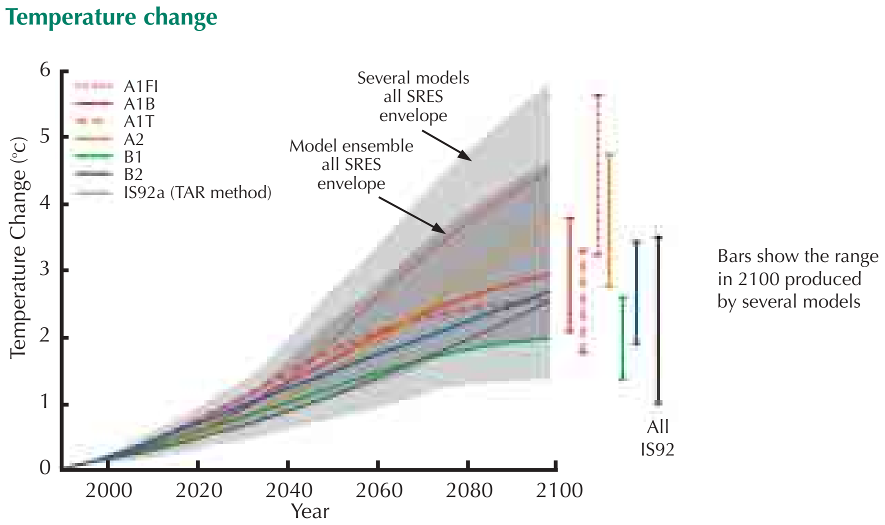


Figure 2.3.
Global mean temperature projections for the six illustrative SRES scenarios using a simple climate model tuned to a number of complex models with a range of climate sensitivities. The darker shading represents the envelope of the set of thirty-five SRES scenarios used to force climate models, using the average of the simple model results (mean climate sensitivity is 2.8°C). The lighter shading is the envelope based on all seven model projections (with climate sensitivity in the range 1.7 to 4.2°C). The vertical bars show, for each of the six illustrative SRES scenarios, the range of simple model results in 2100 for the seven climate model tunings. For comparison, the IPCC IS92 range of warmings in 2100 is also shown. (Adapted with permission from Houghton *et al.*, 2001, Figure 22 (a) of Technical Summary.)

Table 1.

Estimates of increases in global mean surface temperature (°C) for the IS92 scenario range, the full range of SRES scenario projections, and the 'WRE' stabilisation scenarios, all relevant to 1990. The IS92 and SRES scenarios do not extend beyond 2100. The WRE scenarios were developed by Wigley, Richel and Edmonds (see Nature 379, 1996, pp.242–245), and lead to stabilisation of carbon dioxide concentrations (ppm) at levels indicated.

CO_2 scenario	warming at 2100	warming at 2350	equilibrium warming
IS92 revised full range	1.0-3.6	n/a	n/a
SRES B1	1.4-2.6	n/a	n/a
SRES B2	1.9-3.5	n/a	n/a
SRES A1T	1.8-3.3	n/a	n/a
SRES A1B	2.1-3.8	n/a	n/a
SRES A2	2.8-4.8	n/a	n/a
SRES A1F1	3.2-5.8	n/a	n/a
WRE 450	1.2-2.3	1.4-3.0	1.5-3.9
WRE 550	1.6-2.9	1.9-4.0	1.9-5.2
WRE 650	1.8-3.2	2.2-4.7	2.3-6.3
WRE 750	1.9-3.4	2.6-5.4	2.7-7.1
WRE 1000	2.0-3.5	3.2-6.6	3.5-8.7

2.1.4 Projected climate changes (Houghton *et al.,* 2001)

Surface warming

Inserting the SRES emission scenarios into global climate models, which have their own uncertainties, leads to a projected range of global average surface warmings of 1.4 to 5.8 ºC by 2100 (see Figure 2.3, from the TAR), compared to the earlier IPCC IS92 range of 1.0 to 3.5 ºC. This suggests a rate of warming roughly twice to ten times that observed during the 20th century, which was about 0.6 ºC, and much faster than the average warming at the end of the last glaciation. The greater warming at the high end of the range, compared to the IS92 range, is largely due to the SRES scenarios having less sulfur emissions, as these lead to sulfate particles in the atmosphere, which cancel some of the warming due to the greenhouse gases.

Note that about half the range of uncertainty is due to the choice of scenarios, and half to the uncertainty for a given scenario.

In addition to the estimated warmings due to the SRES scenarios, the TAR provides estimates of the ranges of transient and equilibrium warmings due to some pathways to stabilisation at various concentrations of carbon dioxide from 450 to 1000 ppm. These are based on scenarios provided by Wigley *et al.* (1996), and are referred to as the WRE scenarios after the names of the authors. 'Transient' warmings are warmings reached at a certain date or carbon dioxide concentration, while the climate system is still undergoing change. 'Equilibrium' warmings are reached at a time when the climate system has stopped changing and settled down into a new, stable state.

The TAR-estimated transient and equilibrium warmings are summarised in **Table 1**. The IS92 full range is added for comparison, and includes emissions scenarios drawn up in 1992 and used in the IPCC Second Assessment Report.

Note that there is a large uncertainty range for each scenario and stabilisation level, due essentially to the uncertainty of the sensitivity of climate to a given increase in carbon dioxide concentrations. Reductions in the uncertainty about climate sensitivity is a high priority for further research.

Note also that the central estimates of the warming by 2100 in each of the stabilisation scenarios is clearly in the bottom half of the range of warmings for the SRES range of scenarios. Thus even following a development pathway aimed at stabilisation at 1000 ppm of carbon dioxide would substantially reduce impacts at 2100 relative to the impacts of the higher SRES emissions scenarios. There is relatively little difference in transient warmings at 2100 (although greater differences later) for stabilisation targets above about 650 ppm, due to the relatively small difference in cumulative emissions by 2100 implied by the different stabilisation pathways. However, differences in central to upper estimates of warmings due to different stabilised carbon dioxide concentrations at the time of temperature stabilisation (which occurs centuries beyond 2100) are substantial. Thus we can say that stabilisation pathways for any goal up to 1000 ppm would limit impacts and risks by 2100, but the higher the stabilised carbon dioxide concentrations, the greater the impacts and risks beyond 2100. This analysis is further supported by Swart *et al.* (2002).

New or revised transient or stabilisation scenarios of emissions will of course lead to different estimates of global warming at any time in the future. However, provided their cumulative emissions fall within the range of the scenarios shown in **Table 1**, their consequent estimated warmings will also lie in the range estimated here.

Regional warmings

Global climate models are in broad agreement on the patterns of warming around the globe. Greater warming is projected in continental interiors and in the Northern Hemisphere, and lesser warming over the oceans and windward coastlines, with least surface warming over the Southern Ocean due to its large capacity to transport surface heat into the deep ocean. Warming may be greater in the eastern tropical Pacific than in the west, leading to a more El-Niño-like mean state.

After stabilisation of greenhouse gas concentrations in the atmosphere, warming will continue for centuries in the Southern Ocean, leading to ongoing regional climate change in the vicinity, especially in Australia.

Precipitation and evaporation

Global average precipitation (rain or snow) and evaporation are projected to increase during the 21st century by about 1 to 9% by 2100, depending on which scenario and climate model is used. However, projected rainfall changes are more regionally varying, with increases over northern mid- to high latitudes and Antarctica in winter. At lower latitudes there are both regional increases and decreases over land areas, with some differences between different global climate models, but also areas of strong agreement.

Extreme events

Changes in some extreme events are likely and would have major impacts in some regions (**Table 2**). Increases in daily maximum and minimum temperatures, and in the number of hot days are very likely, with fewer cold and frost days and in general a reduced diurnal temperature range (the difference between daily maximum and minimum temperatures).

Table 2.

IPCC TAR estimates of confidence in observed and projected changes in extreme weather and climate events.

Confidence in observed changes (latter half of the 20th century)	Changes in phenomenon	Confidence in projected changes (during the 21st century)
Likely	Higher maximum temperatures and more hot days over nearly all land areas	Very likely
Very likely	Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely
Very likely	Reduced diurnal temperature range over most land areas	Very likely
Likely, over many areas	Increase of heat index[1] over land areas	Very likely, over most areas
Likely, over many Northern Hemisphere mid- to high latitude land areas	More intense precipitation events[2]	Very likely, over many areas
Likely, in a few areas	Increased summer continental drying and associated risk of drought	Likely, over most mid-latitude continental interiors (Lack of consistent projections in other areas)
Not observed in the few analyses available	Increase in tropical cyclone peak wind intensities[3]	Likely, over some areas
Insufficient data for assessment	Increase in tropical cyclone mean and peak precipitation intensities[3]	Likely, over some areas

Footnotes:

[1] The heat index is a combination of temperature and humidity that measures effects on human comfort.

[2] For other areas there are insufficient observations or conflicting modelling results.

[3] Past and future changes in tropical cyclone location and frequency are uncertain.

An increase in the heat or discomfort index is very likely in most tropical and mid-latitude areas. More intense precipitation events are very likely over many areas (with implications for more frequent flooding), and increased summer drying is likely over mid-latitude continental interiors, with an associated increased risk of drought. Increased intensity of tropical cyclone winds and peak rainfalls is likely. Greater extremes of flood and drought are likely with the El Niño-Southern Oscillation cycle (El Niño and La Niña), which is expected to continue. These are summarised in **Table 2.**

Knox (2000) reviews the paleo records of natural floods resulting from excessive rainfall or snowmelt. He finds the magnitude and frequency of floods are highly sensitive to even modest changes of climate equivalent to or smaller than those expected from global warming in the 21st century, and suggests that times of rapid climate change have a tendency to be associated with more frequent occurrences of large and extreme floods. Consistent with this, Milly *et al.* (2002) document that great flood events in 29 river basins around the world have increased in frequency since 1953, and project on the basis of climate models that the frequency of such large floods will increase further during the 21st century by a factor of two to eight. Using a high-resolution climate model, Christensen and Christensen (2002) find that an increase in the amount of precipitation that exceeds the present 95th percentile (a 1-in-20 event) is very likely in many parts of Europe, despite a possible reduction in summer rainfall over a large part of the continent. Thus, severe flooding may become more frequent, despite a general tendency toward drier summers. Further support for projections of more intense rainfall comes from Wilby and Wigley (2002), who analyse grid point rainfall from two General Circulation Models (GCMs) and find that the proportion of total precipitation derived from extreme and heavy events will continue to increase relative to that from light to moderate events.

A more extensive discussion of the occurrence, trends, modelling, projections and impacts of extreme weather events is contained in the March 2000 issue of the Bulletin of the American Meteorological Society, largely by the contributors to the TAR (Meehl *et al.*, 2000a and b; Changnon *et al.*, 2000; Parmesan *et al.*, 2000), and these are also reviewed by Easterling *et al.* (2000). The latter authors point out that some apparently gradual biological changes are linked to responses to extreme weather and climate events, while Changnon *et al.*(2000) argue that a large part of the observed increase in deaths and financial losses from extreme events in recent decades is due to population growth and demographic shifts into hazardous locations. This means that societies are becoming more vulnerable to extreme events. de Freitas (2002) presents a highly selective view of this literature, but is refuted by Hennessy and Walsh (2003).

A global study by Yonetani and Gordon (2001), using the CSIRO coupled model, mapped large-scale changes in seasonal and annual frequencies of extreme temperatures and rainfall. Increases in extreme high temperatures, especially in the tropics, and extreme large precipitation events occurred much more frequently where average rainfall increased, and extreme low rainfalls occurred much more frequently where average rainfall decreased.

Trenberth *et al.* (2003) have critically examined the performance of some climate models in simulating the daily average rainfall cycle. They suggest that the models tend to underestimate the intensity of rain, and overestimate its frequency on an hourly basis (which is seldom looked at in climate models). The authors argue that under global warming conditions the most likely situation is that extreme high rainfall rates will increase, and the number of light rain days will decrease, probably more than is at present simulated by climate models. The paper argues that the main changes in rainfall to be experienced will be due to the greater available moisture in the atmosphere, leading to higher rainfall rates, and greater intervals between rain events while higher evaporation restores the balance of the hydrological cycle. While the theory remains to be proven, it is plausible, and is now the subject of a new research program at the National Centre for Atmospheric Research in the United States (see <http://www.rap.ucar.edu/projects/watercycles/>). In fact, the new CSIRO Cubic Conformal climate model, which has spatially variable resolution, does correctly simulate the timing of the daily rainfall cycle (McGregor and Nguyen, 2003), but in this case it has not yet been used to investigate changes in rainfall intensity.

Large floods and widespread drought, in Australia and elsewhere, are commonly due to one or other extreme of naturally occurring variations in circulation patterns including the North Atlantic Oscillation (NAO) and the ENSO (Glantz, 2001; Glantz, 2002; Ropelewski and Halpert, 1987; Hoerling and Kumar, 2003). These phenomena also influence other important climatic events such as the favoured tracks of storms in the North Atlantic and the location of tropical cyclones. How global warming affects these circulation patterns is thus very important.

A progressive shift in the NAO toward its more positive phase has been observed since 1950, and has been associated by Hoerling *et al.* (2001) with a slow warming of the tropical oceans. This is supported by an analysis of observed and modelled trends in global sea level pressure patterns by Gillett *et al*. (2003), which may also have implications for storm tracks and rainfall patterns in the Australian region (see section 2.2.1).

Cai *et al.* (2001b) documented the time-varying nature of the relationship between ENSO and rainfall in the north-east of Australia, with variations in both the pattern and magnitude of the correlations over the last century. Such variability is also found in a 373-year chronology based on coral cores in the Great Barrier Reef indicative of runoff from the Burdekin River in Queensland. Other paleoclimatic data and model simulations (Huber and Caballero, 2003) suggest little change in ENSO behaviour even under warmer Earth conditions. In contrast, Timmermann *et al.* (1999) and Timmermann (2001) find more frequent El Niño events and that global warming changes the stability of the simulated ENSO oscillation. Model results depend in part on how well they simulated ENSO, and most climate models have underestimated the amplitude of ENSO variations. For example, both the Bureau of Meteorology Research Centre (BMRC) coupled ocean-atmosphere model and the CSIRO Mark 2 model simulate an ENSO variation that is weaker than observed. Wu *et al.* (2002) report that in a BMRC model simulation there are no significant differences in ENSO behaviour between the control runs and enhanced greenhouse (global warming) runs. On the other hand, Cai and Whetton (2000 and 2001a) report simulations in which a more La Niña-like pattern occurs up to 1960, followed by a reversal to a more El Niño-like pattern out to 2030. They attribute this reversal to initial warming in extra-tropical waters, which is subducted into the tropics where it is upwelled.

The interim conclusion must be that changes in the ENSO pattern may occur, but these are still very uncertain. So far published results from simulations with the CSIRO Mark 3 GCM show a more realistic amplitude for the ENSO in the control climate (Cai *et al*., 2003), and that it does trend with global warming to a weak El Niño-like mean state response, but this has yet to be verified. This mean state change is consistent with the majority of other global models.

The situation with projections of tropical cyclone behaviour is mixed. As TAR concluded, it is likely that tropical cyclones will become more intense, by 5–10% around 2050, with corresponding rainfall peak intensities increasing by about 25%. There could also be substantial changes in region of formation due to changes in ENSO, although there is no evidence for changes in total numbers globally. So far there is no evidence for a substantial increase in poleward movement of tropical cyclones (Walsh *et al*., 2003).

A category of extratropical cyclones known as explosively developing cyclones or "bombs", which includes some east coast low pressure systems off Australia, can cause severe flooding and high winds. Consistent with modelling by McInnes *et al.* (1992), which suggested that east coast lows might intensify with higher sea surface temperatures, Lim and Simmonds (2002) have detected a statistically significant increase in explosively developing cyclones in the Southern Hemisphere from 1979 to 1999.

The frequency and severity of other extreme climate-related events, some not discussed in the TAR because of their small scale and relative neglect in relation to climate change, are also likely to be affected by climate change. These include the occurrence of flash flooding, severe thunderstorms and hail (Mills and Colquhoun, 1998), landslides (Flentje and Chowdhury, 1999), extreme sea level events (McInnes and Hubbert, 2001; Queensland Government, 2001); and bushfires (Williams *et al*., 2001; Cary, 2002). Some of these will be discussed further in sections 2.3.2, 4.4.1 and 4.4.2.

Sea level rise

TAR projections of global sea level rise are in the range of 9 to 88 cm by 2100 for the full range of SRES scenarios (see **Figure 2.4**). This is appreciably lower than the SCOPE estimate of 20 to 165 cm made in 1986 (Bolin *et al*., 1986). However, it differs little from the estimates in the Second Assessment Report in 1996 despite the higher upper limit estimates of global warming in the TAR. Beyond 2100, if greenhouse gas concentrations were stabilised (even at present levels), the TAR notes that sea level would continue to rise for hundreds of years due to the slow but continuing warming of the deep oceans, while the polar ice sheets will continue to react to climate change during the next several thousand years, even if climate is stabilised.

The TAR provides estimated contributions by 2100 from thermal expansion of sea water of 11 to 43 cm, accelerating through the 21st century, with the next largest contribution coming from melting mountain glaciers (1 to 23 cm). However, these separate contributions are based on the IS92a scenario (including the direct aerosol effect), and the relative contributions vary with the sensitivity of the climate model

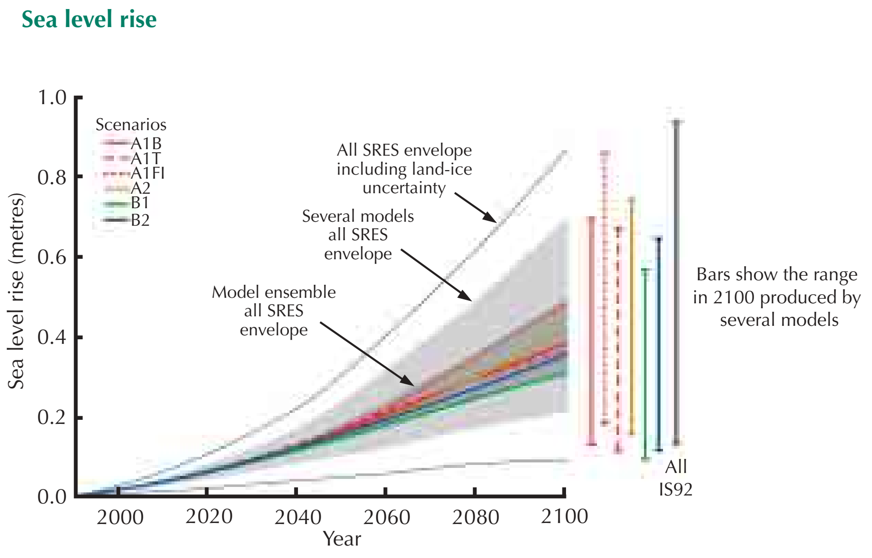


Figure 2.4.
Projections of global average sea level rise from 1990 to 2100 for the SRES scenarios. Each of the six lines in the key is the average of seven different model calculations for one of the SRES illustrative scenarios. Dark shading shows the range of the average model projections for all 35 SRES scenarios. The range of uncertainty associated with each individual SRES illustrative scenario is shown by the vertical bars on the right. Note that up to 2100 most of the range of uncertainty is due to uncertainty in the calculations of thermal expansion, ice melting etc., rather than uncertainty about which scenario is correct. This is because a large part of sea level rise in the next 100 years is determined by global warming to date. Beyond 2100 the differences due to different scenarios becomes more important.

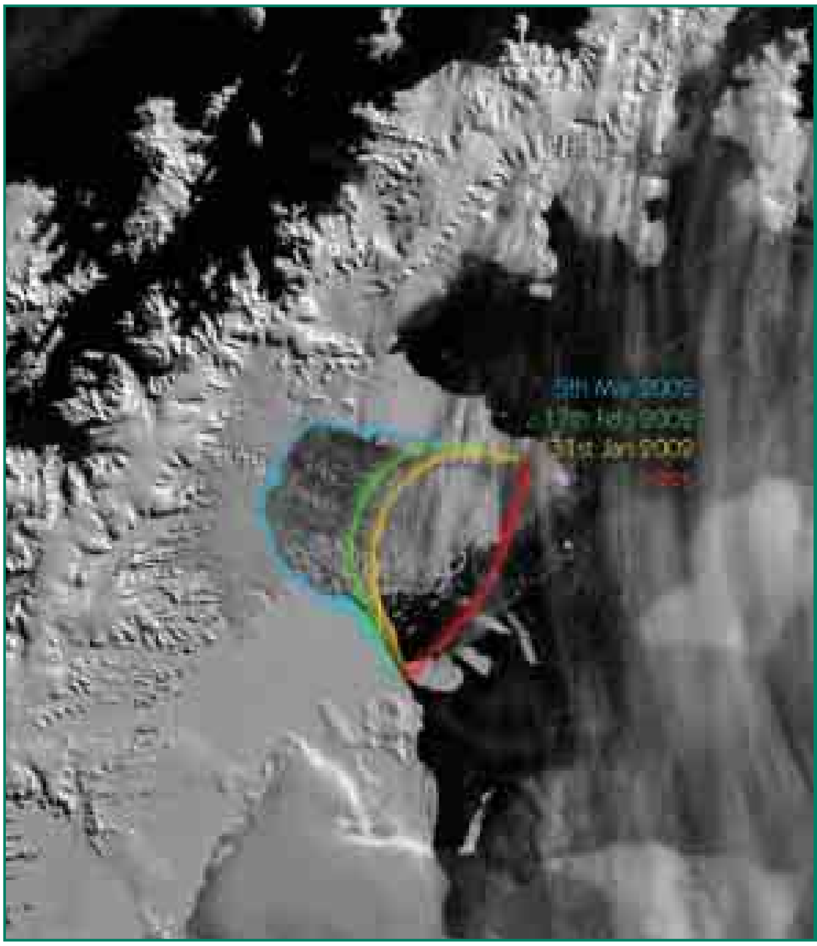


Figure 2.5.
Composite satellite image of the collapse of the Larsen B ice shelf on the eastern side of the Antarctic Peninsula. The red line shows the edge of the shelf in 1995. The yellow line shows its location at 31st January 2002, the green line its location on 17th February 2002, and the blue line its location on 5th March 2002. Subsequent to the collapse of the ice shelf, the tributary glaciers descending from the mountains at the left have greatly accelerated, adding to the sea level. (Image courtesy Ted Scambos, U.S. National Snow and Ice Data Center, University of Colorado.)

used. Greenland is most likely to add a little to sea level rise (–2 to + 9 cm), while Antarctica may make a negative contribution due to increased snow accumulation (–17 to + 2 cm).

However, the contribution from Antarctica is particularly uncertain, with the possibility of surprises. Floating ice shelves, notably the Wordie and Larsen A and B shelves, broke up very rapidly during the 1990s, following regional warming of about 2.5 ºC over the previous 50 years (see **Figure 2.5**). The rapid regional warming around the Antarctic Peninsula is not well predicted by climate models, and its cause remains contentious (Vaughan *et al.*, 2001). Until it is better understood, future warming in the region, and its possible penetration further south, remains uncertain.

Whatever caused the regional warming, the breakup of the Wordie and Larsen Ice Shelves was probably due in part to basal melting, and to summer meltwater draining through crevices, leading to major fractures in the shelves (Rott *et al.*, 1996; Vaughan and Doake, 1996). In the case of the Larsen Ice Shelves this has been followed by an acceleration and active surging of a number of former contributory glaciers (De Angelis and Skvarca, 2003). This has led to the strengthening of an earlier theory that ice shelves tend to hold back contributory glaciers (Mercer, 1978). De Angelis and Skvarca (2003) suggest that the increased glacier outflow in the Larsen Ice Shelf region is already making a small but significant contribution to sea level rise.

De Angelis and Skvarca (2003) go on to suggest that these observations should cause a rethink as to the stability of the much larger West Antarctic Ice Sheet (WAIS). The Ross and Filchner-Ronne Ice Shelves, which may stabilise the WAIS, are not immediately threatened, as it would require a further 10 ºC warming in their vicinity before the critical –5 ºC mean isotherm reaches their ice fronts. However, increases in basal melt rates under the ice shelves due to ocean warming and changing circulation beneath the ice shelves are also possible (Williams *et al.*, 2002). The call by De Angelis and Skvarca (2003) for a rethink is not supported by the IPCC TAR (Houghton *et al.*, 2001, pp. 678–679), nor by Bill Budd (Antarctic CRC, personal communication, May 2003). Budd argues that accelerated outflow following the break-up of floating ice shelves is already taken into account in the IPCC TAR.

Regarding the possible effects of processes not adequately represented in present models of sea level rise, the TAR cites two risk assessment studies involving panels of experts. These studies concluded that there was a 5% chance that by 2100 the WAIS could make a substantial contribution to sea level rise, of 16 cm (Titus and Narayanan, 1996) or 50 cm (Vaughan and Spouge, 2002). These studies also noted a 5% chance of the WAIS contributing a sea level fall of 18 cm or 40 cm respectively, due to increased snow accumulation.

Models agree on the qualitative conclusion that the range of regional variation in sea level change is comparable to the global average sea level rise (Gregory *et al.*, 2001). This is due to different rates of regional subduction of warming into the deep oceans (and thus of thermal expansion of the water), changes in atmospheric pressure and surface winds, and in ocean currents. However, confidence in the regional distribution of sea level change from coupled ocean-atmosphere models is low because there is little similarity in results for regional variations between models, although nearly all models project greater than average rise in the Arctic Ocean and less than average rise in the Southern Ocean.

Church *et al.* (2003) compare model projections with observations from tide gauge records and the TOPEX/POSEIDEN satellite altimeter. They conclude that the best estimate of mean sea level rise globally for the period 1950 to 2000 is about 1.8 to 1.9 ± 0.2 mm per year, and that sea level rise is greatest (about 3 mm per year) in the eastern equatorial Pacific and western equatorial Indian Ocean. Observed rates of rise are smallest (about 1 mm per year) in the western equatorial Pacific and eastern Indian Ocean, particularly the north-west coast of Australia. Regional variations in the rate of sea level rise are weaker for much of the rest of the global oceans.

Further, land movements, both isostatic and tectonic, will continue through the 21st century at rates that are unaffected by climate change. It can be expected that by 2100 many regions currently experiencing relative sea level fall will instead have a rising relative sea level. Lastly, extreme high water levels will occur with increasing frequency as a result of mean sea level rise. Their frequency may be further increased if storms become more frequent or severe as a result of climate change. Projections of local sea level rise and its impacts thus need to be quite location-specific.

Abrupt changes, thresholds and instabilities

Climate and other complex systems do not behave in a simple linear fashion, that is to say they do not always vary in a smooth fashion that enables easy extrapolation. This is the case for climate, where sudden changes in regime can occur over wide areas, apparently associated with some shift in the circulation pattern. The mathematical theory of such regime changes is still being developed (Palmer, 1999; Crommelin, 2002; Stewart, 2003).

Such abrupt changes have occurred in Australian rainfall (Vives and Jones, 2003). Summer half-year rainfall increased over large parts of eastern Australia around 1945, largely reversing a decrease in the 1890s, while there was a sudden decrease in rainfall in the south-west of Western Australia around 1967–72, which has not reversed since (e.g., Deacon, 1953; Kraus, 1954; Gentilli, 1971; Pittock, 1975; Allan and Haylock, 1993). Warner (1987) partitioned eastern Australia into drought and flood-dominated regimes. This was contested by

Kirkup *et al.* (1998) but confirmed by Franks (2002) and Franks and Kuczera (2002). Such abrupt changes have also been found in climate model simulations (Yonetani and Gordon, 2001). These abrupt changes may or may not be predictable, as they occur as part of natural climate variability on a multi-decadal time-scale. They may also be precipitated by gradual changes that slowly move the climate to some critical point where it 'flips' to another regime.

This also happens in ecological systems (Scheffer *et al.*, 2001; Bennett and Radford, 2003). Studies on lakes, coral reefs, oceans, forests and arid lands have all shown that smooth change can be interrupted by sudden shifts to some contrasting state (e.g., see Scheffer *et al.*, 1993; Van de Koppel at el., 1997; Nystrom *et al.*, 2000). Such sudden changes in system behaviour often arise from an element of the system reaching a limit or threshold at which instability sets in, and the system moves into a new stable state. When a system is close to such a threshold, even quite small random events or trends can force the system into a different state. In more mathematical terms, it may take the form of a switch from a negative to a positive feedback. Distance from a threshold of this sort is a measure of system resilience or ability to cope with small variations in conditions (Scheffer *et al.,* 2001).

Such thresholds are part of a wider variety of thresholds or critical levels that may be reached in a system, at which drastic and perhaps unacceptable change in system function may occur. In relation to climate change impacts, impact thresholds can be grouped into two main categories: biophysical thresholds that mark a physical discontinuity on a spatial or temporal scale (Bennett and Radford, 2003), and behavioural thresholds, where reaching that state triggers a change in behaviour in the form of a social or economic outcome (Jones, 2000a).

Threshold events may signal a distinct change in conditions, or be a nominated level or benchmark. Climatic thresholds include frost, snow or monsoon onset. Biophysical thresholds represent a distinct change in conditions, such as drying of a wetland, cessation of flow in a river, floods, or breeding events. Behavioural thresholds are set by benchmarking a level of performance such as crop yield per hectare or net income. Operational thresholds might include sustainable herd size for grazing grasslands, design standards for buildings or drain sizes, heights of levee banks or size of dam spillways. One example is the damage to buildings caused by wind gusts, which Australian insurance figures indicate rise dramatically for peak wind gusts in excess of 25.8 metres per second (i.e., 50 knots, see **Figure 4.5**, section 4.4.1). Movements of variables across such thresholds can have much larger consequences than similar magnitude movements that stay below the thresholds. Thresholds also apply to decision-making, where critical levels of evidence or persuasion tip the balance for or against a certain course of action.

Large-scale singular events

Large-scale singular events are an especially important category of abrupt or threshold events. Working Group II (McCarthy, 2001) emphasised the potential importance of plausible abrupt or irreversible Earth system events, which, although uncertain and possibly taking more than a century to come about, might have such large impacts globally that it would be an important part of any risk analysis. In the technical summary they state: "Human-induced climate change has the potential to trigger large-scale changes in Earth systems that could have severe consequences at regional or global scales. The probabilities of triggering such events are poorly understood but should not be ignored, given the severity of the consequences."

More recently, the U.S. National Research Council issued a major report entitled 'Abrupt Climate Change: Inevitable Surprises' that provides a comprehensive treatment of abrupt climate change (NRC, 2002). This has been summarised by Alley *et al.* (2003) who state that "...it is conceivable that human forcing of

Table 3.

Examples of different types of large-scale discontinuities or irreversible changes in Earth systems, caused by gradual changes in the climate system.

Type of event	Cause	Potential impacts
Non-linear response of ocean circulation	Changes in salinity and temperature could result in slow-down or regional shutdown of sinking of dense water in the North Atlantic or around Antarctica. Effects may be delayed until critical thresholds reached (TAR WGI, Chapters 2, 7 and 9).	Slowing or stopping of Gulf Stream and heat transport to western Europe. Possible regional effects elsewhere, including North America. Reduced oxygen levels and carbon uptake in deep ocean.
Melting of Greenland ice sheet and disintegrating of West Antarctic Ice Sheet (WAIS)	Melting of Greenland ice over centuries due to locally warmer temperatures. WAIS disintegration could be initiated irreversibly this century, but would take centuries to be complete (TAR WGI Chapters 7 and 11).	Rapid global sea level rises of several metres over several centuries, threatening many coastal cities and settlements and millions of people.
Runaway carbon dynamics	Climate change could reduce the uptake of carbon by the oceans and vegetation, possibly turning vegetation into a source. Gas hydrate reservoirs may also be destabilised, releasing much methane into the atmosphere (TAR WGI, Chapter 3).	Would increase rate of warming and consequent impacts of all sorts.

SOURCE: Extracts adapted from TAR WGII, Table 19-6, which contains references to relevant published papers and sections of the TAR WGI.

climate change is increasing the probability of large, abrupt events. Were such an event to recur, the economic and ecological impacts could be large and potentially serious.” They go on to say that “slowing the rate of human forcing of the climate system may delay or even avoid crossing the thresholds [that would lead to abrupt climate change].”

Events of this type include complete or partial shutdown of the North Atlantic and Antarctic Deep Water formation, disintegration and melting of the West Antarctic and Greenland Ice Sheets, and major changes in the carbon cycle due to biospheric effects. These are summarised in **Table 3**.

Determining the timing and probability of occurrence of large-scale discontinuities is difficult because these events are triggered by complex interactions between components of the climate system. The actual discontinuous impact could lag the trigger by decades or centuries. These triggers are sensitive to the magnitude and rate of climate change (Schaeffer *et al.*, 2002). Large global warmings have the potential to lead to large-scale discontinuities in the climate system (Stocker and Schmitter, 1997).

The slow-down or complete cessation of convective overturning of the waters in the North Atlantic and around Antarctica can arise due to several causes. These include surface warming due to the enhanced greenhouse effect, and lower salinity of surface waters (due to increased rainfall and influxes of freshwater from rivers and melting glaciers). Around Antarctica the main cause of convective overturning is the freezing of seawater, which leads to a rejection of salt, and thus to dense highly saline water which sinks. Global warming would lead to a reduction in sea ice formation.

Evidence for the plausibility and impact of such events comes both from past events recorded in the paleo-record of climate and sea level, and from computer modelling both of past and possible future events (Stocker, 1999, 2000; Stocker and Marchal, 2000; Lockwood, 2001; Bard, 2002). There is also observational evidence suggesting that such a process may already be underway (Delworth and Dixon, 2000; Matear *et al.*, 2000; Hansen *et al.*, 2001; Kim *et al.*, 2001; Dickson *et al.*, 2002; Gille, 2002). Besides direct impact on surface climate (e.g., Vellinga and Wood, 2002), reduced overturning of the oceans would reduce oceanic uptake of carbon dioxide, and thus further increase the carbon dioxide concentration in the atmosphere (Matear and Hirst, 1999).

Melting of the Greenland ice sheet and/or disintegration of the West Antarctic Ice Sheet (WAIS), both of which could be triggered by global warming, but which would take centuries to complete, are potentially irreversible. These events are probably inevitable unless carbon dioxide were to be taken out of the atmosphere in sufficiently large quantities as to substantially reduce the carbon dioxide concentration in the atmosphere, and thus reverse global warming. Failing this reversal, the Greenland and West Antarctic ice sheets would each contribute several metres to global mean sea level over the next thousand years or so. As discussed above, the time scale for disintegration of the WAIS is still under debate.

Several mechanisms exist which could lead to an acceleration of global warming via positive feedbacks (i.e., amplification mechanisms) associated with the carbon cycle. One is destabilisation of the methane reserves stored in crystalline structures (hydrates) on the seabed (Suess *et al.*, 1999; Wood *et al.*, 2002; Lorenson *et al.*, 2002). There is evidence that such a process has occurred in the past (Hinrichs *et al.*, 2003; Kennett *et al.*, 2003), but uncertainty exists as to its likelihood in the next century.

Other possible feedbacks on the carbon cycle include decreased efficiency of the oceanic and terrestrial biospheric sinks of carbon due to global warming (Matear and Hirst, 1999; Cox *et al.*, 2000; Freidlingstein *et al.*, 2001).

The effects of a slowdown or cessation of Antarctic Bottom Water formation were investigated by Matear and Hirst (1999 and 2003). Using a simulation up to 2100 and later multi-century climate change simulations from the CSIRO Mark 2 climate model, they projected the impact on marine biogeochemical cycles. Key results were:

- reductions in the global oceanic uptake of carbon dioxide by about 14% by 2100 (Matear and Hirst, 1999)
- reductions in dissolved oxygen levels in the ocean interior over several centuries, causing expansion of an anoxic region in the mid-water of the eastern equatorial Pacific (Matear and Hirst, 2003)
- reductions in nutrient concentrations in the upper ocean causing an expansion of regions that are nutrient limited and reducing biological production in the upper ocean (Matear and Hirst, 2003).

Cox *et al.* (2000) estimate that the terrestrial biosphere, which presently acts as a sink of carbon dioxide, could become a source by 2050, and balance the oceanic sink of some 5 GtC per year by 2100. Recent variability in carbon dioxide uptake varies due to changes in ocean circulation (the ENSO cycle), carbon dioxide fertilisation of terrestrial forests, and temperature and rainfall effects on terrestrial biota growth rates (Francey *et al.*, 1995; Bousquet *et al.*, 2000). The main reason for the expected change of the terrestrial biota from a sink to a source by 2050 is expected to be increased respiration and decay of the increased biomass and soil carbon, especially at higher temperatures. Increasing fire frequencies and intensities (Cary, 2002; Lavorel, 2003) may also affect growth rates of atmospheric carbon dioxide. Widespread forest and peat fires have been observed to contribute significantly to increases in annual growth rates in 1994/95 and 1997/98 when large biomass burning took place in tropical and boreal regions (Page *et al.*, 2002; Langenfelds *et al.*, 2002).

There are also possibilities of major changes in the behaviour of the continental monsoons, the El Niño-Southern Oscillation and other patterns of climate variability (TAR WGI, sections 7.7.3, 9.3.5.2, and 9.3.6.2, and WGII section 11.5.1).

The importance of such events to global estimates of risk, and in cost/benefit analyses as to the optimal timing of mitigation action to reduce the risk of such events, has been identified by several recent studies (Keller *et al.*, 2000; Baranzini *et al.*, 2002; Vellinga and Wood, 2002; Azar and Lindgren, 2003; Howarth, 2003; Tol, 2003).

Relevance of thresholds, abrupt changes and large-scale singular events to Australia

As discussed above, exceeding a threshold can lead to impacts that are much larger than if the same change occurred below that threshold. In Australia that is obviously important in many areas such as flood magnitude, water resources, engineering standards, and zoning for coastal or riverine flood setbacks.

As already noted, the TAR concluded, and more recent economic studies have confirmed, that large-scale instabilities and changes may dominate the global estimates of risk. Although such events are uncertain as to timing and probability, if and when they occur they may have disastrous consequences. While this may be true globally, and may thus affect the international policy response, here we need to address what the regional effects of such instabilities may be on Australia.

Obviously, globally disastrous impacts, such as a regional cooling in Western Europe leading to serious economic effects, would impinge on Australia via trade and other relationships. Any acceleration in global change due to reductions of terrestrial and oceanic carbon sinks, or release of trapped methane, would also have implications for Australia, by accelerating the rate of climate change, reducing the time available to adapt to climate change or to reduce greenhouse gas emissions. However, there may be more direct impacts on Australia.

Most studies of the impacts of a slowdown or complete cessation of deep water formation in the world oceans have focussed on possible impacts on the Northern Hemisphere, and indeed most have not considered regional effects related to the cessation of Antarctic Bottom Water formation. For example, the study by Vellinga and Wood (2002) considered the global effects of a freshening of the waters of the North Atlantic, which would bring about a collapse of the North Atlantic deep water formation, and thus of the Gulf Stream. However, it did not consider the additional effects of a cessation of overturning in the Antarctic Ocean that might accompany the retreat of sea ice and the stabilisation of the surface layers around Antarctica. Thus Vellinga and Wood's conclusions regarding the Southern Hemisphere are suspect.

Many studies of paleo-climatic analogies are similarly suspect in that they have focussed only on the global scale impacts of rapid changes in the North Atlantic associated with sudden influxes of meltwater from icebergs or glacial lakes into the North Atlantic. Notable amongst the episodes investigated has been that of the Younger Dryas event, which was probably set off by a surge of meltwater down the St. Lawrence River from glacial lakes (Alley and Clark, 1999). Even so, impacts of this event have been found in paleo-evidence from places as far afield as western and central Europe (Isarin and Bohncke, 1999), North America (Reasoner *et al.*, 2001; Anderson *et al.*, 2002; Friele and Clague, 2002), Africa (Olago and Odada, 2001), China, Japan, and even New Zealand (Denton and Hendy, 1994). A similar event occurred about 8,200 years BP ('Before Present' where 'present' is by definition 1950), and was also evident in paleo-records from Europe, North America and North Africa (Renssen *et al.*, 2001). However, little evidence of impacts of such events, which originated in the North Atlantic, has come from Australia. This could be in part due to the smoothing effects of the large heat capacity of the Southern Ocean.

Nevertheless, as noted above, Matear and Hirst (1999 and 2003) have investigated the effects of a slowdown or cessation of Antarctic Bottom Water formation on marine geochemical cycles. Besides the global implications, they find that reductions in dissolved oxygen levels may cause an expansion of the anoxic region in the eastern equatorial Pacific, and a reduction in nutrient concentration and reduced biological production in the upper ocean. Consequences for local changes in upwelling, nutrient supply and ocean currents have yet to be investigated. Thus Australian fisheries could be affected on a multi-century timescale.

While little work has been put into assessing the impacts of a large sea level rise on Australia, it is obvious that impacts, were this to happen, would be widespread and serious in the ports and lower-lying areas of our major coastal cities, greatly affecting infrastructure for trade, transport and industry. Even spread over several centuries, this would require major readjustments to capital investments, industry and population distribution. Effects would also be widespread in other coastal and estuarine areas, affecting tourist resorts, agriculture and natural ecosystems. Many coastal wetlands would be flooded, often without the possibility of retreat inland due to existing land use and infrastructure.

Large sea level rises in low lying countries would also lead to significant problems of dislocation of population, adding pressure on international aid and related policies (Westing, 1992; Myers and Kent, 1995; Edwards, 1999; Barnett and Adger, 2001; Hay and Beniston, 2001).

Possible circulation changes due to synergistic effects of ozone depletion, enhanced greenhouse gases, and other radiative forcings

In the TAR Working Group I Report (Houghton *et al*, 2001), Chapter 6, changes in radiative forcing are shown for the combined effect of all the greenhouse gas changes from 1750 to 2000 (their Figure 6.7a), and for stratospheric ozone depletion over the period 1979 to 1994 (their Figure 6.7b). These show that the radiative forcing due to the enhanced greenhouse gases over the longer period ranges from +1 W/m^2 in southern polar regions to +3 W/m^2 near the Equator, thus increasing the low- to high-latitude gradient in forcing. The surface radiative forcing due to the ozone depletion in recent decades is near zero at the Equator, but around -0.5 to -0.9 W/m^2 near the Antarctic coast. This also increases the low-to high-latitude gradient in radiative forcing, so the two forcing changes would act to reinforce each other's climatic impact in recent decades. The same appears to be true in the Northern Hemisphere, but to a lesser degree.

Changes in other possible radiative forcings, due to tropospheric ozone, black carbon, mineral dust, and the direct and indirect effects of sulfate aerosols, aircraft contrails, land use changes and solar variability are also shown in the same Figure (Houghton *et al*, 2001, their Figure 6.7). Apart from solar variability, the radiative effects of the various short-lived pollutants are predominantly regional and confined in the main to the Northern Hemisphere and parts of Africa.

Not all of these effects are taken into account in most climate change model simulations, which mainly have considered enhanced greenhouse gases and the direct effects of sulfate aerosols, with a few taking account of stratospheric ozone depletion and/or some indirect aerosol effects.

In a separate discussion in Chapter 2 of Houghton *et al*. (2001), unusual trends were noted in the North Atlantic Oscillation, with lower surface pressure over the Arctic and a strengthening of the sub-polar westerlies in the North Atlantic region. This was linked to precipitation increases over Scandinavia and decreases over the European Alps, causing advances and retreats, respectively, of glaciers. The TAR also noted a phenomenon where the surface pressure over Antarctica and the high latitude Southern Ocean has decreased, while that north of 50S has increased, and the high latitude westerly winds have strengthened.

Since the TAR was finalised in 2000, the changes in radiative forcing have been linked to the observed circulation changes. Most notable is a paper by Hartmann *et al*. (2000) entitled "Can ozone depletion and global warming interact to produce rapid climate change?" Hartmann *et al.* note that in middle to high latitudes of both hemispheres there are modes of variability in atmospheric circulation that are roughly annular around the poles and extend from the surface to the stratosphere (upper atmosphere around 10 to 30 km altitude). These are described in more detail in Thompson and Wallace (2000), who point out that they are stronger in winter in the Northern Hemisphere, and spring in the southern, and interact with lower latitude tropospheric circulations.

Hartmann *et al.* (2000) point to observed strong cooling and ozone depletion in the polar lower stratosphere of both hemispheres over the last 30 years, along with an increase in the wintertime westerly winds circulating around the poles (the polar vortices). They argue that there are strong dynamic links between the troposphere (lower atmosphere) and the stratosphere such that changes in either can affect the other. These observations and connections are further documented in a paper by Thompson *et al.* (2000).

Hartmann *et al.* (2000) go on to argue that stratospheric ozone depletion and enhanced greenhouse warming at the surface may both be producing increased equator to pole temperature gradients, and hence momentum fluxes (leading to stronger westerly winds), in the extra-tropical lower stratosphere and upper troposphere, and thus acting to produce large trends in both surface and stratospheric climate. As the stratospheric ozone losses only became noticeable in the early 1970s, this would have led to an acceleration of trends due to the enhanced greenhouse effect that started earlier. Hartmann *et al.* also discuss possible links between strengthening of the high latitude westerlies in the Northern Hemisphere and movements of Arctic pack ice and possible effects on the Gulf Stream and the oceanic thermohaline circulation.

Observed trends in the Southern Hemisphere tropospheric circulation and surface temperatures over Antarctica are further documented by Thompson and Solomon (2002), and related to a strengthening of the westerly wind vortex around Antarctica and associated ozone depletion. The circulation changes are consistent with warming of the Antarctic Peninsula and cooling over eastern Antarctica and the Antarctic plateau. They suggest that the memory in the temperature of the stratospheric polar vortex from spring through summer and the coupling to the troposphere may provide predictive skill for Southern Hemisphere tropospheric climate on month-to-month time scales.

The Canadian CCCma climate model was used by Fyfe *et al*. (1999) to show a strengthening of the annular mode in both the Artic and Antarctic in a set of three simulations from 1900–2100, with forcing due to greenhouse gases and aerosols.

Similarly, Kushner *et al*. (2001) used the GFDL climate model to simulate changes in the Southern Hemisphere zonally-averaged circulation under transient warming scenarios due to increases in greenhouse gases and sulfate aerosols, but without ozone depletion. They find a poleward shift of the westerly jet stream and accompanying atmospheric circulation of about 1° of latitude by the mid-21st century.

McInnes *et al*. (2002b), in a report on climate change in South Australia, show a map of the consistency between ten global climate models in the sign of the projected annual pressure change based on scenarios of increasing greenhouse gases (mostly without ozone depletion). They find that the models agree strongly (at least eight out of ten models) on decreases in surface pressure polewards of 60 degrees latitude in both hemispheres, and on increases in surface pressure in the belt between 30S and 60S. (A similar increase in surface pressure is only shown in the northern hemisphere over the North Atlantic.) The report relates this change in surface pressure to projected decreases in rainfall across southern Australia, again in at least eight out of ten climate models, particularly in the southwest of Western Australia. Cai *et al*. (2003) go on to relate these changes to a strengthening of the annular mode in the southern hemisphere under increasing greenhouse gas concentrations, but to a reversal of this tendency once stabilisation of greenhouse gas concentrations is reached. They relate this to the lag in surface warming induced by the large heat capacity of the Southern Ocean.

Gillett *et al*. (2003) compare observational data sets of the northern hemispheric circulation with several climate model simulations that have increasing greenhouse gases and sulfate aerosols. The observations show a trend from 1948 to 1998 with decreases in surface pressures over the polar regions of both hemispheres, and an increase in pressure over the subtropical North Atlantic, southern Europe and North Africa, and to a lesser extent over some mid-latitude regions of the Southern Hemisphere. They find that these trends are closely related to major regional temperature and rainfall trends in parts of Europe, but that similar trends are present but underestimated in the climate model simulations.

The difference in simulated and observed trends over the Antarctic is partly attributed by Gillett *et al.* (2003) to stratospheric ozone depletion. They note that simulated sea level pressure changes in simulations with the UK HadCM3 climate model that included stratospheric ozone changes were larger over the Antarctic, although they did not do better over the Northern Hemisphere.

Marshall (2003) confirms the trend in the Southern Hemisphere annular mode towards a strengthening of the circumpolar vortex, especially since the late 1970s. Ostermeier and Wallace (2003) examine trends in the Northern Hemisphere annular mode, comparing that in recent decades with earlier changes. They find that the recent trends towards a strengthened annular mode are more hemispheric than earlier trends that were confined to the Atlantic sector.

What these changes in the annular mode in the Southern Hemisphere mean to weather is examined by Fyfe (2003) in relation to the frequency of extratropical cyclones or low pressure centres in the Antarctic Ocean (south of 60S), and the sub-Antarctic Ocean (40-60S). He finds a statistically significant decrease in the number of cyclones in the Sub-Antarctic Ocean, and a statistically significant increase in the Antarctic Ocean, between 1900 and 2100. Despite some concern about the quality of the observational data, a similar trend is found both in the observations and in simulations with the Canadian CCCma climate model with forcing by greenhouse gases and sulfate aerosol. Fyfe's conclusions are consistent with those of Simmonds and Keay (2000).

Geng and Sugi (2003) also look at effects of enhanced greenhouse gases and sulfate aerosols on the occurrence of extratropical cyclones using the Japan Meteorological Agency high resolution climate model in simulations of the present climate and of that around 2050 AD. They find that the total cyclone density tends to decrease in mid-latitudes in both hemispheres in both summer and winter, but that strong cyclones become more frequent. Geng and Sugi also find increases in strong cyclones at higher latitudes especially around Antarctica. They relate the decrease in cyclone activity in mid-latitudes to a decrease in baroclinicity (a measure of the tendency for smooth atmospheric flow to break down into large turbulent eddies). In the Northern Hemisphere they attribute this to a decrease in the north-south temperature difference, but in the Southern Hemisphere to an increase in static stability due to relatively less surface warming over the Southern Ocean.

Sulfate aerosols may affect climate in several ways (Haywood and Boucher, 2000; Ramanathan *et al.*, 2001; Williams *et al.*, 2001; Anderson *et al.*, 2003), including the direct effect due to scattering and reflection of sunlight, absorption of sunlight and infrared radiation, and effects on clouds through increased cloud condensation nuclei which decrease cloud droplet size and thus affect cloud radiation properties and effects on cloud lifetimes and rainfall.

In general, clouds can provide either a positive feedback (a reinforcing effect) or a negative feedback (a dampening of the effect) on global warming, depending on their properties, altitude and latitude and the season. This is one of the most uncertain areas of climate modelling. However, aerosols have a short lifetime of in the lower atmosphere so their direct and indirect effects (via clouds) are closely related to current emissions of sulfur, in contrast to the cumulative effects of past and present carbon dioxide emissions, due to the longer effective lifetime of carbon dioxide in the atmosphere. The short lifetime of sulfate aerosols also means that their effects are concentrated near or downwind of regions where large quantities of sulfur are emitted, except in so far as their regional effects may propagate globally via atmospheric dynamics.

Sulfur emissions increased with economic activity from the 1850s to the 1990s (Lefohn *et al.*, 1999), although they have levelled off or decreased in the U.S., the former U.S.S.R., and in Western Europe in recent decades. They have continued to increase in parts of south and east Asia but may level off there also due to pollution controls to manage urban pollution and acid rain (Carmichael *et al.*, 2002). This is consistent with the SRES scenarios, and means that effects of sulfate aerosols, even if they are significant up to the present, are likely to decrease in future relative to the enhanced greenhouse effect.

Rotstayn and Ryan (2000) and Williams *et al.* (2001) both simulated the changes in the climate system due to the indirect effects of anthropogenic aerosols. Both studies, using different climate models, found that the aerosols led to a relative cooling of the surface in the Northern Hemisphere, leading to a southward shift in the inter-tropical convergence zone and its associated rainfall pattern.

We will briefly examine how these various forcings may have already affected rainfall patterns over Australia in section 2.2.1 below.

2.1.5 Time lags and persistence

Emphasis is placed in the TAR on the considerable time lags and persistence of many

Box 2. The Policy-Relevance of Inertia and Time-Lags

Inertia and time-lags are widespread inherent characteristics of the interacting climate, ecological, and socioeconomic systems. Thus some impacts of anthropogenic climate change may be slow to become apparent, and some could be irreversible if climate change is not limited in both rate and magnitude before associated thresholds, whose position may be poorly known, are crossed.

Several important policy-relevant considerations follow from the effects of inertia:

Stabilisation of the climate and climate-impacted systems will only be achieved long after anthropogenic emissions of greenhouse gases have been reduced.

Stabilisation at any level of greenhouse gas concentrations requires ultimate reduction of global net emissions to well below current emissions, and it will take centuries to reduce carbon dioxide concentrations substantially below the highest levels reached. The reason is illustrated in **Figure 2.6**.

Social and economic time scales for change are not fixed. They can be changed by policies, and by choices made by individuals.

Higher rates of warming and multiple stresses increase the likelihood of crossing critical thresholds of change in climatic and ecological systems.

Inertia and uncertainty in the climate, ecological, and socioeconomic systems mean that safety margins should be considered in setting strategies, targets and timetables for avoiding dangerous levels of interference in the climate system.

Inertia makes adaptation inevitable and already necessary in some cases, and affects the optimal mix of adaptation and mitigation strategies.

The pervasiveness of inertia and the possibility of irreversibility in the interacting climate, ecological and socioeconomic systems are major reasons why anticipatory adaptation and mitigation actions are beneficial.

SOURCE: TAR Synthesis Report, Q.5, pp.87–96.

of the projected changes. Global temperature is expected to continue to increase after stabilisation of greenhouse gases, but at a much reduced rate, except possibly in the Southern Hemisphere where more rapid warming will continue. The latter is due to the present lag of warming in the Southern Ocean, which means that it will continue to catch up with the changed surface radiation balance, possibly reversing some regional trends that depend on changing north-south temperature differences. The policy relevance of these time lags is discussed in **Box 2**, from the IPCC TAR Synthesis Report, Question 5.

Inertia in the climate system is expected to have a particularly important effect on Australia. This is due to the delay in the warming of the Southern Ocean due to its large heat capacity. As long as the globe is in a transient warming phase, i.e., as long as the concentration of greenhouse gases continues to increase in the global atmosphere, the Earth's surface will continue to warm at average rates similar to those shown in **Figure 2.3** (which depend on which emissions scenario is followed). However, warming will be least in the Southern Ocean region (and in a limited area in the North Atlantic), due to the heat transfer into the deep ocean. However, once greenhouse gas concentrations are stabilised in the atmosphere, global average warming will slow down considerably, except over the Southern Ocean, where the ocean will continue to warm until it has caught up with the change in atmospheric composition (Hirst, 1999; Goosse and Renssen, 2001). The practical significance of this is that impacts on Australia will continue to develop

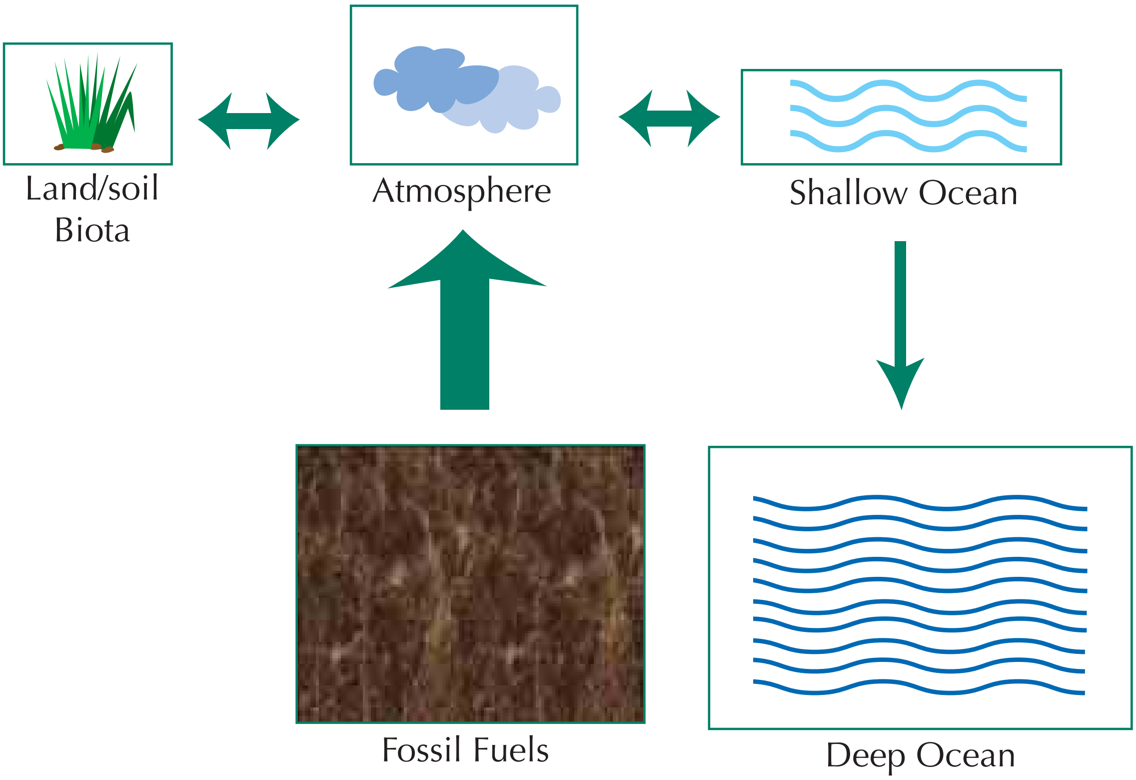


Figure 2.6.
The schematic diagram above illustrates the reason for the time lag between industrial emissions of carbon dioxide into the atmosphere and its final removal from the climate system. Fossil fuel emissions (very large upwards arrow) are exchanged and equilibrated with carbon in the land and soil biota and in the shallow oceans—processes taking only one to 10 years. However, carbon dioxide is only slowly removed into the deep ocean, a process that takes hundreds to thousands of years. The portion that stays in the atmosphere is known as the 'airborne fraction' and is currently about 50%. This may decrease as the shallow oceans get warmer, because warmer water can hold less dissolved carbon dioxide, and there will be less mixing into the deep oceans. Carbon dioxide concentrations in the atmosphere will stabilise only when the rate of emissions is reduced to the rate of deposition or sequestration into the deep oceans (or, as represented in this diagram, not until the two vertical arrows are of the same size). Alternatively, there is the possibility of artificially increasing the rate of sequestration of carbon or carbon dioxide into the deep ocean or into subterranean storages (artificially widening the downwards arrow). Artificial sequestration into the oceans is controversial, while subterranean sequestration is less controversial and is already happening in some experimental situations.

long after greenhouse gas emissions have been reduced, and will be dictated largely by cumulative emissions in the past century and the coming decades. Circulation and rainfall changes may in some cases be reversed due to an ongoing warming of the Southern Ocean relative to the tropics (Whetton *et al.*, 1998).

Now that we have looked at brief summaries of what the IPCC scientists concluded regarding the science of climate change in its Third Assessment Report, largely written in 1999 and 2000, and at some more recent developments, it is useful to put these conclusions in perspective and to consider how they affect Australia.

2.2 Observed Changes in Australian Climate and Ecosystems

2.2.1 Climatic trends in Australia

Trends identified in the region continue to be generally consistent with those identified elsewhere in the world, namely gradual increases in average temperatures in nearly all locations, especially in overnight minima, but also in daily maxima, and more complex patterns of rainfall change with location and time. Research on regional trends has been summarised in Salinger *et al*. (1996) and in specific studies by Plummer (1996), Torok and Nicholls (1996), Holbrook and Bindoff (1997, 2000), Lavery *et al*. (1997), Plummer *et al*. (1997 and 1999), Zheng *et al*. (1997), McKeon *et al*. (1998), Collins and Della-Marta (1999), Hennessy *et al*. (1999), Manton *et al*. (2001) and Nicholls (2003b).

Australian average temperatures have risen by 0.7 ºC over the past century, with a commensurate increase in the frequency of very warm days and a decrease in the frequency of frosts and very cold days (Plummer *et al*., 1999; Collins *et al*., 2000). Night-time temperatures have risen faster than daytime temperatures; hence the diurnal temperature range has decreased noticeably in most places. The past decade has seen the highest recorded mean annual temperatures.

Nicholls *et al*. (1996b) examined the relationship between rainfall and temperature in order to remove that part of the year-to-year variability due to rainfall, which cools the surface via cloud cover and evaporation. They found that the temperature in the period 1973–92 tended to be higher, for any given value of rainfall, than had been the case in the period 1910 to 1972. Nicholls (2003a) has now extended this analysis to 2002 and finds that the temperature associated with a given annual mean rainfall is higher again in the period 1993 to 2002 than in 1973–92. Thus, the warming observed over Australia over the last few decades does not reflect rainfall changes, and is in this sense anomalous.

The result, both for residual mean minimum and mean maximum temperature anomalies over the Murray-Darling Basin is an increasing linear trend from 1952 to 2002, as shown in **Figure 2.7** for mean maximum temperature. Since 1952, mean maximum and mean minimum temperatures in this region have been increasing at rates of 1.75 ºC and 1.74 ºC per century, respectively. This has the effect, noted by Karoly *et al*. (2003) and Nicholls (2003b), of increasing the severity of drought, for a given rainfall deficiency, through further or more rapid reduction in soil moisture and greater water demand. This is likely to have had a very significant deleterious impact during the 2002–03 drought.

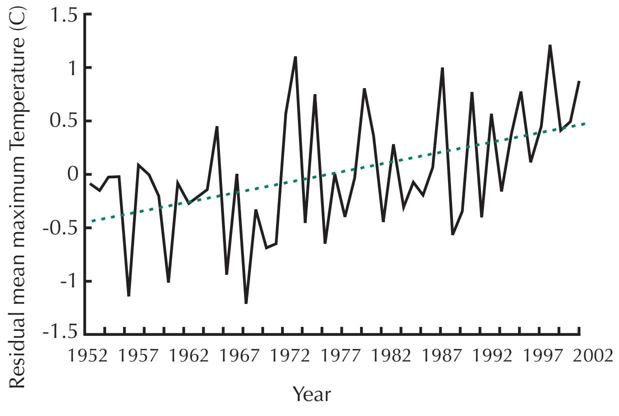


Figure 2.7.
Residual mean maximum temperature (ºC) for the Murray Darling Basin, after using a linear regression relationship to remove the variability of temperature associated with variations in rainfall. The dotted line is the linear regression with time, which shows a trend of 1.75 ºC per century. From Nicholls (2003b).

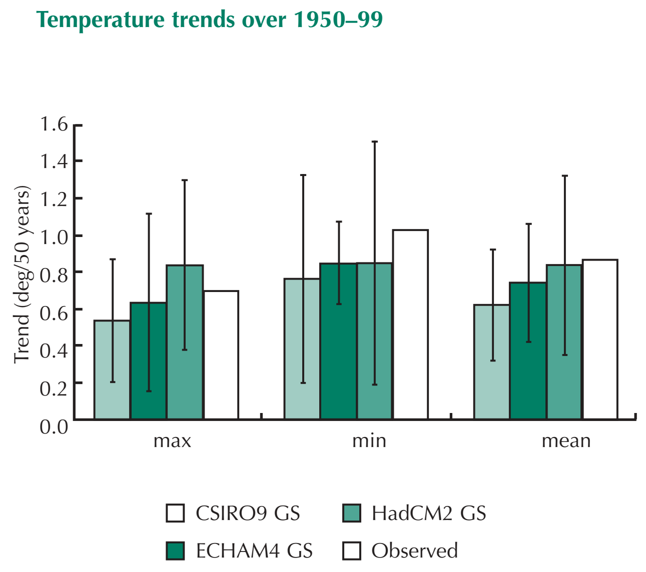


Figure 2.8.
Observed trends in Australian average daily maximum (max), minimum (min), and mean temperatures over the period 1950-1999 compared with simulated trends from three different global climate models forced by observed increases in greenhouse gases and aerosols. The three climate models have been developed by CSIRO Australia, the Max Planck Institute for Meteorology in Germany (ECHAM4), and the Hadley Centre in the UK (HadCM2). The error bar on each of the simulated warming trends is the uncertainty (90% confidence interval) in the 50-year trend associated with internal climate variability simulated by that model (Karoly *et al.*, 2003).

Karoly *et al.* (2003) have looked at temperature changes in the Australian region. Using both instrumental observations and climate model data, they show that the warming trend over the last 50 years in Australia cannot be explained by natural climate variability alone and that most of this warming is likely due to the increase in greenhouse gases in the atmosphere. **Figure 2.8** shows that the actual trend in Australian temperatures since 1950 is now matching climate model simulations of how temperatures respond to increased greenhouse gases in the atmosphere. It should be noted that temperature trends over the years 1910 to 1999 (available at the Bureau of Meteorology's website <http://www.bom.gov.au/climate/change/seatrends.shtml>) show warming over most of Australia, but a small cooling over the Murray Darling Basin region. This may be associated with the wet period in this region after 1945 (Pittock, 1975; Vives and Jones, 2003), as it is particularly apparent in daily maximum temperatures.

In general, Collins *et al.* (2000) and Manton *et al.* (2001) found increasing trends in the frequency of warm nights and hot days over Australia, and decreasing trends in cold nights and cool days.

Trends in rainfall are less clear. Australian annual mean rainfall has increased by about 6% over the past century (Collins and Della-Marta, 1999; Hennessy *et al.*, 1999). While this trend was not statistically significant at the 95% confidence level, updated calculations using data to 2002 by Ian Smith (personal communication) do show significance at the 95% level. From 1951 to 2002 there have been strong increases in the north-west, but decreases in the south-west of Western Australia and over much of the south-east and east coast (see **Figure 2.9**). Significance at the 95% confidence level was found over a considerable fraction of Australia, and in a spatially coherent manner suggesting the changes may not be due to chance (Smith, personal communication 2003). Along the south coast this represents a decrease in the dominant winter rainfall, while the increase in the north-west is in summer rainfall. No such spatial coherence is found in the previous 50-year period.

The largest and most statistically significant change has been a decline in rainfall in the winter-rainfall-dominated region of the far south-west of Western Australia, where in the period 1910 to 1995, winter (June-July-August) rainfall declined by 25%, mainly during the 1960s and

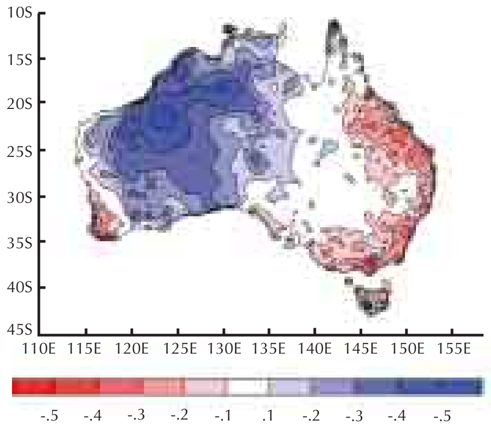


Figure 2.9.
Trends in annual rainfall, 1950-2002, expressed as the correlation coefficient of annual values against year. Correlation coefficients enable the statistical significance of the trends to be compared across the continent. In general values at individual points exceeding +0.3 or less than –0.3 are statistically significant at the 95% confidence level, however the overall statistical significance of the changes is more complex due to spatial correlations (Livezey and Chen, 1983) and has not yet been determined. Map from Smith (2003).

1970s. Several studies (Wright, 1974; Allan and Haylock, 1993; Yu and Neil, 1993; Smith *et al.*, 2000) have noted this decrease and relate it to atmospheric circulation changes, notably an increase in surface pressure in the vicinity. These studies leave open how much of the change can be attributed to natural variability versus the enhanced greenhouse effect. A similar decline is projected by most climate models that include enhanced greenhouse gases and direct effects of aerosols, for the first half of the 21st century. The Indian Ocean Climate Initiative report (IOCI, 2002) concluded that "most likely" the enhanced greenhouse effect has contributed to part of the decline, and may be expected to maintain or strengthen the decline in coming decades. IOCI is a major research program funded by the Western Australian Government, aimed at addressing the causes of the recent decline, and developing methods for seasonal prediction of rainfall in the area as a means of adaptation.

It should be noted, however, that relatively abrupt shifts in rainfall have occurred several times in Australia since good records began in the 1890s, notably widespread decreases in large areas of New South Wales and Queensland in the 1890s, and increases in

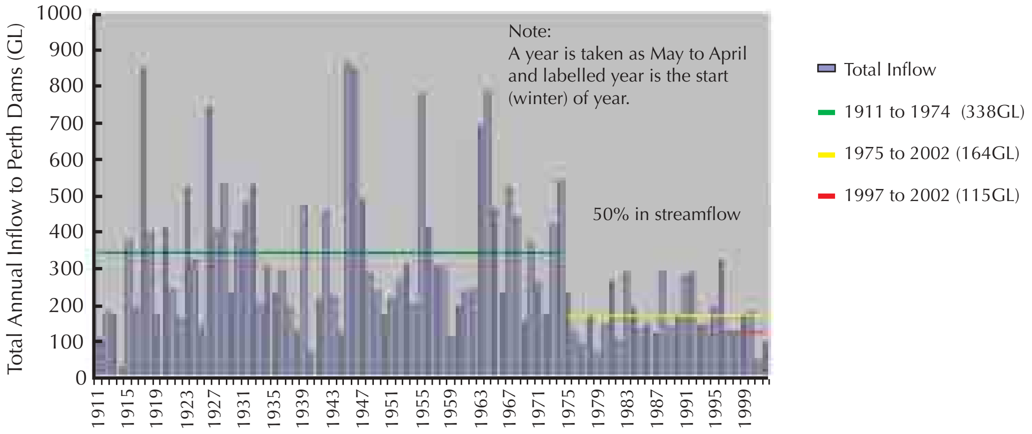


Figure 2.10.
Annual streamflow into Perth's water supply dams, with averages before and after the rainfall decrease of about 10-20% (depending on location), which occurred in 1974-75. Note that the decrease in water supply is around 50%. This has had to be made up by increased withdrawal of groundwater. Data from the Water Corporation, via Ian Foster (2002).

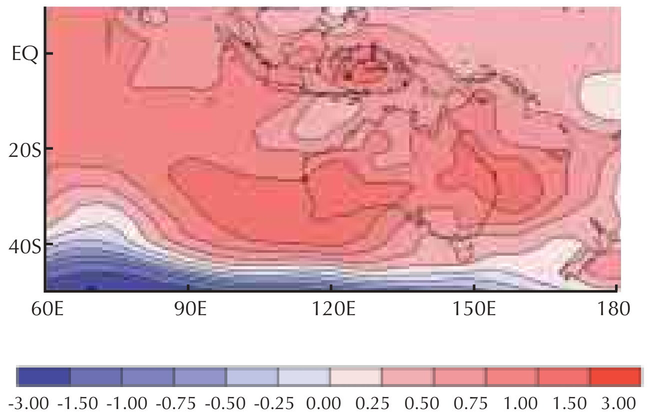


Figure 2.11. Map of the difference between mean sea level pressure in June, July and August of 1976 to 2001 (after the decline in rainfall in the south-west of Western Australia) and that for 1958 to 1975 (before the change in rainfall). Note that there is higher pressure in a belt from the south-east of the Indian Ocean west of Perth across Australia to the mid-east coast. This is broadly consistent with the observed rainfall changes in the winter rainfall areas, indicated for the longer period before and after 1952 in **Figure 2.9**.

Victoria and New South Wales around 1945 (Vives and Jones, 2003). The same analysis shows a sharp decrease in rainfall around 1967–72 in the south-west of Western Australia, and widely scattered increases further east. The reason for such abrupt changes is not yet understood, but is presumably largely natural. Yonetani and Gordon (2001b) have mapped abrupt changes in simulations of climate with the CSIRO coupled climate model. They conclude that abrupt changes are a predominant part of regional climate changes on decadal time scales. This requires more work to understand its application to past and future climate change in Australia.

The observed decline in rainfall in the south-west of Western Australia is reflected in a several-fold larger decline in inflow into the Perth metropolitan reservoirs (see **Figure 2.10**). This has led to increased utilisation of groundwater, a large investment in improving water supplies for Perth, more conservative water management and the funding of the Indian Ocean Climate Initiative (Sadler, 2002). The seriousness of the decline, and its ongoing nature, is demonstrated by the average inflow amounts. From 1911 to 1974 this was 338GL per annum, but from 1975 to 2002 it was only 164 GL, and in the years 1997–02 it was even lower at 115 GL. Despite conservative water management (Sadler, 2003), this represents a critical problem for the Perth water supply.

More recently, a trend has also been observed in April-July rainfall in parts of south-eastern Australia (Wright and Jones, 2003). This trend is relatively minor until about 1997, but has apparently strengthened since then, leading to water shortages in the Melbourne catchments, and is entirely consistent with a recent trend to increasing surface pressures over southern Australia in April-July (David Jones, Bureau of Meteorology, personal communication).

A map of the observed pressure changes in winter (June-August) over Australia from before to after the main change in rainfall in the south-west of Western Australia around 1975 is presented in **Figure 2.11** (IOCI, 2002). While the rainfall changes mapped in **Figure 2.9** are not for exactly the same years, there is a strong overlap in time, and they are broadly consistent with the changes in pressure for the winter rainfall areas. Thresher (2003) has noted a trend in the latitude of the high pressure ridge over south-eastern Australia consistent with **Figure 2.11**. This trend goes back to the early 20th century.

As discussed at the end of section 2.1.4 above, Gillett *et al.* (2003) compared observed global pressure changes with those simulated by a number of climate models, and found qualitatively similar trends, with a tendency for pressures to increase in the sub-tropics and to decrease at higher latitudes in more recent years. Gillett *et al.* found that the observed changes are stronger than those simulated by the models, and they ascribe this to deficiencies in the models, including the absence of ozone depletion effects. If the changes represent trends due to enhanced greenhouse forcing, as Gillett *et al.* suggest, this in turn suggests that trends projected by the models for the next several decades may in fact have occurred earlier. Gillett *et al.* note, that the situation in the Southern Hemisphere is complicated by the larger influence of ozone depletion on the climatic patterns than is the case in the Northern Hemisphere.

Thompson and Wallace (2000) analysed trends in sea level pressure fields for the 30-year period 1968–97 separately for each calendar month, and found a trend toward greater pressure in high southern latitudes and lower pressure in mid-latitudes. They speculate that it may be due to stratospheric ozone depletion, or the effects of greenhouse gases and aerosols, as suggested in model results by several earlier workers. Kushner *et al.* (2001) find a similar circulation response in the Southern Hemisphere due to the enhanced greenhouse effect, but it becomes significant only in the 21st century.

As discussed in section 2.1.4 above, Hartmann *et al.* (2000) suggested that the annular mode of circulation in both hemispheres is strengthened both by increased greenhouse gases and by ozone depletion, leading to a polewards movement of the westerlies, and by implication, of the associated rainfall belts in mid-latitudes (see **Figure 2.12**). Similarly, Marshall (2003) confirms the observed trend to a strengthening of the annular mode with lower surface pressures at high latitudes and higher pressures in mid-latitudes, and Ostermeier and Wallace (2003) find a similar trend in the Northern Hemisphere. Fyfe (2003) and Geng and Sugi (2003) both find that these changes affect a reduction in the number of mid-latitude cyclones in the Southern Hemisphere, in climate change models with direct aerosol and enhanced greenhouse effects, and in observations.

Other suggestions have been made as to the possible cause of the rather abrupt rainfall change in the south-west of Western Australia in the early 1970s. Local land use change due to land clearing in the south-west after World War II has been suggested, but this is unlikely to have caused the far more widespread surface pressure changes, nor the continuation and strengthening of the trend in later years.

Baines *et al.* (in preparation, P.G. Baines, CSIRO Atmospheric Research, private communication) suggest that anthropogenic aerosols increased rapidly after the 1950s and may have contributed to a number of atmospheric changes that occurred in the late 1960s, including a southward movement of the Inter-Tropical Convergence Zone (Rotstayn *et al.*, 2000) and a weakening of the wintertime westerlies in mid-southern latitudes.

Clearly, it is desirable to carry out more rigorous attribution studies on the various suggested causes of the rainfall changes over the south-west, and more recently the south-east, of Australia. These need to consider the time evolution and seasonality of the various suggested forcings, and perhaps look at year-to-year correlations of indices of the various forcings with rainfall variations, as one test of causality.

Projections of changes in the various forcings may also prove useful in anticipating whether the rainfall changes in southern Australia are likely to continue. The enhanced greenhouse effect is very likely to continue, with increasing effect. Stratospheric ozone depletion, while it has probably reached its maximum extent (Newchurch *et al.*, 2003), will take several

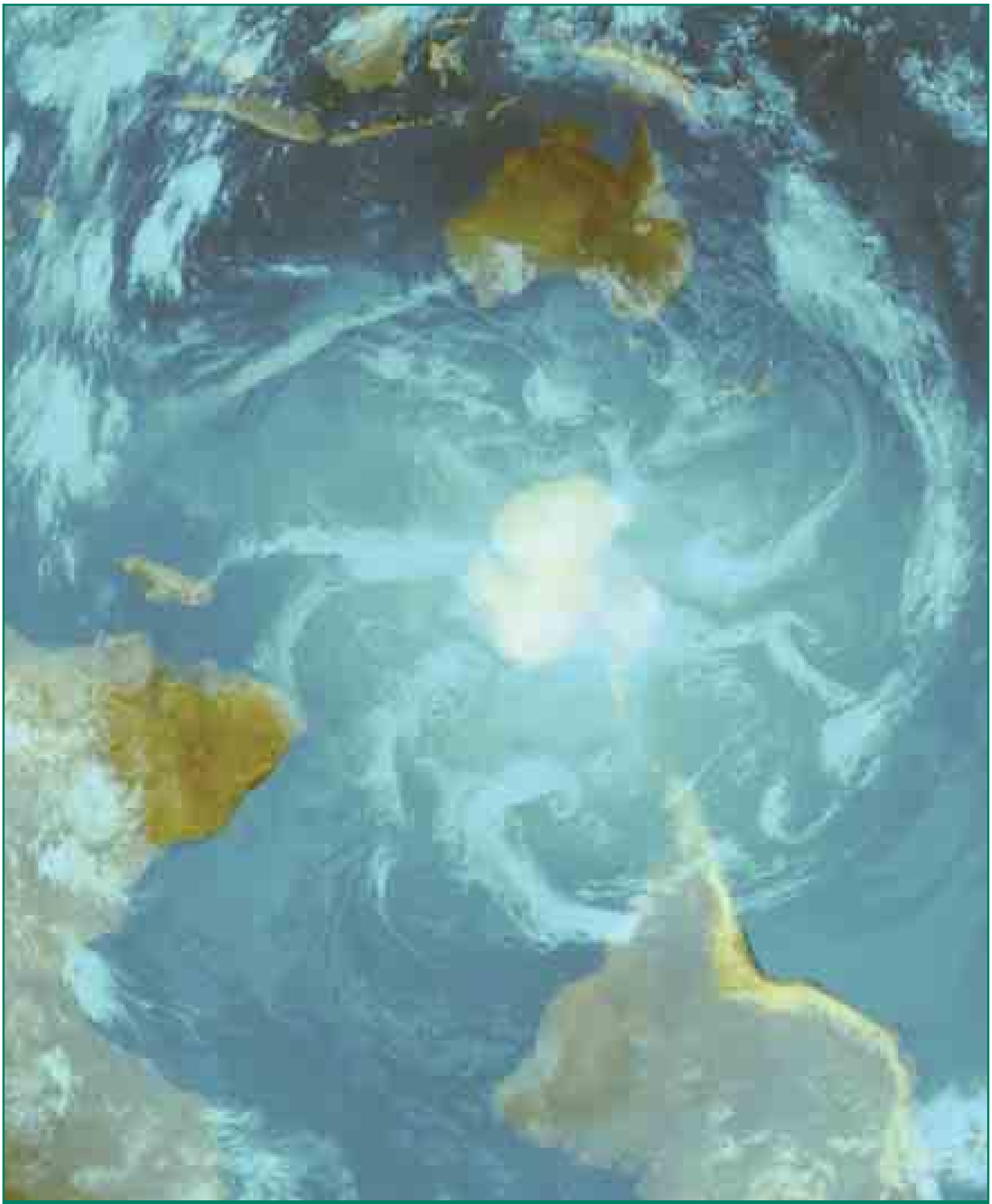


Figure 2.12.
This image shows the typical cloud pattern associated with the low pressure systems and cold fronts which travel around Antarctica from West to East in the mid-latitude westerly winds, delivering rainfall to the mid-latitude southern hemisphere continents, including southern Australia. Observations indicate that these systems have moved to more southerly latitudes in recent decades, and climate models suggest this may be due to a combination of the effects of increasing greenhouse gases in the atmosphere and of stratospheric ozone depletion (see sections 2.1.4 and 2.2.1. The image is a southern hemisphere mosaic comprising separate images on 1 September 1999, taken by several geostationary meteorological satellites, namely USA's GOES-E and GOES-W, Europe's Meteosat-5 and Meteosat-7, and Japan's GMS-5, using infrared channels. The mosaic has been produced and colour enhanced with added topography, by the Commonwealth Bureau of Meteorology.

decades to recover, by which time the synergistic enhanced greenhouse effect will have increased. On the other hand, sulfur emissions, which lead to anthropogenic aerosols, have already started to decline in North America and Europe (Lefohn *et al.*, 1999) and are expected to decline in Asia in the next several decades (Carmichael *et al.*, 2002), due to efforts to reduce regional air pollution and acid rain. Since aerosols have a short lifetime in the lower atmosphere, their influence on climate is likely to decline relative to that of greenhouse gases.

It must be concluded, therefore, that there is a substantial risk that the observed decline in rainfall in south-western and south-eastern Australia will continue for the next several decades, unless natural variability fortuitously leads to a reversal. What Sadler (2003) has termed "informed adaptation" may be necessary to cope with this ongoing risk.

Based on records since 1910, increases in the frequency of heavy rainfalls are significant in many parts of Australia (Haylock and Nicholls, 2000; Hennessy *et al.*, 1999). This is confirmed by Manton *et al.* (2001), based on the shorter period 1961–98, who find increases in the frequency of daily rainfall exceeding the mean 99th decile across many parts of mainland Australia except in the south-west and south-east. They also find that the average intensity of these extreme rainfalls has increased.

The strength of the relationship between eastern Australian climate and ENSO has been observed to vary over the past century. This seems to be linked to longer term climate oscillations such as the North Pacific Decadal Oscillation (NPDO) (e.g., Power *et al.*, 1999a, b). These fluctuations in rainfall are partially explained by the increase in El Niño conditions over recent decades. Nicholls (2003b) has shown that since 1973, the relationship between Australian rainfall and land temperature has changed, such that temperatures are higher for a given rainfall amount. In particular, droughts have become hotter.

There is some evidence of long-term variations in the Australasian region in storm frequency and tropical cyclones (Nicholls *et al.*, 1996a; Radford *et al.*, 1996; Hopkins and Holland, 1997; Leighton *et al.*, 1997). Nicholls *et al.* (1998) show that although there has been a decrease in tropical cyclone numbers from 1969 to 1996 in the Australian region (105°E to 160°E), there has been an increase in the frequency of intense tropical cyclones with central pressures of less than 970 hPa. Explosively developing cyclones, which include severe east coast lows off the New South Wales coast, have been found by Lim and Simmonds (2002) to have a statistically significant increasing trend in the period 1979–99. One of these was responsible for the disastrous low which claimed six lives in the 1998 Sydney-Hobart yacht race (Buckley and Leslie, 2000). These lows cause high winds, storm surges and heavy rainfalls along the New South Wales coast.

The average rise in sea level in the Australia/ New Zealand region over the past 50 years is about 20 mm per decade (Rintoul *et al.*, 1996; Salinger *et al.*, 1996), which is within the range of the current estimate of global sea level rise (IPCC, 1996, WGI Section 7.2.1). The State of the Environment Report (2001, p.25) estimates the rise around the Australian coast as 12 to 16 cm over the last 100 years. There has been a weak warming trend in ocean temperatures to 100 m depth in the south-west Pacific (39°S to 49°S, 141°E to 179°E) of about 0.13 °C during the 34-year period 1955 to 1988 (Holbrook and Bindoff, 1997), and there have been shorter period sea-surface temperature fluctuations associated with ENSO.

2.2.2 Observed trends in Australian ecosystems

Hughes (2003) has reviewed observed trends in Australian species and ecosystems, including vegetation, wetlands, terrestrial vertebrates, marine birds and coral reefs. She points out that long-term datasets are scarce (Westoby, 1991) and that in many cases the relative role of climate change versus other factors is poorly understood. In the case of vegetation, while the potential role of recent climate and atmospheric change has been noted, most changes in composition and age structure have been attributed to grazing or to changes in fire regimes following European settlement (e.g. Lunt, 1998, 2002).

A marked increase in woody biomass at the landscape scale has been reported for a wide variety of environments (Archer *et al.*, 1995; Henry *et al.*, 2002; Bowman *et al.*, 2001). This phenomenon, known as vegetation thickening, has been generally viewed as an example of vegetation recovery and succession following episodic disturbance events such as drought, fire and clearing (Gifford and Howden, 2001). Where this has occurred in grazed rangelands it is known as the woody weed problem. While not the primary cause, atmospheric change may also be involved in this thickening (Archer *et al.*, 1995). The potential role of CO_2 fertilisation in these changes has been investigated by Berry and Roderick (2002). They conclude that increasing carbon dioxide would have exacerbated the problem.

Changes in rainfall patterns have also been implicated in some vegetation trends. For example, historical survey of eucalypt savannas in Litchfield National Park in the Northern Territory showed that forest coverage has increased from 5% to nearly 10% over some 50 years, while areas of grassland have decreased (Bowman *et al.*, 2001). While the cessation of Aboriginal landscape burning may be the primary cause, the period of increased rainfall in the 1970s may also have been an influence. Similarly, Fensham *et al.* (2003) documented a general increase in overstorey cover in central Queensland over the second half of the 20th century, during a period of higher than average rainfall. A contrasting trend in Tasmania toward an increased incidence of drought and alterations in seasonal rainfall patterns has been implicated in eucalypt dieback (Kirkpatrick *et al.*, 2000). A positive relationship between the magnitude of drought and eucalypt dieback was also found in North Queensland savanna (Fensham and Holman, 1999).

Expansion of rainforest at the expense of eucalypt forest and grasslands in Queensland over the past two centuries has been well documented (Harrington and Sanderson, 1994; Hopkins *et al.*, 1996). In the Bunya Mountains in south-east Queensland, aerial photographs over a 40-year period (1951 to 1991) demonstrated that both eucalypt forest and rainforest had invaded, and in some cases completely engulfed, grasslands that occur in a range of landscapes (Fensham and Fairfax, 1996). In North Queensland, comparisons of aerial photographs from the 1940s and the early 1990s indicated that rainforest had invaded large areas of wet sclerophyll eucalypt forest (Harrington and Sanderson, 1994) with widespread thickening of the canopy across both vegetation types. Once again, cessation of active traditional Aboriginal land management has been suggested as the primary cause, but climatic changes cannot be discounted. Recent invasions of warm temperate rainforest species to higher elevations in northern New South Wales and expansion of *Nothofagus* into eucalypt woodland on plateaus in the Barrington Tops region have also been documented (Read and Hill, 1985). At present it is unclear whether this migration is a response to recent warming or whether the vegetation is still responding to the major climate changes following the last glacial maximum.

Encroachment by *Eucalyptus pauciflor*a into subalpine grasslands near Mt Hotham, Victoria, has been documented by Wearne and Morgan (2001). All invading saplings were estimated to be less than 31 years old, and the majority (54%) were established between 1991 and 1995. Most (66%) occurred within 5 m of the forest-grassland boundary and some of the recently established plants are now reproductively mature trees (1–8 m in height), suggesting an ecotonal change is underway.

The landward transgression of mangroves into saltmarsh environments in the estuaries of Queensland, New South Wales, Victoria and South Australia over the past five decades is a widespread trend, with saltmarsh losses ranging up to 80% (Saintilan and Williams, 1999). While direct human disturbance is undoubtedly a factor in these trends (e.g., revegetation of areas cleared for agriculture, increases in nutrient levels and sedimentation), increases in rainfall and altered tidal regimes have also been implicated (Saintilan and Williams, 1999).

In some areas of the Northern Territory, dramatic expansion of some tidal creek systems has occurred since the 1940s. In the Lower Mary River system, two creeks have extended more than 4 km inland, invading freshwater wetlands (Woodroffe and Mulrennan, 1993; Bayliss *et al.*, 1997; Mulrennan and Woodroffe, 1998). Rates of extension of saltwater ecosystems inland in excess of 0.5 km per year have been measured (Knighton *et al.*, 1992). The saltwater intrusion has had dramatic effects on the vegetation of formerly freshwater wetlands with more than 17,000 ha adversely affected and a further 35–40% of the plains immediately threatened (Mulrennan and Woodroffe, 1998). These changes most likely have multiple causes, but both sea level rise and increases in rainfall may have contributed (Woodroffe and Mulrennan, 1993; Bayliss *et al.*, 1997).

Changes in the date of pairing of the sleepy lizard *Tiliqua rugosa* collected in mid-north South Australia (Bull and Burzacott, 2001 and 2002), and in the distributions of two reptile ticks for which the sleepy lizard is a host, have been monitored. These changes have been related to changes in the seasonality of rainfall in the region.

In the alpine zone, there is evidence of shifts in vertebrate ranges to higher elevations over the thirty-year period to 1999. Wildlife Atlas records indicate a higher maximum altitudinal distribution for all three macropod species and for four species of feral mammals (Green and Pickering, 2002). Other evidence for increasing activity by feral mammals at higher altitudes supports this trend. In the 1970s, Snowy Plains (1370 m) was regarded as climatically marginal for rabbits, yet during the summer of 1998/99 the National Parks and Wildlife Service was forced to institute a rabbit control program at Perisher Valley (Green and Pickering, 2002).

A trend toward earlier arrival of migratory bird species in the alpine zone in the 1980s and/or 1990s, compared with the 1970s has also been documented (Green and Pickering, 2002). For the 11 bird species for which there are sufficient data, the record of earliest arrival was in the 1990s for five species and in the 1980s for four. The particular foraging techniques and biology of the individual bird species were associated with the trends in their arrival. The two species that appear not to arrive earlier despite changes in snow cover over the three decades are the grey fantail *Rhipidura fuliginosa*, which catches insects in flight, and the silvereye *Zosterops lateralis*, which is involved in long migratory flights, the timing of which may be independent of local events (Green and Pickering, 2002).

The range of *Pteropus poliocephalus*, the grey-headed flying fox, has contracted south from its northern boundary by about 750 km since the 1930s (Tidemann, 1999). Along with the southward contraction in range by *P. poliocephalus, P. alecto* (the black flying fox, a more tropical species) has apparently extended its range south by a similar distance, with its southern limit progressively extending from Maryborough to Bowraville, New South Wales. Increases in rainfall and temperature in eastern Australia over the period have possibly favoured *P. alecto*, which cannot tolerate frosts (Tidemann, 1999).

There have been some major changes in seabird breeding distribution since the late 19th century in the transition zone between tropical and temperate seabird species in the region between

Staghorn and Plate corals in various stages of bleaching on Trunk Reef, after heavy rainfall and high water temperatures. 20 April 1998
Photographer: R. Berkelmans
Copyright: GBRMPA

Large Acropora on Trunk Reef bleached white, after heavy flooding and high water temperatures in the region. 21 April 1998
Photographer: J. Jones
Copyright: GBRMPA

Bleached Plate and Staghorn corals on reef crest at Otter Reef show signs of bleaching and eutrophication, after heavy flooding and high water temperatures in the region 23 April 1998
Photographer: R. Berkelmans
Copyright: GBRMPA

Figure 2.13.
Examples of coral bleaching. Photos courtesy of the Great Barrier Reef Marine Park Authority.

the Houtman Abrolhos and the Naturaliste and Leeuwin Capes, off the coast of Western Australia (Dunlop, 2001). At least eight species have formed new breeding locations well to the south of their historical range and/or have seen marked population increases at their more southerly colonies. The rate of establishment and/or growth of new colonies seems to have accelerated since the early 1980s. The El Niño phase of the Southern Oscillation increased in frequency with every couple of decades of the 1900s such that what was once an unusual climatic pattern has become more common in the last two decades of the century, with major events in 1982–83, 1987–88, 1991–94 and 1996–97. Since the behaviour of the Leeuwin Current is strongly influenced by ENSO, it is likely that this is the ultimate cause of the shifts in the seabird fisheries and changing population dynamics (Dunlop, 2001).

Since 1980, the Australasian gannet (*Morus serrator*) population has increased threefold in Australian waters, from 6600 breeding pairs to approximately 20,000 pairs in 1999–00, a rate of 6% per year (Bunce *et al.*, 2002). In colonies where nesting space is not limiting, the breeding population has expanded at rates as high as 24% per year. Bunce *et al.* (2002) suggest that the population increase may be associated with the increased ENSO activity over this time because increased upwellings of nutrient-rich cold subantarctic waters during ENSO events are positively correlated with increases in several commercially important fish stocks. A gradual long-term warming trend in Bass Strait and waters off south-eastern Australia may also have positively affected the distribution and local availability of pilchards and other prey species, as has been shown in other parts of the world (Bunce *et al.*, 2002). While these correlations are suggestive of a climate influence on gannet populations, it is possible that changes in the fishing practices of several major commercial fisheries in south-eastern Australia, resulting in an increase in discarded bycatch, may also be important (Bunce *et al.*, 2002).

Since the late 1970s there has been a global increase in the number and scale of coral-bleaching events (see **Figure 2.13**) and the extent, timing and severity of many such events have been correlated with warmer than normal seawater temperatures (Jones *et al.*, 1997; Lough, 2000). In 1998, tropical sea surface temperatures were the highest on record, topping off a 50-year trend for some tropical oceans (Reaser *et al.*, 2000). In the same year, coral reefs around the world suffered the most extensive and severe bleaching on record. The mortalities that followed these events were higher than any in the previous 3000 years (Aronson *et al.*, 2002). The geographic extent, increasing frequency, and regional severity of mass bleaching events are an apparent result of a steadily rising baseline of marine temperatures, combined with regionally specific El Niño and La Niña events (Hoegh-Guldberg, 1999; Lough, 2000).

One of the best records of recurrent bleaching events comes from the inshore fringing reefs of Magnetic Island on the Great Barrier Reef, where bleaching has been observed in the summers of 1979–80, 1981–82, 1986–87, 1991–92 and 1993–94 (Jones *et al.*, 1997). Average daily seawater temperatures exceeded 31 °C for 14 days and 31.5 °C for two days during the bleaching event of 1991–92 and exceeded 31 °C for 10 days and 31.5 °C for two days during the 1993–94 event.

A severe and widespread bleaching on the Great Barrier Reef occurred from February to April 1998, with inshore reefs being the worst affected (Berkelmans and Oliver, 1999; Wilkinson, 2002a,b). While Australian coral reefs were less affected than many elsewhere (3% loss compared to 46% in the Indian Ocean, Wilkinson, 2000), damage was nonetheless severe at many sites (see section 4.2.7). At the worst affected sites, most staghorn and other fast-growing corals were killed, while the very old corals had high rates of survival. The level of thermal stress at the majority of bleaching sites was unmatched in the period 1903 to 1999 (Lough, 2000). Reefs elsewhere around Australia were similarly affected. Lowered seawater salinity as a result of river flooding between Ayr and Cooktown early in 1998 probably exacerbated the effects of warming on the inshore reefs (Berkelmans and Oliver, 1999). At Scott Reef off the north-west coast, most corals to a depth of 30 m died and have since recovered only slightly (Sweatman *et al.*, 2002).

Extensive coral bleaching re-occurred in the summer of 2001–02 and the Great Barrier Reef was again subject to a complex mosaic of cool and warm anomalies. Bleaching was more extensive than in 1998 and the inshore reefs were again the most affected. In the cooler areas no damage was found but significant coral mortality was seen in the hottest patches (T. J. Done, unpublished observations, cited in Sweatman *et al.*, 2002; Wilkinson, 2002b). Surprisingly, the ubiquitous hard corals previously thought to be the most sensitive (e.g., family *Pocilloporidae*) survived relatively well whereas others (*Acroporidae* and *Faviidae*) suffered significant injury and mortality (T. J. Done, cited in Sweatman *et al.*, 2002)

Evidence of warming oceans also comes from examination of annual variation in the density of calcium carbonate skeletons in some massive coral species such as *Porites* (Lough and Barnes, 1997; Lough, 2000). When examined over 50-year periods, a record more than two centuries long shows constant rates of calcification until the most recent period, when calcification significantly increases by about 4%, matching the observed rise in seawater temperatures (Lough, 2000). Coral bleaching is discussed further in section 4.2.7.

2.3 Scenarios for Australia

2.3.1 Previous scenarios of temperature and rainfall changes

In general, impacts assessments take time and are therefore often based on climate change scenarios that are not the latest by the time the impact assessment is completed. This has affected the TAR, and in particular the results reported in the TAR for Australia, many of which were based on the CSIRO (1996a) scenarios, which were superceded by CSIRO (2001). The CSIRO (1996a) scenarios included two sets of rainfall scenarios that were based on results from the equilibrium slab-ocean GCM and transient coupled ocean-atmosphere GCM (AOGCM) simulations.

In line with the TAR conclusions, more recent scenarios (e.g., Hulme and Sheard, 1999; Carter *et al.*, 2000; CSIRO, 2001) rely exclusively on coupled models. These are also based on the newer emissions scenarios from the IPCC's Special Report on Emissions Scenarios (SRES) rather than the IS92 scenarios described in IPCC (1996). This leads to some changes in the regional scenarios, both in terms of patterns of change and magnitude.

It is important to note that, compared to the CSIRO (1996) scenarios, the CSIRO (2001) scenarios have narrowed the uncertainty range in rainfall changes predicted for southern Australia, with a tendency to more drying on the mainland. This means that the results of impact studies that used the earlier wider range of rainfall scenarios (e.g., Schreider *et al.*, 1996 for water supply, and Williams *et al.*, 2001 for fire danger), should be reinterpreted to focus on the drier end of the previous range. This is consistent with more recent studies by Kothavala (1999) and Arnell (1999).

Some recent Australian impact studies have used regional scenarios of temperature and rainfall changes per degree of global warming, based on the CSIRO Regional Climate Model (RCM) transient simulations, scaled to the range of uncertainty of the global warming derived from the IPCC Second Assessment Report (SAR) range of scenarios. For example, Hennessy *et al.* (1998) give scenarios for six regions of New South Wales, based on a simulation with a 60 km resolution. Ranges are given for estimated changes in maximum and minimum temperatures, summer days over 35 °C, winter days below 0 °C, seasonal mean rainfall changes, and numbers of extremely wet or dry seasons per decade. However, these scenarios are based on only one GCM (CSIRO Mark 2) in which the regional model has been nested. Impact studies using these scenarios, such as that on fire danger in the Australian Capital Territory by Cary (2002), need to be reinterpreted in the light of the range of results from other GCMs.

It should be noted that in some cases, RCM results may change the sign of rainfall changes derived from coarser resolution models, because of local topographic and other effects (Whetton *et al.*, 2001). Statistical downscaling (discussed in detail in McCarthy *et al.*, Chapter 3) provides a method of deriving finer regional detail from climate models. It has not been used extensively in Australia apart from the south-west of Western Australia (Charles *et al.*, 1999), the Murrumbidgee region (Charles *et al.*, 2002) and south-east Queensland (Charles *et al.*, 2003).

Global warming continues for centuries after stabilisation of greenhouse gas concentrations (Wigley, 1995; Whetton *et al.*, 1998; TAR WGI Chapters 9 and 11) but at a much reduced rate as the oceans gradually catch up with the stabilised radiative forcing. Importantly for the Australian region, simulated patterns of warming and rainfall changes in the Southern Hemisphere change dramatically after stabilisation of greenhouse gas concentrations. This is because of a reversal of the lag in warming of the

Southern Ocean relative to the rest of the globe (Hirst, 1999; Goose and Renssen, 2001). This lag increases up to stabilisation but decreases after stabilisation (Whetton *et al.*, 1998), with consequent reversal of changes in the north-south temperature gradient, the mid-latitude westerlies, and associated topographically influenced rainfall trend patterns (notably over Tasmania).

2.3.2 Latest CSIRO climate change projections for the 21st century

CSIRO issued climate change projections in May 2001 (CSIRO, 2001). Changes in future Australian temperature and rainfall were derived from simulations by nine different climate models, in which the level of greenhouse gas concentrations was enhanced. Each of these models was found, by comparison with observations, to have an acceptable simulation of Australia's climate under current conditions.

Ranges of change were presented that incorporate quantifiable uncertainties associated with the IPCC range of future emission scenarios, the range of global responses of climate models, and model-to-model differences in the regional pattern of climate change.

The ranges, shown in **Figure 2.14**, are based on:

- the global warming projections in **Figure 2.3**, which provide information on the magnitude of the global climate response over time
- the regional response in terms of local change (in °C for temperature and in percentage for rainfall) per °C of global warming. A range of local values is derived from the differing results of nine recent climate model simulations.

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

Temperature

Simulated ranges of warming for Australia are shown in **Figure 2.14**. By 2030, annual average temperatures are 0.4 to 2.0 °C higher over most of Australia, with slightly less warming in some coastal areas and Tasmania, and the potential for greater warming in the north-west. By 2070, annual average temperatures have increased by 1.0 to 6.0 °C over most of Australia with spatial variation similar to that for 2030. The range of warming is greatest in spring and least in winter. In the north-west, the greatest potential warming occurs in summer.

Model results indicate that future increases in daily maximum and minimum temperature will be similar to the changes in average temperature. This contrasts with the greater increase in minima than maxima observed over Australia in the 20th century.

Changes in daily temperature extremes can be influenced by changes in daily variability and changes in average maximum or minimum temperature. CSIRO modelling results for Australia indicate that future changes in variability are relatively small and the increases in average maximum and minimum temperature mainly determine the change in extremes. Changes in extreme temperatures, assuming no change in variability, are given in **Tables 4 and 5**. Changes in the number of days with particular extreme temperatures depend in part on the present underlying range of temperatures at each location. This is because a uniform shift in the frequency distribution of temperature leads to large changes in frequency near the tails of the distributions.

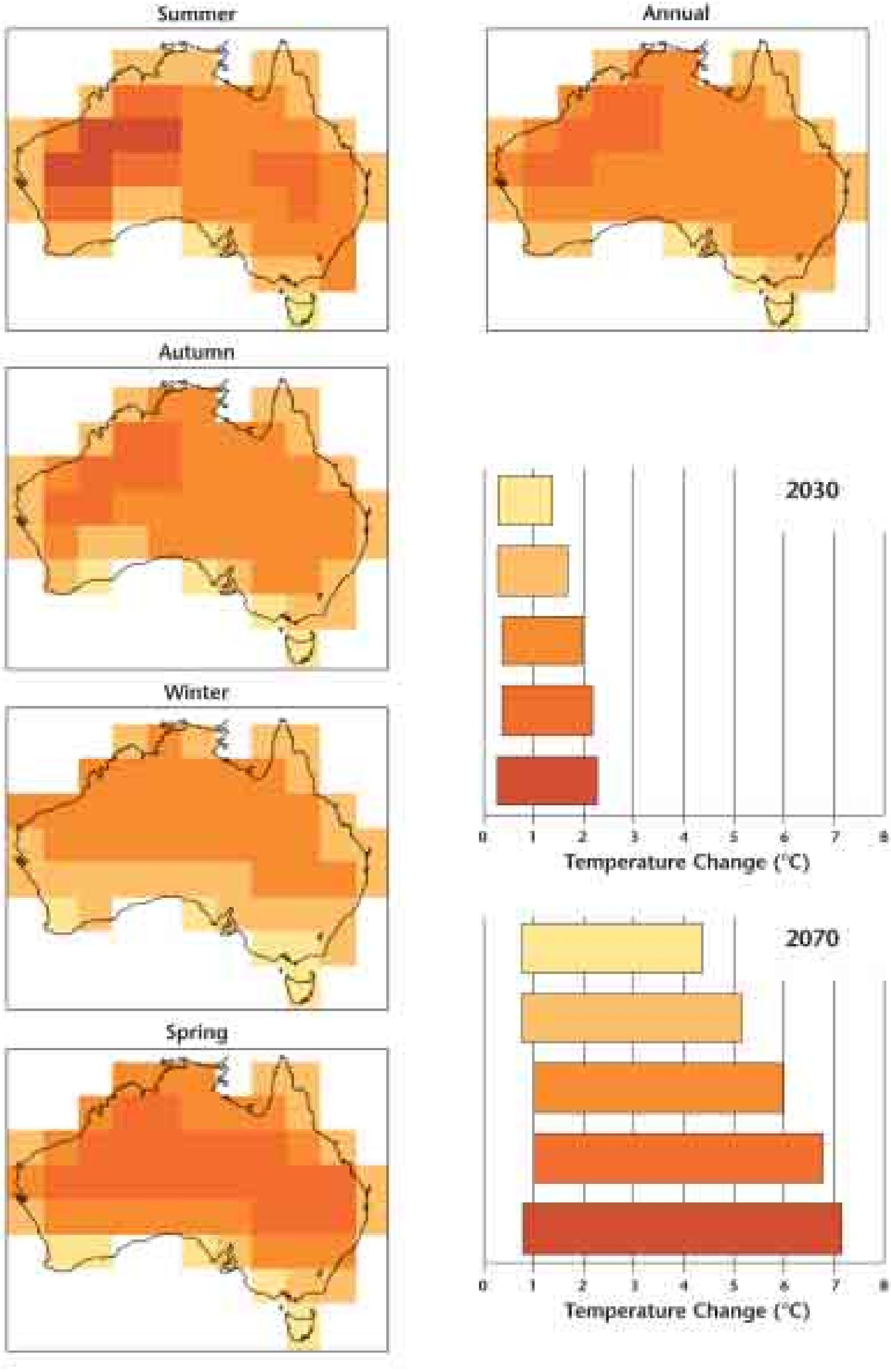


Figure 2.14.
Average seasonal and annual warming ranges (°C) for around 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps.

Table 4:
The average number of summer days over 35 °C at capital cities (excluding Darwin) for present conditions, 2030 and 2070.

Number of summer days over 35 °C

	Present	2030	2070
Hobart	1	1-2	1-4
Sydney	2	2-4	3-11
Brisbane	3	3-6	4-35
Canberra	4	6-10	7-30
Melbourne	8	9-12	10-20
Adelaide	10	11-16	13-28
Perth	15	16-22	18-39

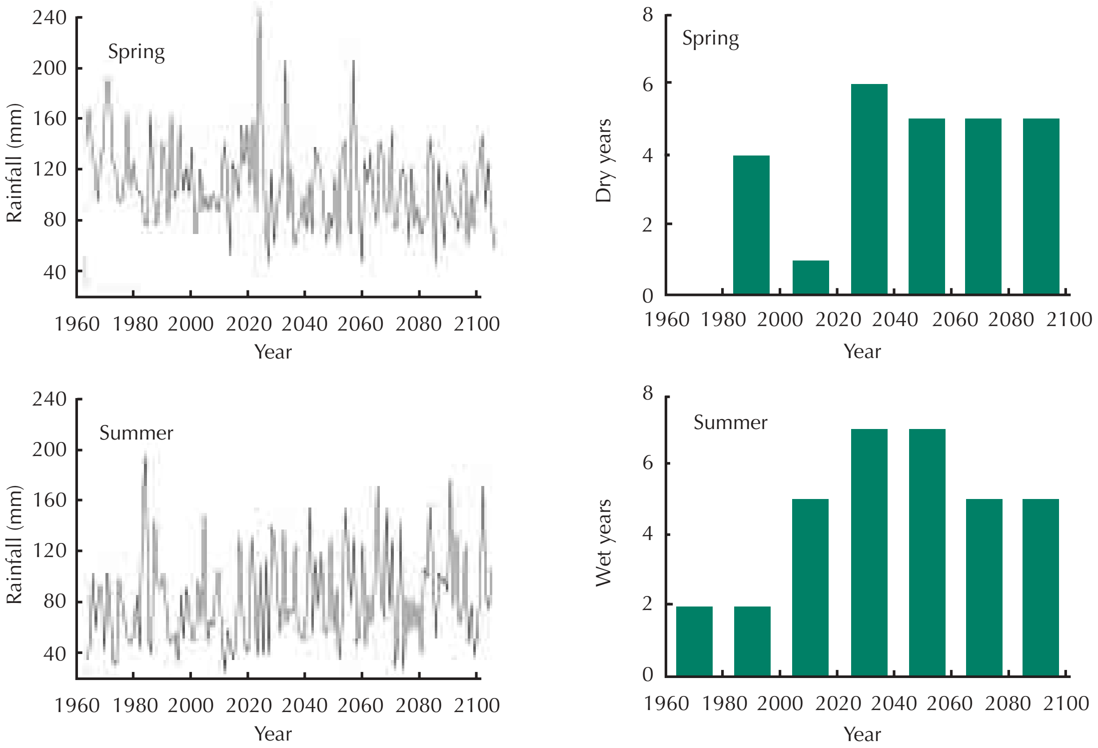
Table 5:
The average number of winter days below 0 °C at selected sites for present conditions, 2030 and 2070.

Number of winter days below 0 °C

	Present	2030	2070
Canberra (ACT)	44	31-42	6-38
Orange (NSW)	38	18-32	1-27
Launceston (TAS)	21	10-18	0-14
Tatura (VIC)	15	6-13	0-9
Wandering (WA)	14	5-11	0-9
Dalby (QLD)	10	3-7	0-6
Nuriootpa (SA)	9	2-7	0-5

Changes in rainfall extremes: An example

Changes in average rainfall can affect the frequency of wet and dry seasons. To illustrate this effect, results from the CSIRO regional model for south-west New South Wales are considered. In this case, summers become about 15% wetter and springs become about 10% drier by 2030 (Figure a). The number of extremely dry springs more than doubles after 2020, as does the number of extremely wet summers (Figure b).



Box 3
Regional climate model simulation for south-west NSW for (a) spring and summer total rainfall, and (b) the number of extremely dry springs (below the 4th driest year from 1961-2000) or extremely wet summers (above the 4th wettest year from 1961 to 2000) each 20 years. Results are based on the IPCC IS92a scenario (see Figure 2.3).

Rainfall

Figure 2.15 shows ranges of change in Australian rainfall for around 2030 and 2070. Projected annual average ranges tend toward decrease in the south-west (-20% to +5% by 2030 and -60% to +10% by 2070, rounded to the nearest 5%), and in parts of south-east Australia and Queensland (-10% to +5% by 2030 and -35% to +10% by 2070). In some other areas, including much of eastern Australia, projected ranges are –10% to +10% by 2030 and -35% to +35% by 2070. The ranges for the tropical north (-5% to +5% by 2030 and -10% to +10% by 2070) represent little change from current conditions.

In summer and autumn, projected rainfall ranges for most locations are –10% to +10% by 2030 and –35% to +35% by 2070 or tend toward increase (–10% to +20% by 2030 and –35% to +60% by 2070). The latter occur mainly in parts of southern inland Australia in summer and inland areas in autumn. In some parts of northern and eastern Australia in summer, and inland Australia in autumn, the tendency for wetter conditions is -5% to +10% by 2030 and -10% to +35% by 2070. However, for the far south-east of the continent and Tasmania, projected rainfall tends to decrease in both seasons (-10% to +5% by 2030 and -35% to +10% by 2070).

In winter and spring most locations tend toward decreased rainfall (or are seasonally dry). Ranges are typically -10% to +5% by 2030 and -35% to +10% by 2070. Projected decreases are stronger in the south-west (-20% to +5% by 2030 and -60% to +10% by 2070) while Tasmania tends toward increases in winter (-5% to +20% by 2030 and -10% to +60% by 2070).

Individual locations within a classification may show significantly narrower ranges of change. Where scenarios are required for a location-specific application, CSIRO recommends obtaining more detailed information from the Climate Impact Group (<http://www.dar.csiro.au/impact>).

Where average rainfall increases, there would be more extremely wet years, and where average rainfall decreases there would be more dry spells (see example in **Box 3**).

Most models simulate an increase in extreme daily rainfall leading to more frequent heavy rainfall events. This can occur even where average rainfall decreases. Reductions in extreme rainfall occur where average rainfall declines significantly. Increases in extreme daily rainfall are likely to be associated with increased flooding.

Evaporation and moisture balance

Higher temperatures are likely to increase evaporation (see **Figure 2.16**). CSIRO has calculated projections of change in potential evaporation (atmospheric water demand) from eight climate models. The results show that increases occur in all seasons and, annually averaged, range from 0 to 8% per °C of global warming over most of Australia, and up to 12% over the eastern highlands and Tasmania. The increases tend to be larger where there is a corresponding decrease in rainfall.

The difference between potential evaporation and rainfall gives a net atmospheric water balance. In general, Australia has an annual net moisture balance deficit, and our environment is largely moisture-limited. When the simulated increases in potential evaporation are considered in combination with simulated rainfall change, the overall pattern shows decreases in moisture balance on a national basis. The 8-model-average is shown in **Figure 2.16**. Average decreases in annual water balance range from about 40 to 130 mm by 2030, which means greater moisture stress for Australia. This represents decreases of 15 to 160 mm by 2030 and 40 to 500 mm by 2070. The simulated changes show the greatest consistency between

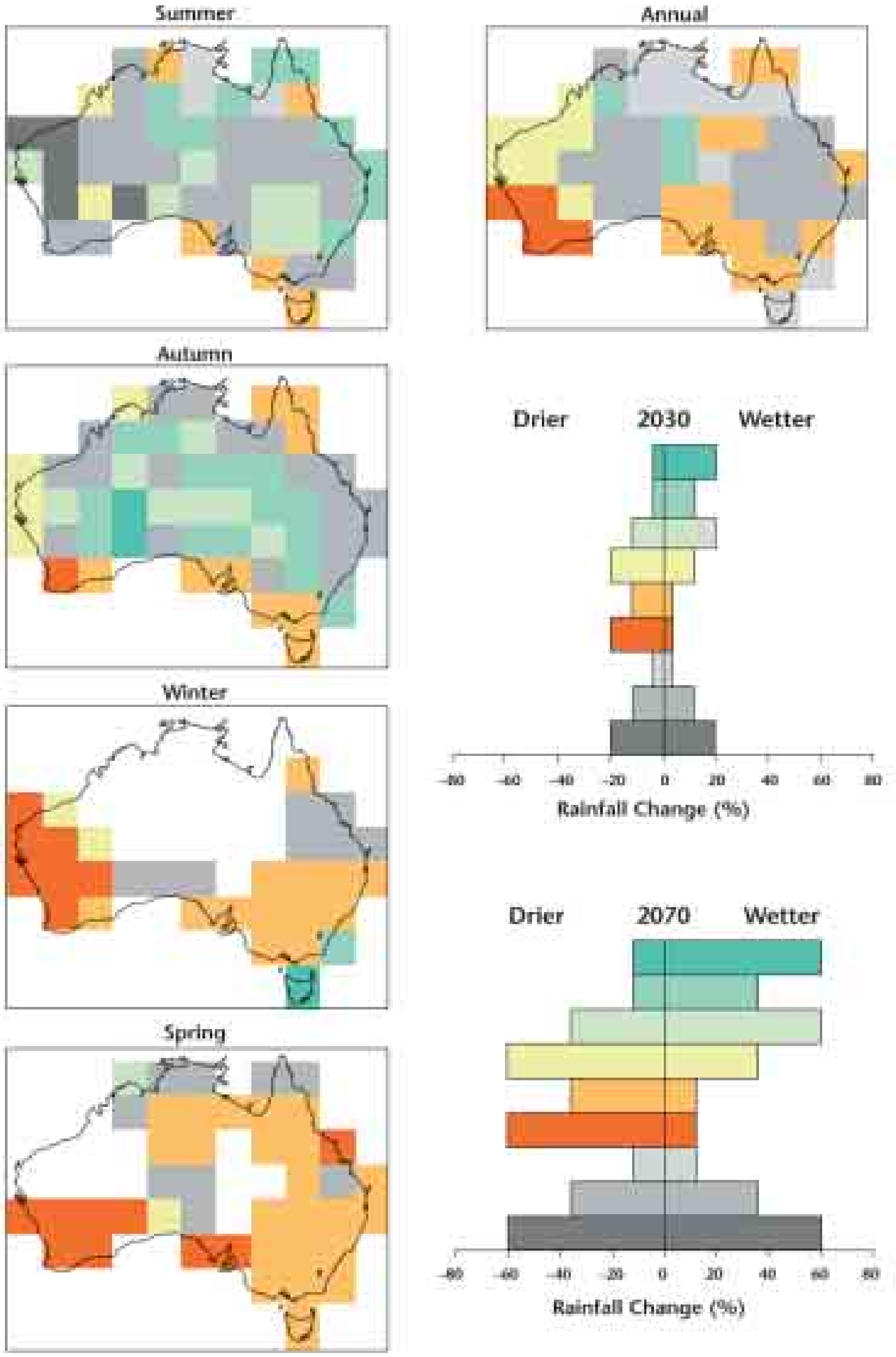


Figure 2.15.
Ranges of average seasonal and annual rainfall change (%) for around 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps. Ranges are not given for areas with seasonally low rainfall because percentage changes in rainfall cannot be as reliably calculated or applied in such regions.

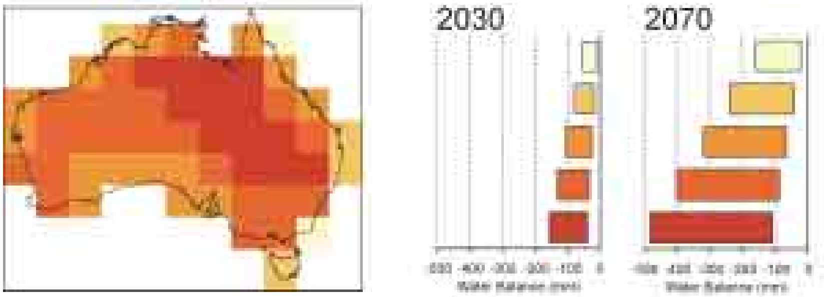


Figure 2.16.
Map of projected change in annual water balance (rainfall minus potential evaporation). Left scale: Projected change for 2030. Right scale: Projected change for 2070.

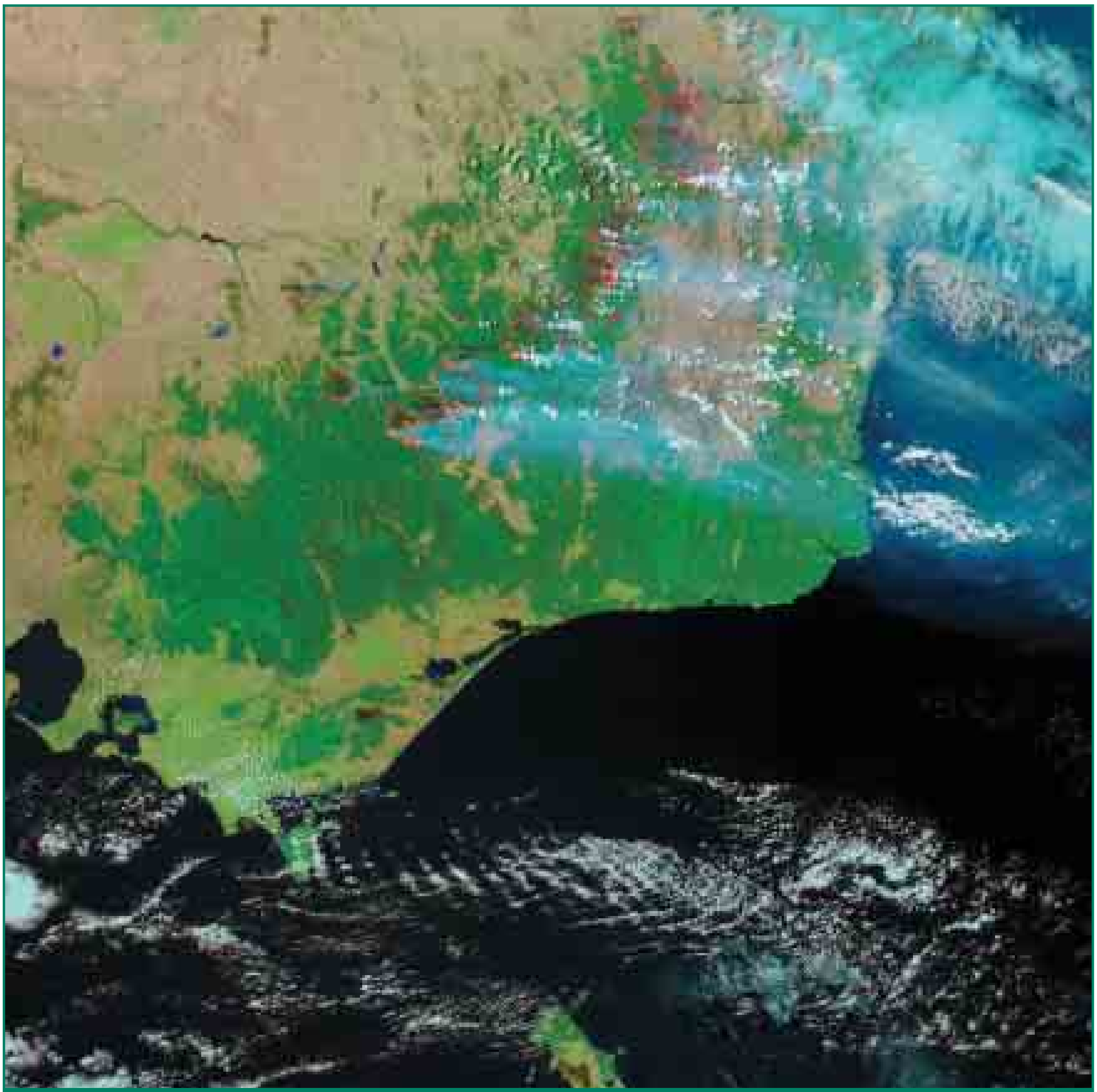


Figure 2.17.
Satellite photo of fires in south-east Australia on 21 January 2003. Red indicates fire fronts. Light blue plumes are smoke. These fires burnt for several weeks at the end of an El Niño-induced drought that may have been exacerbated by a global warming trend (Nicholls, 2003b).

models in spring. Decreases in spring are greatest over eastern Australia.

Tropical cyclones

While regional and decadal variations in the frequency of tropical cyclones have been observed worldwide, no significant global trends have been detected. Projections are difficult since tropical cyclones are not well resolved by global or regional climate models. Present indications are:

- regions of origin are likely to remain unchanged
- maximum wind-speeds may increase by 5–20% in some parts of the globe by the end of the century
- preferred paths and poleward extent may alter, but changes remain uncertain
- future changes in frequency will be modulated by changes in the El Niño-Southern Oscillation.

Tropical cyclones are associated with the occurrence of oceanic storm surges, gales and flooding rains in northern Australia. The frequency of these events would rise if the intensity of tropical cyclones increases. Projected rises in average sea level will also contribute to more extreme storm surges.

El Niño-Southern Oscillation

The El Niño-Southern Oscillation has a strong influence on climate variability in many parts of Australia, and this will continue. However, it is likely that global warming will enhance the drying associated with El Niño events due to increased potential evaporation. Climate models do not give a consistent indication of future changes, although some simulations suggest more El Niño-like average conditions.

Fire frequency and intensity

Fire frequency and intensity are not normally projected as part of climate change scenarios, but are derived properties depending on many factors of which climate is one. However, as bushfires cut across many sectors, notably ecosystems and conservation, agriculture and forestry, and settlements and industry, it seems best to include them here.

In Australia widespread bushfires are usually associated with drought. In many regions ignition of small fires is common in most dry seasons due primarily to lightning strikes, although human agencies are responsible for an increasing number of ignitions in more settled areas. Many small fires fail to spread and are extinguished naturally or by fire-fighting. The critical factor in a small fire becoming a large one is the abundance and dryness of the fuel, and the occurrence of suitably hot and windy conditions that cause fire to spread, especially by "spot fires" well in advance of fire fronts due to wind-borne burning embers.

Kershaw *et al.* (2002) document a history of fire in Australia, noting a strong correlation with climatic changes, but also a large influence due to human occupation around 40,000 years ago, and again in the early phase of European settlement. Currently, on average approximately 5% of the Australian land surface is burned each year, mostly in northern Australia, and approximately 10% of the net primary productivity of the continent is consumed in these fires (Meyer *et al.*, 2001). A correlation of widespread forest fires with climatic variations, especially during dry years and El Niño years, has been noted in the Pacific North-west region of the USA (Heyerdahl *et al.*, 2002).

Beer and Williams (1995), Williams *et al.* (2001), and Cary (2002) have studied the potential impact of climate change on bushfire danger in Australia. These studies each found a general increase in fire danger, as measured by the McArthur Forest Fire Danger Index (FDI), with the enhanced greenhouse effect. Beer and Williams (1995) used simulated daily data from the CSIRO 4-level and 9-level climate models, and in both cases found increased FDI for doubled CO_2 climate. They found that the average daily relative humidity was the most important variable in estimating annual fire danger. Williams *et al.* (2001) used daily data from an improved version of the CSIRO 9-level climate model, and again found an increase in fire danger throughout Australia under doubled CO_2 climate conditions. They found that an increase in the number of days of very high and extreme fire danger was mainly due to increases in daily maximum temperatures.

Cary (2002) has comprehensively reviewed work on climate change and fire. He used output from the CSIRO regional climate model to examine four scenarios of potential changes in fire regimes in the Australian Capital Territory, using the FIRESCAPE fire regime model (McCarthy and Cary, 2002). One of the four scenarios was for the present climate, and three spanned the range of temperature change in the CSIRO (1996) scenarios: low, moderate and high change. Cary found small to moderate increases in the FDI, but more significant decreases in the inter-fire interval (IFI) for the moderate and high change scenarios. IFI varied from an average of about 43 years (present conditions) to 20 years (moderate change scenario) and 12 years (large change). Moderate increases in average fire line intensity were also found with warmer climate, a decrease in fire extinguishments (fire going out in a particular grid-cell), and an average increase in fire spread, which varied strongly with season according to the projected changes in seasonal rainfall. Projected changes in fire behaviour would doubtless alter with further updated scenarios, but the overall picture is not expected to change significantly. This is because extreme fire danger is well correlated with periodic drought conditions, leading to drying of fuel, and extremely hot summer and autumn days conducive to fire spread. Both these conditions are expected to increase with global warming under all plausible scenarios, at least in southern Australia.

The International Geosphere-Biosphere Programme (IGBP) has recently developed a conceptual framework for the study of regional vulnerability to fire (Lavorel *et al.*, 2001), and the 18 January 2003 fires which destroyed parts of Canberra have been used (Lavorel, 2003) as an example of the need to further investigate the links between global change, fire and society.

Regional and sectoral scenarios

Various regional and sectoral studies have been carried out to develop climate change scenarios for particular regions or states, or for application in particular industries. In most cases more detailed analysis has been done using regional climate models driven at their boundaries by output from global climate models, usually the CSIRO model. This has often extended to the analysis of daily output for studies of changes in extreme temperatures, frost frequencies, wet spells or dry spells, or other impact-relevant variables such as fire danger (see above).

Examples include studies for Victoria that have included results from eight global climate models and the CSIRO regional model at 60 km resolution. Ranges of seasonal average temperature and rainfall changes were calculated along with changes in number of summer days over 35 °C and of winter days below 0 °C (Whetton *et al.*, 2001, 2002). Similar studies have been done for Queensland (Walsh *et al.*, 2001) with special attention to possible changes to tropical cyclones and ENSO (which has major effects on droughts and floods in Queensland), and for New South Wales (Hennessy *et al.*, 1998) and South Australia (McInnes *et al.*, 2002).

Other studies have looked at variables particularly relevant to certain industries, e.g., dairy cattle (Jones and Hennessy, 2000), wine growing (McInnes *et al.*, 2003) and gas supply (Suppiah, *et al.*, 2001). For dairy cattle in the Hunter Valley (New South Wales) heat stress scenarios were developed, while for wine growing changes in rainfall, temperature, water stress and moisture were derived. For the gas industry, projections were made of the trend in heating degree-days for 2003–07 for Melbourne. This took account of both global warming and local warming due to urbanisation.

Summary of scenarios

In summary, the results suggest annual average warming over much of inland Australia in the range of 1 to 6 ºC by 2070, and slightly less in coastal regions. Rainfall results are more complex regionally and seasonally, but overall they suggest a likelihood of decreasing rainfall over most of Australia (particularly the south-west and south-east mainland) as the 21st century progresses. However, consistent with conclusions in the TAR, an increase in heavy rainfall is projected, even in regions with small decreases in mean rainfall. This is a result of a shift in the frequency distribution of daily rainfall toward fewer light and moderate events and more heavy events. This could lead to more droughts and more floods.

Calculations of the evaporation and moisture balance suggest that substantial decreases in average soil moisture are likely, in the range of 40 to 130 mm in annual average by 2030. These are likely to be reflected in decreased runoff.

To date, impact and vulnerability studies in Australia in general have not taken account of specific socioeconomic scenarios for the future, such as those laid out in the SRES. Thus, vulnerabilities have been based on projected climate change impacts and adaptations, assuming the present socioeconomic situation, in some cases with a qualitative allowance for expected socioeconomic trends (e.g., increased competition for water supplies, and increased population and investment in coastal zones). A range of socioeconomic scenarios for Australia have been developed by several agencies (see section 1.4.4), and it would be interesting to see how these affect climate change impacts and vulnerability.

2.3.3 Uncertainties and probabilistic scenarios

Uncertainties about future human behaviour and shortcomings in climate modelling limit our climate change projections to ranges of change for some variables, and qualified statements on possible changes for others. Uncertainties have been quantified where possible, accounting for various future greenhouse gas emissions scenarios and model-to-model differences in simulating both global and regional climate responses. Greenhouse gas emissions are subject to uncertainties concerning population growth, technological change and social and political behaviour. Climate model responses are most uncertain in how they represent feedback effects, particularly those dealing with changes to cloud regimes, biological effects and ocean-atmosphere interactions. The coarse spatial resolution of climate models also remains a limitation on their ability to simulate the details of regional climate change. Future climate change will also be influenced by other, largely unpredictable, factors such as changes in solar radiation, volcanic eruptions and chaotic variations within the climate system itself. Rapid climate change, or a step-like climate response to the enhanced greenhouse effect, is possible but its likelihood cannot be defined. Because changes outside the ranges given here cannot be ruled out, these projections should be considered with caution.

Quantification of potential changes in extreme events, tropical cyclones and ENSO also are major uncertainties. Other conceivable lower probability, high-impact changes such as changes in ocean circulation, could have important regional impacts (see section 2.1.4).

Probabilistic scenarios for risk and adaptation analyses, based on the quantifiable range of uncertainties, have been explored by CSIRO (Pittock, 1999; Jones, 2000b; Pittock and Jones, 2000; Jones and Page, 2001; Jones and Pittock, 2002). In such risk assessments, the probabilities of exceeding thresholds for impacts of various magnitudes, which may relate to system performance or failure, are estimated. In a changing climate, probabilistic risk assessments can indicate the time available until critical thresholds would be reached, enabling adaptive measures to be taken to avoid undesired consequences. An example, regarding environmental flows for bird breeding, is discussed in section 4.1.2, and another, related to whether and when irrigation demand will exceed irrigation supply at a particular location, is given in section 5.6.

2.3.4 Changes in extreme events and sea level

Pittock *et al.* (1999) have summarised the past importance of extreme events for Australia and prospects for the future. Major climatic hazards arise in Australia from tropical cyclones, floods, droughts, windstorms, wildfires, landslides, hail, lightning, heat waves, frost, and storm surges. Events that are directly related to temperature are more predictable (more heat waves, fewer frosts) than those associated with wind and rain (see **Table 2**). The incidence of wildfire in Australia is expected to increase with global warming (Beer and Williams, 1995; Pittock *et al.*, 1999; Williams *et al.*, 2001; Cary, 2002), as is that of landslides and storm surges (the latter because of both higher mean sea level and increased storm intensities). Changes in hail and lightning frequencies are uncertain, although there are some arguments for expecting increases (Price and Rind, 1994; McMaster, 1999; Pittock *et al.*, 1999).

Drought is discussed more fully in section 4.3.6. Suffice to say here that the projected increases in temperature (see **Figure 2.14**) will in general increase potential evaporation and, even in combination with changes in rainfall of either sign (see **Figure 2.15**) reduce the water balance (see **Figure 2.16**). This would lead to a greater incidence of drought, as has been projected by several modelling studies (Arnell, 1999; Kothavala, 1999; Meehl and Washington, 1996). A trend in recent decades to increased annual average surface temperatures for the same rainfalls has been documented by Nicholls *et al.* (1996b) and Nicholls (2003 a and b). This has the strong implication that droughts as traditionally defined in Australia by rainfall deficit are becoming more severe as measured in terms of moisture deficit, which is the relevant measure for water supply and agriculture. Such a tendency is expected to continue.

More intense tropical cyclones in the Australian region (see **Table 2** and section 2.1.4, and Walsh and Ryan, 2000) would have serious implications for storm-surge heights, wind damage, and flooding. If cyclones were to travel further polewards (Walsh and Katzfey, 2000), they would be more likely to impact on coastal regions in the south-west of western Australia, southern Queensland, and the northern New South Wales coastal region. The locations of tropical cyclone genesis in the region are correlated with ENSO (Evans and Allan, 1992; Basher and Zheng, 1995), so any change in the mean state of the tropical Pacific may affect the risk of tropical cyclone occurrence in particular locations.

Mid-latitude storms also may increase in intensity (see McCarthy *et al.*, 2001 Table 3-10, and discussion in section 2.2.1), and their frequency and location could change—for example, as a result of changes in the latitude of the westerlies and in ENSO. This would impact return periods for mid-latitude storm surges, high winds, and other phenomena.

Interannual variability in ENSO leads to major floods and droughts in Australia. Such variations are expected to continue under enhanced greenhouse conditions, though possibly with greater hydrological extremes as a result of more intense rainfall in La Niña years and more intense drought resulting from higher rates of evaporation during El Niño years (Walsh *et al.*, 1999; McCarthy *et al.*, 2001, Table 3–10). A more El Niño-like mean state of the tropical Pacific Ocean, which is projected by some but not all climate models (Cai and Whetton, 2000) would imply greater drought frequency (Kothavala, 1999; Walsh *et al.*, 2000), as does the drying trend found over the Murray-Darling Basin in recent simulations (Arnell, 1999).

Mean sea level is expected to increase, with local and regional variations as a result of land-sea movements and changes to ocean currents and climatic forcing (see section 2.1.4). In addition, local and regional weather systems lead to temporary fluctuations in sea level and extreme events that may cause coastal inundation. Storm surges in tropical Australia can be several metres due to tropical cyclonic forcing and shallow continental shelves (Hubbert and McInnes, 1999a,b; McInnes *et al.*, 1999), but are generally one metre or less in temperate latitudes.

The actual height reached by a storm surge depends not only on the location and intensity of the storm, but also on its timing relative to the tides, coastal bathymetry and topography, and slower variations such as those from ENSO. The latter contribute to significant local sea level variations around the coasts of Australia (Chiera *et al.*, 1997). In addition, any changes in storm intensities, frequencies, and locations will change the average time between surges of a given magnitude at particular locations.

3

Potential impacts of climate change: the global picture

3. Potential impacts of climate change: the global picture

3.1 What do we mean by Impacts of Climate Change?

Climate change will obviously affect many natural and human systems and activities. We know this from observations of effects of year-to-year and longer-term changes in the past, and indeed from differences between regions with different average climates. However, the impact of a given climate change on a particular system or activity depends on its vulnerability and adaptability. If the system or activity does not adapt to the change, the impacts will be larger. Adaptation may be automatic, or it may be conscious and planned. Automatic adaptation tends to occur in natural systems, such as migration of fauna or flora to more suitable environmental regions. Planned adaptation tends to occur in human systems. This might be as simple as delaying planting of a crop until there is rainfall, or planting a smaller area if a drought is feared. Or it may be more complex, involving research, planning and investment, for example in developing or selecting a different cultivar or crop variety, developing an irrigation system, or switching from growing wheat to grazing cattle or even developing a tourism industry.

Therefore, when we talk about climate change impacts we need to be clear whether we are talking about the direct effects without adaptation, or the effects after some automatic or planned adaptation. In agricultural impact studies, most impact assessments in the 1980s and early 1990s used the assumption of no adaptation, and therefore may have over-estimated the adverse impacts. On the other hand, the same studies often ignored other possibly adverse effects such as from extreme events, insects or disease. Other, more recent studies used the opposite assumption, that there is perfect foresight or prescience and optimal adaptation. However, perfect adaptation depends on perfect anticipation of the climate changes. As this is not possible, adaptation will never be perfect. Moreover, even in the case of perfect foresight, adaptation will have costs as well as benefits, and these also should be taken into account – otherwise the prescient assumption leads to an under-estimate of impacts.

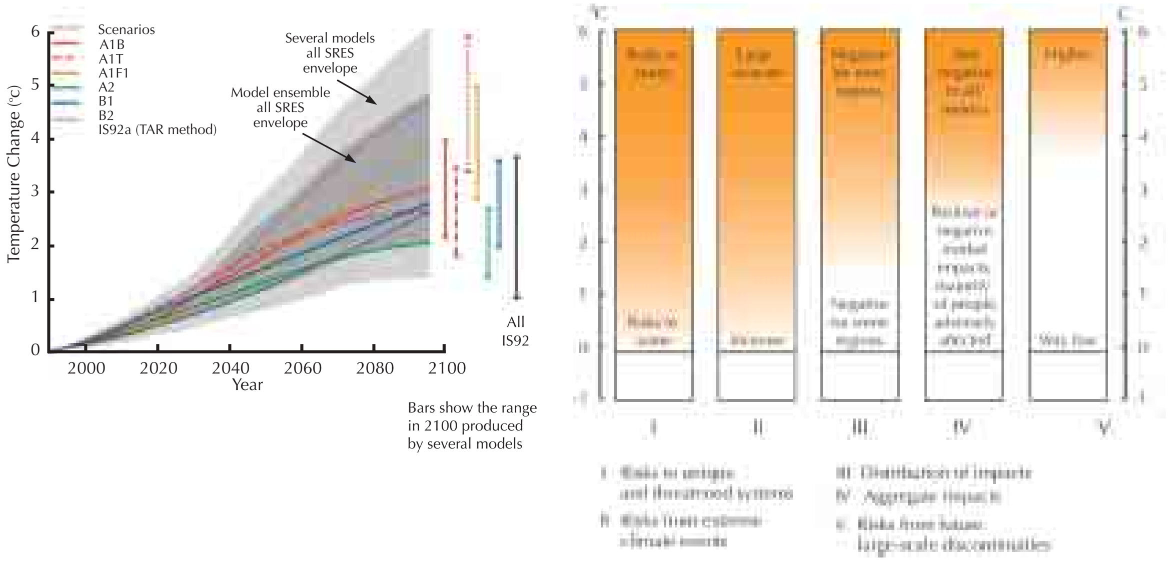
One of the aims of climate change science is to improve the accuracy and credibility of projections of climate change and associated impacts, in order to improve the ability to make optimal adaptations.

The degree to which particular impact assessments have taken adaptation and its costs into account is often not clear, and future adaptation will depend on future technological and social developments which cannot be perfectly predicted. So any estimates of realistic impacts can only be approximate and provide guidelines to what may occur and how it might be optimised. Part of any scientific assessment of impacts must be to take into account likely adaptations. This was attempted by the IPCC in its Third Assessment Report (TAR), and is further attempted here.

3.2 IPCC Conclusions Regarding Impacts and Their Costs

The IPCC assesses the published literature but does not carry out new, targeted research, so it is inevitable that the TAR's answer to the question of effects and costs is only an approximation. For the most part the IPCC has only sample projections of impacts and costs for climate changes assumed to impact instantaneously on society as it is now. These projections are uncertain because of poor understanding of changes in extreme events, adaptive capacity, the effects of the rate of change, and changes in exposure and adaptive capacity associated with different socioeconomic and technological futures. Moreover, many of the potential costs cannot be expressed in monetary amounts, despite the understandable desire of economists to do so. 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.

Instead of attempting to express all costs in monetary terms, the TAR summarised the effects in terms of estimated ranges of warmings up to the year 2100 resulting from the range of 'plausible' greenhouse gas emissions according to the SRES, and qualitative estimates of impacts in terms of five major categories or 'reasons for concern'. These conclusions are summarised in **Figure 3.1**, adapted from the Synthesis Report, figure SPM-3.



Bars show the range in 2100 produced by several models

Figure 3.1.
Projected global warming up to 2100 for the range of SRES scenarios (left), and a qualitative representation of five major reasons for concern (right). The reasons for concern are discussed in the text. Ranges of uncertainty of warmings at 2100 for individual SRES scenarios are shown in the middle. Note that these indicate that, even with the uncertainties, the warming ranges for different SRES scenarios can differ significantly by 2100. As indicated in the right hand columns, these ranges of warmings lead to quite different degrees of risk (with darker shading in the columns indicating more negative impacts), for each of the five reasons for concern.

Although the estimated impacts in **Figure 3.1** are expressed qualitatively at the global scale, they are for the most part based on numerous quantitative local examples for a range of scenarios. The impacts clearly become more severe in the global aggregate as warming increases, and probably more severe with greater rates of warming (although there are fewer studies on this point). The five categories are the result of synthesising many hundreds of climate change impact studies. They are:

- *Risks to unique and threatened systems:* Natural systems are vulnerable to climate change, and more systems will be damaged irreversibly as global warming increases.
- *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 these risks have been demonstrated by a rise in damages from such events. Irrespective of whether this rise is due to changes in extremes or to changes in exposure (such as increasing population and investment in hazardous areas), the recent increase in damages shows increasing vulnerability (McCarthy *et al.*, 2001, chapter 8; Changnon and Changnon, 1999; Changnon *et al.*, 2000; Pielke and Landsea, 1998).
- *Distribution of impacts:* Numerous but incomplete impacts studies lead to the broad conclusion that adverse impacts are likely to be greater and occur earlier in low-latitude 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.
- *Aggregate impacts:* These are poorly quantified and multiple measures are needed because many impacts cannot be expressed objectively in monetary terms. The consensus is that net global market impacts may be small (positive or negative, 1 or 2% of GDP) at small global warmings (less than 2 or 3 °C), but will become increasingly negative at greater warmings. Most people are expected to be negatively affected even at small warmings.
- *Risks from future large-scale discontinuities:* There is an unquantified potential for large-scale and possibly irreversible changes in Earth systems resulting in impacts at regional and global scales. **Table 3** summarises some of these discontinuities, which are caused by gradual changes in the climate system.

In regard to aggregate impacts, efforts have been made to quantify impacts in terms of monetary costs, and to weigh these costs against those of mitigation (reducing greenhouse gas emissions) in some sort of decision-making framework. However, this runs into a number of difficulties, including the large uncertainties about impacts at particular levels of greenhouse gases, the uncertainties about the efficiency and acceptability of mitigation policies which might lead to those levels, and the subjectiveness of monetary costings for such things as human life, health, or the loss of biological diversity or cultural heritage. There is also the complication that lags in the climate and social systems mean that actions taken, or not taken, today may have consequences many years, even centuries, into the future (see section 2.1.5). This requires decisions about how we treat future costs of delayed impacts in relation to present costs of mitigation. Such treatment usually involves the controversial topic of discount rates (Portney and Weyant, 1999). These issues are discussed in the TAR Working Group III report (Metz *et al.*, 2001).

Newell and Pizer (2001) argue that, as future discount rates are uncertain, this uncertainty should be included in any integrated cost-benefit analysis, and that doing so leads to a marked rise in the valuation of future costs from climate change. Tol (2003) goes further and argues that the possibility of major climate disasters can make the discount rate go negative, thus placing a large premium on taking mitigation action now.

The TAR's estimated ranges of warming for different scenarios, and qualitative estimates of impacts for the five reasons for concern, are shown in **Figure 3.1**. The objective of the UNFCCC, in Article 2, is to avoid a concentration of greenhouse gases that might lead to "dangerous interference with the climate system". The TAR is far from providing a precise quantitative estimate of what would cause such interference. What we have is a qualitative assessment of five reasons for concern. What is needed, given the uncertainties, is a more quantitative multi-dimensional risk assessment. **Figure 3.1** at least hints at the dimensions of this risk. IPCC assessments provide technical information, however, the judgement of what would constitute 'dangerous interference' essentially is a matter for decision by governments.

3.3 Putting Impacts in a Risk Assessment Framework for Decision-Making

Many everyday decisions are made on the basis of a conscious or unconscious risk assessment, where risk is defined in terms of the probability of a particular climatic outcome multiplied by the consequences of that outcome. As we have seen in section 2.1.4, consequences will not vary in direct proportion to the magnitude of climate change, due to the possibility of abrupt changes, physical, ecological and societal thresholds for effects, and instabilities in physical, ecological and social systems. Many examples of such thresholds and instabilities are given later in this report. Smoothly varying "cost functions" are thus gross simplifications of reality, even at the global aggregate level if the possibility of major disasters are taken into account.

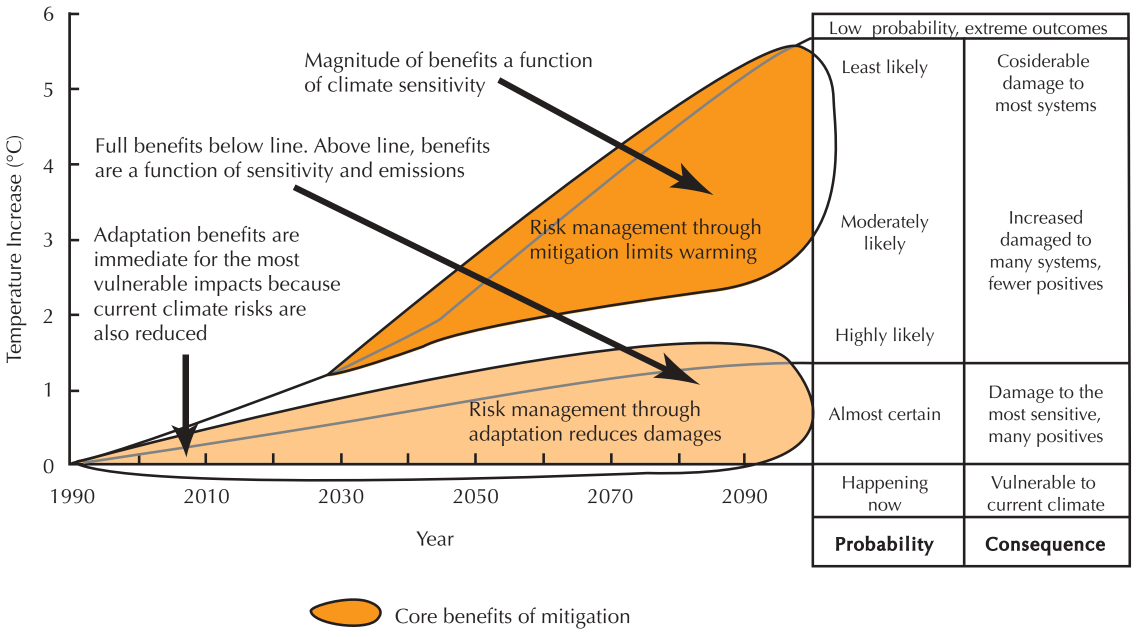
Decisions made at a global level ideally would take account of the sum total of probabilities and consequences for a myriad of local and regional effects, which will fall unevenly between locations depending on the existing climate, geographical situations and socioeconomic circumstances. Even decisions made on the balance of risks at a national level will involve many subjective judgements and imponderables. They must weigh up the interests of different segments of society that may be impacted differently, of impacts incurred at different times in the future, and of impacts that cannot be readily costed in economic terms such as loss of species, heritage or sustainability. Moreover, impacts at the national level will be conditioned by, and include effects of, impacts elsewhere in the world. This may affect economic growth, terms of trade, political stability and conflict, the need for aid, and population movements and pressures (some of these issues are discussed in sections 4.3.9 and 4.5.8).

Recent attempts to weigh up the risks and to try to answer the question of what constitutes a dangerous level of greenhouse gases, or even a dangerous level of climate change, include the Synthesis Report of the IPCC Third Assessment (Watson and Core Writing Team, 2002).
The Synthesis Report makes the important general point that climate change decision making is essentially a sequential process under uncertainty. It is about determining what the best course is for the near-term given the expected long-term climate change and accompanying uncertainties, and requires frequent revision as new information comes to hand which alters the level of uncertainty.

Put simply, risk management is about avoiding unacceptable consequences. In the climate change context there are two strategies or broad categories of responses or action which might be taken to avoid unacceptable consequences. These are adaptation and mitigation.
Adaptation is a strategy that reduces the adverse consequences, and increases the positive consequences, of any level of climate change. Mitigation is a strategy that reduces the level of climate change, or, given uncertainty, reduces the probability of reaching a given level of

climate change. Adaptation allows larger levels of climate change to be acceptable, while mitigation reduces the probability of exceeding the adaptive capacity of the system.

Given the inertia in the climate and socioeconomic systems (see section 2.1.5), some level of climate change is now inevitable. Also, given that even present climate variability leads to adverse impacts (e.g., the impact of major floods, droughts or tropical cyclones), a level of adaptation is necessary to cope with any unavoidable level of global warming and associated effects. Adaptation is thus a necessary strategy for at least coping with the inevitable climate changes. It is doubtful, however, whether the adaptive capacity exists to cope with large climate change. This will depend on the severity of the change, location and socioeconomic circumstances. The strategy must be to reduce the probability of reaching levels of climate change to which we cannot adapt. This is neatly summarised in **Figure 3.2** developed by Jones (2003), and can be read in conjunction with **Figure 3.1** where the consequences, in terms of the five major reasons for concern identified by McCarthy *et al.* (2001), are qualitatively displayed.



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

Figure 3.2.
Schematic diagram showing, for a range of projected global warmings, the relative benefits of risk management through adaptation (when expected warming is relatively small) in contrast to mitigation which limits warming and thus reduces the high warming scenarios. The first column at the right shows the likelihood of exceeding given levels of warming (as indicated on the scale at left. Low warmings are most likely to be exceeded, and extremely high warmings are least likely. At the far right are summaries of consequences in terms of damages from climate change. This relates directly to the five reasons for concern in Figure 3.1. From Jones (2003).

Various attempts have been made to arrive at estimates of what constitutes a 'dangerous level of greenhouse gases', for example, see O'Neill and Oppenheimer (2002) and Schneider (2001). However, in view of the above discussion, these must be seen as interim attempts, fraught with uncertainty and, as is inevitable, to some extent subjective in their judgements.

Moreover, the question of assigning probabilities to future levels of greenhouse gases and degrees of climate change is contentious, and how this should be incorporated into decision-making is still being debated (e.g., see New and Hulme, 2000; Gritsevski and Nakicenovic, 2000; Schneider, 2001; Pittock *et al.*, 2001; Katz, 2002; Heal and Kristrom, 2002; Tol, 2003). Titus and Narayanan (1996) and Vaughan and Spouge (2002) have both used groups of experts to arrive at estimated probabilities of major contributions to global average sea level rise from disintegration of the West Antarctic Ice Shelf, and find non-negligible chances of effects by 2100 (see discussion in section 2.1.4). Jones (2001) developed a risk assessment/ management framework for climate change impacts that hinges on estimating the probabilities of climate change in excess of key threshold for impacts. With reference to **Figure 3.2**, this means estimating the cumulative probability of global warming exceeding some threshold amount in °C that would lead to unacceptable outcomes. Estimating such cumulative probabilities is less uncertain (i.e., more robust) than estimating the chance of a particular scenario of change occurring.

As discussed in section 2.1.4, large-scale singular events or catastrophes may dominate any long-term risk assessment due to the possible existence of low-probability events of very large impact. Tol (2003) even argues that such events could result in negative economic growth that would logically lead to negative economic discount rates, meaning that costs borne in the distant future would loom increasingly larger than present costs in any cost-benefit analysis.

3.4 Links to Issues of Equity, Sustainability and Other Environmental Problems

The TAR, and especially the Synthesis Report (Watson and the Core Writing Team, 2001) make the general point that climate change impacts are part of the larger question of how complex social, economic and environmental subsystems interact and shape prospects for sustainable development. Most subsystems that will be affected by climate change are already affected by other global changes and stresses, so the effects are either additive or synergistic, and often reach critical thresholds where apparent effects suddenly become large and sometimes unacceptable or catastrophic (see discussion in section 2.1.4).

Some of these interconnections apply to questions of inter-group, inter-regional, inter-national or inter-generational equity (Munasinghe, in Pachauri *et al.*, 2000). Some groups, regions, nations and generations may be more at risk than others. This then involves decision-makers in basing action either on self-interest or on wider standards of equity and justice. Moreover, the capacity to adapt is strongly dependent on the economic and other strengths of a given society, which vary from country to country and generation to generation (McCarthy *et al.*, 2001, chapter 10).

Socioeconomic growth will impact on society's capacity to adapt, its vulnerability to impacts, and its capacity to limit and/or reduce greenhouse gas emissions. For example, societies that become more dependent on mono-cultural agriculture for survival may expose themselves to adverse effects of particular pests or diseases, or climatic factors affecting key crops. Similarly, societies in which population increase and economic growth is concentrated in low-lying coastal zones, particularly in cyclone-prone regions, are becoming more vulnerable to sea level rise and more intense cyclones. Thus, particular patterns of societal development are important for impacts, adaptation and mitigation, and these effects need to be anticipated in development strategies and planning.

Sustainable development is a key issue in both developing and developed countries. It is defined in the IPCC Synthesis Report as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This concept is closely related to that of inter-generational equity, and requires that economic development takes place in such a way as not to lead to 'dangerous interference in the climate system'. The range of development pathways in the SRES scenarios, which the SRES authors regard as plausible, lead to a wide range of greenhouse gas emissions scenarios, and thus to a wide range of possible future climates. The choice of development pathways, both in developing and so-called developed countries, is thus critical to future climate, as well as having other implications for future societies, including their capacity to adapt to climate change.

The links between issues can lead to mutual benefits from action tackling one problem in a way that also benefits another problem, but can also lead to the possibility of actions that benefit one problem but simultaneously impose penalties in relation to another problem. An example is the possible use of farm or plantation forestry to sequester carbon as a climate change mitigation action. This may simultaneously contribute positively to the control of wind erosion by providing shelter, and to reducing dryland salinity by lowering the water table, but it may also adversely affect water supply by increasing water demand and reducing runoff as the young trees grow. Such co-benefits and conflicts can be difficult to anticipate and to resolve, and thus require a holistic approach that integrates action on climate change with action on other issues. These good or bad side effects also complicate any cost-benefit analysis (Metz *et al.*, 2001, chapter 1; Watson and the Core Writing Team, 2001, question 8).

3.5 Impacts of Stabilisation of Concentrations of Greenhouse Gases at Various Levels

At the time the IPCC TAR went to press there was, apart from some preliminary studies with the global integrated model IMAGE (Alcamo *et al.*, 1998), no refereed study in the literature that had looked at the projected impacts of long-term stabilisation of greenhouse gas concentrations in the atmosphere. There was, however, a UK study that has now been published (Arnell *et al.*, 2002).

This study reported on an assessment of the global scale implications of the stabilisation of atmospheric carbon dioxide at 750 ppm (by 2250), and 550 ppm (by 2150), relative to a scenario of unmitigated climate change. Simulated climate changes, obtained using the UK HadCM2 climate model, were derived for the IPCC IS92a, S750 and S550 scenarios (stabilisation of carbon dioxide concentrations at 750 and 550 ppm respectively). The S750 and S550 scenarios differ from the WRE stabilisation scenarios (Wigley *et al.* 1996) in their timing, and none of the scenarios used included aerosol forcing. The resulting climate projections were applied in single impact models for each of six sectors, namely natural vegetation, water resources, coastal flood risk, wetland loss, crop yield and related food security, and malaria. The studies used a single set of population and socioeconomic scenarios for the future, similar to that adopted in the IS92a emissions scenario.

IPCC authors felt unable to place much emphasis on these results, despite their great interest, because at the time they were unrefereed, and came from only a single climate model and a single set of impacts models. A further source of concern was that precipitation changes associated with each of the stabilisation scenarios, obtained using thirty-year means, were only statistically significant at some locations and seasons (Mitchell *et al.*, 2000). This raised doubts as to how well the precipitation changes were determined in the assessment, and thus as to the quantitative reliability of estimated impacts dependent on precipitation changes. This was critical to the assessments of changes in water resources, crop yields, and possibly also for malaria.

Arnell *et al.* (2002) found that the S750 scenario delayed the temperature increase by 2050 in the IS92a scenario by 50 years. The loss of tropical forest and grassland, which occurred in the IS92a projection, was delayed until the 22nd century, and the projected switch of the biosphere from a carbon sink to a carbon source was delayed from the 2050s to the 2170s. Coastal wetland loss was slowed, and major impacts on water resources, and population at risk of hunger or malaria were delayed until the 2080s.

In the S550 scenario, Arnell *et al.* (2002) report no substantial loss of tropical forest or grassland, even by the 2230s, and the biosphere reached a new equilibrium with the atmosphere regarding carbon storage by around 2170. Coastal wetland loss was slowed considerably, and coastal flooding risk was greatly reduced relative to the IS92a scenario. Water resource stress was much less than under the unmitigated scenario. Reported projections of effects on malaria and food production have regional anomalies which are attributed largely to rainfall effects, and in the case of food to the competing effects of increasing carbon dioxide, temperature and rainfall. Indeed, Arnell *et al.* (2002) list several caveats on their projections, including the use of a single climate model and a single set of impacts models. They also note that the projected rainfall changes are difficult to distinguish from 'natural climate variability' in the simulations. This is because too few climate simulations were done with the two stabilisation scenarios to obtain adequate statistics on rainfall, which is highly variable. They also point to the need to consider changes in future population and socioeconomic conditions.

Despite these caveats, Arnell *et al.* (2002) conclude that, in general, mitigation as under the stabilisation scenarios delays or completely avoids some adverse impacts, but even stabilisation at 550 ppm of carbon dioxide involves some adverse impacts, so that adaptation to the projected changes will still be necessary.

It is significant that stabilisation of carbon dioxide concentrations takes place as late as 2170 in the S550 scenario, and at 2230 in the S750 scenario. This lies outside the time frame of up to 2100 considered by the IPCC before the TAR. The UNFCCC objective requires consideration of impacts at stabilisation so impact assessments are necessary on a multi-century timescale. Moreover, stabilisation of greenhouse gas concentrations does not lead to short-term stabilisation of climate: global average temperatures continue to warm, albeit more slowly, for centuries beyond the time of stabilisation of concentrations, and sea level continues to rise, almost unabated, for many centuries. Moreover, in certain regions, notably the southern mid-latitudes, climate changes will continue to evolve as the Southern Ocean continues to warm following its large time lag behind the change in the surface radiation balance. This changes the north-south temperature gradients in the Southern Hemisphere, with complex effects on local climates.

Meeting the formal requirements of the UNFCCC thus requires assessments that take account of effects well beyond 2100. This is also necessary to take account of issues of inter-generational equity and sustainability (Munasinghe, in Pachauri *et al.*, 2000). Moreover, with the possibility of large-scale discontinuities in the climate system, as discussed above, these longer-term effects may be very large and could even dominate the overall climate change risk equation.

High priority is therefore necessary for assessments of scenarios involving large climate changes, and at time scales well beyond 2100. How we are
to deal with the complex issue of changes in socioeconomic conditions on these long time scales, which will determine vulnerability, adaptive capacity, and technological capabilities, is a thorny question, as is the related question of what discount rate to apply in discussions of inter-generational equity on multi-century timescales (Metz *et al.*, 2001, section 7.2.5).

4

Potential impacts of climate change: Australia

4. Potential impacts of climate change: Australia

4.1 Water Supply and Hydrology

4.1.1 Introduction

The IPCC TAR noted that observed trends in streamflows were found in many regions of the globe, but some were increases and others decreases, with only low confidence that they were due to climate change. There was higher confidence that an observed seasonal shift toward more winter flows was due to higher temperatures and thus less snow storage, but this is not generally important in Australia where there is little snow storage.

As stated in Chapter 2, an increase in global-average precipitation is expected in the 21st century, but changes will not be globally uniform. Increases are anticipated over northern mid- to high latitudes and Antarctica in winter. At lower latitudes, models simulate both regional increases and decreases over land areas. The IPCC concluded that projected changes in streamflow largely follow regional precipitation changes, but this may be less applicable in Australia where runoff is a smaller fraction of rainfall than in most other places. In Australia, pre-existing soil moisture, vegetation and rainfall intensity may play larger roles.

Other IPCC conclusions were that water quality generally would be degraded by higher water temperatures; flood magnitudes and frequency are liable to increase; and low flow events are likely to be more extreme. The IPCC also noted that demand for water is likely to increase due to population growth and economic development, and due to increased evaporative losses in irrigation areas. According to the IPCC, climate change will increase uncertainty in water management, and places a premium on integrated management.

Vorosmarty *et al*. (2000) found that a large proportion of the world's population already is stressed by inadequate water supply, and that population growth generally will increase demand and outweigh the impacts of climate change. The applicability of this last generalisation to Australia is dubious, especially because of the high variability of Australian water supply and the projected increase in the extremes of flood and drought, which were not considered in the global study. Although the Vorosmarty *et al*. study only examined changes in mean annual flow, their conclusion remains valid that "an integrated approach bringing together climate change, water resources, and socioeconomic communities appears essential to future progress". Ecological concerns are also important, with growing interest worldwide in allocating water to preserve riverine and wetland ecological systems and environmental services (Naiman *et al*., 2002; Bunn and Arthington, 2002; Arthington and Pusey, 2003; and section 4.1.3).

The issue of climate change versus 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 seven billion people in 60 countries will be faced with water scarcity, at best 2 billion in 48 countries, depending on factors like population growth and policy-making. Climate change will account for*

an estimated 20% of this increase in global water scarcity … Water quality will worsen with rising pollution levels and water temperatures."

The importance of changes in seasonality and variability of flow is brought out in a number of overseas studies, notably that of Arnell (2003) for six catchments in the UK. Arnell concluded that "changes in mean seasonal runoff due to climate change alone are outside the likely range of natural multi-decadal variability" in many catchments by the 2050s. In northern upland catchments (where snow storage is important) the signal is strongest in winter, and in the southern lowland catchments it is strongest in summer. Arnell found that the effect of climate change is more apparent on low flows than on mean flows. The lowest 5% of flows were projected to decrease in magnitude in all catchments due to climate change, becoming apparent in many catchments by the 2020s.

Increases in extreme high rainfall and runoff events are also widely supported by recent overseas studies. Palmer and Ratsanen (2002) report "the probability of total boreal [Northern Hemisphere] winter precipitation exceeding two standard deviations above normal will increase by a factor of five over parts of the UK over the next 100 years", and "similar increases in probability for the Asian monsoon region in boreal summer, with implications for flooding in Bangladesh".

The Beniston (2002) volume from the Wengen Workshop on Global Change Research in 2000 concludes that "extreme events such as droughts and floods may well become the dominating effects of climate change on water resources." In the same volume Liu and Zheng (2002) report on the increased frequency since 1972 of the lower reaches of the Yellow River in northern China drying up. This is due mainly to increased upstream water withdrawals, but perhaps also in part to climate changes. Elsewhere, Guo *et al.* (2002) examine projected runoff in many parts of China, with varying results by region and depending on which climate model scenario is used. They conclude that climate change or its variability has important implications for the water resource system in China, adding to its uncertainty, and state that integrated water resources management will enhance the potential for adaptation to change.

The Beniston (2002) volume also contains a review of climate change and water resources in Australia, emphasising the management of uncertainty and risk (Jones and Pittock, 2002). Specific results are discussed in the next section.

Higher water temperatures and reduced stream flows will tend to adversely affect water quality. This has been demonstrated by Mimikou *et al.* (2000) for catchments in central Greece, where a transient and an equilibrium warming scenario both led to reduced mean monthly runoff in almost all months, especially in summer, and significant water quality impairment.

Irrigation demand will also increase in many areas due to higher temperature. This will be exacerbated in most mid-latitudinal continental regions by reductions in rainfall and increased incidence of drought. Doll (2002) performed a global analysis of the impact of climate change and variability on irrigation requirements using scenarios for the 2020s and 2070s generated by the ECHAM4/OPYC3 and the HadCM3 general circulation models. Doll found that two thirds of the global area equipped for irrigation in 1995 may face increased water requirements. On up to half of the total global area under irrigation the negative impact of climate change is more significant than that of natural climate variability by as early as the 2020s. However, the study found little change in irrigation demand in the Murray-Darling Basin by the 2020s, at least partly due to simulated earlier planting dates. The author states that the use of "simplistic modelling of the cropping pattern and growing seasons of only two crops (rice or non-rice), causes a high degree of uncertainty in the assessment …".

An example of growing competition for water resources in a developed country is provided by the conflict between the irrigation authority for the Imperial Valley in southern California, the Imperial Irrigation District, and the urban water authority for San Diego, the Metropolitan Water District of southern California (Huck, 2003; and relevant websites <http://www.mwd.dst.ca.us and http://www.iid.com>). Climate change and variability has reportedly played a part in this conflict, with earlier snowmelt in the Sierra Nevada and projections of increasing winter runoff and summer drought frequency (Kim *et al*., 2002).

The relevance of these international developments to the present guide is that they highlight the global nature of the water supply problem and the potential importance of climate change. This is enhanced in Australia by the specific nature of Australian catchments.

Australia has relatively high interannual and interdecadal rainfall variability, such that the storage capacities of Australia's large dams are about six times larger than those of European dams for the same mean annual streamflow and probability of water shortfall (Finlayson and McMahon, 1998). This, and the naturally low flows in most summers in the Murray-Darling Basin and other streams in southern mainland Australia, means that extensive irrigation is necessary for agriculture, outside the wetter coastal fringe, especially in dry years, with large evaporative losses from storages and open channels.

Adelaide and Perth traditionally have been regarded as the most vulnerable metropolitan areas to future water supply problems, including increasing levels of salinity (Schofield *et al.*, 1988; Williams, 1992; PMSEIC, 1998; MDBC, 1999), although Perth recently has decided to spend A$275 million for drought-proofing (Boer, 2000). Water supplies are generally considered adequate for many coastal regions in Australia. However, cumulative shortfalls in inflow to town and city water storages have led to water restrictions in many towns and cities across Australia in recent years, including Melbourne, Sydney and Canberra. Drier inland areas are vulnerable to water shortages during the annual dry season and drought.

Dry conditions in most parts of Australia tend to be associated with El Niño. The link between rainfall and streamflow and ENSO is statistically significant in most parts of eastern Australia (Chiew *et al.*, 1998; Power *et al.*, 1998; Chiew and McMahon, 2002). This has potential for seasonal forecasting of streamflow that may help in adaptation to climate change, but makes Australia vulnerable to any changes in the El Niño-La Niña pattern of variability.

The Murray-Darling River basin is the largest in Australia and is heavily regulated by dams and weirs. About 40% of mean annual flow is used for human purposes, principally through irrigation, and there is high interannual variability. Due to prolonged below-average inflows, the two major water storages, the Hume Reservoir and the Dartmouth Reservoir, were estimated to be at about 4% and 21% of capacity by April 2003, and there had been no net flow past the Barrages at the Murray River Mouth for over 15 months (MDBC, 2003). "New South Wales and Victorian irrigators have been experiencing seasonal allocations lower than in any previous season. South Australia is experiencing the longest period of being limited to Entitlement Flow, which is creating difficulties with low flow levels and high salinities in the lower lakes." Updates are available at <http://www.mdbc.gov.au/>.

A recent survey of the health of the Murray-Darling River Basin found that the overall biological and environmental condition of the River Murray and lower Darling River is degraded throughout those river systems, with increasing degradation toward the river mouth (Norris *et al.*, 2001). More broadly, the National Land and Water Resources Audit (2002) used an aquatic biota index and an environment index to assess 14,000 reaches of rivers across the more intensively used catchments. Further details are given in section 4.2.2, but it is sufficient here to note that significant problems were found, pointing to the need to maintain adequate environmental flows to ensure satisfactory water quality and healthy rivers.

4.1.2 Projections of water supply

The CSIRO (1996a) scenarios, with their wide range of rainfall changes, suggest a possible combination of small or larger decreases in mean annual rainfall, higher temperatures and evaporation. Applied to northern Victorian river systems, these scenarios point to a higher frequency of floods and droughts (Schreider *et al.*, 1996). A study of the Macquarie River basin in New South Wales indicates reductions of inflow into the Burrendong Dam of 10–30% by 2030 and reduced streamflows if irrigation demand remains constant or increases (Hassall and Associates *et al.*, 1998; Jones and Page, 2001).

Studies by Kothavala (1999) and Arnell (1999)—using results from the U.S. National Center for Atmospheric Research (NCAR) Community Climate Model (CCMO) GCM and the HadCM2 and HadCM3 models, respectively—show increases in drought across eastern and southern Australia. Kothavala found that the Palmer Drought Index showed longer and more severe drought in north-eastern and south-eastern Australia. Arnell (1999) found marked decreases in runoff over most of mainland Australia but some increases over Tasmania. For the Murray-Darling Basin, he found decreases in mean flow by the 2050s ranging from about 12 to 35%, with decreases in the magnitude of 10-year maximum and minimum monthly runoff.

More recent projections based on the CSIRO (2001) scenarios, with their wider range of global warmings (consistent with the SRES scenarios) and regional patterns derived from nine different global climate models, give slightly different results. In general they suggest less possibility of rainfall increases in the winter half year in southern mainland Australia than with the CSIRO (1996) scenarios.

Jones and Pittock (2002) used the CSIRO (2001) scenarios to develop a risk assessment approach. The major finding was that the models simulate decreases in winter-spring rainfall (June–November) over the southern half of the continent, while potential evaporation increases in all simulations. Changes in summer-autumn rainfall (December-May) are biased toward increases, especially in the north. Mean atmospheric water demand, measured as rainfall minus evaporation, becomes more negative in most models in most regions (see **Figure 2.15**). These changes suggest a longer and more intense Australian Monsoon (although reduced intensity is possible but less likely). This would lead to greater water surpluses in an area where human use is low. In southern mainland Australia, where winter rainfall is more important and competition for water between natural and human uses is already high, reductions in water supply appear to be much more likely. Tasmania is a possible exception, but it is another area of existing water surplus in most regions, although the State has a significant hydroelectric industry which could benefit from increased water supply.

The consequences of the CSIRO (2001) scenarios for the Macquarie catchment in New South Wales are described in Jones and Page (2001) and Jones and Pittock (2002). The Macquarie Marshes, downstream of the Burrendong Dam and extensive areas of irrigation, are an important nature reserve and Ramsar Convention site. Jones and Page (2001) performed repeated random sampling of the TAR ranges of projected global warming (see **Figure 2.3**), and of seasonal ranges of change in rainfall and potential evaporation from nine climate models. They calculated changes in inflow into the Burrendong Dam, in irrigation allocations under the present management rules, and in environmental flows into the Macquarie Marshes. They found that while the full range of possible changes in flow in 2030 was +10% to -30%, the most likely range (covering 90% of all possible outcomes) was approximately 0% to -15% (see **Figure 4.1**). In 2070, the full range was about +20% to -60% but the most likely range was 0% to -35% (all figures rounded to the closest 5%).

Critical thresholds, which mark the point at which an activity faces an unacceptable level of harm (Jones, 2001), were defined for bird breeding events in the Macquarie Marshes, and for irrigation allocations. The former was taken as ten successive years of inflows less than 350,000 million litres (350 GL), which would lead to no breeding event during a bird life-cycle, and the latter as when the allocations fall below 50% for five consecutive years, which might lead to economic failure for the farmer. Taking account of natural inter-decadal variability, both thresholds were found to be exceeded in 2030 by 20 to 30% in a drought-dominated climate, less than 1% in a normal climate, and much less than 1% in a flood-dominated climate. By 2070 these risks were found to be 70 to 80%, 35 to 50% and 10 to 20% respectively.

In a further development of the Macquarie Basin study, Herron *et al.* (2002) have examined the effects of climate change, inter-decadal variability and afforestation on water supply. Widespread afforestation has been suggested as a means of addressing prevalent problems of dryland and stream salinity, and as a potential means of sequestering carbon for mitigating climate change. For a 10% increase in tree cover in the headwaters of the Macquarie, they found a 17% reduction in inflows into the Burrendong Dam. A mid-case scenario of global warming by 2030 caused an additional 5% reduction in flow, while a reversion to a historically observed dry epoch of inter-decadal variability (1890 to 1948) would add another 20% reduction. Current water use in the basin is largely adapted to the wetter conditions of the post-1949 epoch.

Beare and Heaney (2002) examined changes in river flow and salinity levels (along with economic consequences) for two mid-range SRES scenarios (A1 mid, and B1 mid). They used a different methodology to that in the Macquarie Basin studies, with an emphasis on changes in vegetation affecting evapotranspiration. They found substantial reductions in flow under both scenarios. In the SRES A1 mid-range scenario, flow reductions across the whole Murray Darling Basin catchments were from 16 to 25% in 2050 and between 24 and 48% in 2100. Flow reductions were 4-6% less under the B1 mid-range scenario in 2050, and 8-18% less in 2100. Salt concentrations tended to increase in the tributary rivers above irrigation areas, as surface water runoff declines by a greater proportion than salt loads. Salinity increases in the Goulburn-Broken River system (Victoria) and the Gwydir River (New South Wales) were in the range 13 to19% by 2050 and 21 to 72% in 2100. Salinity levels below irrigation areas, on the other hand, were simulated to remain stable or fall due to reduced recharge of, and discharge from, saline aquifers. Beare and Heaney (2002) point out that lower water tables may have both benefits and costs to agriculture.

Chiew *et al.* (2002) used the CSIRO (1996) scenarios and a conceptual daily rainfall-runoff model for eight catchments distributed through different rainfall regions of Australia. They used a stochastic daily weather generator to translate changes in mean rainfall to daily rainfall. Results suggest that the annual runoff in catchments on the north-east and east coasts of Australia could change by -5 to +15% and -15 to +15% respectively by 2030, relative to 1990. The annual runoff in south-east Australia could decrease by up to 20%, whereas in Tasmania a -10 to +10% change is possible. The model simulates a decrease in the annual runoff in catchments in the South Australian Gulf of up to

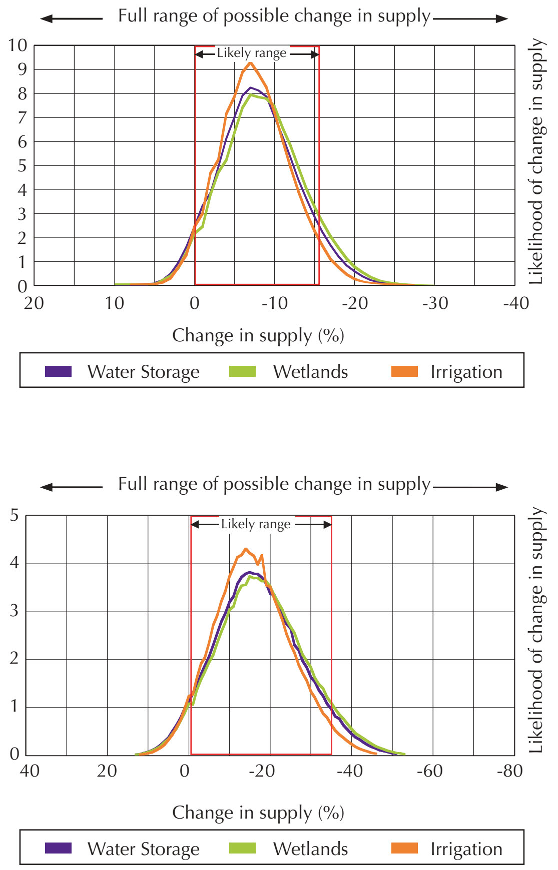


Figure 4.1.
Percent changes to water inflow into the Burrendong Dam, Macquarie River, New South Wales (purple curve), irrigation flow under present management rules (orange curve), and inflow to the Macquarie Marshes (green curve), for the TAR range of global warmings. Results for 2030 are shown in the upper panel, and for 2070 in the lower panel. The 'likely range' was obtained by cutting off the high and low 5% extremes of the range. Graph based on data in the Jones and Page (2001) paper (Roger Jones, CSIRO, personal communication 2003).

25% by 2030, and a change of -25 to +10% on the south-west coast of Australia.

In another study, Chiew *et al.* (2003) examine changes in rainfall and runoff in six small catchments around Australia, using an ensemble of five simulations generated by the CSIRO Mark 2 model and the SRES A2 scenario. This study took account of the changes in daily rainfall distributions generated by the GCM, rather than simply scaling historical daily rainfall by the change in mean rainfall. The results show a decrease in mean annual rainfall and runoff in eastern and south-west Australia, of 3 to 6% and 7% respectively, in 2021 to 2050 relative to 1961 to 1990, but an increase in the extreme daily rainfall. Changes in rainfall are amplified in runoff, with a bigger amplification in catchments with low runoff coefficients.

Evans and Schreider (2002) estimated mean flows and extreme high runoff events for three small catchments entering the Perth region, for a scenario of climate change generated by the CSIRO Mark 1 model. As this is a slab-ocean model (only 50 m deep), it is no longer considered reliable, but it is interesting that their results showed small decreases in mean runoff, and increases in rare flood events. This simulation used a stochastic daily weather generator tuned to the daily output from the model, and emphasises the importance of considering the change in the frequency distribution of daily rainfall. While the study focusses on flood runoff, the results suggest a possible need to manage water supply systems to cope with such large runoff events, which is not consistent with optimising storage for water supply purposes.

Another study (Maheepala and Perera, 2002) focussing on urban water supply looked at the climate change effect on the security of supply for the small Victorian city of Benalla (population about 9000). Using the CSIRO (2001) climate change scenarios, this study estimated that the mean annual flow in the river system was reduced by 12% in 2030, and the system yield reduced by 8%. However, as Benalla uses only a small fraction of the mean river flow, and its reservoirs hold a nine months supply of water, its security of supply was not significantly affected even in dry years. Taking interannual variability into account, however, river flow in dry years would be significantly affected, which would have more serious effects on environmental flows and downstream irrigation supply.

A more severe problem of urban water supply security exists for Perth, where mean rainfall declined dramatically in the 1970s (see section 2.2). An average rainfall decline of 10–20% caused a 40–50% decline in inflow to Perth's dams (Sadler, 2000; AATSE, 2002; IOCI, 2002) (see Figure 2.8) that has persisted since the 1970s. This is roughly what the first Australian scenario for enhanced greenhouse conditions suggested, with low confidence, might occur by 2030 (Pittock, 1988). The IOCI (2002) report summarises climate change simulations with the CSIRO Mark 2 model. Multiple simulations suggest annual rainfall decreases of about 10% by 2100, and soil moisture decreases of about 15%. A simulation with the CSIRO Mark 3 model results in similar estimates. None of these simulations shows significant decreases in the Perth region over the period 1970 to 2000, which is dominated by internal or 'natural' variability. Two overseas climate models that perform well in simulating the present climate over the south-west of Western Australia, the Hadley Centre model and the GFDL model, both simulate decreases in rainfall in the region by 2100, but only the Hadley Centre model shows a similar reduction to that observed, occurring in the years 2000 to 2025. If it is assumed that this is correct, except for an error in timing of about 25 years, then it is possible that the observed reduction in the 20th century may be partly due to the enhanced greenhouse effect. Work is continuing to try to understand the observed drying.

Gillett *et al.* (2003) found that the climate models may all have underestimated the impact of the enhanced greenhouse effect on surface pressure patterns, notably increasing pressures in the sub-tropics and decreasing pressures at high latitudes. If this is so it would help explain the discrepancy between the observed rainfall changes in the south-west of Western Australia and simulated change due to the enhanced greenhouse effect. This would further suggest the possibility of similar rainfall decreases in other locations in southern Australia where rainfall largely comes from low pressure systems embedded in the mid-latitude westerly airstream (see section 2.2.1).

Atolls and low-lying islands, including those in the Torres Strait, rely on rainwater or limited groundwater resources for water supplies. These resources are sensitive to climate variations and in some cases are already stressed by increasing and unsustainable demand in addition to pollution caused by human activity. Saltwater intrusion into aquifers might occur through sea level rise, more frequent storm events, possible reductions in rainfall, and increased water demand due to higher temperatures (see Basher *et al.*, 1998; McCarthy *et al.*, 2001, Chapter 17).

4.1.3 Water allocation and policy

Until recently, water planning in Australia was driven by demand and controlled by engineers, not by economics (Smith, 1998b) or ecological considerations. This situation has changed with growing population and demand (rural and urban/industrial), including rapid growth in irrigation of high-value crops such as cotton and vineyards. There also is an increasing awareness of stress on riverine ecosystems resulting from reduced mean flows, lower peak flows, and increasing salinity and algal blooms (Arthington and Pusey, 2003). Higher temperatures and changed precipitation due to climate change would generally exacerbate these problems and sharpen competition among water users (e.g., see Hassall and Associates *et al.*, 1998). In 1995, the Council of Australian Governments reviewed water resource policy in Australia and agreed to implement a strategic framework to achieve an efficient and sustainable water industry through processes to address water allocations, including provision of water for the environment and water-trading arrangements.

Bunn and Arthington (2002), in a review of the ecological principles of altered flow regimes for aquatic biodiversity, note that a major determinant of the biological condition of any river is its flow regime, but find that to date ecologists are still struggling to predict and quantify biotic responses to altered flow regimes. Arthington and Pusey (2003) arrive at some tentative answers to the question 'How much water does a river need?', which for some Queensland rivers is around 80-90% of the natural flow. Lower figures may apply in other river systems. Whatever the figure, it may be difficult to achieve in the face of other water uses; even without reduced flows due to climate change.

The Agriculture and Resource Management Council of Australia and New Zealand in 1996 adopted a set of National Principles for the Provision of Water for Ecosystems (ARMCANZ and ANZECC, 1996; Arthington and Pusey, 2003), with the following stated goal: "To sustain and where necessary restore ecological processes and biodiversity of water-dependent ecosystems." Implementation of water reforms and national principles has resulted in the definition of conceptual frameworks and practical methods for assessing the water requirements of environmental systems.

In Australia, flow recommendations are commonly developed after water infrastructure projects and dams have been in place for some time, and environmental flows are implemented in river systems that already are experiencing a modified or regulated flow regime (Arthington, 1998; Arthington *et al.*, 1998). This situation is most applicable to adaptation to climate change in existing regulated flow regimes.

The Australian National Principles require that provision of water for ecosystems should use the best scientific information available on the hydrological regimes necessary to sustain aquatic ecosystems. Ideally, environmental flow recommendations are based on establishment of quantitative relationships between flow characteristics and desired geomorphological, ecological, or water-quality outcomes. Methods are available to estimate flow-related habitat requirements of aquatic invertebrates, fish, and aquatic and riparian plants, including wetted perimeter, transect methods and in-stream flow incremental methodology (IFIM) (Bovee, 1982; Milhous *et al.*; 1989, Kinhill, 1988). There are, however, no standard methods for assessing flows that are relevant to the maintenance of key life history processes and ecosystem processes affecting river health. In the absence of robust biological indicators of response to flow regulation, recent research has advocated the use of statistical descriptors of flow regimes. These methods include maintenance of critical flow characteristics within one or two standard deviations of mean parameters (Richter *et al.*, 1996).

A recent further advance on methods for estimating the need for environmental flows has developed through greater understanding of the broader ecological requirements of aquatic biota and their physical/chemical habitats as a consequence of altered flow regimes. There are now several well-developed "holistic" methodologies (Arthington *et al.*, 1992, 1998; 2000; Brizga *et al.*, 2002; King and Tharme 1994; King and Louw, 1998; King *et al.*, 2003) that aim to address the water requirements of the entire riverine ecosystem rather than the needs of just a few taxa. They are underpinned by the "natural flows paradigm" (Richter *et al.*, 1996; Poff *et al.*, 1997) and basic principles of river corridor restoration (Ward *et al.*, 2001), and share a common objective. This is to maintain or partially restore important characteristics of the natural (or modelled unregulated) flow regime and its variability required to maintain or restore the biophysical components and ecological processes of in-stream and groundwater systems, floodplains and downstream receiving waters (e.g., terminal lakes and wetlands, or estuaries).

Within holistic ecosystem approaches, the particular methods, tools and models employed to define the flow requirements of specific ecosystem components vary as a function of the spatial scale of the study and the time and resources available to undertake it. Such methods may include wetted perimeter analysis, the physical habitat module of IFIM (e.g., Dunbar *et al.*, 1998; Gippel and Stewardson, 1998), and the Flow Events Method describing the statistical properties of flow components judged to be of geomorphological or ecological importance (Stewardson and Cottingham, 2002). Other methods include wetland and riparian water budget analysis (e.g., Pettit *et al.*, 2001), and the characterisation of flow pulses (see Junk *et al.*, 1989). The latter method is designed to mobilise sediments, maintain water quality and substrate composition, inundate channel benches, backwaters and floodplain terraces, provide cues that initiate biological events (e.g., fish migration, spawning, flowering and seed set) and drive ecological processes (energy flow, material exchanges between river channels, floodplains or the downstream estuary, see Loneragan and Bunn, 1999; Pusey 2002; Pusey *et al.*, 2000; Tharme and King, 1998; Bunn and Arthington, 2002).

Water reform policy has become a live topic in recent years, with vigorous discussion of increased water storages and diversions versus greater water use efficiency. There has been increasing introduction of economic water pricing and trading policies (to provide incentives to maximise the economic returns from water use) and caps on irrigation supplies (see, for example, ABARE, 1999; Cullen, 2002; Keyworth, 2002; National Competition Council, 2003; Young and McColl, 2003; Williams, 2003; Wentworth Group, 2002). Policy discussions so far have been conducted in the context of increasing demand and competition for water, but projected decreases in supply due to climate change have not yet been factored in.

Keyworth (2002) has reviewed current water management in the Murray Darling Basin and notes some results of water trading in the Victorian jurisdiction. Volumes traded have increased since 1994 to upwards of 700 GL, and prices for permanent transfers in 2002 were around A$900 to A$1000 per ML. Some 11 GL had been traded out of New South Wales and Victoria to South Australia, mainly for use in high-value viticulture industry development. In August 2003 the Council of Australian Governments agreed on the scope of a National Water Initiative. Key elements of the Initiative are: nationally compatible water access entitlements; nationally functioning water markets; integrated management of environmental water; measuring, monitoring and information; and urban water reform.

In the context of climate change, it is relevant to ask: How much will climate change add to the stresses which are driving the present policy debate? Finding answers to this question for a range of Australian rivers is central to the assessment and management of water allocations to sustain water-dependent systems. While climate change has yet to be systematically injected into the water policy debate, at least the impetus is already in place to develop the most appropriate water policies to adapt to changes in water supply and demand. A further consideration is whether water rights or allocations are quantified in absolute terms, which may become untenable if total water supply decreases, or whether rights are specified in terms of a fraction of available water.

4.1.4 Inland and coastal salinisation

Natural salinity and high water tables have been present in Australia for centuries. However, because of changes in land management—notably land clearing and irrigation—salinity is now a major environmental issue in Australia

(Ghassemi *et al*., 1995; MDBC, 1999; Cullen, 2002). About 2.5 Mha are affected in Australia, with the potential for this to increase to 12.5 Mha in the next 50 years (PMSEIC, 1999). Much of this area covers otherwise productive agricultural land. The area damaged by salinity to date represents about 4.5% of presently cultivated land, and known costs include A$130 million annually in lost agricultural production, A$100 million annually in damage to infrastructure (such as roads, fencing, and pipes), and at least A$40 million in lost environmental assets (Watson *et al*., 1997; PMSEIC, 1998). The average salinity of the lower Murray River (from which Adelaide draws much of its water supply) is expected to exceed the 800 EC threshold for desirable drinking water about 50% of the time by 2020.

Although climate is a key factor affecting the rate of salinisation and the severity of impacts, a comprehensive assessment of the effects of climate change on this problem has not yet been carried out. Revegetation policies and associated carbon credit motivational policies designed to increase carbon sinks are likely to have a significant impact on recharge and runoff (Herron *et al*., 2002). Global warming and dryland salinity policies need to be coordinated to maximise synergistic impacts.

In many coastal areas and oceanic islands, development and management of fresh groundwater resources are seriously constrained by the presence of seawater intrusion. Seawater intrusion is a natural phenomenon that occurs as a consequence of the density contrast between fresh and saline groundwater. If conditions remain unperturbed, the saline water body will remain stationary unless it moves under tidal influences. However, when there is pumping of freshwater, sea level change, or changing recharge conditions, the saline body will gradually move until a new equilibrium condition is achieved (Ghassemi *et al*., 1996). This will mitigate against increased reliance on groundwater from coastal aquifers in response to reductions in overland water supply. If the sea level rises to its "best-guess" or extreme predicted value over the next century, this would significantly increase intrusion of seawater into coastal and island aquifers.

4.1.5 Water quality

Water quality would be affected by changes in biota, particularly microfauna and flora; water temperature; carbon dioxide concentration; transport processes that place water, sediment, and chemicals in streams and aquifers; and the timing and volume of water flow. More intense rainfall events would increase fast runoff, soil erosion, and sediment loadings, and further deforestation and urbanisation would tend to increase runoff amounts and flood wave speed. These effects would increase the risk of flash flooding, sediment load, and pollution (Basher *et al*., 1998). On the other hand, increases in plantation and farm forestry—in part for carbon sequestration and greenhouse mitigation purposes—would tend to reduce soil erosion and sediment loads.

Eutrophication is a major water quality problem in Australia (State of the Environment, 2001, p.62). This is a natural process, but it has been greatly accelerated in Australia by human activities, including sewage effluent and runoff from animal farms, irrigation, and stormwater. Low flow, abundant light, clear water, and warmth all encourage algal growth, which affects the taste and odour of water and can be toxic to animals, fish, and humans. Thus, local climate warming and the potential for reduced streamflow may lead to increased risk of eutrophication.

4.2 Ecosystems and Conservation

4.2.1 Introduction

The subject of this section corresponds locally to that of the IPCC Technical Paper on "Climate Change and Biodiversity" (Gitay *et al*., 2002), which was based on earlier IPCC reports, and included new material published between 1999 and 2000. While the IPCC Technical Paper takes a global view, its summary conclusions are pertinent to the Australian situation. In summary, they are:

- At the global level, human activities of many sorts have caused and will continue to cause a loss of biodiversity.
- Changes in climate exert additional pressure and have already begun to affect biodiversity.
- Climate change is projected to affect all aspects of biodiversity, but in the context of other human activities and stresses, including increasing concentrations of carbon dioxide and land-use change.
- In general, human-induced climate change will cause many species to move polewards or to higher elevations, where that is possible.
- Changes in the frequency, intensity, extent and location of disturbances will affect whether, how and at what rate existing ecosystems will be replaced by new plant and animal assemblages.
- Globally, by the year 2080, about 20% of coastal wetlands could be lost due to sea level rise.
- For many species that are already vulnerable, the risk of extinctions will increase.
- Where significant ecosystem disruption occurs, there may be loss in net ecosystem productivity, at least in the transition to a new steady state.
- Changes in biodiversity in response to climate change and other pressures (e.g., land clearing and wild fires) would further affect global and regional climate.
- Modelling the changes in biodiversity in response to climate change presents significant challenges.
- Impacts of climate change mitigation activities (e.g., land-use change and biofuel production) on biodiversity depend on the context, design and implementation of such activities.
- Climate change adaptation activities can promote conservation and sustainability, and reduce the impacts of climate change on biodiversity. Adaptation will be more effective when integrated with broader strategies for sustainable development.

Until recent settlement, Australia was isolated for millions of years, and its ecosystems have evolved to cope with unique climate and biological circumstances (Kemp, 1981; Nix, 1981). Australia has a very limited altitude range and is bounded to the south by ocean, which limits the potential for migration of species. Despite large year-to-year climatic variability, many Australian terrestrial species have quite limited ranges of long-term average climate, of about 1 to 2 °C in temperature and 20% in rainfall (Hughes *et al.*, 1996; Pouliquen-Young and Newman, 1999; Hughes, 2003). Thus, 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.

Rapid land clearance and land-use change have been occurring as a result of human activity in Australia, subsequent to Aboriginal arrival tens of thousands of years ago, and especially since European settlers arrived a little over 200 years ago. This has led to loss of biodiversity in many ecosystems (Wilson, 2003). One of the major impacts has been an increase in weedy species and animal pests (Cheal and Coman, 2003); this is likely to continue, and to be exacerbated by climate change. Land-use change also has led to fragmentation of ecosystems (Bennett, 2003) and to salinisation through rising water tables (Cullen, 2002). These trends can inhibit natural adaptation to climate change via the dispersal/migration response. Some systems and species may therefore become more vulnerable, and some might become extinct. Such problems have been identified by Pouliquen-Young and Newman (1999) in relation to fragmented habitat for endangered species in the south-west of Western Australia, which suggests that survival of threatened species may require human intervention and relocation. In the highly diverse tropical rainforests of northern Queensland, Hilbert *et al.* (2001a) predict highland rainforest environments will decrease by 50% with only a 1 ºC increase in temperature.

Many of Australia's wetlands, riverine environments, and coastal and marine systems are also sensitive to climate variations and changes. A key issue is the effect on Australia's coral reefs of greenhouse-related stresses (Pittock, 1999; Hoegh-Guldberg, 1999) in addition to non-climatic features, such as overexploitation and increasing pollution and turbidity of coastal waters from sediment loading, fertilisers, pesticides, and herbicides (Larcombe *et al.*, 1996). An increase in temperature of 2 ºC will likely modify tropical near-shore communities from coral to algal dominated communities with major implications for reef biodiversity (Howden *et al.*, 2002).

Hughes (2003) presents a comprehensive review of climate change impacts on Australian ecosystems projected to result from climate change. She finds that climate change may have a significant impact on most vegetation types that have been modelled to date, although the generally positive effect of increases in atmospheric carbon dioxide has often not been included in models.

> *"Future impacts on particular ecosystems include increased forest growth, alterations in competitive regimes between C3 and C4 grasses, increasing encroachment of woody shrubs into arid and semi-arid rangelands, continued incursion of mangrove communities into freshwater wetlands, increasing frequency of coral bleaching, and establishment of woody species at increasingly higher elevations in the alpine zone. Modelling of potential impacts on specific Australian taxa using bioclimatic analysis programs such as BIOCLIM consistently predicts contraction and/or fragmentation of species' current ranges. The bioclimates of some species of plants and vertebrates are predicted to disappear entirely with as little as 0.5 to 1.0 ºC of warming."*

Regarding vegetation growth generally, Hughes (2003) notes that a range of different modelling methods has been used to investigate the potential impacts of temperature and rainfall change on Australian vegetation. Elevated carbon dioxide concentrations increase photosynthetic rates and water-use efficiency (Farquhar, 1997; Wullschleger *et al.*, 2002) and may affect the temperature response (Curtis, 1996 and 1998). For example, a modelling study by Rochefort and Woodward (1992) found that incorporating the effects of doubling CO_2 led to no change in Australian plant family diversity, in contrast to an earlier study with the same model that neglected carbon dioxide effects and arrived at a seriously negative impact. Results, however, will depend on the relative changes in temperature, rainfall and carbon dioxide concentrations, which vary from one scenario to another, and with location and time. Changes from increasing carbon dioxide will also be moderated by nutrient stress and other stress factors that are prevalent across Australian forests. Thus considerable uncertainty remains as to the magnitude of CO_2 fertilisation on this continent.

Biological invasions are a risk for many natural and production systems (Low, 1999; Cheal and Coman, 2003; <http://www.weeds.org.au/>). These may be exacerbated by climate change. Kriticos *et al.* (2003) have applied the CLIMEX modelling package, which enables users to predict the potential distribution of organisms primarily based on their present global distributions, to the invasive prickly *Acacia nilotica*. They found that this alien species, which has been declared a weed of national significance, has a potential distribution in Australia vastly greater than its present distribution. Further, it was found to have an increased potential range under projected climate change scenarios, especially with increased atmospheric carbon dioxide concentrations, which increase its water use efficiency. The shrubby vine *Crytostegia grandiflora* was also investigated, with similar results (Kriticos *et al.*, 2003).

Threshold effects and subsequent rapid changes in ecosystems (see Scheffer *et al.*, 2001, and section 2.1.4) are potentially important in Australian ecosystems (Bennett and Radford, 2003). Examples relevant to Australian ecosystems include eutrophication of lakes and estuaries, which is a nonlinear function of nutrient levels and temperature (Carpenter *et al.*, 1999), shifts in reef ecosystems (Done, 1991; McCook, 1999) and fire incidence in rangelands (Walker, 1993).

Disturbance of ecosystems by more or less random or stochastic events may push systems into a different state (Scheffer *et al.*, 2001; Attiwill and Wilson, 2003). Fire is one such disturbance that may increase in importance in Australia with climate change (see sections 2.3 and 4.3.4 below, and especially Cary, 2002).

The importance of ecosystem sustainability was highlighted by the Prime Minister's Science, Engineering and Innovation Council (PMSEIC), which on 31 May 2002 considered a paper prepared for it on the topic of "Sustaining our Natural Systems and Biodiversity" (PMSEIC, 2002). The paper emphasised the great value received by Australians from ecosystems services, such as "fresh air, clean water, nutrients for crop growth, and pollination of crops (amongst) other services". It then went on to say

"… shifting climatic patterns, and climate change itself, both expose Australia to greater risks of invasion by pests, weeds and diseases. Likewise, risks of dryland salinity are liable to be significantly altered by these influences. Moderate investment in analysing the capacity of Australia's natural and production systems to adapt to these changes could well return huge benefits in future."

4.2.2 Forests and woodlands

In Australia, some 50% of the forest cover in existence at the time of European settlement still remains, although about half of that has been logged (Graetz *et al.*, 1995; State of the Environment, 1996). Pressures on forests and woodlands as a whole are likely to decrease as a result of recent legislation relating to protection of forests in some Australian states, and as interest in carbon sequestration increases (Waterworth, 2001).

The present temperature range for 25% of Australian *Eucalyptus* trees is less than 1 °C in mean annual temperature (Hughes *et al.*, 1996). Similarly, 23% have ranges of mean annual rainfall of less than 20% variation. The actual climate tolerances of many species are wider than the climate envelope they currently occupy (due to effects of soil, competition and other factors) and may be affected by increasing carbon dioxide concentrations. Nevertheless, if present-day boundaries even approximately reflect actual thermal or rainfall tolerances, substantial changes in Australian native forests may be expected with climate change. Climate change-induced modifications to vegetation composition, structure and productivity will likely have flow on effects to other components of biodiversity through alterations in the quality and quantity of habitat available to vertebrate and invertebrate fauna. Howden and Gorman

(1999) suggest that adaptive responses would include monitoring of key indicators, flexibility in reserve allocation, increased reserve areas and reduced fragmentation.

Kirschbaum used the forest growth model CenW (Kirschbaum, 1999b) to simulate growth responses of a generic forest to doubling CO_2 and a warming of 3 ºC. The model predicted increases of 25-50% in growth for forests in southern Australia, and negative impacts in the north and some marginal inland areas, with growth reductions of more than 50% in many regions. Responses were generally inversely related to the degree of warming and were strongly sensitive to changes in rainfall. The same model predicted that net primary productivity of Australian forests would decline by about 6% for a scenario of doubled CO_2, +3 °C and -20% rainfall. Net Primary Productivity (NPP) was predicted to increase by about 21% under the same scenario if rainfall increased by 20% (Lucas and Kirschbaum, 1999). Further work is needed to expand the understanding of physiological and environmental determinants of yield parameters under climate change scenarios, and to ground-truth model predictions. A more detailed discussion of these issues is in section 4.3.4 Forestry.

Climate change and elevated levels of atmospheric carbon dioxide may have important impacts on the ecosystems and biodiversity in the rainforests of northern Australia. For example, the extent of highland rainforest environments may decrease by 50% with a 1 ºC temperature increase (Hilbert *et al*., 2001a). Lowland rainforest environments, however, are expected to increase (Hilbert *et al.*, 2001a). Modelling suggests that many of the region's endemic vertebrates, which mostly occur in the uplands, will experience habitat fragmentation and eventually lose all climatically suitable habitat. For example, the golden bowerbird loses 63% of its current habitat with 1 °C of warming and only 2% of its habitat remains after 3 °C of warming (Hilbert *et al.* 2003). Habitat for fauna using the drier parts of the landscape may be more affected by changes in rainfall. Modelling indicates that habitat for the endangered northern bettong would decline in the tropical north if climate warming is accompanied by greater precipitation (Hilbert *et al.*, 2001b). Conversely, available habitat for this marsupial may increase if rainfall decreases with warming (Hilbert *et al*., 2001b). The effects of elevated carbon dioxide in conjunction with warming are largely unknown but Kanowski (2001) suggests that populations of native folivores (leaf-eaters) may decline in abundance due to changes in foliage chemistry and composition that accompany increased atmospheric carbon dioxide. Analyses of long-term permanent forest plots suggest that tree mortality rates increase and that the stocks of biomass and carbon in rainforests decrease with increased temperature (D. Hilbert, personal communication 2003).

Montane cloud forests, which gain at least part of their moisture budget from orographic cloud banks, are rare in Australia, but do occur on Norfolk Island and in parts of Queensland. It has been proposed (Still *et al.*, 1999) that the base of orographic cloud banks may rise due to global warming, thus affecting the viability of associated forests and ecosystems (Pounds *et al.*, 1999). Evidence for global warming as the cause has been contested by Lawton *et al.* (2001) who propose that land-clearing may explain observed changes in orographic cloud in Costa Rica. The issue is as yet unresolved in the Australian context.

Likely increases in fire frequency and intensity are another potentially important consideration for Australia's forests, and the scenarios are discussed in section 2.3.2. Bushfires in Australia are important, not only as causes of damage to life and property, but also as modifiers of natural and managed ecosystems, including native and commercial forests, wildlife, soil erosion, and water quality (Bradstock *et al.*, 2002). This is also true in many other countries, particularly those with Mediterranean-type climates like southern France, and others with marked warm and dry seasons, including parts of the United States, Canada and China. Increased fire frequency is also noticeable in rainforests across the tropics. This is often the result of land clearing and fragmentation of forest edges and fire is episodically more severe during El Niño events. (Cochrane, 2003). The frequency and intensity of forest fires will also be a determinant of the rate of change in the composition of forest ecosystems (including wildlife) in the face of climate change (Mackey *et al.*, 2002), and of the survival of above-ground carbon sinks in forest biomass. Fire is thus relevant not only to the impacts of climate change, but also to the carbon cycle and mitigation policies that involve carbon sequestration in forests (Meyer *et al.*, 2001; Spessa *et al.*, 2003).

4.2.3 Rangelands

Rangelands are important for meat and wool production in Australia. In their natural state, rangelands are adapted to relatively large short-term variations in climatic conditions (mainly rainfall and temperature). However, they are also under stress from human activity, mostly as a result of animal production, introduced animals such as rabbits, inappropriate management, and interactions between all of these factors (Abel *et al.*, 2000). These stresses, in combination with climatic factors, have led to the problems of land degradation, salinisation, woody weed invasion and subsequent decreases in food production. In some cases, native dominant species (mostly plants) have been replaced by exotic species, leading to a decrease in population of many native animal species (Cheal and Coman, 2003). Woody weed invasion has also changed the fire regime in some areas through the formation of "thickets" that do not carry fires, partly as a result of the fire resistance of some species (Noble *et al.*, 1996). Some Australian rangelands are also vulnerable to salinisation resulting from rising water tables associated with irrigation and loss of native vegetation (see section 4.1).

According to the review by Hughes (2003), 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). Sensitivity studies by Hall *et al.* (1998) have indicated that a doubling of carbon dioxide may reduce the potentially negative effects of a combined higher temperature/ reduced rainfall scenario on the carrying capacity of rangelands. Simulations by Howden *et al.* (1999b, d) for native pastures showed that the beneficial effects of doubling CO_2 are relatively stronger in dry years, but that nitrogen limitations may reduce the potential benefits. Positive effects of carbon dioxide are predicted to balance a 10% reduction in rainfall but greater rainfall decreases would result in reduced productivity (Howden *et al.*, 1999b,c,d). Some limited changes in the distributions of C3 and C4 grasses are also suggested (Howden *et al.*, 1999b,c,d), although this will be moderated by any temperature change. Any increase in pasture growth, especially after high rainfall events, is likely to increase burning opportunities that in turn will affect carbon stores and future greenhouse gas emissions (Griffin and Friedel, 1985; Howden *et al.*, 1999e).

Heavy rainfall events may be larger and more frequent with a large reduction in the return period of 100-year events and longer dry spells (Stafford Smith *et al.*, 1994). Runoff and groundwater recharge may increase (Krysanova *et al.*, 1999). This would intensify vegetation patterning and erosion cell mosaic structure in degraded areas (Stafford Smith and Pickup, 1990) and there may also be an increase in dryland salinity. Major changes in vegetation composition will come through shifts in rainfall patterns and increased runoff distribution and will favour establishment of woody vegetation and encroachment of unpalatable woody shrubs in many areas.

4.2.4 Alpine systems

Basher *et al.* (1998) conclude that alpine systems in Australia are particularly susceptible to climate change. Despite the fact that they cover only a small area, they are important for many plant and animal species, many of which are listed as threatened. These systems are also under pressure from tourism activities. The Australian Alps have a relatively low altitude (maximum about 2,000 m), and much of the Alpine ecosystem area and ski fields are marginal. Most year-to-year variability is related to large fluctuations in precipitation, but interannual temperature variations are small compared to warming anticipated in the 21st century. Studies by Hewitt (1994), Whetton *et al.* (1996b) and Whetton (1998) all point to a high degree of sensitivity of seasonal snow cover duration and depth. For Australia, Whetton (1998) estimates, for the full range of CSIRO (1996a) scenarios, an 18-66% reduction in the total area of snow cover by 2030 and a 39-96% reduction by 2070. This would seriously affect the range of particular alpine ecosystems and species (Bennett *et al.*, 1991). Decreases in precipitation and increased fire danger would also adversely affect alpine ecosystems.

Pickering and Hill (2003) had a preliminary look at the effect of snow manipulations, including snow making, snow grooming, snow harvesting and snow fences, on the ecology of the Australian Alps, particularly changes to runoff, erosion processes, and the composition and distribution of native flora. They recommend further research in this area in the light of the region’s high conservation value.

According to the review by Hughes (2003), the distribution of high mountain vegetation in Australia is related primarily to summer temperatures, as in other alpine, arctic and subantarctic regions of the world. Tree growth is limited to areas where the mean temperature of the warmest month is 10 ºC or greater. Elevated summer temperatures may not only increase the growth rates of extant shrubs but promote expansion of woody vegetation into areas currently dominated by herbaceous species (Williams and Costin, 1994).

The future importance of snow cover for populations of alpine vertebrates can be gauged from the response of species to years with shallow cover (Green and Pickering, 2002). In such years there is evidence for a reduction in populations of dusky antechinus, broad-toothed rats and the mountain pygmy possum. The first two species are active under the snow throughout winter (Green, 1998) and are therefore subject to increased predation by foxes when snow cover is reduced (Green and Osborne, 1981). The pygmy possum depends on snow cover for stable low temperatures for hibernation (Walter and Broome, 1998).

There seems to be little opportunity for adaptation by alpine ecosystems in Australia, as they cannot retreat upward very far because of the limited height of Australian hills and mountains. There are various options for the rapidly expanding mountain-based recreation industry, including increased summer recreation and artificial snowmaking (see section 4.4.5). These adaptations would, however, increase stress on alpine ecosystems and water resources and need careful assessment.

4.2.5 Wetlands

The State of the Environment Report (1996) states, "Wetlands continue to be under threat, and large numbers are already destroyed." For example, Johnson *et al*. (1999) estimate wetland loss of about 70% in the Herbert River catchment of Northern Queensland between 1943 and 1996. In the Murray-Darling Basin, the quality of wetlands has been significantly reduced, particularly between the Hume Dam and Mildura (Norris *et al.*, 2001). Hydrological condition in the river channel is poor for all areas, with the extent, timing and duration of floodplain inundation all significantly affected.

Wetland loss is caused by many processes, including water storage; hydroelectric and irrigation schemes; dams, weirs, and river management works (Kingsford, 2000); desnagging and channelisation; changes to flow, water level, and thermal regimes; removal of in-stream cover; increased siltation; toxic pollution and destruction of nursery and spawning or breeding areas (Jackson, 1997); and use of wetlands for agriculture (Johnson *et al.*, 1999). Climate change will add to these factors through changes in inflow, increased water losses, and changes to soil and bank erosion rates due to increases in drought and heavy rainfall events (see sections 2.1.4 and 4.3.6).

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 in northern Australia. 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). Projected impacts for Kakadu raise the possibility that many other Australian coastal wetlands could be similarly affected. Some of these wetlands may be unable to migrate upstream because of physical barriers in the landscape.

Sea level rise has also been considered in the case of the Gippsland Lakes (Gippsland Coastal Board, 2002). This is discussed in more detail in section 4.4.5 below. The main considerations in such estuarine situations are shoreline erosion, made worse by dieback of some reeds and other shoreline plants due to increased salinity, and of course increased salinity of the waters with significant effects on the biota. Increased water turbidity and riverine sand transport, due to possible increases in soil erosion and flood outflows, may also affect the biology of the lakes. In the case of the Gippsland Lakes, sea level rise will probably increase the total area of wetlands. Algal blooms may also become an increasing problem due to higher temperatures and increased nutrient runoff which will affect other wetland biota as well as human health and amenity.

Many inland wetlands are subject to reduced frequency of filling due to water diversion for irrigation (Kingsford, 2000), and they may be seriously affected by reductions in seasonal or annual rainfalls in the catchments due to climate change (Hassall and Associates *et al.*, 1998; Roshier *et al.*, 2001). This may threaten the reproduction of migratory birds (of which some species already are under threat), which rely on wetland habitat for breeding (Kingsford and Thomas, 1995; Kingsford and Johnson, 1998; Kingsford *et al.*, 1999; Roshier *et al.*, 2001).

In particular, large decreases in average inflow due to climate change projected for the Macquarie River and several rivers in northern Victoria by Hassall and Associates *et al.* (1998) and Schreider *et al.* (1996, 1997) would have major impacts on wetland ecosystems.
The situation of the Macquarie Marshes has been studied more recently by Jones and Page (2001). The results are discussed in section 4.1.2, and presented in **Figure 4.1.**

A review by Lake *et al.* (2000) of global change effects on the biodiversity of freshwater ecosystems focusses on the linkages between above-sediment and sediment biota. They note that climate change will lead not only to warmer water, but also to changes in catchment inputs of detritus and nutrients, and in the frequency and intensity of droughts and floods. Climate change will alter riparian vegetation and thus eventually sediment composition. This will include increase in carbon:nitrogen and lignin:nitrogen ratios, which in turn will slow down the decomposition of detritus. Warmer water will affect fish populations, and thus impact on bottom-dwelling invertebrates in streams, lakes and wetlands. More severe droughts would reduce habitats and intensify predation by fish.

In another review of the effects of a changing environment on lake biodiversity Lodge (2001) places climate change impacts fourth behind land use change, exotic species and harvesting, with little direct effects of increased carbon dioxide concentrations on lake biodiversity. While Lodge does not use Australian lakes as examples, the overall message is that climate change effects must be considered in the context of other environmental stresses on lakes and wetlands. In the case of Australian wetlands these other stresses are severe, and climate change could in some cases push the situation across critical thresholds.

4.2.6 Riverine environments

Many Australian river systems, particularly in the south-east and south-west, have been degraded through diversion of water via dams, barrages and channels principally for irrigated agriculture. The National Land and Water Resources Audit (2002) concluded, after assessing about 14,000 reaches of the more intensively used catchments, that:

- one third of the river length has impaired aquatic biota
- over 80% of the reaches are affected by catchment disturbance
- nutrients and suspended sediment loads are higher than is natural in over 90% of reaches, with 33% classified as substantially modified.

The nature of the Murray-Darling Basin as an ecological system is described by MDBC (2001). Its condition is described in a report, *Snapshot of the Murray-Darling Basin River Condition* (Norris *et al.*, 2001), which found that overall the river system is degraded, with worsening conditions toward the Murray mouth.
Fish populations are in very poor condition throughout the Murray, but slightly better in the lower Darling. Macro-invertebrate communities are generally in poor condition and declining toward the lower reaches. Riparian vegetation along the entire river system was assessed as poor, with grazing and alterations to the flow regime being the major causes.

As discussed in section 4.1.3, restoration of environmental flow has now been recognised as necessary to restore ecological processes and biodiversity in water dependent ecosystems (Arthington and Pusey, 2003). Bunn and Arthington (2002) state that the flow regime is the key driver of river and floodplain wetlands ecosystems. They recognise four key principles related to impacts of flow regime on aquatic biodiversity:

- Flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition.
- Aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes.
- Maintenance of natural patterns of connectivity is essential to the viability of populations of many riverine species.
- The invasion by and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes.

If these principles are true of flow regimes altered by water use for irrigation and other purposes, they must also be true of altered flow regimes due to climatic change.

Recent research has shown that river ecosystems are particularly sensitive to extremes in flow. Most research has been on the effects of flood flows. Droughts, as opposed to floods, have a slow onset and although recovery from floods by river flora and fauna is relatively rapid, recovery after drought tends to be slow, may be incomplete, and may lag well behind the breaking of the drought (Lake, 2000). Recovery after a drought is largely determined by the existence of refugia in the form of deep pools, especially if these are relatively unaffected by algal blooms. This is enhanced by retaining snags in rivers, and threatened by sand slugs created by soil erosion (see section 4.2.9 below). Increased drought frequency is a probable consequence of climate change (see section 2.1.4) and will have serious implications for inland riverine environments and wetland systems (Walsh *et al.*, 2000). Floods and droughts interact with nutrient supply (Hildrew and Townsend, 1987; Biggs, 1996), so the effects of any possible changes in their frequency and magnitude need to be evaluated within the context of other human activities and climate-induced land-use change.

Current ranges of scenarios tend to suggest reductions in mean flow in many rivers in south-eastern Australia. This is discussed above in section 4.1.2. Drought is expected to increase in intensity and frequency, and is discussed in section 4.3.6 below.

Poff *et al.* (2001) review effects of global change on fish diversity in streams and rivers. They note the need for refugia, and the advantage for species survival of large catchments spanning many different climates. They illustrate this using data on the current number of species in Australian rivers, where there is a strong tendency for more species diversity in large catchments. They argue that more arid conditions, as projected for some large river basins in Australia, are akin to reducing the catchment size. They suggest that hydrological variability (projected to increase with climate change) may also mitigate against species diversity.

Implications of these findings for riverine ecosystems and estuaries (Vance *et al.*, 1998; Loneragan and Bunn, 1999) and possible adaptations have yet to be investigated in detail, although reduced diversions from rivers, in order to increase environmental flows, is one possibility. This could be achieved through increased water use efficiency, imposition of caps on water diversions, or water pricing and trading, but the latter two measures are controversial and would have strong implications for rural industry (e.g., see ABARE, 1999). Increased efficiency in water delivery for irrigation is currently the favoured option for restoring environmental flows in the heavily depleted Snowy River system in south-eastern Australia and other riverine environments.

4.2.7 Coastal and marine systems

Australia has some of the finest and most extensive coral reefs in the world. These reef systems stretch for two thousand kilometres along the north-east coast. Others exist off-shore of the Kimberley coast and further south at the Monte Bello and Dampier Islands. Coral reefs in the Australian region are subject to greenhouse-related stresses including increasingly frequent bleaching episodes, changes in sea level, and probable decreases in calcification rates as a result of changes in ocean chemistry (Kleypas *et al.*, 1999; Wilkinson, 2002b; Sweatman *et al.*, 2002).

Mass bleaching has occurred on several occasions in Australia's Great Barrier Reef (GBR) and elsewhere since the 1970s (Glynn, 1993; Hoegh-Guldberg *et al.*, 1997; Jones *et al.*, 1997; Wilkinson, 2002a) – see **Figure 4.2** below. Particularly widespread bleaching, leading to the death of some corals, occurred globally in 1997–98 in association with a major El Niño event, and again in 2002. Bleaching was severe on the inner GBR but less severe on the outer reef in 1997–98 (Wilkinson, 2002b; Berkelmans and Oliver, 1999). This episode was associated with generally record-high sea surface temperatures (SSTs) over most of the GBR region. This was a result of global warming trends resulting from the enhanced greenhouse effect and regional summer warming from the El Niño event, the combined effects of which caused SSTs to exceed bleaching thresholds (Lough, 1999, 2000). Three independent databases support the view that 1997–98 SST anomalies were the most extreme in the past 95 years and that average SSTs off the north-east coast of Australia have significantly increased from 1903 to 1994. Lowered seawater salinity as a result of flooding of major rivers between Ayr and Cooktown early in 1998 is also believed to have been a major factor in exacerbating the effects in the inshore GBR (Berkelmans and Oliver, 1999). Solar radiation, which is affected by changes in cloud cover and thus by El Niño, may also have been a factor (Brown, 1997; Berkelmans and Oliver, 1999).

Off Western Australia, the Ashmore and Cartier Reefs, Scott and Seringapatam Reefs and Rowley Shoals all showed coral bleaching in 1998, some down to 30 metres depth. Scott and Seringapatam Reefs suffered reductions in hard coral cover from 41% before the event to 15% after, and these reefs have shown only slow recovery. There has been almost a complete failure of coral recruitment at Scott Reef since 1998 and recovery could take decades or longer, provided there are no repeats of major bleaching events (Wilkinson, 2002b). The Cocos (Keeling) Island reefs escaped bleaching in 1998, but were affected in 1996. Many reefs in the Dampier Archipelago and Monte Bello Islands were affected by bleaching in 1998.

The 2002 bleaching event in the Great Barrier Reef affected 60% of all reefs, with some inshore reefs suffering up to 90% coral death. This event was due to a widespread temperature anomaly, with reefs in a 500,000 square km area affected. Localised cooler patches showed no damage from bleaching, but in the warmest patches there was significant bleaching, although some species of coral seemed more heat tolerant (Done *et al.*, 2003a; Sweatman *et al.*, 2002). See also Woods (2002) and Liu *et al.* (2003).

Although average warming in Australia's coral reef regions is expected to be slightly less than the global average, according to the SRES global warming scenarios it may be in the range of 2-5°C by 2100. This suggests that unless Australian coral reefs can adapt quickly to these higher temperatures, they will experience temperatures above present bleaching thresholds (Berkelmans and Willis, 1999) almost every year well before the end of the 21st century (Hoegh-Guldberg, 1999). Hoegh-Guldberg (1999) notes that apparent thresholds for coral bleaching are higher in the northern GBR than further south, suggesting that some very long-term adaptation has occurred. Coral reef biota may be able to adapt, at least initially, by selection for the more heat-tolerant host and symbiont species and genotypes that survived the 1997-98 summer, and by colonisation of damaged sites by more heat-resistant genotypes from higher latitudes arriving as planktonic larvae (Baker, 2001). However, it is generally believed that the rate and extent of adaptation will be much slower than would be necessary for reef biota to resist the frequency and severity of high SST anomalies projected for the middle third of the 21st century (Hoegh-Guldberg *et al.*, 2002; Dennis, 2002). The most likely outlook is that mass bleaching, leading to death of corals, will become a more frequent event on Australian coral reefs in coming decades (Done *et al.*, 2003b).

Done *et al.* (2003b) modelled the effects of two climate change scenarios, based on high and low warming trajectories from the SRES A1 scenarios. They simulated the effects on the reef's biodiversity, ecology and appearance, based on plausible assumptions on the relationships between increasing heat stress and impacts. Both scenarios suggested lowered rates of progression of the reefs, although the in-shore reefs fared better, perhaps due to greater acclimatisation to warmer waters. They described various levels of bleaching impacts from sub-lethal, with virtually zero setbacks in appearance and ecology, to catastrophic, with a 10-year setback to reef appearance and a 50-year setback to reef ecology. They studied one coastal reef (Magnetic Island), one offshore reef (Myrmidon Reef) and one mid-shelf reef (Davies Reef). All three reefs show a substantial chance of setbacks from bleaching within coming decades. At Davies Reef, the low climate change scenario bought about two decades for appearance relative to the high warming scenario, but only a few years for ecology. Until 2030, the major ecological changes were masked by maintenance of high coral cover, but by 2050, appearance too was projected to be greatly set back. Even at Magnetic Island, which was found to be least affected, both the appearance and ecology were substantially setback by 2050. The authors pointed out that improved water quality should enhance the resilience of the reef systems, i.e., the ability to recover following disturbances.

Increasing atmospheric carbon dioxide concentrations will decrease the carbonate concentration of the ocean, thereby reducing calcification rates of corals (Gattuso *et al.*, 1998, 1999; Kleypas *et al.*, 1999; LeClerq *et al.*, 2002). This is complicated, however, by the effects of possible changes in light levels, freshwater discharge, current patterns and temperature. For example, Lough and Barnes (2000) report a historic growth stimulus for the Porites coral that they correlate with increasing average SSTs. Thus, the net effect on Australian reefs up to 1980 appears to have been positive, but it is unclear whether decreased carbonate concentration resulting from rapidly increasing carbon dioxide concentration will outweigh the direct temperature effect later in the 21st century, especially if regional SSTs reach levels not experienced by the corals of the GBR during the Holocene.

As noted in McCarthy *et al.* (2001, chapter 6) expected rates of sea level rise to 2100 would not threaten healthy coral reefs (as most Australian reefs are), although it might favour the faster growing corals, and indeed could invigorate growth on reef flats. However, decreased calcification rates might reduce the potential ability of the reefs to keep up with rapid sea level rise. Likely increases in tropical cyclone intensity with global warming would also impact coral reefs, along with nonclimatic factors such as overexploitation and increasing pollution and turbidity of coastal waters by sediment loading, fertilisers, pesticides and herbicides (Larcombe *et al.*, 1996). Climate change could affect riverine runoff and associated stresses on the reefs, including

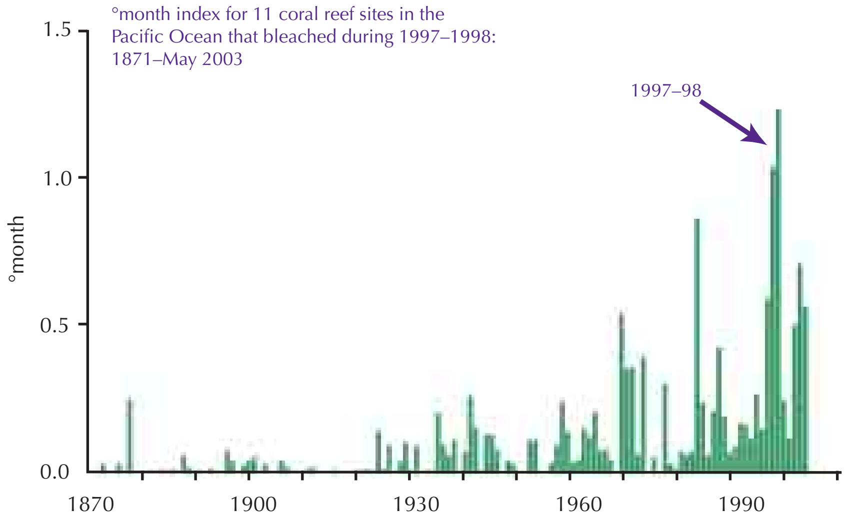


Figure 4.2.
Coral bleaching records showing the large number of events recorded in 1998. From Lough (2000), with permission.

low-salinity episodes. Coupled with predicted rises in sea level and storminess, bleaching-induced coral death could also weaken the effectiveness of the reefs in protecting the Queensland coast and adversely affect the biodiversity of the reef complex.

In October 2002 a group of 15 world-leading researchers on coral reefs met in Townsville to assess threats to coral reefs and a prognosis for the future. They issued a public declaration which listed the three main threats to coral reefs as overfishing, pollution, and climate change. In their statement they said that the first two threats are understood, while the third presents scientists and managers with a huge challenge to integrate knowledge and expertise and offer effective management solutions to deal with this threat (Pockley, 2003). They stated "Coral reefs are global canaries, as they are showing rapid responses to climate change at the global scale. Scientists, managers and policy makers can use reefs to examine the effectiveness of international attempts to understand and respond to the impact of global warming."

Australia has more than 1000 estuaries, which support fisheries, aquaculture, ports and recreational activities. The National Land and Water Resources Audit (2002) assessed 979 estuaries and coastal waterways, and found that 28% were in a modified or extensively modified condition. Nearly one third were classified as wave-dominated, mainly in the southern temperate regions, and some 55% as tide-dominated, mainly in the northern tropical regions. These will be affected differently by mean sea level rise, storm surges and changes in wave energy. Mangroves occur mainly along the tide-dominated coasts and estuaries.

On the whole, mangrove processes are less understood than those for coral reefs (Ellison, 1996). Mangroves occur on low-energy, sedimentary shorelines, generally between mean- and high-tide levels. Australian mangroves cover approximately 11,500 square km (Galloway, 1982). It is anticipated that they are highly vulnerable but also highly adaptable to climate change. Studies over glacial/interglacial cycles show that in the past mangroves have moved landward during periods of rising sea level (Woodroffe, 1993; Wolanski and Chappell, 1996; Mulrennan and Woodroffe, 1998). However, in many locations this will be inhibited now by coastal development.

Tidal range, salinity, sedimentology, community composition and topography will all affect the fate of mangroves (Semeniuk, 1994). On many macro-tidal coasts such as the north-west of Western Australia erosion occurs naturally at rates similar to that which might result from projected sea level rise, and mangroves are migrating landwards over gentle slopes. However, in other micro-tidal coasts, especially if there is a steep shoreline, a sea level rise of the order projected by 2100 may well inundate the existing mangroves (Semeniuk, 1994).

Mangroves, like other plants, may benefit from higher concentrations of carbon dioxide in the atmosphere, although experimental studies (Ball *et al.*, 1997) suggest that such benefits may only occur where the mangroves are not limited by high salinity or humidity.

Coastal wetlands are nursery areas for many commercially important fish (e.g., barramundi), prawns, and mudcrabs, so wetland survival has wider significance for fisheries and biodiversity. Possible effects on some estuarine wetlands are discussed in section 4.2.5.

Over a long period, warming of the sea surface is expected (on average) to be associated with shoaling (thinning) of the mixing layer, lowering of phytoplankton growth-limiting dissolved inorganic nutrients in surface waters (Harris *et al.*, 1987; Hadfield and Sharples, 1996), and biasing of the ecosystem toward microbial processes and lowered downward flux of organic carbon (Bradford-Grieve *et al.*, 1999). However, this would be modified regionally by any change in the Pacific Ocean to a more El Niño-like mean state. Warming may also lead to decreased storage of carbon in coastal ecosystems (Alongi *et al.*, 1998).

South of the subtropical front, primary production is limited by iron availability (Boyd *et al.*, 1999), which has varied in the past. It is not certain how or whether aeolian (wind-borne) iron supply to the Southern Ocean in the south-west Pacific (Duce and Tindale, 1991) may be altered by climate change. However, it could be affected by changes in aridity and thus vegetation cover over Australia as well as by strengthening of the westerlies, which may increase the frequency and intensity of wind erosion (see section 4.2.9 below). In any case, Harris *et al.* (1988) demonstrate that the strength of the westerly winds is linked to recruitment of stocks of spiny lobsters over a wide area. Other possible effects on fish are discussed in section 4.3.5 below.

If reduction or cessation of North Atlantic or Antarctic bottom-water formation were to occur (Manabe and Stouffer, 1994; Hirst, 1999), this could lead to significant changes in deep ocean chemistry and dynamics, with wide ramifications for marine life. Reductions in oxygen concentrations in the deep ocean could affect some fish species (see Matear and Hirst, 1999 and 2003, and section 2.1.4). The common Southern Hemisphere copepod *Neocalanus tonsus* could be affected because it spends part of the year at depths between 500 and 1,300 m but migrates seasonally to surface waters, becoming the prey of animals such as sei whales and birds (Bradford-Grieve and Jillett, 1998).

4.2.8 Flora and fauna

The above sections of chapter 4.2 have included discussions of some flora and fauna species that are largely associated with particular habitats. Other studies of impacts on flora and fauna overlap the above sections, and are discussed below.

Reynolds (2002) has presented a partisan view of the impact of climate change on nature in Australia, entitled *Warnings from the Bush*. However, Reynolds's claims are generally supported by the more objective scientific review of Hughes (2003) and the primary scientific literature.

Projections of habitats suitable for particular species under a changed climate are commonly made with computer programs such as BIOCLIM (Busby, 1991) and CLIMEX (Sutherst *et al.*, 1998). These have limitations, especially when not combined with soil and other overlays to account for other non-climatic influences. They are also sensitive to missing data on present distributions, competition between species, and assume some degree of equilibrium with the climate. Nevertheless, carefully applied, they can be strong indicators of potential changes in plant and animal distributions.

Several studies in Australia over the last decade have looked at the effect of climate change on the distributions of various plants and animals. Brereton *et al.* (1995) found that of 42 vertebrate species examined, most with threatened status, 41 had their range reduced and 15 were projected to lose range completely for a 3 ºC warming under a 'most likely' rainfall scenario. The mountain pygmy possum *Burramys parvus* lost its climatic habitat with a 1 ºC warming. Dexter *et al.* (1995) looked at 58 threatened species of vertebrates, and found that over 80% suffered a contraction of core climatic habitat under the scenarios used. Chapman and Milne (1998) studied the ranges of a number of plants and animals, some not under threat at present, using bioclimatic modelling with vegetation and soil types considered. Some species showed large reductions in range but others were either unaffected or gained a little in distribution. Studies by Hilbert *et al.* (2001b) and Hilbert (2003) are discussed in section 4.2.2.

In a forested area in the south-west of Western Australia that Myers *et al.* (2000) listed as one of

25 global "biodiversity hotspots" for conservation priority, Pouliquen-Young and Newman (1999) used the BIOCLIM program (Busby, 1991) to generate a climatic envelope from the present distribution of species. They assessed the effects of three incremental temperature and rainfall scenarios on three species of frogs, 15 species of endangered or threatened mammals, 92 varieties of the plant genus *Dryandra*, and 27 varieties of *Acacia* in the south-west of Western Australia. The scenarios were based on the spatial pattern of change from the CSIRO regional climate model at 125 km resolution, scaled to the IS92 global scenarios. For plant species, suitability of soils was also considered. The results indicate that most species would suffer dramatic decreases in range with climate warming. All of the frog and mammal species studied would be restricted to small areas or would disappear with 0.5 °C global-average warming above present annual averages, as would 28% of the *Dryandra* species and one Acacia. At 2 °C global average warming, 66% of the *Dryandra* species, as well as all of the *Acaci*a species would disappear. Adaptation opportunities were considered minimal, with some gain from linking present conservation reserves and reintroducing endangered species into a range of climatic zones.

Beaumont and Hughes (2002) have assessed potential changes in the distribution of 77 butterfly species restricted to Australia. Even under very conservative climate change projections they found 88% of species distributions decreased by 2050, and under more extreme climate change projections 83% of species decreased in range by at least 50%.

A study by Newell *et al.* (2001) modelled the bioclimatic profiles of 12 plant species in Victoria, using regional climate model results from CSIRO. Projections at 5-year intervals until 2100 showed decline in suitable land areas in each case. However, the authors consider that the modelling was over-constrained and is revising its methodology.

A more recent Victorian study (Hood *et al.*, 2002) was done mainly for adaptation and planning purposes and focussed on commercially useful crops including the native Blue Gums (*Eucalyptus globulus* varieties). Projections were made until 2050. This is reported in section 4.3.11 below.

The few published studies that have investigated the response of Australian plant species to both climate change and elevated carbon dioxide have mostly focussed on woody species grown under non-limiting conditions of light, nutrients and water: *Eucalyptus* species (Duff *et al.*, 1994; Roden and Ball, 1996; Lawler *et al.*, 1997; Gleadow *et al.*, 1998; Roden *et al.*, 1999), *Acacia* species (Atkin *et al.*, 1998, 1999; Evans *et al.*, 2000), *Rhizophora* (Ball *et al.*, 1997), and rainforest trees (Berryman *et al.*, 1993; Kanowski, 2001). Several C4 grasses have also been tested (Ghannoum *et al.*, 2001). Under these conditions, the impacts of elevated carbon dioxide on plant growth have been consistent with studies elsewhere; with elevated carbon dioxide generally enhancing photosynthesis and growth, improving water use efficiency, increasing the C:N ratio and reducing the concentration of nitrogen. Most studies have been in ideal laboratory conditions, without competition from other species or under the range of nutrient-limited conditions typical of many Australian soils.

Some vertebrates will be affected by elevated carbon dioxide. Mammals that feed on leaves will be sensitive to foliage chemistry (Cork and Foley, 1991). They cannot compensate for reduced nitrogen in the leaves by increased consumption, because this would cause greater losses of nitrogen in faeces (Cork, 1996). In particular, Kanowski (2001) projects a decline in the abundance of the lemuroid ringtail possum *Hemibelideus lemuroides*, in the elevated rainforest of the Atherton Tablelands. Many herbivorous invertebrates may also be adversely affected by higher ambient carbon dioxide concentrations (Hughes, 2003).

Marine invertebrates may also be affected by warming of the waters (O'Hara, 2002), especially along the Victorian coast, and in south-eastern Tasmania where they cannot retreat further south (Edgar *et al.*, 1997).

4.2.9 Landscape management for conservation and adaptation

Ecosystems that are used for food and fibre production form a mosaic in a landscape in which natural ecosystems also are represented. Aquatic systems, notably rivers and groundwater, play a crucial role in these landscapes. Given the issues of fragmentation and salinisation in many parts of Australia, landscape management as an integrated approach (PMSEIC, 1999) may be one of the best ways of achieving conservation goals and human needs for food and fibre in the face of multiple stresses, of which climate change is only one.

The complex interconnection of issues in land management is evident in most parts of Australia. For example, in the tropical coastal zone of Queensland, rapid population and economic growth has to be managed alongside agricultural land use that impacts on soil and riverine discharge into the waters of the Great Barrier Reef, as well as a growing tourist industry, fisheries, Indigenous people's rights, and the climatic hazards of tropical cyclones, floods, and droughts. Climate change and associated sea level rise is just one of several major issues in this context that may be significant in adding stress to a complex system.

The impact of climate change on the availability of habitat for vertebrate and invertebrate fauna will present a considerable land management challenge in the decades to come. On a continental scale, reductions in geographic range are expected for most vertebrate species, although some species may undergo range expansion. Shifts in species distribution have already been observed in some groups. In general terms, bats and birds have shifted toward the south, alpine mammals have migrated to higher elevations and the distribution patterns of birds and semi-arid reptiles are shifting along changing rainfall contours (Hughes, 2003).

The impact of climate change may be especially dramatic for some vertebrate species.
The distribution of 41 south-eastern Australian vertebrate species is predicted to decline with climate change-induced habitat contraction.
The endangered mountain pygmy possum, which occupies a narrow alpine habitat, may disappear completely with a temperature rise of 1 °C (Brereton *et al.*, 1995). The range of a further five vertebrate species will be lost with an increase of 2 °C, and an increase of 3 °C will result in the loss of habitat for a further nine species. Other authors have made similar projections regarding climate change-induced loss of habitat (Dexter, 1995; Chapman and Milne, 1998; Pouliquen-Young and Newman, 1999).

Invertebrate species will also be affected by climate change. Beaumont and Hughes (2002) reported that under a conservative climate change scenario of 0.8-1.4 °C temperature increase by 2050, the distribution of 88% of Australia's native butterfly species would contract and 54% of species distributions would decrease by at least 20%. Other climate change impacts are also exerted on invertebrate populations, especially under the combined influences of increased temperature and elevated carbon dioxide levels. Johns *et al.* (2002) found that the moth, *Dialectica scalariella*, introduced as a biological control agent for the weed Paterson's curse, showed longer development times, higher mortality and reduced adult weight when fed on foliage grown under elevated carbon dioxide conditions.

Similar complexities arise in managing other major areas such as the Murray-Darling Basin, where control of land degradation through farm and plantation forestry is being considered as a major option, partly for its benefits in controlling salinisation and waterlogging and possibly as a new economic option with the advent of incentives for carbon storage as a greenhouse mitigation measure.

Soil erosion due to the action of wind and water is another major land management issue that will be affected by climate change. Wind erosion has historically been associated with land clearing and drought, with major events dominating the record, such as dust storms with haze sometimes extending as far as New Zealand (McTainsh *et al.*, 1990). During the 1930s and 1940s wind erosion was particularly severe in the Mallee region of Victoria and New South Wales, and was variously attributed to drought, overgrazing, farming and rabbits. However, Ward (1984) suggested that increased windiness and changes in wind direction may have contributed.

McTainsh *et al.* (1990) mapped dust storm totals over eastern Australia for the period 1960-1984. They found that dust storms are more frequent in the more arid west and along river plains, and that the major environmental factor controlling wind erosion is soil moisture. McTainsh *et al.* (2001) extended the analysis to cover the whole of Australia, and demonstrated a sharp increase in the mean dust storm index for stations with median annual rainfall less than about 400 mm. They found that dust storms were very frequent during the 1994 drought, but much less so in the following wetter years. Major dust storms were again in evidence during the 2002-03 drought, with a huge dust cloud 1500 km long and more than 400 km wide recorded in satellite images on 23 October 2002 as shown in **Figure 4.3**.

The annual off-site costs of wind erosion have been estimated by Williams and Young (1999) for South Australia to be between A$3 million and $23 million. The lower estimates include damage to buildings, electricity transmission, air travel and road accidents. The higher estimates include health effects due to dust causing asthma, absenteeism, disability and death, and this constitutes some 85% of total costs, but is still very uncertain. It is notable that these estimates are off-site, and thus do not take account of loss of both soil fertility and sustainable farm production. Nevertheless, these estimates indicate that overall Australia-wide costs of dust storms may be quite large.

Clearly, any increase in aridity in Australia, as projected in section 2.3.2, and in drought frequency, is likely to lead to increased dust storm frequency and wind erosion, with further loss of sustainability and other costs, but this has not yet been quantified. Lu and Shao (2001) have developed an integrated wind-erosion modelling system that could be applied to this problem. Quantification of observed wind erosion is possible using Caesium isotope (^{137}Cs) measurements (Van Pelt *et al.*, 2002). Adaptation strategies to minimise wind erosion are well known, and include reduced stocking in dry conditions, minimal tillage, planting wind breaks and moving to more deep-rooted perennial cropping.

Water erosion has also been a major feature of the Australian landscape since European settlement (Scott, 2001). Historically, increased water erosion has been caused by a number of factors including land clearance, heavy grazing, increased runoff from cleared areas and increased erodability of disturbed soil. Potential soil loss increases greatly when ground cover falls below about 70%. Scott (2001) documents the increase in water erosion in the Murray-Darling Basin from before first settlement to the 1930s, and a gradual improvement through better land management from 1945 onwards.

There are four main types of water erosion:

- Sheet erosion, in which a fairly uniform layer of soil is removed.
- Rill erosion, in which small eroded channels form, which can be removed by subsequent tillage.

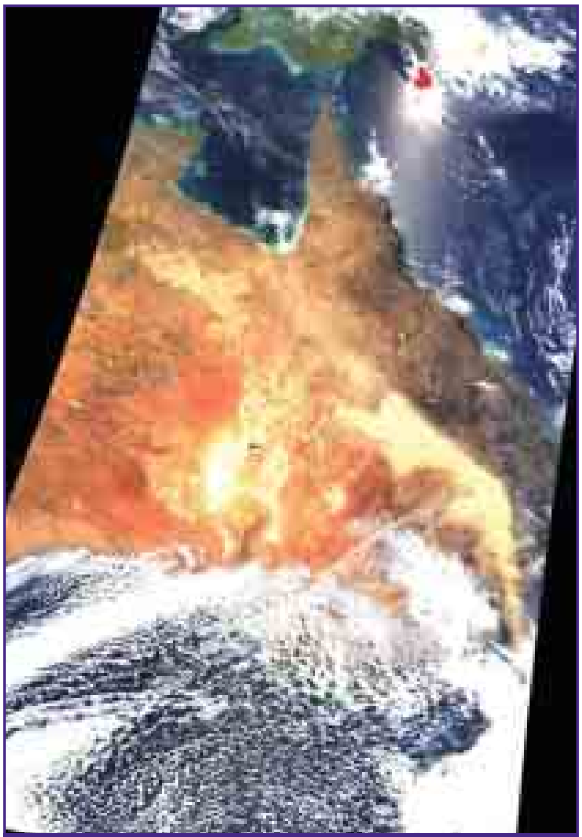


Figure 4.3.
A dust storm that swept across parts of eastern Australia on 23 October 2002. It is seen as a pale yellow band extending from the Gulf of Carpentaria, down across Queensland, and tapering off toward Sydney. The high density section was about 1500 km long, about 400 km wide, and about 2500 m thick. It was a result of strong winds and the drought associated with the 2002 El Niño event. This image is from the NASA MODIS instrument, courtesy of Geoscience Australia.

- Gully erosion, in which flowing water removes soil to form deep channels that are difficult to remove or control.

- Streambank erosion, which refers to undermining and collapse of banks of rivers and streams.

Direct consequences of accelerated soil erosion include loss of plant nutrients, loss of organic matter that sustains the desirable characteristics of the soil, decrease in soil depth and water storage capacity, and damage to infrastructure such as fences, roads and buildings. Off-site effects include increased sedimentation and turbidity of downstream rivers, lakes and estuaries. These can lead to increased nutrient concentration, the formation of large 'sand slugs' in river channels and the filling in of pools, and siltation of estuaries and lakes.

Warner (1995) argues that significant differences in river channels and flood plains result from drought-dominated and flood-dominated regimes and worries about possible effects of the enhanced greenhouse effect in leading to an effectively flood-dominated regime. Patterns of erosion and sediment transport in rivers are reviewed by Prosser *et al.* (2001). Yu (1998) and Lu and Yu (2002) have developed a rainfall erosivity model that has been used to map rill and sheet erosion across Australia. Rainfall erosivity is highly dependent on rainfall intensity, and erosivity models could be used to examine the effects of scenarios of changing rainfall intensity with the enhanced greenhouse effect. Present projections of increasing rainfall intensity, and more severe droughts (section 2.3.2), which would reduce vegetation cover, suggest that water erosion might well increase, with significant consequences for hydrology, ecosystems and sustainable agriculture.

Water erosion may well increase under enhanced greenhouse conditions due to projected increased fire frequency and intensity (see section 2.3.2), since this would decrease vegetation cover.

4.3 Agriculture, Forestry and Fisheries

4.3.1 Introduction

Some 60% of the Australian landmass is used for commercial agriculture (Pestana, 1993). Only 2% is used for broad acre and intensive crop production and 4% is sown to pastures. Soil and topography are major constraints on cropping, which produces about 50% of the gross value of farm production—the rest being divided equally between meat production and livestock products such as wool and milk.

Russell (1988) identifies climatic "frontiers" affected by climate change and interdecadal variability in rainfall—namely, the inland limit to agriculture (mean annual rainfall >300 mm in the south and >750 mm in the north), the southern limit of effective summer rainfall, and the lower rainfall limit of high value crops (on the order of 1000 mm). Temperature also is limiting, with some temperate crops held south of their high-temperature (northern) limit, and other more tropical crops held at their low-temperature (southern or high-altitude) limit. Large areas of the interior and west are desert or very arid rangelands with low yields and some of this land is now returned to Aboriginal management, particularly in the Northern Territory.

There is great interannual variability, especially in the interior and more northern regions, associated mainly with ENSO, convective rainfall, and tropical cyclones. Australia is known as a land of droughts and flooding rains. Secondary factors such as wildfires also account for losses of fodder, animals and farm infrastructure (sheds, fences, machinery), and hail causes significant crop losses. Accordingly, drought and disaster relief policies are matters of ongoing concern (O'Meagher *et al.*, 1998, 2000; Pittock *et al.*, 1999), as is sustainability in the face of economic pressures and global change (Abel *et al.*, 1997).

4.3.2 Pastoral farming

Howden *et al.* (1999g) have summarised and updated work by Hall *et al.* (1998), McKeon *et al.* (1998), and Howden *et al.* (1999b, d). They find that although a rise in carbon dioxide concentration alone is likely to increase pasture growth, particularly in water-limited environments, there also is strong sensitivity to rainfall, so that an average 10% reduction in rainfall could counter the 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, reducing farm income. The latest scenarios (CSIRO, 2001), which include substantial reduction in rainfall in many parts of Australia, would tend to reduce productivity, particularly at the extreme ends of the rainfall/temperature changes where 'dustbowl' conditions may develop (Crimp *et al.*, 2003).

Doubled CO_2 concentrations are likely to increase the deep drainage component under pastures, which may increase the risk and rates of salinisation where the potential for this problem exists (Howden *et al.*, 1999g; Van Ittersum *et al.*, 2003). Doubled CO_2 concentrations and increased temperature are likely to result in only limited changes in native C3 and C4 grass distributions (Howden *et al.*, 1999b).

A comprehensive study by Crimp *et al.* (2002) using the pasture production model GRASP explored the effects of four different scenarios of climate change on native grasses. Under a scenario of a small increase in temperature and reduced rainfall pasture growth was reduced in 2030 by 10-50% across different parts of Australia, with larger reductions by 2070. Pasture responded favourably to a scenario of a small increase in temperature and increased rainfall. In a scenario of large warming and increased rainfall there were moderate gains in production by 2030, particularly in tropical Queensland, but little change in more southerly regions. Results were more negative by 2070. Lastly, with large warmings and reduced rainfall, average growth across the continent was reduced by between 30 and 70% by 2030, with greatest reductions in more southerly regions. By 2070 the simulated reductions in pasture production increased to between 30 and 100%.

Davison *et al.* (1996) carried out a comprehensive assessment of the response of dairy cattle to heat stress in New South Wales and Queensland. Physiological effects of heat stress include reduced food intake, weight loss, decreased reproduction rates, reduction in milk yields, increased susceptibility to parasites, and, in extreme cases, collapse and death. Heat stress can be reduced by the use of shade and sprinklers, and thresholds for their use can be determined. Jones and Hennessy (2000) applied this adaptation to the Hunter Valley in New South Wales, using probabilistic estimates of temperature and dewpoint changes resulting from climate change for the IS92 range of scenarios to 2100. They then estimated the probabilities of given milk production losses as a function of time and calculated the economic benefits of provision of shade and sprinklers. They conclude that heat-stress management in the region would be cost-effective. However, such adaptation may not be as cost-effective in a hotter or more humid climate.

Howden and Turnpenny (1997) and Howden *et al.* (1999a) also have looked at heat stress in beef cattle. They find that heat stress already has increased significantly in subtropical Queensland over the past 40 years, where there has been a warming trend, and increases in atmospheric water vapour pressure in some seasons (McKeon *et al.*, 1998). Heat stress in beef cattle will increase further with greenhouse-induced global warming. Heat stress already affects productivity in northern Australia (e.g., Petty *et al.*, 1998) and this is likely to increase such that on most days, some level of heat stress will be evident in beef cattle, with implications for productivity. 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).

Climate change adaptations for the dairy sector particularly need to be developed in context with other economic imperatives currently facing the industry. The Dairy Structural Adjustment program is currently being implemented and final payments under this scheme will occur during 2008. Export markets are being sought for new products such as casein, and trade and competition issues are emerging with New Zealand, which produces dairy products at lower cost. Genetically modified milk products, disease and food additives are more immediately pressing issues for the dairy industry than adapting to climate change. However, the industry is in a phase of rapid change. Managing potentially lower irrigation water availabilities, with their accompanying higher prices due to lower rainfall, will likely emerge as a key climate change impact for this industry (Howden *et al.*, 2003a).

4.3.3 Cropping and horticulture

Wheat is the major crop in Australia by value and volume, although a diverse range of crops are grown, including barley, sorghum, oats, rice, cotton, pulses, and oilseeds. Cane sugar is also grown extensively in coastal areas of Queensland. Many of these crops are highly affected by climate variations, particularly being subject to frost limitations and to water stress in dry spells. Consequently, they are also likely to be affected by climate changes.

Changes in the cropping industries as a result of climate change will be the net effect of 1) the effects of increased CO_2 concentrations which will increase crop water-use-efficiency but tend to reduce grain quality, 2) the negative effects of reduced water availability due to both reduced rainfall in some regions and increased potential evaporation, 3) both positive and negative effects of increased temperatures, 4) the management adaptations taken to reduce negative impacts and enhance positive ones including changes in the genetic base, and 5) any shifts in the balance of world grain trading induced by climate change. These interactive factors were assessed for the wheat cropping industries across Australia by Howden *et al*. (1999f, 2001) looking at yields, grain quality, and gross economic margins. Their results were used by Howden and Jones (2001) to investigate likely impacts across the full range of climate change and CO_2 scenarios. When aggregated to national levels, and taking account of adaptation, they found a two in three chance of a small increase in grain production (up to 10%) by 2070, but a one in three chance of a decrease of up to 25%. The estimated value of the national crop showed a slightly more than even (55%) chance of an increase of up to A$220 million per year, but a slightly less than even (45%) chance of a possible decrease of as much as A$800 million per year: the scale of the potential negative impacts is considerably greater than that of the potential positive impacts. These figures are based on current values and are estimated in the absence of any shifts in the balance of world grain trading. When combined with expected population growth and increased consumption in domestic industries (e.g., feedlotting), there is a high likelihood of reduced export income by 2070: 72% with mid-range population projections (Howden and Jones 2001). Actual outcomes will depend on the change in CO_2 concentration and the effect this (and other greenhouse gases) has on the mean and variability of regional climates in Australia: all of these factors are currently highly uncertain.

Perhaps even more important than the national aggregate outcomes was the markedly different projected regional outcomes. Howden and Jones (2001) found a high likelihood (52–97% depending on region) that the productivity and value of Western Australian wheat crops will be below current levels in 2070. By 2070 regional declines in Western Australia are expected to be in the order of A$13 million to A$104 million (3-15% depending on region) but under the harshest climate change scenarios, annual reductions of A$100 million to A$130 million per region are possible. In South Australia, Victoria, New South Wales and southern Queensland the likelihood of negative impacts and positive impacts appear more evenly balanced; however, the scope of the negative impacts is, in most cases, larger than the scope of the positive impacts. With high emissions scenarios (and implicitly at later dates when warmings have increased) there would be much larger negative impacts, with cropping potentially becoming unviable over entire regions, especially in Western Australia, with major socioeconomic implications for the rural communities there.

Increasing CO_2 concentrations increases grain yield but at some cost in grain quality (specifically grain protein levels). For example, doubling CO_2 would reduce grain nitrogen content by 4-14%, assuming no management adaptation but including anticipated climate changes (Howden *et al.*, 1999f). Such reductions in grain quality would represent a downgrade of one to two quality classes (Howden, 2002) and a loss of up to A$70 a tonne (about 30%) paid on prices over the past decade. Offsetting such reductions in grain protein would require increases in the use of nitrogen-based fertilizer of 40-220 kg/ha or increased rotations of nitrogen-fixing plants (Howden, 2002) – both of which have a range of issues relating to sustainability. Declines in grain protein caused by elevated CO_2 concentrations and increased temperatures (+3 °C) may be offset, in financial terms, by the increase in yield (van Ittersum *et al.*, 2003), but strategies such as optimising fertiliser application or breeding new cultivars better adapted to higher CO_2 levels are likely to be advantageous to maintain crop quality (Howden, 2003).

Some crops are subject to direct heat stress or deterioration during heat waves. For example, wheat grain protein composition deteriorates after several days above 35 °C (Burke *et al.*, 1988; Behl *et al.*, 1993), making it less suitable for high-value uses such as pasta and breadmaking (although there are currently no price penalties for affected grain). Intuitively, it would seem that global warming should increase the risk of heat stress-affected grain. However, increased temperatures will result in faster phenological development and possibly earlier planting schedules, resulting in flowering and ripening in the cooler months and thus little change in heat shock risk up to a 4 °C mean warming (Howden *et al.*, 1999f). Independently, as noted above, increasing CO_2 can result in a decrease in wheat grain protein content—also leading to a decrease in breadmaking quality (Rogers *et al.*, 1998).

Various farm-level adaptations of cropping systems to climate change have so far been evaluated. Whilst there remain many more to be explored with farmers, there is also a need to evaluate options at the landscape and regional scales as well as policy options at State and national levels (Howden *et al.*, 2003). Effective adaptation options are likely to arise from the combination of management changes and advances in plant breeding. Targets for plant breeding include adaptation to higher ambient CO_2 concentrations, increased temperature and reductions in rainfall. Maximisation of water and nutrient use will be needed, for example by increasing the rooting zone and/or the ability to grow in less hospitable subsoils (Richards, 2002) or through increased use of minimum tillage. The return on investment on adaptation options is likely to be high with even simple options being worth A$50 million to A$500 million per year (today's prices) in increased crop value by 2070 (Howden and Jones, 2001).

Some issues relating to climate changes and adaptation can be illustrated by looking at the Emerald region of north-east Queensland, where landuse competition occurs between wheat cropping and the beef cattle industry and where farmers have responded to patterns of climate variability. Emerald is at the northern margin of the Australian wheat-cropping zone with the local cropping industry developing in importance over the last three decades in response to a unique climatic period that has favoured consistently high yields (Howden *et al.*, 2001). If this climatic pattern is part of longer-term variability, then cropping will likely decline in the region as conditions return to those favouring beef cattle production. However, if these conditions are related to climate change, then wheat cropping is likely to persist in the region, particularly with the yield-enhancing effects of increased CO_2. Adaptation strategies will need to be flexible and integrate strategies to manage other pressures on sustainable crop production, including variations in climate at a range of scales, changing land use, market factors and causes of environmental degradation, especially salinity. There is also evidence that the cropping industry around Emerald is already adapting to warmer, less frosty conditions by planting crops earlier. This strategy maintains risk at previous levels but substantially increases gross margins (Howden *et al.*, 2002)

Adaptation strategies for the cropping sector need to integrate both anticipated climate change and dryland salinity. Deep drainage (water loss below the root zone) is the main cause in Australia of sub-soil salt mobilisation that leads to surface soil salinity. Hence, deep drainage is an important externality of agricultural production (van Ittersum *et al.*, 2003). While elevated CO_2 concentrations are likely to increase wheat crop yields, deep drainage is also likely to be slightly higher. However, under higher temperature scenarios and in low precipitation scenarios deep drainage was reduced, notwithstanding the CO_2 effects. As such, climate change is likely to affect both crop production and dryland salinity risk through its affect on deep drainage. The impact may vary according to soil and management conditions such that both 'win-win' and 'lose-win' outcomes may eventuate and trade-offs between salinity risk and production will likely occur under climate change (van Ittersum *et al.*, 2003).

Horticulture in Australia includes cool temperate fruit and vegetables in the south and at higher elevations, extensive areas of tropical fruits in the north-east and in irrigated areas in the north-west, and a rapidly expanding viticulture industry in cool and warm temperate zones.

Many temperate fruits require winter chill or vernalisation—which in some cases can be replaced by chemical treatments—and are strongly affected by disease and hail. Other more tropical fruit are subject to disease outbreaks and severe damage from hail, high winds, and heavy rain from tropical storms. These fruits are all likely to be affected by climate change, but few studies have been made (but see Hennessy and Clayton-Greene, 1995; Basher *et al.*, 1998).

Chilling requirements for most cultivars of pip-fruit are easily satisfied. However, some common cultivars have shown an adverse reaction to excessively warm conditions, with problems such as sunburn, water-core, and lack of colour.

Viticulture is a rapidly expanding industry in Australia. The relation between wine growing and climate has long been recognised (Spellman, 1999), and extensive studies relating climate and climate change to wine varieties, production and quality exist for European wines (Kenny and Harrison, 1992; Jones and Davis, 2000; Schultz, 2000). Some of these claim to have detected changes in phenology and quality related to observed climate trends, and this is also true in the United States (Nemani *et al.*, 2001). Smart (1989) has looked at the prospects for climate change and the New Zealand wine industry in the 21st century, while early work was done in Australia by Boag *et al.* (1988) and Dry (1988).

More recently, McInnes *et al.* (2003) have presented climate change scenarios for the Australian viticultural regions, and commented on possible impacts. Warming is likely, with drier conditions particularly in winter and spring. More rapid phenological progression is expected, with earlier ripening and possible reductions in quality. In cooler climates such as the Mornington Peninsula in Victoria, and in Tasmania, warming may allow new varieties to be grown. Higher carbon dioxide concentrations may lead to more canopy growth and shading, leading to potential decreases in fruitfulness. Water supply problems for irrigation may increase.

Vineyards have a life of 30 years or more, so vines planted now will experience significant climate change within the investment cycle of the industry. Moreover, the Australian wine industry is highly exposed to international competition, notably from Europe, the United States, Chile, South Africa and New Zealand. Climate change impacts on production in these other regions may thus have major impacts on the Australian industry. Investment planning, therefore, needs to take account of the need to adapt to projected climate change, both as it affects domestic production and overseas competition.

Adaptation strategies for the horticulture industry include matching varieties to sites and aligning crop production schedules with new climate scenarios (Howden *et al.*, 2003a). Determining the effect of increased temperature and carbon dioxide on specific horticultural and viticultural crops is an important area for future research as is the likely effects of reduced rainfall in key horticultural regions.

4.3.4 Forestry

When Europeans arrived in Australia in 1788, there were approximately 70 million hectares of forests. Since then, 40% has been cleared and a similar amount has been affected by logging; only about 25% remains relatively unaffected (Graetz *et al.*, 1995; State of the Environment, 1996). Nationally, land clearing still exceeds planting, although this varies greatly across the states, and occurs mainly in areas defined as woodlands. Plantations have been expanding in Australia at an increasing rate since 1990, currently well in excess of 50,000 hectares per year (National Greenhouse Gas Inventory, 2000). Much of this planting is occurring on farmed land and receives federal government support (Race and Curtis, 1997). Additional plantings are occurring to ameliorate land degradation problems such as erosion, waterlogging, and salinisation, and further plantings are associated with the establishment of carbon sinks (Barrett-Lennard, 2002; Clarke *et al.*, 2002).

Given the huge forest resources in the United States, distributed over many different climatic zones, research in the United States on the relationship between climate change and forests raises many issues relevant to Australian forestry. This is only partly because of the position of the United States as a significant competitor in the international timber market. Common issues of the role of drought (Hanson and Weltzin, 2000), fire (Flannigan *et al.*, 2000) and herbivores and pathogens (Ayres and Lombardero, 2000) are relevant to Australian forestry. A recent review by Shugart *et al.* (2003) summarises many of the issues.

Shugart *et al.* (2003) find for the United States that species generally will migrate polewards or to higher altitudes in response to increased temperatures, but that species mix may change and rates of migration will depend on seed dispersal, the spread of insects and disease, and the role of wildfire and human intervention. Salvage of damaged forests after disturbance is seen as a useful industry response until productivity increases in new areas. They find that productivity is likely to decrease in the more southern parts of the US, which are more comparable to Australian conditions, due to the development of more arid conditions, while more northern regions may experience increases in production.

Ayres and Lombardero (2000) find that in the United States warming will tend to accelerate insect development and facilitate range expansions of pests, while climate change will tend to leave mature trees less matched to their environment and thus more vulnerable to herbivores and pathogens. Hanson and Weltzin (2000) argue that drought leads to a net reduction in primary productivity, increased mortality of seedlings and saplings, and increased susceptibility to insects and disease. Moreover, drought-induced reductions in decomposition rates may cause a build-up of organic material on the forest floor, with ramifications for fire regimes and nutrient recycling. As drought is projected to increase in Australia (see sections 2.3 and 4.3.6), this has implications for Australian forests. Regarding forest fires, Flannigan *et al.* (2000) conclude that the fire seasonal severity index rating over most of North America will increase under a 2 x CO_2 climate by 10-50% (with largest increases in the south-east and north-west), with likely increases in area burned and fire intensity or severity. They suggest that fire has the potential to overshadow the direct effects of climate change on species distribution and migration, and that it will require manipulations of fuel type, load and arrangement to help protect local areas of high value. In Australia, forest fire frequency and intensity is expected to increase with global warming (Cary, 2002, and see section 2.3.2).

Climatic factors are well known to influence species distributions (Hughes *et al.*, 1996; Austin *et al.*, 1997) and productivity (Landsberg and Waring, 1997) in Australia. Carbon dioxide concentrations also have a direct effect on species distributions (Curtis and Wang, 1998). Kirschbaum (1999a,b) has used a forest growth model to assess response to climate change and carbon dioxide increases for a site near Canberra. Howden and Gorman (1999) review this and other work on the impact of global change on Australian temperate forests.

In summary, productivity of exotic softwood and native hardwood plantations is likely to be increased by CO_2 fertilisation effects, although the amount of increase is limited by various acclimation processes and environmental feedbacks through nutrient cycling. Where trees are not water-limited, warming may expand the growing season in southern Australia, but increased fire hazard and pests may negate some gains. Reduced rainfall in more recent scenarios would have adverse effects on productivity and increase fire risk. Projected changes in fire risk and intensity have been estimated by Cary (2002) and are discussed more fully in section 2.3.2. Increased rainfall intensity would exacerbate soil erosion problems and pollution of streams during forestry operations. In *Pinus radiata* and *Eucalyptus* plantations, fertile sites are more likely to have increased productivity for moderate warmings, whereas infertile sites could have decreased production.

Considerable effort in Australia is going into providing advice and planning for new forest plantations and on-farm forestry for timber production, the control of salinity and soil erosion, enhanced biodiversity, bioenergy production and carbon sequestration (Nambiar and Brown, 2001; Stirzaker *et al.*, 2002; Dury *et al.*, 2002). Improved species climatic profiles have been developed (Jovanovic and Booth, 2002), and also improved forest growth models (Sands and Landsberg, 2002). The viability of these plantation projects will depend in part on adequate planning for climate change and variability, control of fire and interactions with soil moisture and water supply. Immature forests are particularly susceptible to drought, and reduce runoff for downstream water supply, due to their shallow rooting and high water demand (Herron *et al.*, 2002).

To date, large uncertainties have lowered the priority of climate change in management considerations. Priority adaptation research areas include:

- more detailed assessment of drought tolerance in commercially important species
- improved knowledge of the climatic requirements of particular genotypes
- identification of optimal strategies for high growth and risk aversion for particular sites, tree species and timber products (Howden *et al.*, 2003a).

Additional areas for adaptation research identified by Howden *et al.* (2003a) include:

- evaluation of the impact of climate change on establishment strategies
- investigation of interactions between high atmospheric carbon dioxide concentrations, drought risk and tree mortality (including fire risk)
- assessment of implications for species planted near their climatic extremes, especially species at their high-temperature limit
- improvement and application of process-based models, to extend findings from individual sites to large areas.

4.3.5 Fisheries

Australia specialises in high-value, low-tonnage fisheries such as lobsters, pearl oysters, prawns, abalone and tuna. In 2000–01, the gross value of Australian fisheries production (including a growing aquaculture sector) was A$2.5 billion (Australian Bureau of Statistics, 2003). As such, these fisheries are a significant local primary industry. Tonnage produced is very small by world standards because Australian surface waters generally are low in nutrients as a result of prevailing winds and boundary currents (Kailola *et al.*, 1993).

Distributions of *ca*. 3200 species of estuarine, coastal and continental shelf fish broadly mapped by CSIRO (1996b) show that while many of the species reside in tropical waters less than 4% of tropical species are endemic and with well known distributions, compared to 40% of temperate species. A number of these temperate endemics are highly restricted in specialised habitats. For example the endemics in the very salty estuarine gulfs of St. Vincent and Spencer in South Australia, the relatively shallow sea of Bass Strait which separates Tasmania and the mainland, the unique relic Port Davey environment in south western

Tasmania and the endangered Handfish species, which is found only in the Derwent Estuary, Tasmania. 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.

In a fisheries oceanography study of several commercial pelagic (near surface) tunas off the east coast of Australia, Lyne (2000) and Lyne *et al.*, (1999) found that surface satellite temperature patterns are linked to the distributional patterns of the various species. Similarly, while not much is known of the distribution of pelagic invertebrates, such as squid, around Australia, work elsewhere (Sims *et al.*, 2001) shows a link between water temperatures and the timing of migration patterns and peak local population abundance. Sims *et al.* (2001) conclude that squid populations respond to "temperature changes independently of time of year". Thus, there is reason to suspect that climate change will have direct impacts on both pelagic fish and invertebrates.

There is some evidence of southward extensions of the ranges of some native and introduced marine pests, possibly related to climatic warming. The New South Wales native sea urchin, *Centrostephanus rodgersii*, extended its range to the Tasmanian east coast beginning in the late 1970s (Edgar, 1997), and now causes extensive "urchin barrens" along that coast. The range extension of the introduced European shore crab, *Carcinus maenas*, from Victoria to Tasmania in the early 1990s has been linked (Thresher *et al.*, 2003) to a series of unusually warm years and stronger than usual East Australian Current (EAC). Other reported poleward spread include a number of sub-tropical fish to eastern Victoria and north-east Tasmania, and the recent spread of the introduced New Zealand Screw Shell (*Maoriculpus rosaceus*) to Bathurst Harbour, south-west Tasmania (V. Lyne, personal communication 2003).

Relationships have been established between recruitment of some fish species and climate variations, suggesting that fisheries in the region will be sensitive to climate change. Quasi-decadal (*ca.* 11 year) cycles of fish landings and/or reproductive success, linked to variability in temperate region winds, have been reported for gemfish, South Australian rock lobster and Southern Hemisphere stocks in general (Harris *et al.*, 1988; McGarvey and Matthews, 2001). Wind effects on gemfish were confirmed by independent studies on the species in New Zealand (Renwick *et al.*, 1998a,b). Koslow and Thresher (1999) and Thresher (2002) suggest variation in persistence of strong zonal winds underlies this variability, and that long-term decline due to a poleward shift in climate systems underlies recent stock declines, although earlier analyses (Smith, 1996) suggested a combination of fishery pressure and poor recruitment as the cause. Recruitment appears to correlate with climatic cycles (Thresher, 1994). Smith (1996) developed a quantitative framework to evaluate management strategies for this and other fisheries.

It is uncertain how local winds and boundary currents that advect larvae and affect upwelling of nutrients might respond to projected climate changes, and downscaling from relevant global climate change model fields has not yet been done.

Understanding of existing processes suggests that if El Niño were to become a more prevalent condition, the Indonesian Throughflow and the Leeuwin current (Meyers, 1996) could weaken. If winds were favorable for upwelling, the west coast of Australia could undergo a dramatic shift from a low-production, high-biodiversity ecosystem to a more productive ecosystem typical of temperate shelves.

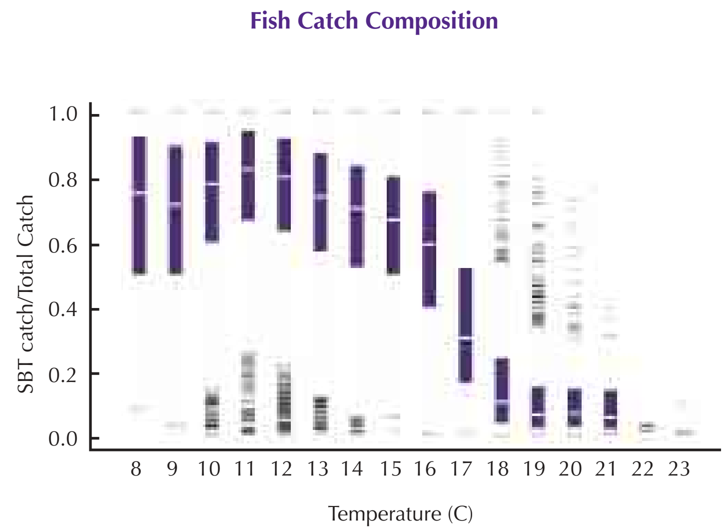


Figure 4.4.
Ratio of catch of cold-water species to warm-water species east of Tasmania, as a function of water temperature. The sharp transition occurs where the tropical waters of the East Australian Current meet the cooler waters of the Sub-tropical Convergence. The 'box and whiskers' plots show that 50% of the time catch lies within the purple boxes, with the most frequent catch size ratio indicated by the central white line (Cleaveland, 1994, p.139). Vincent Lyne (CSIRO Marine Research), personal communication 2003.

Australia's single largest fishery is the western rock lobster at A$260 million per year (ABARE, 2000). Presently, settlement of larval lobsters (and adult catch rates some years later) is much higher in La Niña years (high coastal sea level, high sea surface temperature, strong Leeuwin current) than in El Niño years (Pearce and Phillips, 1994). Because the mechanism appears to be through larval advection processes, however, it is unclear whether the species' spawning strategy would adapt to a sustained shift to a weaker Leeuwin current. Many other Western Australian fisheries also correlate (some positively, some negatively) with ENSO (Caputi *et al.*, 1996; Lenanton *et al.*, 1991), through unknown mechanisms. Whether these mechanisms would continue to operate under the combined influence of a sustained weaker Leeuwin current (which tends to reduce temperatures) and a worldwide rise in sea surface temperature is unknown. Southern bluefin tuna spawn where the Indonesian Throughflow enters the Indian Ocean, but the impact of a possibly reduced throughflow is unknown.

Conditions on the south coast of Australia also are influenced, but to a lesser degree, by the Leeuwin current, which tends to keep near-surface nutrient levels low. In addition, winds are favorable to downwelling, except during some summers, when Australia's only example of strong classical wind-driven coastal upwelling occurs off Portland, Victoria. Small meridional shifts of the subtropical high-pressure ridge modulate summer upwelling. The ecosystem impacts of upwelling are poorly known.

On the east coast of Australia, the EAC is a dominant influence on coastal marine ecosystems. The EAC enhances upwelling and primary production (Hallegraeff and Jeffrey, 1993) and presumably fisheries, although this has yet to be demonstrated apart from its effect on the distribution of several tuna species (Lyne *et al.*, 1999). However, off the east coast of Tasmania primary productivity undergoes marked interannual changes. This appears to be related to upwelling of nutrients, which is closely related to water temperatures. Upwelling of nutrients supports krill and jack mackerel, which in turn support many other species, including tuna, seals and seabirds. Commercial catch is thus closely related to temperature, with a marked fall in the ratio of catch of cold-water species (e.g., southern bluefin) relative to warm species (e.g., yellow fin) for SSTs above about 17 ºC (see **Figure 4.4**). This transition occurs where the tropical waters of the EAC meet the cooler waters of the Sub-tropical Convergence

Zone, and is likely to shift with climate change (V. Lyne, personal communication 2003).

Some fish and prawn species recruitment and catches are correlated to variability in 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. They will thus be affected by projected changes in north Australian rainfall and its variability, although uncertainty about future behaviour of ENSO and tropical cyclones makes projections uncertain and increases risk.

Marine aquaculture is now an important industry, including Atlantic salmon, Pacific oysters, abalone and even seahorses. Several cultivated species are temperature-sensitive, and Atlantic salmon are at the edge of their heat tolerance in southern Tasmania (V. Lyne, personal communication 2003). Projected warming over the next century will greatly exceed natural inter-annual variability.

Trends, over more than 60 years, of temperatures at the surface and 50 m depth at a long-term monitoring station on the continental shelf at Maria Island on Tasmania's east coast (Lyne, unpublished analyses) show that, with the exception of July, all other months have warmed at rates of from 0.6 to 3 degrees per 100 years. When combined with the quasi-periodic 7-10 year cycle seen in Hobart air temperatures, the recent peak in this cycle has had a detrimental impact on caged salmon in southern Tasmania. An unusual sequence of very warm summers over the last decade has increased stress and mortality, and decreased growth rates of farmed Atlantic salmon, threatening the viability of the industry. In contrast, the warmer conditions appear to favour the production of oysters.

Recent episodes of coral bleaching (Wilkinson, 1998; Berkelmans and Oliver, 1999; Lough, 2000; Liu *et al*., 2003) are projected to become more frequent (Hoegh-Guldberg, 1999), which will likely adversely affect fisheries recruitment in tropical coastal waters. This is discussed more fully in section 4.2.7.

Finally, it should be noted that, if the wildcard of possible reduction or cessation of North Atlantic or Antarctic bottomwater formation were to occur (see section 2.1.4 and Manabe and Stouffer, 1994; Hirst, 1999; Alley *et al*., 2003), this could lead to significant changes in deep ocean chemistry, ocean dynamics, and nutrient levels on century time scales. This could have wide, but presently unknown, ramifications for fisheries in Australian waters.

4.3.6 Drought

As described in section 2.1.4, the IPCC TAR (McCarthy *et al*., 2001) states that increased summer continental drying and risk of drought is likely in most mid-latitude continental interiors (see **Table 2**). Observed trends in Australian climate in the later half of the 20th century (see section 2.2.1) indicate reduced rainfall in the southern mainland and in the far east (see **Figure 2.9**), in a period during which the observed warming trend appears to have become increasingly similar to that projected from climate models that include the enhanced greenhouse effect (see **Figure 2.8**). A rather sudden decrease in rainfall in the south-west of Western Australia occurred in the 1970s, and has persisted to the present. This drying seems to be related to a shift to higher surface pressure in a belt from the south-east of the Indian Ocean to the mid-east coast, and could be related to a systematic shift southward in the mid-latitude high pressure belt (Thresher, 2003; Thompson and Wallace, 2000; Kushner *et al*., 2001; Gillett *et al*., 2003). If the trend is related to the enhanced greenhouse effect (and perhaps to stratospheric ozone depletion over Antarctica), as some of these authors suggest, it might be expected to continue, although overlaid with natural inter-annual and inter-decadal fluctuations.

Moreover, Nicholls *et al*. (1996b) and Nicholls (2003 a and b) have documented a trend to increased annual average surface temperatures over Australia for the same annual average rainfalls. This removes trends in rainfall as an explanation for the long-term warming trend, and means that higher temperatures and thus higher potential evaporation are occurring during droughts as traditionally defined in Australia. Karoly *et al.* (2003) and Nicholls (2003 a and b) point out that higher potential evaporation will exacerbate drought for the same rainfall deficit.

Australian droughts are closely related to major drivers of year-to-year and decadal variability such as ENSO, Indian Ocean SSTs, the Antarctic Circumpolar Wave (White and Peterson, 1996; Cai *et al.*, 1999; White and Cherry, 1999), and the Interdecadal Pacific Oscillation (Mantua *et al.*, 1997; Power *et al.*, 1998; Salinger and Mullan, 1999), as well as more or less chaotic synoptic events. These are all likely to be affected by climate change (see section 2.1.4, and Houghton *et al.*, 2001, chapters 9 and 10).

Using a transient simulation with the NCAR CCMO climate model at coarse resolution (R15) (Meehl and Washington, 1996), Kothavala (1999) found for north-eastern and south-eastern Australia that the Palmer Drought Severity Index indicated longer and more severe droughts in the transient simulation at about 2 x CO_2 conditions than in the control simulation. This is consistent with a more El Niño-like average climate in the enhanced greenhouse simulation. Similar but less extreme results were found by Walsh *et al.* (2000) for estimates of meteorological drought in Queensland, based on simulations with the CSIRO RCM at 60 km resolution, nested in the CSIRO Mark 2 climate model.

A global study by Arnell (1999), using results from an ensemble of four enhanced greenhouse simulations with the HadCM2 GCM and one with HadCM3, show marked decreases in runoff over most of mainland Australia, including a range of decreases in runoff in the Murray-Darling Basin in the south-east by the 2050s of about 12-35%. The HadCM3 model results show large decreases in maximum and minimum monthly runoff. This implies large increases in drought frequency.

Recurring interest in Australia in policies on drought and disaster relief is evidence of a problem in managing and attempting to adapt to existing climate variability (O'Meagher *et al.*, 1998). Present variability causes fluctuations in Australian GDP on the order of 1-2% (White, 2000c). The drought of 2002–03 caused the net value of farm production to fall by 80% according to preliminary reports, which led to wide-ranging discussion of drought policies and causes (Australian Financial Review, 2003). Links have also been made to stress in forests and the severity of bushfires (see section 2.3.2 and Hanson and Weltzin, 2000; Flannigan *et al.*, 2000; Macken in Australian Financial Review, 2003). Drought and disaster relief helps immediate victims and their survival as producers (e.g., QDPI, 1996) but does not reduce costs to the whole community. Disaster relief may in fact prolong unsuitable or maladapted practices (Smith *et al.*, 1992; Daly, 1994), especially under climatic change. Farm productivity models are being used to simulate past and present farm production and to assess causes of and management options for coping with drought (Donnelly *et al.*, 1998; Keating and Meinke, 1998; Stafford-Smith and McKeon, 1998; White *et al.*, 1998). This is contributing to the development of drought assistance and advisory policies.

Under the National Drought Policy (White, 2000a, b), if drought conditions are so intense and protracted that they are considered beyond the bounds of normal risk management practices, the federal Minister for Agriculture, Fisheries and Forestry may declare affected areas as experiencing 'drought exceptional circumstances' (DEC). Six core criteria were adopted in October 1994 as the basis of a DEC declaration. These are:

- meteorological conditions
- agronomic and livestock conditions
- water supplies
- environmental impacts
- farm income levels
- scale of the event.

A review in 1997 modified these criteria to include a rare and severe event, the effects of which must result in a severe downturn in farm income over a prolonged period. Furthermore, the event must not be predictable or part of a process of structural adjustment (White, 2000a).

A change in climate toward drier conditions as a result of lower rainfall and higher evaporative demand would likely trigger more frequent or longer drought declarations under current policy, which relies on historical climate data and/or land-use practices as the basis of an expectation of historical climatic variability. A major issue for operational drought schemes is the choice of the most relevant historical period for the relative assessment of current conditions (Donnelly *et al.*, 1998). One possible way of adapting to climate change would be to base drought declarations on only a very recent period, but natural variability dictates the use of a multi-decadal period, and if climate change is rapid this becomes inappropriate as the climate may change within the chosen period. White (2000b) discusses some of the implications of climate change for drought policy.

A further complication is that meteorological drought in Australia is currently defined in terms of serious or severe rainfall deficiency (BOM, 2003). The problem here is that, while drought measured in terms of a rainfall deficiency may be appropriate in a stable climatic situation, it becomes less appropriate if there is a trend in factors affecting soil moisture and water supply other than rainfall. Many different drought indices have been proposed and used in different countries and for different purposes. This is reviewed for the United States by Heim (2002) who describes a range of indices developed for more complex problem-specific purposes. Heim states that any comprehensive drought index that can be applied on a national scale must address the total environmental moisture status and that no single definition of drought works in all circumstances. Heim supports the institution of a new 'Drought Monitor' (DM) for the United States, which uses multiple indices and "attempts to assess the total environmental moisture status by looking at all the indicators available". This is further discussed in Svoboda *et al.* (2002), and the DM is currently distributed in the U.S. via the Internet at: <http://enso.unl.edo/monitor/monitor.html>.

The potential impact of drought on the Australian economy has declined, in relative economic terms, over time in parallel with the decline in the importance of agriculture to the economy (ABARE, 1997; Wilson and Johnson, 1997). In 1950–51, the farm sector constituted 26.1% of GDP, whereas currently (1997–98) it constitutes 2.5%. Similarly, the contribution of the farm sector to Australian exports has fallen from 85.3% (1950–51) to 19.6% (1997–98), with a reduction in the total farm sector labour force of about 6%. This is despite the fact that farm production has increased over the same period. However, drought also impacts on water supply (section 4.1.3), water quality (section 4.1.5), environmental flows (section 4.1.3) and sustainability (section 4.3.8) including soil erosion via dust storms and post-drought sheet erosion (section 4.2.9). These are all issues of increasing concern in Australia both for rural and urban communities. Thus, drought remains an important issue throughout Australia for social, political, geographical and environmental reasons (Gibbs and Maher, 1967; West and Smith, 1996; Flood and Peacock, 1999).

Stehlik *et al.* (1999) studied the impact of the 1990 drought on more than 100 individuals from 56 properties in central Queensland and northern New South Wales to document the social experiences of dealing with drought. They conclude that there is strong evidence that the impact of the extended drought of the 1990s is such that rural Australia will never be the same again: "There is a decline in population, a closing down of small businesses, fewer and fewer opportunities for casual or itinerant work, more and more producers working 'off-farm' and a reduction in available services."

Examples of Australian government involvement in rural industries that have been subject to decline in commodity prices over several decades (e.g., wool) suggest that the industries will be supported until the cost to the overall community is too high, and the long duration or high frequency of drought declarations is perceived as evidence that the drought policy is no longer appropriate (Mercer, 1991; Daly, 1994). In the case of wool, the shift of government policy from that of support to facilitation of restructuring has involved a judgment about future demand and therefore prices (McLachlan *et al.*, 1999) and only occurred after an extended period of low prices (Johnston *et al.*, 1999). With a change in climate toward drier conditions, drought policy probably would follow a similar path.

Science has a major role to play in assessing the probability that recent and current climatic conditions could be the result of natural variability and/or increasing greenhouse gas concentrations. These assessments can be presented in probabilistic terms (e.g., Trenberth and Hoar, 1997), but the recent work of Nicholls *et al.* (1996b), Nicholls (2003 a and b) and Karoly *et al.* (2003) point to a changing relationship between rainfall and surface temperature, which supports the idea that the enhanced greenhouse effect is already affecting Australian droughts. The public and its representatives will have to judge what constitutes evidence of anthropogenic effects and to what extent future climate change projections and their impacts should be acted on. Because of their impact, droughts provide a very public focus for assessing the issues of climate change in relation to natural variability.

One source of adaptation is seasonal and long-lead climate forecasting. This is one area in which climate science already is contributing to better agricultural management, profitability, and, to some extent, adaptation to climate change (Hammer *et al.*, 1991, 2000; Stone and McKeon, 1992; Stone *et al.*, 1996a; Johnston *et al.*, 1999). Indeed, empirical forecasting systems already are revealing the impact of global warming trends (Nicholls *et al.*, 1996b; Stone *et al.*, 1996b), and these systems already are adapting to climate change through regular revision and improvements in forecasting skill. Appropriate land-use and management practices can be reassessed by using agricultural system models with carbon dioxide and climate projections from climate models (Hall *et al.*, 1998; Howden *et al.*, 1999g, h; Johnston *et al.*, 1999). However, political judgments between the alternatives of supporting existing land use or facilitating reconstruction are likely to require increasing confidence in the results of climate models.

4.3.7 Pests, parasites and pathogens

Cropping, horticulture, livestock and forestry industries in Australia are vulnerable to changes in the incidence of existing pests, parasites and pathogens, and invasion by new varieties for which there are no local biological controls (Sutherst *et al.*, 1996; Chakraborty *et al.*, 1998; Cheal and Coman, 2003; White *et al.*, 2003). The likelihood that such pests, parasites and pathogens—particularly those of tropical or semi-tropical origin—will spread southward, or become established once introduced, increases with climate warming. Aspects of climate change, including increases in temperature, atmospheric carbon dioxide concentrations and nitrogen depositions may favour existing or invasive species that are physiologically-adapted to exploit such conditions (Dukes and Mooney, 1999).

Vertebrate pests such as wild dogs, foxes and rabbits directly impact on Australia's livestock industries through predation and competition for pasture. The economic costs of these impacts are estimated to total at least A$420 million per year (Bomford and Hart, 2002). A further A$60 million per year is spent on controlling these vertebrate pests.

Invasive plants or weed species reduce the productive capacity of agricultural systems and threaten the biodiversity value of natural ecosystems. In 1987, agricultural weeds were estimated to cost the Australian economy A$3.3 billion annually, through lost agricultural production and control costs (Combellack, 1987). The costs of environmental weeds, or weeds of natural ecosystems, are more difficult to quantify although weed invasions are considered one of the most serious threats to biodiversity and nature conservation in Australia (Williams *et al.*, 2001).

In-depth case studies have been conducted in Australia to test the performance of pest impact assessment methodologies for estimating the vulnerability of local rural industries to pests under climate change (Sutherst *et al.*, 1996).

The vulnerability of horticultural industries in Australia to the Queensland fruit fly *Bactrocera (Dacus) tryoni* under climate change was examined by Sutherst *et al.* (2000). Vulnerability was defined in terms of sensitivity and adaptation options. Regional estimates of fruit fly density, derived from the CLIMEX model, were fed into an economic model that took account of the costs of damage, management, regulation, and research. Sensitivity analyses were used to estimate potential future costs under climate change by recalculating costs with increases in temperature of 0.5, 1.0, and 2.0 °C, assuming that the fruit fly will occur only in horticulture where there is sufficient rainfall or irrigation to allow the crop to grow. The most affected areas were the high-altitude apple-growing areas of southern Queensland and New South Wales and orange-growing areas in the Murrumbidgee Irrigation Area. Apples and pears in southern and central New South Wales also were affected. A belt from southern New South Wales across northern Victoria and into South Australia appeared to be the most vulnerable.

Adaptation options were investigated by considering, first, their sustainability under present conditions and, second, their robustness under climate variability and climate change. Bait spraying is ranked as the most sustainable, robust, and hence most promising adaptation option in both the endemic and fruit fly exclusion zones, but it causes some public concern. The sterile insect technique is particularly safe, but there were concerns about costs, particularly with large infestations. Exclusion is a highly effective approach for minimizing the number of outbreaks of Queensland fruit fly in fly-free areas, although it is vulnerable to political pressure in relation to tourism. These three techniques have been given the highest priority.

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.* (2003). They considered impacts on European, zebu and cross-bred cattle having different levels of resistance to cattle ticks. The outcome showed considerable expansion in potential geographical impacts. In the absence of adaptation measures, they found projected losses in live weight gain ranging from some 7800 tonnes per year by 2030 to some 21,600 tonnes per year by 2100, compared to present estimated losses of 6600 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. Estimates of costs of live weight loss showed the greatest costs were incurred in the southern parts of the current tick distribution in Queensland, and potentially in northern New South Wales if the present quarantine barrier were to fail. White *et al.* (2003) found that if adaptation measures were adopted, losses were not sensitive to uncertainties in the climate change scenarios. However, they found that uncertainties about the ability to maintain effective quarantine measures and cost-effective treatments, in the face of growing resistance by ticks to treatment, dominated the projected outcomes. These results lead Sutherst (2001), in a review of human and animal vulnerability to parasites, to ask "If society is unable to optimise management [of parasites] under current conditions, what hope has it of preparing for future change?"

The potential impact of climate change on economically significant plant diseases has been reviewed in a global context by Chakraborty and Pangga (2003). Climate warming can cause a significant increase in accumulated heat above critical thresholds affecting crop physiology and host resistance, and break down heat-sensitive resistance genes in many plants. Pathogen dispersal is also controlled by rain intensity and winds in complex ways, and shifts in location of host plants will alter pathogen distributions, although this depends on changes in both temperature and rainfall, and host-pathogen relationships may change.

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. However, the wide variety of hosts, including wheat and other cereals, sugarcane, deciduous fruits, horticulture, grapevines and forests, and of climatic zones, means that impacts will vary from reduced to increased, or little change in different diseases and locations. 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 takes a long time, more research is urgently needed.

4.3.8 Sustainability

Ecological and indeed economic sustainability has become a major issue in Australia (e.g., Moffatt, 1992). Australian government policy has been to integrate sustainability issues within a raft of polices and programs relating to topics such as national heritage, land care, river care, wetlands and carbon sequestration (Commonwealth of Australia, 1996). Land-use change and exotic pests and diseases, notably feral animals and invasive weeds, are threatening many native species and ecosystems (Low, 1999; Cheal and Coman, 2003; <http://www.weeds.org.au/>). This is exacerbated by land degradation, notably soil erosion and increasing salinisation brought about by loss of vegetative cover and rising water tables resulting from reduced evapotranspiration in catchments and irrigation with inadequate drainage.

These issues have been reviewed in several recent papers and reports, including a paper prepared for the Australian Prime Minister's Science, Engineering and Innovation Council

(PMSEIC, 1999). This paper states that continued degradation is costing Australia dearly in terms of lost production, increased costs of production and rehabilitation, possible damage to a market advantage as a producer of "clean and green" goods, increasing expenditures on building and repairing infrastructure, biodiversity losses, declining air and water quality, and declining aesthetic value of some landscapes. PMSEIC (1999) states that the Australian community expects the use and management of resources to be economically, environmentally, and socially sustainable, which will require changes in management processes backed by science and engineering innovation. The report emphasises that individual problems are linked and that an integrated approach is necessary to combat degradation and pursue remediation.

Stoneham *et al.* (2003) have reviewed the concepts of sustainability in relation to Australian agriculture. They emphasise the distinction between weak sustainability, which allows trade-offs between the various forms of capital (natural, human and social), and strong sustainability, which insists that stocks of natural capital, such as soil, biological diversity, etc., are not diminished through time. In some ways, climate can be considered to be part of the natural capital, and climate change can affect other aspects of natural capital such as soil and the viability of species.

Climate change may also exacerbate problems of sustainability by increasing opportunities for colonisation by exotic species (e.g., woody weeds), by affecting the water balance and water tables, and by increasing erosion rates and flood flows through heavier rain events. Increased fire frequency may also threaten remnant forest and other ecosystems and impact on soil degradation. Drought-induced dust storms are a dramatic case of loss of natural capital in the form of soil erosion (AUSGEO, 2002; State of the Environment, 2001, p.50-51; McTainsh *et al.*, 1990; section 4.2.9).

4.3.9 Global markets

The impacts of climate change on food and fibre production in Australia will be direct and indirect, the latter through changing global supply and demand influenced by climatic changes in other parts of the globe. Because a large proportion of food and fibre production is exported, the effect of commodity prices is already a major influence on the areas and mix of plantings and production, as well as profitability (Stafford Smith *et al.*, 1999). Adaptation has taken the form of changes in the mix of production between, for example, wool, lamb and beef, dairy products, horticulture and viticulture, and, most recently, farm and plantation forestry, as well as increasing exports of value-added and processed products. Increased variability of production resulting from climate change may restrict expansion of such value-added products. Response to markets has led to rapid changes in some sectors, but this is more difficult for commodities that require longer investment cycles, such as viticulture and forestry. Nevertheless, adaptation to a highly variable environment is a feature of Australian agriculture, and adaptations to climate change also may contribute to exports of agricultural technology. Improved forecasts of commodity prices and longer term trends in supply and demand, taking into account seasonal climate and ENSO forecasts, are a major means of adaptation. This will be especially important for climate change impacts and will require an understanding of global effects.

The increased risk of catastrophic climate events associated with climate change has emerged as an important issue for the insurance industry over recent years (Tucker, 1997; Salt, 2000). The literature currently focusses more on the risk of catastrophic climatic events to urban infrastructure than agricultural systems, given the risk to insurers is probably higher in the first instance. The issue of insurance risk and climate change will likely intensify in years to come as the incidence of climatological deviations increases, and may lead to global changes in the insurance market affecting Australia (see section 4.4.3).

Climate-related catastrophes and anomalies (including floods, drought and fire) impact on the general public, businesses and the government sector by positively or negatively affecting agricultural production, forestry, tourism, the health and viability of fisheries and the quality and quantity of water resources. As Glantz and Adeel (2000) note, the nature and severity of the impacts of climatic events is related to the intensity of the impact as well as to the level of vulnerability of the affected society. For example, the recovery time from an El Niño-related bushfire will depend on the economic and human resources, including institutions, available to manage the problems. In this sense, underprivileged communities and developing countries will be particularly vulnerable to climate change-related catastrophes and anomalies (Glantz and Adeel, 2000). Such differential impacts, and related economic and policy responses overseas, may well impact on Australian trade, aid and other aspects of our external relations.

4.3.10 Indigenous resource management

Recent recognition of indigenous land rights in Australia has caused a much greater proportion of land to come back under the management control of Aboriginal and Torres Strait Islander peoples (Coombs *et al*., 1990; Langton, 1997; Baker *et al*., 2001). In many situations, this has led to less intense economic exploitation, with more varied land use, (e.g., for low-intensity farming and pastoralism, combined with some horticulture, fishing, and ecotourism). Non-indigenous people have much to learn from traditional indigenous knowledge of land management, including the traditional custodianship ethic—particularly with regard to climatic fluctuations, extreme events, and sustainability (Yibaruk *et al*., 2001). Indigenous knowledge may well lead to greater exploitation of native species for nutritional and medicinal purposes. On the other hand, the indigenous people also have much to gain from greater economic and technical expertise related to markets and new technologies and products (Baker *et al*., 2001).

For example, traditional Aboriginal fire management regimes permitted reproduction of fire-dependent floral species and widespread savannas suitable for grazing. Through the creation of buffer zones, these regimes protected fire-intolerant communities such as monsoonal forests (Langton, 2000) and led to significant modifications of the natural landscape, even in Tasmania (Lehman, 2001). Removal of Aboriginal groups into settlements led to situations where wildfires, fuelled by accumulated biomass, caused extensive damage. Recent research in collaboration with traditional Aboriginal owners has played a key role in joint management of National Parks where customary Aboriginal burning is promoted to conserve biodiversity.

Andersen (1999) looks at the commonly accepted contrast between European ("scientific") and Aboriginal ("experiential") perspectives in fire management and concludes that in fact, European fire managers often lack clear land management goals and are no more "scientific" than Aboriginal fire managers. He argues that the task now is to introduce clearly defined goals into both European and Aboriginal fire management, the evaluation of management options to achieve the goals (including Aboriginal fire management approaches) and the rigorous testing of the effects of these management options upon implementation. This may be particularly applicable in adapting to changing vegetation patterns and increased fire danger in a changing climate. Integrating knowledge of historic and existing patterns of fire management into future fire management planning will be a critical land management challenge in the coming years, when fire patterns and behaviour will be influenced by climate change in addition to a suite of anthropogenic management objectives. The general problem of cross-cultural interaction in relation to land-management in Australia is further explored in Baker *et al*. (2001) and especially the section entitled “Sharing knowledge: tools and communication”.

4.3.11 Adaptation

Adaptation clearly involves the selection of species, and indeed of land use, appropriate to a changing climate, with sufficient forward planning to minimise the cost of change and to optimise any benefits. This requires greater knowledge and location-specific planning tools.

A major Victorian study (Hood *et al.*, 2002) has developed a linkage between scenarios of climate change provided by CSIRO and models of commodity growth responses for a number of land use options for Gippsland, including viticulture, silviculture and pasture. Outputs from the climate change scenario modelling tool OzClim (CSIRO, 1996b) were applied, using a Geographic Information System (GIS), to produce maps of probabilistic land use suitability for Gippsland for the years 2000, 2020 and 2050. Maps were generated for cool climate grapes (including chardonnay, pinot gris, pinot noir and traminer), high yield pasture (perennial rye/ white sub-clover) and Blue Gums (*Eucalyptus globulus vars*.). The general conclusion of this pilot study was that climate change will impact different agricultural activities in diverse ways over time and space. Some areas within this climatically and topographically diverse region will become more suitable for certain activities while others will become less suitable. Further work will consider more detailed analysis of the outputs to assist development of appropriate long-term responses, and the methodology will be applied to other regions of Victoria.

A summary of the key priorities for climate change adaptation strategies for the main Australian agricultural sectors is presented in **Table 6**.

4.4 Settlements and Industry

4.4.1 Introduction

Climate change will affect settlements and industry through changes in the average climate and changes in the frequency and intensity of

Table 6.

A summary of priorities for climate change adaptation strategies for the main Australian agriculture sectors (based on Howden *et al.*, 2003a, with some additions).

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 rules to be more opportunistic depending on environmental condition (e.g., soil moisture), climate (e.g., frost risk) and markets
- Develop warnings prior to planting of likelihood of very hot days 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 spelling of paddocks
- Develop regionally safe carrying capacities i.e., constant conservative stocking rate

Table 6. continued

- 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 management
- Further selection for cattle lines with greater thermoregulatory control.

Viticulture

- Change varieties of grapes grown in a region and look for new sites
- Undertake risk assessment to assess sustainability in more marginal areas
- Analyse chilling requirements
- Assess vine management needed for CO_2-induced increased growth and changed water requirements
- Assess vine and water management to reduce variability in yield and quality
- Modify management of the inter-row environment. This will vary between regions.

Horticulture and vegetables

- 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).

Sugar

- Increase water-use efficient cropping systems in present and potentially water-limiting regions
- Assess cost-benefit of effective seawater barriers
- Improve coordination of cane supply between sectors taking climate into account
- Diversify mill products.

Forestry

- Develop detailed assessment of drought tolerance of important species
- Improve knowledge of the climatic requirements of particular genotypes
- Identify the optimal strategy between high growth (e.g., dense stands with high leaf area) and risk aversion (e.g., sparse stands with low leaf area) for particular sites and particular trees/products
- Evaluate changes to establishment strategies as a result of climate changes
- Assess vulnerability of species planted near their high-temperature limit
- Reassess fire management strategies.

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
- Develop a better understanding of sustainable yield and environmental flows taking climate change into account
- Minimise water loss from storages, canals and irrigation systems
- Recycle waste water.

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.

extreme events. Changes in average climate affect design and performance, including variables such as heating and cooling demand, drainage and structural standards. However, in many cases average climate is only a proxy for design standards that are developed to cope with extreme demands or stresses such as flooding rains, gale-force wind gusts, heat waves, and cold spells.

If the severity, frequency, or geographic spread of extreme events changes the impact of such changes on infrastructure may be severe. For instance, the likely intensification of tropical cyclones, or their possible movement further south into areas where infrastructure is not designed to cope with them, would have significant implications for building design, safety and emergency services.

Disproportionate changes in climatic extremes and associated damages may occur from changes in averages of climate. For example, Coleman (2002) cites a 650% increase in building damages from a 25% increase in peak wind gusts, based on Insurance Australia Group claims data (see **Figure 4.5**.). Evidence from global observations (Mills *et al.*, 2001) supports this generalisation.

The impact of extreme climatic events already is very costly, and as documented for Australia by Pittock *et al.* (1999), the major causes of damage are hail, floods, tropical cyclones, and wildfire. The International Federation of Red Cross and Red Crescent Societies (1999) estimates damages from a combination of drought, flood, and high wind (including cyclones, storms, and tornadoes) in Oceania (Australia, New Zealand, and the Pacific islands) to be about US$870 million per year over the years 1988–1997. This figure apparently does not include hail damage, which is a major cost (see section 4.4.3).

The rate and nature of degradation of infrastructure is directly related to climatic factors. Computer models to predict degradation as a function of location, materials, and design and construction factors have been developed (Cole *et al.*, 1999a,b,c,d and 2000). Buildings and infrastructure that are being constructed now will have projected lives until 2050 or longer, therefore placement, design and construction changes to guarantee this life against climate change are needed. Moreover, the effects of degradation and severe meteorological events may have an unfortunate synergy. 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.

A report for the Bureau of Transport Economics (BTE, 2001) estimates the economic costs of natural disasters in Australia. Estimates are uncertain because of difficulties in quantifying indirect costs, especially that of disruption to business (Gentle *et al.*, 2001). Total estimated costs of all natural disasters exceeding A$10 million each for the period 1967 to 1999 was A$37.8 billion, of which only about A$5 billion was due to non-climate-related disasters (namely earthquakes). Floods were the most costly, exceeding A$10 billion, but severe storms and tropical cyclones were not far behind at about A$9 billion each. Cost of bushfires exceeded A$2 billion, but landslides were much less. In each category insurance costs were less than half the total, and much less for floods, which are not covered in many insurance policies. Total costs were dominated by disasters that exceeded A$50 million each. The annual costs are extremely variable, with a few very large events dominating the picture. As has been found globally (McCarthy *et al.*, Chapter 8), the annual number of events shows an increasing trend. This is due in part to better reporting and probably to increasing population and investment in vulnerable areas such as tropical coastal zones and river valleys (Changnon *et al.*, 2000).

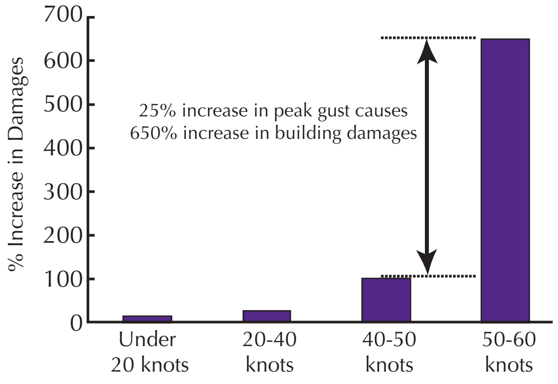


Figure 4.5.
Insurance Group Australia building claims versus peak wind gust speeds, showing disproportionate increase in claims cost from small increases in peak wind gust speed – that is, a 25% increase in peak gusts causes 650% increase in building damages (Coleman, 2002) (1 knot ≈ 0.5m/s).

Australian society is thus becoming more vulnerable to natural disasters, at least in terms of economic costs, and these disasters are primarily climate-related. Any increase in the intensity or frequency of floods, severe storms or tropical cyclones might thus be expected to have a significant effect on total disaster costs unless steps are taken to minimise damages through adaptive planning.

Whilst human settlement has demonstrated an extraordinary capacity to adapt to a wide range of climates, the rate of adaptation that may be required, and the impact that climate change may have on existing settlements and infrastructure is of concern. Business and industry may be particularly affected because the rapid change may require the modification or complete replacement of present buildings and infrastructure before they have reached the end of their useful life. This also suggests that 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).

Many small and remote settlements in Australia are highly dependent on particular industries, be they farming, mining or tourism. Where such industries are threatened by climate change, communities dependent on them for income and employment may themselves be threatened. This may happen in areas of rainfed agriculture subject to drying trends, as is likely in parts of the southern mainland (see section 4.3.6), and perhaps in some tourist towns which may be adversely affected by a decline in the ski industry (section 4.4.5) or in the attractiveness of the Great Barrier Reef (section 4.2.7). On the other hand, new growth opportunities could arise with the emergence of renewable energy industries such as wind farms or biomass energy production.

4.4.2 Infrastructure

A scoping study by Queensland Transport (1999) has identified vulnerabilities for the Queensland transport infrastructure that will require adaptation. Infrastructure assessed in the report includes 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. Three weather systems combining extremes of several of these variables—tropical cyclones, east coast lows and tropical depressions—were also assessed.

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 prioritised 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. Many ports and coastal communities already suffer from occasional storm-surge flooding and wave damage. A series of studies identifies particular vulnerabilities in some Queensland coastal cities (Smith and Greenaway, 1994; AGSO, 1999; Granger *et al.*, 1999), while inland and coastal communities are also vulnerable to riverine flooding (Smith *et al.*, 1997; Smith, 1998a). A key feature of these vulnerability studies is the nonlinear nature of damage response curves to increased magnitude and frequency of extreme events. This is partly because present design standards are exceeded and because of the generally non-linear nature of the damage/stress relationship, with the onset of building collapse and chain events from flying or floating debris (Smith, 1998a).

A study by McInnes *et al.* (2000 and 2003) estimates the height of storm tides in the city of Cairns in northern Queensland, for the present climate and for an enhanced greenhouse climate. Based on the findings of Walsh and Ryan (2000), the central pressure of tropical cyclones was lowered by about 10 hPa and the standard deviation of central pressure (a measure of variability) was increased by 5 hPa but the number of cyclones was unchanged. Cairns is a low-lying city and tourist centre, with a population of about 100,000 that is growing at about 3% per year. Under present conditions, McInnes *et al.* (2000) found that the 1-in-100-year event is about 2.3 m in height, while under the enhanced greenhouse conditions it would increase to about 2.6 m. With an additional 10 to 40 cm sea level rise, the 1-in-100-year event would be about 2.7-3.0 m (see **Figure 4.6**)

The extent of inland flooding implied by the storm surge heights under the present climate is shown in **Figure 4.7 (a)** for the highest 5% of storm tide simulations, and corresponds to the 100-year return period flood. This Figure indicates that much of the township of Cairns remains above the flood line, with the inundation largely confined to the wetlands and Admiralty Island to the south-east of the township. Approximately 32 square km is inundated. However, this does not allow for wave effects, and is only an approximate figure.

Figure 4.7 (b) shows estimated inundation for simulated storm surges under enhanced greenhouse conditions at year 2050, also for the highest 5% of storm surges simulated. The areal extent of inundation is now about 71 square km, or more than twice that in the control climate, and includes much of downtown Cairns. Such results, even if only approximate, suggest a possible need for changes in zoning, building regulations, and evacuation procedures.

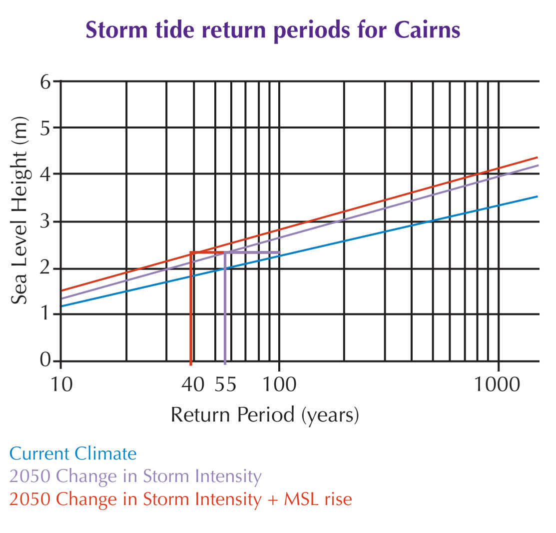


Figure 4.6.
Return periods for storm tides at Cairns under present (lowest line) and enhanced greenhouse conditions. The middle line is for the projected increase in storm intensity only, while the upper line includes an additional mid-range estimate of mean sea level rise of 20 cm. McInnes *et al.* (2003).

Urban areas are vulnerable to riverine flooding (Smith, 1998a) and flash floods exacerbated by fast runoff from paved and roofed areas (Abbs and Trinidad, 1996). Considerable effort has gone into developing methods to improve estimates of extreme precipitation under present conditions (Abbs and Ryan, 1997; Abbs, 1998). Schreider *et al.* (2000) applied a rainfall-runoff model to three different catchments upstream of Sydney and Canberra under doubled CO_2 conditions. They found increases in the magnitude and frequency of flood events, but these effects differed widely between catchments because of the different physical characteristics of each catchment.

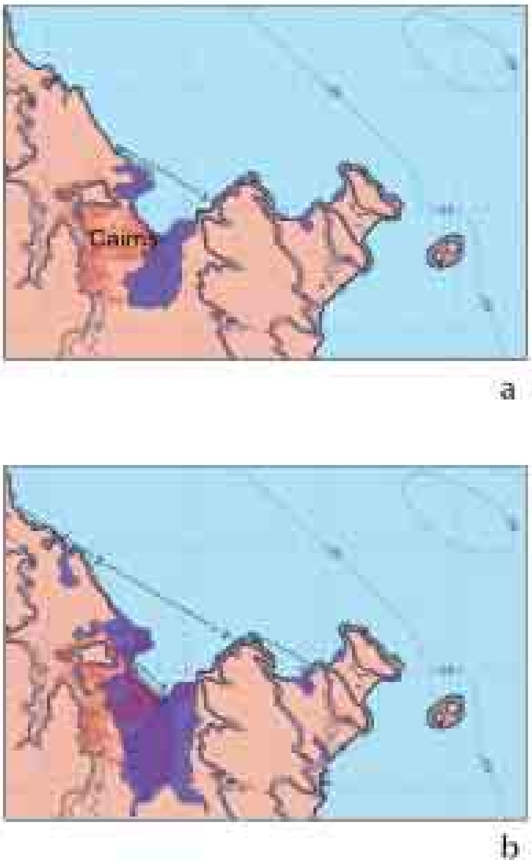


Figure 4.7.
Average area of flooding produced by the top 5% of modelled storm surges (corresponding to a return period of 100 years or greater), in (a) the present or control climate, and (b) in the enhanced greenhouse climate. Flood levels are in 1 m contour intervals and are relative to the land surface over land and mean sea level over water. Dashed contours are bathymetric depths. McInnes *et al.* (2003).

An integrated modelling system has been developed which couples a high-resolution atmospheric model of storm events with a non-linear flood event model suitable for use in urban areas (Abbs *et al.*, 2000). This has been applied to the historic case of flooding by Cyclone Wanda, and by integrating the modelling system with a GIS, flood levels and damage estimates were made for the Gold Coast region. Climate change impacts would occur for a similar storm due to changes in storm intensity and in sea level due to both storm surge effects and mean sea level rise. In the paper by Abbs *et al.* (2001) only the effects of mean sea level rise for 2050 were included. This led to an increase of between 3 and 18% in the number of dwellings and people affected, depending on the amount of sea level rise, which was between 10 and 40 cm.

A similar integrated modelling system named URBS was documented by Abbs *et al.* (2001), and applied to flooding in the Albert-Logan Rivers system inland of the Gold Coast by Shipton (2003). The modelling system was used to explore the sensitivity of the flooding to increases in storm intensity, varying the time sequence of rainfall, and varying its spatial pattern. The study also looked at the effects of differing wetness of the catchment prior to the storm. Results showed that for each 1% increase in rainfall intensity there would be a 1.37% increase in peak runoff. Large variations in peak runoff resulted from changes in time sequences and smaller changes from variations in the direction of approach of the storm. Antecedent wetness was also significant. This means that an increase in intensity of storms due to climate change has the potential to increase runoff and flooding significantly, but this could be partially compensated for by any long-term reduction in average rainfall, which would reduce soil wetness prior to such a storm.

The safety of publicly owned and private dams also is a major issue (ANCOLD, 1986; Webster and Wark, 1987; Pisaniello and McKay, 1998) that is likely to be exacerbated by increases in rainfall intensity and probable maximum precipitation (Pearce and Kennedy, 1993; Fowler and Hennessy, 1995; Abbs and Ryan, 1997; Hennessy *et al.*, 1997).

Vulnerability depends not only on the severity of the potential impacts but also on the hazard mitigation measures put in place (including time- and location-specific hazard prediction), crisis management capability, and policies that avoid or minimise the hazard. These matters are discussed in Smith (1998a), Handmer (1997) and Kouzmin and Korac-Kakabadse (1999).

4.4.3 Investment and insurance

Internationally, there has been growing concern about climate change in the insurance and finance industries (Salt, 2000; McCarthy *et al.*, 2001, chapter 8; Innovest, 2002; UNEP Finance Initiatives, 2002). The UNEP "CEO Briefing" recommends that financial institutions and professionals should:

- become more familiar with the threats and opportunities posed by climate change issues
- incorporate climate change considerations into all their business processes
- work directly with policy-makers on effective strategies for mitigation and adaptation.

Based on Insurance Council of Australia figures (Pittock *et al.*, 1999; Coleman, 2002), insurance losses from major climatic catastrophes from1967 through 1996 averaged A$942 million per year. Of these losses, one third was from floods, 30% from severe storms, 28% from cyclones, and 8% from fires (see **Table 7**).

In an Australian study of insurance and climate change, Leigh *et al.* (1998a) examined four major climatic disasters: the Brisbane floods of 1974, the South Australian bushfires of 1983, the Nyngan floods of 1990, and the New South Wales bushfires of 1994. Total estimated damage from these four events was A$178 million, A$200-400 million, A$47 million, and A$168 million, respectively, however, the insurance industry bore only 39, 31, 9, and 33% of the cost, respectively. Government relief assistance was roughly equal to that from the insurance industry, and about 70-90% of that was provided by the federal government. The Sydney hailstorm of March 1990 caused insured losses of A$384 million, while the largest cost for a single event was the Sydney hailstorm of April 1999 at A$2200 million, of which A$1700 million was insured (BTE, 2001). Coleman (2002) comments that such severe storms that have tracked over densely populated areas make up a disproportionate amount of the total storm claims total. Possible changes to the nature of hailstorms with global warming are thus very important, but so far scientific information on such changes is not decisive (McMaster, 1999). Accordingly, the Insurance Australia Group has initiated studies of the sensitivity of hailstorms to small changes in the atmosphere and ocean (Coleman, 2002).

Leigh *et al.* (1998b) report on the potential for adaptation to climate change by the Australian insurance industry by setting out an array of reactive and proactive options. Responses include reducing insurers' exposure or controlling claims through risk management to encourage disaster mitigation measures. The latter has the advantage of reducing overall losses to the community, rather than merely redistributing them among stakeholders. Natural disaster insurance can be more selective, so that good risks are rewarded and poor risks are penalised. Such rate-based incentives can motivate stakeholders to more effectively minimise exposure to disasters. However, some individuals and businesses may

Table 7.

Average cost of Australian natural disasters by State and Territory for the period 1967–1999 (excluding death and injury costs) (BTE, 2001).

Average Annual Cost ($ million)

State	Flood	Severe Storms	Cyclones	Earthquakes	Bushfires	Landslide	Total
NSW	128.4	195.8	0.5	141.2	16.8	1.2	484.1
QLD	111.7	37.3	89.8	0.0	0.4	0.0	239.2
NT	8.1	0.0	134.2	0.3	0.0	0.0	142.6
VIC	38.5	22.8	0.0	0.0	32.4	0.0	93.6
WA	2.6	11.1	41.6	3.0	4.5	0.0	62.7
SA	18.1	16.2	0.0	0.0	11.9	0.0	46.2
TAS	6.7	1.1	0.0	0.0	11.2	0.0	18.9
ACT	0.0	0.1	0.0	0.0	0.0	0.0	0.2
Total	314.0	284.4	266.2	144.5	77.2	1.2	1087.5
Proportion of total %	28.9	26.2	24.5	13.3	7.1	0.1	100.0

Note Figures may not add to totals due to rounding.

have difficulties if some previously insurable properties become uninsurable against flood because of an increase in location-specific flood frequency. Government intervention and possible co-insurance between government and insurers were also canvassed. Cooperation between insurers and governments to ensure development and enforcement of more appropriate building codes and zoning regulations was regarded as desirable.

Climate change may also affect property values and investment through disclosure of increased hazards and possible reduced or more expensive insurance cover. This is of concern in coastal settlements in relation to storm surges and sea level rise, and in places subject to increased risk from riverine flooding, as well as from tropical cyclones. Yeo (2003) has discussed this issue in relation to flood hazard liability under existing climatic conditions, since in many jurisdictions this is not mandatory or else is poorly determined. Floodplain mapping is regarded as an essential input for sensible flood risk management that is achieved by land use planning, warning systems and public education (Askew and Pilgrim, 1979). However, floodplain mapping can adversely affect property values. This conflict is sharpened when risks change on existing properties, since it may affect many properties that were formerly considered not to be at risk. In the case of tourist facilities such as hotels, it may also adversely affect patronage in seasons of high risk, such as the cyclone season in northern Australia. Clearly, such issues need to be addressed.

4.4.4 Energy and minerals

Energy use is the dominant source of greenhouse gas emissions in Australia. It contributes 55% of the nation's total emissions (Australian Greenhouse Office, 2003). Previous studies have demonstrated that energy demand is linked to climatic conditions (Sailor, 2001). With warmer weather, decreased demand is typical in cold climates, while increased demand is typical of warmer climates. A net increase in demand may result in positive feedbacks in the global climate system through increased greenhouse gas emissions provided energy sources do not change and other adaptations to climate change do not occur (Howden and Crimp, 2001).

In the more tropical parts of Australia particularly, energy demand, essentially for air conditioning, is likely to increase in the warmer seasons (Lowe, 1988; Howden and Crimp 2001). However, this increase will be partly compensated with global warming by reduced winter demand for heating. The balance between these trends will differ between cities with the net effect on demand being less for some cities (e.g., Sydney and Melbourne) than for others (e.g., Brisbane and Adelaide), with substantial increases in overall per capita energy demand with temperature increases (Howden and Crimp, 2001). Similar results were obtained for Sydney by Hart and de Dear (2001). 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.

Electricity usage in Australia has increased 3.4% per year over the past decade (National Greenhouse Gas Inventory, 2001). This increase in demand is due largely to economic growth and also to greater usage of air conditioners in residential and commercial situations (Howden and Crimp, 2001). The link between hot weather and increased electricity demand is also evident in other countries where use of air conditioners has increased (Lam, 1998). Ensuring peak electricity demands are met is already a challenge for some regions of Australia (e.g., Adelaide), especially on hot summer days.

Although Howden and Crimp (2001) did not specifically investigate adaptive mechanisms such as physiology (e.g., that air conditioning is turned on at relatively higher threshold temperatures in warmer climates than in cooler climates) and building design (e.g., shade, insulation and breezeways), there does appear to be significant and consistent adaptation to the existing climate in Australian cities. While inappropriate building design is still common, increasing adaptation has the potential to minimise increases in energy demand.

Gas is widely used for domestic heating in Melbourne. In the light of lower demand in 1999 and 2001 due to exceptionally warm winters, Suppiah *et al.* (2001) projected heating demand in Melbourne for 2003–07 using heating degree-days (HDD) for various scenarios of increases in daily maximum and minimum temperatures. They found a baseline for the year 2000 of 1175 HDD, with a range of 1125–1227. Allowing for both enhanced greenhouse warming and the growth of the urban heat island effect, they found a projected warming of 0.09 to 0.26 ºC by 2007, and a range of HDDs from 1061 to to 1205, with a mid-point of 1132. This is very close to the estimate based on a simple extrapolation of the linear trend using observed temperatures from 1965 to 2000. Increasing population would be expected to add to the actual demand for gas, while more energy-efficient housing would tend to decrease demand.

The other major uses of energy in Australia are transport and manufacturing. Transport demand generally will increase because of population growth, but may be significantly affected by the changing distribution of population across the continent, which in turn may be affected by climate change. Transport is the fastest growing emissions sector in Australia (Australian Greenhouse Office, 2003). It accounts for 73.9 million tonnes of Australia's total net greenhouse gas emissions, which represents about 16% of

Australia's total emissions (Australian Greenhouse Office, 2003). Approximately 90% of these emissions come from road transport vehicles including cars, trucks and buses. Greenhouse gas emissions from the transport sector have risen by 20.3% from 1990 levels (Australian Greenhouse Office, 2002). In the absence of reduction measures, the Bureau of Transport Economics projects that emissions from the transport sector will rise by 38% between 1990 and 2010 (Australian Greenhouse Office, 2003). Significant opportunities for greenhouse gas abatement exist across the transport sector. The use of alternative fuel sources including compressed natural gas (CNG) and liquified petroleum gas (LPG) are key strategies for reducing emissions from the transport sector (Australian Greenhouse Office, 2003). More energy efficient vehicles, urban design and public transport are other options (BTRE, 2002; RTD, 2002).

Thomas (2002) reviewed possible climate change impacts with reference to energy intensive industries, and possible adaptations. The paper lists various likely impacts on electricity generation from climate change:

- warming by 1 ºC can lead to a 3% decrease in thermal efficiency in some facilities, and a decrease in transmission line efficiency
- changes in demand, especially affecting peak generation capacity required for air conditioning
- changes in rainfall and snowmelt affecting the supply and competition for water for power generation
- changes in cloud cover affecting solar generation
- changes in winds affecting wind power
- changes in plant growth affecting bioenergy production and carbon sequestration in soils and forests
- heightened storm events affecting wave and tidal power generation
- storms, strong winds and floods affecting infrastructure performance and security, including shipping, pipelines, transport and distribution systems.

In view of the importance of extreme events and their disproportionate impacts (section 4.4.1), the last dot point is particularly important for the security of energy supply and possible interruptions to production in many industries. Fire, flood and extreme winds can play havoc with distribution systems, but this has not been intensively studied in Australia in a climate change context.

Thomas (2002) went on to list various possible technological developments that might facilitate adaptation, including opportunities for investment. These include cleaner fossil fuel based technologies, renewable and sustainable technologies, energy end use efficiency and transport options. It also pointed out that because of the large existing infrastructure investment, change will not occur quickly, but will evolve in part due to market pressures over the next 30-50 years. The paper points to the need for a broad portfolio of viable technological and policy options and lists various research and development options.

4.4.5 Coastal development and management, tourism

Economic development is proceeding rapidly in many coastal and tropical areas of Australia. This is fuelled partly by general economic and population growth, but it is amplified in these regions by resource availability, shipping access for exports, attractive climates and landscapes, and the growth of the tourism industry.
This selective growth in investment is leading to greater community risk and insurance exposure to present and future hazards (section 4.4.3), while many classes of hazard are expected to increase with global warming (see **Table 2**). Thus, present development trends are likely to make the impacts of climate change worse, especially for sea level rise and increasing

intensity of tropical cyclones. Particular attention should be paid to the implications for the risk to life and property of developments in coastal regions, as well as ways to reduce vulnerability to these hazards. Possible adaptations include improved design standards, zoning, early warning systems, evacuation plans and emergency services.

CSIRO issued a brochure on climate change and coastal communities (CSIRO, 2002) that reviews relevant climate change projections and discusses likely impacts and uncertainties. It must be emphasised that local sea level rise projections may vary significantly from the global average, so that estimates must be quite location-specific (see section 2.1.4). A book on coastal management in Australia summarises the present situation (Harvey and Caton, 2003) but while it mentions climate change and sea level rise, it has only a minimal discussion of the implications.

Besides the vulnerability studies regarding infrastructure in Queensland coastal communities referred to in section 4.4.2, there is a major joint project between the Queensland Government, the Bureau of Meteorology and other agencies, looking at the magnitude of the ocean threat from tropical cyclones. This project is intended to update and extend the present understanding of the storm tide inundation threat in Queensland, including the effects of storm wave conditions in selected areas, and estimates of possible enhanced greenhouse impacts (Queensland Government, 2001). A primary objective of this project is to improve the real-time forecasting capability for storm tide heights, wave climate and inundation. This requires improvements in the database and in the modelling of storm tides and wave setup. The report recommends that for the assessment of long-term storm tide risks allowance should be made for the current estimates of enhanced greenhouse sea level rise and a 10-20% potential increase in maximum potential intensities of tropical cyclones (applicable to a doubled CO_2 climate, likely about mid-century). Although no significant increase in frequency of occurrence or geographical coverage of tropical cyclones is anticipated in the study, the report considers it prudent to investigate the sensitivity of storm tide statistics to a 10% variation in these aspects of the climatology of tropical cyclones under enhanced greenhouse conditions.

Other regional initiatives include a study commissioned by the Gippsland Coastal Board (2002), which looked at shore erosion and a revegetation strategy in the Gippsland Lakes region in the light of increasing salinity and projected sea level rise due to global warming. Sea level rise may be exacerbated locally due to possible subsidence resulting from oil and gas extraction in Bass Strait. The lakes are an internationally recognised wildlife sanctuary under the Ramsar Convention, and a major recreational and tourist attraction, with extensive development of water-side estates. Salinity has increased largely due to the construction of a permanent opening to the sea in 1889, and has caused fringing reed beds to die back. This process is expected to continue, further reducing protection from wave erosion. The majority of lake shorelines are eroding, and this is the greatest current management issue. Possible increases in river-borne sand deposition during flood events could partially counter erosion of some shorelines. The river-borne sand burden partly arises from earlier land clearing and mining operations (see section 4.2.9, and Scott, 2001 for other examples). Projected increases in floods would accelerate transport of this sand into the lakes.

Despite projected sea level rise, the Gippsland Coastal Board (2002) report considers that very few high-value infrastructure assets are threatened by erosion over the next century, however, some wetlands separated from the main lakes by narrow sandy barriers are under threat. The report recommends little additional action other than further study, localised mending of eroding beaches and that new

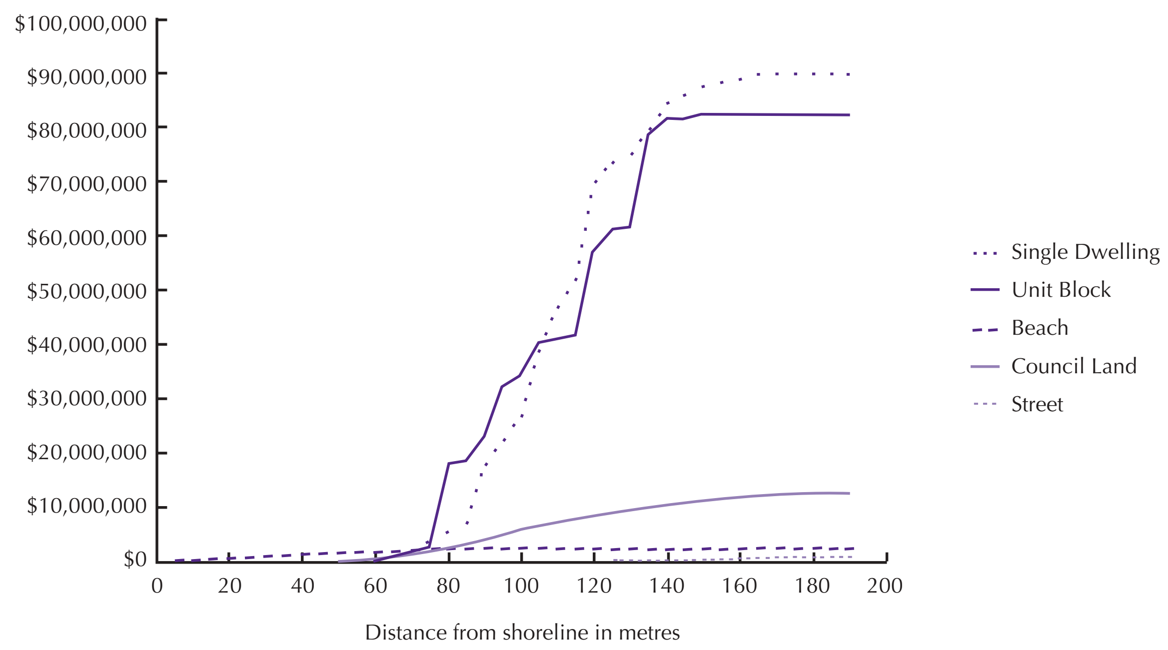


Figure 4.8
Illustrates the results in terms of cumulative loss for different land use classes in A$ for various distances of penetration of sea level rise and storm damage from the existing shoreline.

permanent structures should only be located after taking account of erosion by specifying suitable buffer zones. However, the report does state “in the longer term, the extent of shore erosion will increase dramatically as the anticipated sea level rise due to enhanced Greenhouse Effect begins to take effect by the middle of this century.” Potential breaching of the outer sand barrier along the Ninety Mile Beach producing additional entrances to the Gippsland Lakes is mentioned, but is dependent on possible changes in storm climatology, and does not appear to have been evaluated.

In many coastal locations adequate data for detailed impact assessments are not currently available. Hennecke *et al.* (2000) have developed GIS tools to assess levels of vulnerability to sea level rise and storm scenarios using ranges of results for plausible site parameters, in order to identify areas of high risk. This enables local governments or other responsible authorities to prioritise the needs for more detailed research. Greve *et al.* (2000) have applied these tools to the Collaroy/Narrabeen Beach in Sydney, Australia. This beach is one of the most intensely capitalised shoreline developments in New South Wales, and thus presents a high level of risk. Results of the study demonstrate the large financial risk associated with intense coastal development (see **Figure 4.8**), and lead to a discussion of adaptation options, ranging from expensive coastal protection to the use of setback lines for building, buy-back schemes and building restrictions.

Cowell and Zeng (2003) estimated erosion at Fingal Beach, New South Wales, for a mean sea level rise of 86 cm and super-imposed storm erosion, using a GIS-based model and incorporating ranges of uncertainty. They find average erosion over a distance of 12 m for sea level rise only, increasing to 90 m with storm erosion. Uncertainties lead to possible maximum erosion of 52 m and 120 m respectively.

Many northern Australian coastal tourist resorts rely heavily on the attractiveness of coral reefs, notably those associated with the Great Barrier Reef (GBR) in Queensland, but also others in Western Australia. Fringing reefs provide some protection from shoreline erosion, by reducing wave energy. However, the attractiveness, and in the longer term, the function of the reefs, is threatened by global warming through more frequent coral bleaching. If severe and frequent enough, coral bleaching can lead to the death of corals and their replacement by algae and weed-based ecosystems which are far less attractive. This is discussed in more detail in section 4.2.7, which discusses other concurrent threats to the health of the reefs including pollution, tropical cyclone damage and increased flood runoff. Climate change may affect and interact with several of these threats. Recent reports of coral bleaching including major bleaching events in 1998 and 2002 affecting Australian reefs include Woods (2002); Pockley (2003); AIMS (2002); Wilkinson (2002) and Liu *et al.* (2003).

The AIMS (2002) report states: "Coral bleaching and subsequent mortality, as a result of unusually high seawater temperatures has recently loomed as a major threat to the GBR and coral reefs worldwide. While a number of significant bleaching events were documented on the GBR between 1980 and 1997, the extent of the bleaching in 1998 was massive in comparison. Very extensive bleaching also occurred in the summer of 2001-02. With sea temperatures expected to continue to rise as a result of global warming, extensive coral bleaching and subsequent coral death is a major threat to coral reefs everywhere. The threat is not amenable to management in the short to medium term and affects pristine reefs…."

Management of waste and pollution from settlements and industry will become more critical because of the potential for flood and waste discharge to impinge on water quality, including inland and coastal algal blooms, as well as adverse effects on ecotourism associated with damage to coral reefs (section 4.2.7). Sediment and pollution fluxes into the GBR lagoon are already a major concern (Larcombe *et al.*, 1996; Lobb, 2002). Greater flood flows (see sections 2.1.4 and 4.1.1) and increasing population and development pressures could exacerbate these fluxes. Higher temperatures will accentuate algal blooms (section 4.1.5), which can also be exacerbated by flood runoff of fertiliser and other nutrients from farms. Algal blooms and shoreline erosion related to sea level rise are also factors affecting tourism in other locations such as the Gippsland Lakes in Victoria (Gippsland Coastal Board, 2002, 2003).

Several overseas studies have looked at tourist preferences in relation to climate, particularly temperature and thermal comfort (Palutikof and Agnew, 2001; Matzarakis, 2001; Lise and Tol, 2002). Lise and Tol find that in general OECD tourists prefer a temperature of 21 ºC (average for the hottest month of the year) at their choice of holiday destination. Palutikof and Agnew (2001) use statistical models of present day tourism activity and surveys of public perceptions of seasonal extremes of weather and its impact on vacation plans. They expect that responses to climate will differ between tourists from hot and milder countries. Matzarakis (2001) explores the use of a thermal comfort index. With some regional variations, the same considerations might apply to tourism to and within Australia, but this has not been documented. Increasing thermal indices and physiological discomfort, and a possible increased risk of tropical cyclones, might reduce tourism in some tropical destinations in Australia, while warmer conditions may make some cooler destinations more attractive.

As is the case for energy use in general (section 4.4.4), a warming climate may affect energy usage and thus profitability of hotels in Australian tourist destinations. Bohdanowicz and Martinec (2001) note that about 50% of overall energy consumption in hotels is due to air conditioning. They discuss this with a view to adaptation by varying thermal comfort standards according to climate, and educating tourists to the conservation value of moderating standards to be closer to the outside climate.

The ski industry is also likely to be affected by climate change, with significant reductions in natural snow cover (section 4.2.4). Konig (1998) in a survey at three major ski resorts in New South Wales found that if there were little natural snow Australian ski resorts would lose 44% of their skiers. Some 38% of skiers said they would ski overseas rather than in Australia, and 6% said they would give up skiing. Some 56% of respondents said they would remain skiing in Australia, 25% as much as before and 31% less often. It is unclear if the respondents were assuming there would be more artificial snow-making, although snow-making occurs now in those resorts sampled.

Studies in Europe (Elsasser and Burki, 2002) and North America (Scott *et al.*, 2001 and 2003) suggest that reduced snow cover, especially at the beginning and end of the skiing seasons, may seriously impact on some resorts, depending on their location and marginality. Adequate snow cover in relation to peak holiday periods is important in some cases, and the availability of higher altitude slopes is critical. Adaptation via artificial snowmaking is common to cope with poor seasons at present, and projections suggest it may cope in future but with substantial increases in snowmaking, which may or may not be economic. Snowmaking is effective for down-hill skiing but less so for cross-country (Nordic) skiing and snowmobiling in Canada (Scott *et al.*, 2001).

In Australia, ski resorts range at present from marginal to reliable. Some resorts at elevations above about 1700 metres may retain good natural snow cover well into the second half of the 21st century with the SRES of climate change (Whetton *et al.*, 1996b; Whetton, 1998). Three studies under contract to the skiing industry regarding the use of snow-making have been made more recently by CSIRO Atmospheric Research, but the results are not public. The most recent study estimated the increase in snowmaking facilities needed to cope with climate change by 2020 and 2050 at particular resorts. It allowed for decreased natural snow, increased snow melt and fewer days with temperatures low enough for snowmaking. However, this study did not include likely advances in snowmaking technology, water limitations, and impacts on ecosystems (see section 4.2.4, and Pickering and Hill, 2003). The lowest warming scenario by 2020 required a small increase in snowmaking capacity, while the warmest scenario required modest increases at high-elevation resorts and larger increases at low-elevation resorts. Effects on profitability were not examined. Further research may consider some of these additional factors.

Finally, as the potential ranges of certain agricultural pests such as the fruit fly (section 4.3.7) and disease vectors such as mosquitos (section 4.3.7) increase, possible transfer of such pests and associated vector-borne diseases across internal or international quarantine barriers through tourism may become an increasing issue.

4.4.6 Adaptation and risk management

As a result of the large uncertainties associated with possible future climate, as well as the stochastic nature of extreme events, there is great need for a risk management approach to development planning and engineering standards. In accordance with the precautionary principle, uncertainty should not be allowed to stand in the way of risk reduction measures, which in any case will often have other benefits such as protection of coastal and riverine environments.

It is often argued that in the face of uncertainty, risk management is best achieved through increasing resilience to natural variability (Barnett, 2001; Lempert and Schlesinger, 2000). While this is appropriate for coping with hazards associated with variations within the range of historical experience, i.e., those due to natural variability, it may become increasingly expensive and/or inadequate if variations move outside the historical range, particularly if the climatic change increases the frequency or intensity of one extreme and not the opposite extreme. Planned adaptation based on probabilistic scenarios and risk assessments, such as establishing larger setbacks from flood plains or low-lying coasts, and a capacity to re-evaluate strategies as greater changes occur with time or when there is new information, may be more appropriate. Nevertheless, there is much to be learnt from traditional adaptive coping mechanisms, such as those employed by indigenous communities living in hazardous areas. This includes the people of the remote communities of the Gulf of Carpentaria, who have historically been exposed to frequent tropical cyclones (King *et al.*, 2001; McLachlan, 2003), and other Aboriginal communities living in areas prone to extreme climatic events (Skertchly and Skertchly, 2000).

Australia and New Zealand have jointly developed a risk management standard (Standards Australia and Standards New Zealand, 1999) that is designed to provide a consistent vocabulary and assist risk managers by delineating risk management as a four-step process that involves risk identification, risk analysis, risk evaluation, and risk treatment. Beer and Ziolkowski (1995) specifically examined environmental risk management and produced a risk management framework. Examples of the application of a risk analysis approach are given in sections 4.4.2 for storm surges, and 5.6 for irrigation water demand.

Some settlements which are highly dependent on particular industries, for example agriculture, forestry or tourism, may be adversely affected by climate change (see sections 4.4.1, 4.4.5, 4.2.7 and 4.3.6) which might reduce their employment and income bases. Key adaptation strategies in such cases may include diversification, industry restructuring and aid packages. Early warning of risks to the local viability of such industries would facilitate a smoother and more efficient adaptation process.

4.5 Human Health

4.5.1 Introduction

Impacts of climate and climate change on health can be direct or indirect. Direct effects that are readily attributed to climate include heat stress and the consequences of natural disasters. However, the resulting burden of disease and injury may be less than that from indirect effects such as disrupted agriculture and reduced food security in developing countries, or increased incidence of some vector- or food-borne diseases in developed countries. Positive and negative effects can be anticipated, with the balance depending on location and many other factors including health services and the individual and societal capacity to take necessary precautions.

Amongst the general conclusions reached by the IPCC TAR (McCarthy *et al.*, 2001, chapter 9) regarding impact of climate change on health were several relevant to Australia:

- many vector-, food- and water-borne infectious diseases are known to be sensitive to changes in climatic conditions

- projected climate changes will be accompanied by an increase in heat waves, often exacerbated by increased humidity and urban air pollution, which would increase heat-related deaths and illness
- reduced winter deaths would occur in some regions where such deaths are common
- there is likely to be an increase in the range of potential transmission of malaria and dengue fever and in the incidence and seasonality of these and other diseases within their range
- any increase in flooding will increase the risk of drowning, diarrhoeal and respiratory diseases
- for each anticipated health impact there is a range of social, institutional, technological and behavioural adaptation options to lessen that impact
- overall the adverse health impacts of climate change will be greatest in vulnerable lower income populations, especially the elderly, sick and those without access to good housing including air conditioning and adequate fresh water supply.

Estimation of the overall economic costs of climate change impacts on health have not been attempted in the TAR nor in Australia because there is considerable debate about the derivation and interpretation of monetary costs of human life and well-being. In general, both monetary and non-monetary metrics have been used by the IPCC (McCarthy *et al.*, 2001, chapter 2; Metz *et al.*, 2001, chapter 7). In the case of human health, these include numbers of lives lost or whose quality is diminished. Where there are disadvantaged groups within a country, considerations of equity also apply. Indirect costs of health problems may also be important, for instance quarantine and travel restrictions, and fear of infection and their impacts on the tourist industry, as has recently been illustrated by the outbreak of Severe Acute Respiratory Syndrome (SARS), which has affected tourism, some exports, and the airline industry. Debate on how to factor the value of human life into environmental regulations in the United States is reported in Kaiser (2003).

Following on from the TAR chapter on climate change and health many of the same authors contributed to the book *Environmental Change, Climate and Health* (Martens and McMichael, 2002), and there has been a relevant editorial in the Medical Journal of Australia (McMichael and Woodruff, 2002).

A major Australian report, the Climate Change Health Risk Assessment (CCHRA) (McMichael *et al.*, 2003) has been prepared. The CCHRA provides a risk assessment of various potential health impacts of climate change over the coming decades (particularly 2020 and 2050) in Australia and, in specified instances, neighbouring populations of New Zealand and the Pacific Islands. There are large uncertainties in climate change health risk assessments. To address this, a range of climate change scenarios (CSIRO, 2001) was used to represent uncertainties around projections of future climate, and population projections were based on the Australian Bureau of Statistics projections (Trewin, 2000). Additional statistical uncertainties exist around the dose-response relationship between climate and each health impact, and the potential modifying effects of future adaptation.

The pathways by which climate change affects human health are illustrated in **Figure 4.9.**

The rest of section 4.5 draws heavily on the CCHRA report, and indeed is framed around the key findings of that report, with some amplifying details where appropriate.

4.5.2 Effects of extreme temperatures

According to the CCHRA study (McMichael *et al.*, 2003), temperature-related deaths currently

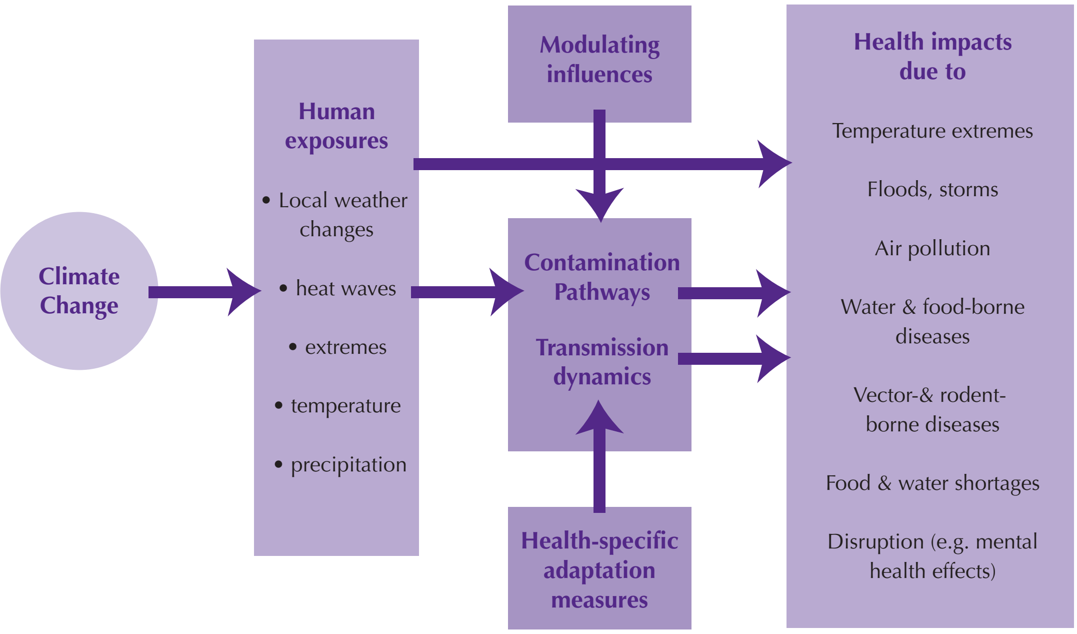


Figure 4.9
Pathways by which climate change affects human health, including local modulating influences and the feedback influence of adaptation measures (adapted from McMichael *et al.*, 2003, based on Patz *et al.*, 2000).

amount to some 1100 people aged over 65 each year, summed over ten major Australian cities. Including the effect of population growth and aging the projected rise in temperature for the next 50 years is predicted to result in a total of three to five thousand additional heat-related deaths per annum, in the absence of adaptive measures. Exact numbers vary with the scenarios used. Temperate cities show higher rates of deaths due to heat than tropical cities, due to greater temperature extremes. Global warming is projected to reduce the number of cold winter days, but it is only in Canberra that fewer annual deaths may occur in the short-term. In the medium to long-term, however, any health gains would be greatly outnumbered by additional heat-related deaths.

The number of current temperature-related deaths in the CCHRA study is considerably higher than that reported historically for Australia by Coates (1996), and in related research in the United States reported by Posey (1980). This may be due to the definition of heat-related deaths, which in the CCHRA study are deaths estimated from the overall relationship between temperature and mortality rates from any cause that are in excess of the average for that time of year. The Coates (1996) figures are deaths directly attributed to heat (i.e. via the processes of heat exhaustion and heat stroke), which are acknowledged as an underestimate of the real toll of heat-associated deaths.

A previous Australian study (Guest *et al.*, 1999) indicated that expected increases in summer mortality due to global climate change would be roughly equalised by corresponding decreases in winter mortality. In the CCHRA analysis, the estimated increases in heat-related deaths were predicted to be far greater than the decreases in cold-related deaths. This different finding may relate to the fact that the previous studies mentioned were not able to adjust for the effect of air pollution. Air pollution is higher in urban areas and, typically, in winter, due to additional particulate pollution from home heating

(Kjellstrom and Shrestha, personal communication 2003). In many temperate zone cities, daily mortality is also much higher in winter than summer—although it has not been possible, in general, to distinguish between seasonal effects in winter (e.g., activity patterns and dietary micronutrient variation) and cold temperature per se. Therefore, if the health effect of temperature is analysed without accounting for air pollution, cold temperatures will appear to have a greater effect on mortality than is really the case. After adjusting for air pollution, it was estimated that it is only in Canberra that a small number of cold-related deaths currently occur (three per year). Canberra may experience positive effects from a reduced number of cold winter days in the short-term, but in the medium- to long-term these health gains are predicted to be outnumbered by additional heat-related deaths. Additionally, the current analysis has used the most recent climate projections: these predict a greater degree of future warming than the earlier projections used by Guest *et al.* (1999).

The cities in the CCHRA analysis cover a broad range of latitude, with much variation in average seasonal temperatures. A higher number of deaths per capita is found to occur in Perth and Adelaide due to the high frequency with which maximum temperatures above 40 °C are recorded in summer. Conversely, the cities in the tropical zone (Darwin, Cairns, Townsville, and to a lesser extent Brisbane) recorded the lowest baseline rates, and have far fewer days above 32 °C. Although the tropical cities have high average maxima, the daily maximum temperatures across a typical summer month vary little, and maximum temperatures typically remain in the low thirties. In Perth and Adelaide, however, within an average month large temperature fluctuations can occur, including days in the high thirties and low forties.

Adaptive measures include development of community-wide heat emergency plans, the development of heat-forecasting systems, better heat-related illness management plans, and better education on behavioural changes (Patz *et al.*, 2000). The extent to which population acclimatisation and adaptation (through increased use of air conditioners, additional intake of fluids, changed work hours, better insulation and building design, etc.) will affect these figures has not been calculated. Some studies have suggested that, even if people acclimatise to the increased warmth, the rapid pace of predicted climate change is likely to mean that summer mortality would increase markedly anyway (Kalkstein and Greene 1997), depending on the scale at which people are able to adapt (i.e., annual, or longer). Nevertheless, level of socioeconomic status can be expected to influence a population's capacity to adapt, and this aspect of the future relationship warrants further research. Indeed, given that the world is now apparently committed to undergoing some degree of climate change, no matter what, there is a need to consider, and evaluate, adaptive strategies in relation to many different types of risks to health.

4.5.3 Flood-related deaths and injuries

Flooding can cause immediate, medium-term, and longer-term effects on communities. The immediate health effects include deaths and injuries by drowning or from being hit by heavy or sharp objects. At least 2213 people were estimated to have died in floods during the period 1788 to 1996 (Coates, 1999), an average of 10.5 deaths per year. There has been an overall decrease in flood fatalities in Australia since the 1850s. Deaths due to flooding were much higher in the early days of European settlement of Australia, when knowledge of the landscape and climate patterns of the country were less developed (for example 36% of the 250 people living in Gundagai were killed in 1852) (Coates, 1999). Improvement in flood mitigation infrastructure, better warning systems and rescue services have also led to a general decline in deaths (Coates, 1999).

Estimates of flood risk in 2020 and 2050 compared to a baseline of the decade 1961–1970 were made in the CCHRA report (McMichael *et al.*, 2003), based on the methodology used by McMichael *et al.* (2002). Weaknesses of this methodology as applied include the very short baseline period and the neglect of possible changes in rainfall variability, as only projected changes in monthly mean rainfalls were considered. Rainfall change projections for three emissions scenarios were based on only two climate models, the CSIRO Mark 2 and the ECHAM4. Results must therefore be considered preliminary. In view of widespread modelling results which suggest that the frequency of high rainfall events may increase (see section 2.1.4), the results here may be conservative.

The CCHRA report concluded that extreme rainfall events (the 1-in-10-year event) are expected to increase in almost all Australian states and territories by 2020. Annual flood-related deaths and injuries may also increase by up to 240% (in the southern areas of New South Wales near the Murray River) or decrease by up to 35% in north-eastern Tasmania, depending on the projected regional rainfall changes. The situation by 2050 is also mixed. As the climate changes, parts of Australia (notably the south-west of Western Australia, southern South Australia, south-west Victoria and parts of Tasmania) are projected to have substantially less rainfall, and in these places the risk of flooding is predicted to decrease. Other parts of the country (notably central Australia, Queensland and parts of New South Wales) are still predicted to be at a greater risk of flood-related deaths and injuries than at present.

4.5.4 Malaria

At the global level, malaria is considered the world’s most important vector-borne disease: approximately 40% of the world's population is at risk of contracting the disease, and malaria is endemic in 92 countries (World Health Organization, March 2002). In Australia, the disease is no longer endemic, with eradication achieved in the 1960s. Only 12 locally acquired cases of malaria have been reported in Australia since 1962, all in far northern Queensland (Brookes, 1997; Walker, 1996).

Some mosquitoes of the genus Anopheles transmit malaria. *An. farauti sensu lato* is the only mosquito species conclusively shown to have transmitted malaria in Australia (in an outbreak in Cairns in 1942, Walker, 1998), and observations since the 1900s suggest this species is the most important Australian vector (Bryan *et al.*, 1996; Cooper *et al.*, 1995; Sweeney *et al.*, 1990). Circumstantial evidence supports the assumption that *An. annulipes* was the vector in isolated cases of transmission in the south in early outbreaks (Sydney, Bega and Melbourne).

The CCHRA analysis considered where malaria transmission *could* occur, in terms of climatic conditions. The climatic limits to the malaria receptive zone in Australia are assumed to correspond with the climatic requirements of the only competent vector of malaria in Australia, namely *An. farauti sensu lato*. The model results indicate that there is a hypothetical risk of the malaria receptive zone expanding southwards under climate change, to include regional towns such as Rockhampton, Gladstone and Bundaberg, if human adaptive measures (such as an increase in epidemiological surveillance and vector control) do not occur in these regions. Although the probability of the re-introduction of malaria into Australia is currently very low, there is a need for continued surveillance and a rapid response to any introduced cases (Walker, 1998a). Surveillance would be necessary to ensure that malaria does not recur in the international tourist spots of coastal northern Queensland (Walker, 1998), particularly as the total population density and the number of infected travellers is expected to increase. The outbreak of vivax malaria at Cape Tribulation in 2002 highlights the threat that ecotourism can play in an area of high malaria receptivity.

The ability to treat malaria is not certain in the longer term, given the rate at which the parasites are developing resistance to available drugs, and the apparent limited effectiveness of new prophylactic drugs. This was illustrated by the recent high incidence of malaria amongst Australian defence forces in East Timor, where primaquine-tolerant parasites existed and doxycycline failed to prevent some infections (Kitchener *et al.*, 2000). With the potential for increased rates of migration of infected people into Australia from neighbouring islands in the tropical Pacific that are stressed by climate change, the pressure on the public health system from imported malaria is likely to increase. This may be less than the threat to Australians travelling in the region with increasing prevalence of drug resistance.

The overall conclusion in the CCHRA report (McMichael *et al.*, 2003) is that in the foreseeable future malaria is not a direct threat to Australia, either under the current climate or under climate change, as long as a high priority is placed on prevention via the maintenance and extension of public health and local government infrastructure.

4.5.5 Dengue fever

Transmission of dengue viruses is influenced by climate, among many other factors (Gubler, 1997). The development, dynamics, abundance and geographic distribution of the vectors and virus are related to ambient temperature, moisture and humidity, and hence are expected to be affected by climate change (Martens, 1998). The north and central areas of Queensland are considered potentially receptive to the establishment of dengue, but the evidence suggests that the virus is not endemic in Australia at present (Mackenzie *et al.*, 1996). *Aedes aegypti* is the only dengue vector that is currently present in mainland Australia. Since the 1940s cases have been confined to Queensland, and principally to the northern and eastern parts of that state (Mackenzie *et al.*, 1996). Dengue has also been reported in Western Australia (from Carnarvon, Broome and Wyndham) and in the Northern Territory (Darwin). Key factors in the emergence and then later disappearance of the vector from these regions have been the increasing urbanisation of society, including the conversion from rainwater tanks to a reticulated supply, the use of refrigerators instead of water-cooled safes, diesel- rather than steam-powered trains, and the use of domestic insecticides (Gubler, 1998; Mackenzie *et al.*, 1996; Reiter, 1996).

Since the commencement of national reporting in 1991, 2595 cases of dengue have been recorded, approximately 250 cases per year (Communicable Diseases Network Australia New Zealand, 2002). Imported cases are regularly diagnosed in all capital cities of Australia. In addition, local transmission following the importation of the virus has caused several outbreaks in recent years: in Charters Towers in 1993 (26% of the non-immune population were infected) (McBride *et al.*, 1998), in Cairns and the Torres Strait in 1996 (201 cases), and in the Cairns region in 1998 (500 cases, Hanna *et al.*, 2001).

There are four serotypes of the dengue virus. Dengue haemorrhagic fever and dengue shock syndrome are life-threatening complications that are thought to result from a second dengue infection, with a virus different in serotype to that which caused the primary infection (Halstead *et al.*, 1970). The large numbers of tourists that travel between Australia and countries in Asia and the Pacific, where dengue is endemic, has greatly increased the risk of introduction of the virus (McBride 1999; Mackenzie *et al.*, 2003). The potential for epidemics of dengue haemorrhagic fever or dengue shock syndrome in northern Queensland has increased in recent years, following widespread infection of several populations with dengue type 2.

Climate change is likely to increase the area of land with a climate suitable for *Ae. aegypti*, the main dengue vector in Australia. *Ae. aegypti*, given predicted vapour pressure constraints, may expand its range to include the towns south-west as far as Carnarvon, and south-east as far as Rockhampton, Bundaberg, Maryborough and Gympie. If no other contributing factors were to change, a larger number of Australians living in northern parts of Australia would be at risk of dengue infection—between 300,000 and 500,000 in 2020, and 750,000 and 1,600,000 in 2050.

The CCHRA report (McMichael *et al.*, 2003) used an empirical model (Hales *et al.*, 2002) to estimate the region climatically suitable for dengue transmission. The model did not account for the possibility of adaptive strategies, which would likely reduce the risk of transmission substantially. Projected population change is accounted for in the future estimates. Validation for the methods used to derive these results have been published by Hales *et al.* (2002). Model estimates for the current potential dengue risk region, based on climatic risk factors only, included the major towns of Broome, Darwin and Katherine. A narrow section of the coastline south of Townsville and north of Mackay was also defined as “at risk”. **Table 8** gives the population estimates of the number of people living in those regions: now, at 2020 and 2050. The model slightly underestimated the current region where dengue transmission has been reported. Epidemic dengue transmission has been reported from towns not included in the current zone—such as Cairns, Charters Towers and Townsville. However, the model did estimate that these towns were on the very edge of climate suitability. The grid cell covering Cairns, for example, had a probability of 0.46, and the cell for Townsville had a probability of 0.48 (the criterion for suitability was 0.5). Owing to the cities in northern Queensland excluded from risk by the model, the figure of 0.17 million currently living in a dengue risk region is an underestimate.

Table 8. Australian populations estimated to be living in a region suitable for maintenance of *Ae. aegypti.* and thus for dengue transmission.

Baseline (million)	Scenarios	2020 (million)	2050 (million)
0.17	Mid		
	CSIROMk2	0.33	0.77
	ECHAM4	0.34	1.16
	High		
	CSIROMk2	0.51	1.24
	ECHAM4	0.49	1.61
	Low		
	CSIROMk2	0.30	0.78
	ECHAM4	0.29	0.75

These results predict that the risk of dengue transmission, based on climate factors alone, would increase (i.e., a greater geographic area was predicted to become suitable for transmission). However, this increase in risk need not necessarily translate into an increase of dengue cases, provided there is (i) a continuation and expansion of the public health response to dengue, and (ii) a continuation of quarantine efforts to ensure that the secondary dengue vector, *Ae. albopictus*, does not become established in the country.

Although both dengue and malaria are diseases with a human host and a mosquito vector, a number of factors combine to make dengue a greater public health threat than malaria. First, there is more potential for dengue outbreaks to spread rapidly within populations. Effective, fast-acting treatments are available for malaria that kill the parasite, and malarious people remain infectious for a much shorter period. No treatments are available that reduce the period of viraemia with dengue. Second, the dengue mosquito is a morning/evening biter that prefers to breed in the urban environment and to feed on humans. Prevention requires constant attention to clearing or treating domestic containers that hold water, such as buckets, pot-plant bases and tyres, and infrastructure such as sump pits and telecommunication pits, and to applying mosquito repellents during outbreaks. In addition, an appropriate design of pot-plant holders, rainwater tanks, sumps and telecommunication pits should be considered to make them less suitable as mosquito breeding sites. The malaria mosquito does not breed in urban environments and is a night biter, and bed nets provide a simple form of protection. For these several reasons, the risk of exposure is higher with the dengue vector.

In summary, suitable conditions for the transmission of dengue may expand south-west down to Carnarvon, and south-east down to Maryborough and Gympie by 2050. If no other contributing factors were to change, a larger number of people living in northern parts of Australia would be at risk of dengue infection (a total of 0.3-0.5 million in 2020, and 0.8-1.6 million in 2050). This increased risk need not mean an increase in dengue cases, provided there is (i) continuing expansion of vector control and public health surveillance, and (ii) quarantine efforts to ensure that a secondary dengue vector, *Ae. albopictus*, does not become established in the country.

4.5.6 Food- and water-borne disease

In general, the incidence of diarrhoea increases as the weather warms (the "seasonal effect"). Higher temperatures promote proliferation of bacteria such as *Escherichia coli* in contaminated foods (Black, 1995). Spore maturation of *Cyclospora cayetanensis* quickens as temperatures increase (Smith *et al.*, 1997). In Peru and Australia the incidence of cases of food-borne disease has been found to significantly increase in the summer months (Lester, 1997; Madico *et al.*, 1997). High temperatures linked to El Niño were associated with marked increases in diarrhoea and dehydration in Lima, Peru (Salazar-Lindo *et al.*, 1997). A study in the UK (Bentham and Langford, 2001) found the monthly incidence of food poisoning to be associated with temperature (especially in the previous month). Using data on the relationship between reported and actual numbers of cases of food poisoning, it was estimated that annually there might be an additional 179,000 cases of food poisoning by the year 2050 as a result of climate change (Bentham and Langford, 2001), assuming no adaptive measures were taken. Some diarrhoeal diseases are more prevalent in winter than summer. Globally, rotavirus is reported to be more common in the cooler months, although seasonal peaks of infection can vary broadly from autumn to spring, depending on the climate zone (Cook *et al.*, 1990). In most countries, food-borne disease is increasing due to changes in behaviour, food consumption, and commerce.

Excessive rainfall events, in certain watersheds, can transport faecal contaminants (human and animal) into waterways and drinking water supplies. People can also be exposed through recreational activities such as swimming (Rose *et al.*, 2001). The high density of farm animals in many parts of the country, and the fact that many communities rely on surface water sources, means that some Australian water supplies may also be at risk of contamination from this source following extreme rainfall events (see also Leder *et al.*, 2002).

Coastal waters in Australia are sometimes contaminated with untreated sewage. Temperature changes also affect coastal water quality, with higher sea surface temperatures favouring pathogen survival and proliferation (McCarthy *et al.*, 2001, chapter 9). Extreme rainfall events may potentially increase nutrient levels in freshwater and seawater. It is possible that these combined effects may favour the production of harmful marine algal biotoxins (resulting in fish and shellfish poisoning) although these relationships require further elucidation (for a discussion see McCarthy *et al.*, 2001).

The most important pathogenic agents of diarrhoeal diseases in developed countries have been classified as: bacterial (*Campylobacter, Salmonella, E. coli, and Shigella*), viral (*Calicivirus, Rotavirus*), and parasitic (*Cryptosporidium, Giardia*) (Tauxe and Cohen, 1995). Gastrointestinal infections due to these organisms are transmitted from person-to-person (faecal-oral route, or respiratory), animal-to-person, or are food-borne or water-borne. In Australia, an estimated 2 to 4 million cases of food-borne infectious disease occur annually (ANZFA, 1999).

Hall *et al.*, 2002 reviewed the seasonality of food-borne disease notifications in Australia. They reported an upward trend in *Campylobacter* notifications between 1991 and 2000, while *Salmonella* numbers increased at first then stabilised in recent years. Notifications of *Salmonell*a infections increased in summer, peaking in March. For *Campylobacter*, notifications increased in spring, peaking in November. Much food-borne disease in the community is not reported to the notifiable system, since this depends on the affected person visiting a doctor, submitting a stool specimen, and obtaining a positive laboratory result that is notifiable (Hall *et al.*, 2002). Thus, these figures are undoubtedly a large underestimate of the true incidence.

Improvements in food practices and water sanitation in the last century have resulted in the control of some of the most deadly infections in the developed world (Tauxe and Cohen, 1995). In developing countries, economic status and educational level have been found to affect diarrhoeal incidence through factors such as hygiene, sewage disposal, inadequate food storage and preparation, child feeding patterns, and lack of potable water (Black, 1995).

Housing and environmental infrastructure for people living in remote Aboriginal communities in Australia is often inadequate (Bailie 2002). Ewald and Hall (2001) conducted a review of housing and health in a remote central Australian Aboriginal community. They noted that while many studies have documented poor environmental conditions and poor health amongst Aborigines, few have systematically demonstrated a causal association between the two. Nonetheless, the quantity of anecdotal evidence is persuasive, and numerous ethical and methodological issues stand in the way of traditional epidemiological studies being conducted in these communities. A recent study of 155 communities in Western Australia found that over 30% had water supply or sanitation problems, and 30% had waste disposal difficulties and a problem with pests (Gracey 1997). Rates of salmonellosis are much higher in the Northern Territory and northern Western Australia, where remote Aboriginal populations comprise a significantly higher proportion of the total state population compared to the southern States of Australia (Roche 2001).

A quantitative analysis of the relationship between climate and diarrhoeal incidence has not been conducted in developed countries. Due to the comparative wealth of developed versus developing countries, their access to sanitation infrastructure, education, and higher standards of housing, it was not appropriate to generalise the results from the Peruvian or Fijian studies to the broad Australian population. Living conditions and access to services in many remote Aboriginal communities of Australia are extremely poor, however, and it is reasonable to compare their facilities and capacity to adapt with that of people living in developing nations. Consequently, the CCHRA analysis examined the impact of increasing temperatures on the incidence of severe all-cause diarrhoeal disease for Aboriginal people living in central Australia.

For the purpose of the CCHRA analysis, it was assumed that diarrhoea among Aboriginal people living in the central Australian region was likely to respond to increases in temperature in the same manner as has occurred in populations in Lima, Peru, and in Fiji, as has been documented by Checklet *et al.* (2000) and Singh *et al.* (2001) respectively. The mid-point estimate of these two studies was used to provide the dose-response relationship. That is, a 5% increase in risk of severe diarrhoea was assumed for each 1 °C increase in predicted future temperatures. Relative risks were calculated by multiplying the projected increase in temperature by the dose-response value. The resulting increase in relative risk was multiplied with the baseline annual diarrhoeal admission estimate to provide an estimate of the possible future numbers of admissions.

The CCHRA study focussed on diarrhoeal admissions to the Alice Springs hospital for children under 10 years of age from December 1996 to June 2002. On average there were 624 episodes of diarrhoea recorded each year over this period, with a seasonal pattern of admissions similar to that observed in Lima, Peru. Peak admissions occurred with a 1-2 month lag following peak summer temperatures, and admission numbers dropped sharply as average monthly temperatures dropped in winter.

Using the same scenarios as in other parts of this CCHRA report, predicted increase in admissions was relatively insignificant by 2020. By 2050, however, an increase in annual admissions of 11% (5-18%) was found. These admissions represent the most severe diarrhoeal cases among Aboriginal children in the central Australian region (i.e., those serious enough to result in hospital admission). The impact of rising temperatures on the transmission pathway leading to less severe diarrhoea (i.e., not requiring hospitalisation) is not clear, although it is biologically plausible to assume a similar order of magnitude increase in the number of cases.

Climate is only one of the many environmental and social factors that have been related to the incidence of diarrhoeal disease. Water quality depends not only on weather events, but also on the management of water resources, and the disposal of sewage into fresh and seawater bodies. As coastal populations increase, so does the level of sewage produced. Recent conflict over sewage disposal into seawater off Sydney's beaches, for example, highlights the potential health risks associated with increasing urbanisation in Australian cities. Although this analysis has focussed on remote Aboriginal issues, other communities in Australia may also be at greater risk of diarrhoeal disease as temperatures rise. Successful adaptation to these conditions would require the continued upgrading of sewerage systems and safe food storage infrastructures. However, food contamination typically occurs early in the production process, rather than just before consumption, and increasing trends in food importation mean that improved surveillance and preventive measures would also be needed (Tauxe, 1997).

In summary, higher temperatures and increased rainfall variability are predicted to increase the intensity and frequency of food-borne and water-borne disease. Successful adaptation to the projected climate changes will require the upgrading of sewerage systems, and safer food production and storage processes. Due to their poor living conditions and access to services, Aboriginal people living in remote arid communities are likely to be at increased risk. An increase of 10% in the annual number of diarrhoeal admissions among Aboriginal children living in the central Australian region is projected by 2050.

4.5.7 Other health impacts

Ross River virus

Ross River virus (RRv) is an arbovirus that is widely distributed throughout Australia.
The virus causes epidemic polyarthritis, which consists of arthritic symptoms that persist for several months and can be severe and debilitating. In some people the disease has been reported to linger for years (Westley-Wise *et al.*, 1996). 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.

The epidemiology of RRv disease varies across Australia (Russell, 1994) reflecting the multiple vector and host species implicated in transmission, and the impact of diverse climatic and environmental conditions on their biological processes. The primary enzootic cycle is between reservoir vertebrate hosts (typically marsupials) and the mosquito vector. Given low immunity in the host population and suitable climatic conditions, massive virus amplification occurs, resulting in a spill-over of infection into human populations. 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. In tropical and sub-tropical regions temperature and rainfall levels enable adult vectors to remain active all year (Kay and Aaskov, 1989), a continuous transmission cycle results, and the disease is endemic. In colder, temperate regions, mosquitoes are active only during the warmer months (Nov-Apr) (Dhileepan, 1996), and viral activity is typically epidemic.

Several studies have identified a relationship between single climate variables and breeding and survival of the RRv vector mosquitoes (Dhileepan, 1996; Lindsay *et al.*, 1989). The complex ecology of RRv has meant that, to date at least, analyses of the climate-disease relationship are confined to the local or regional level. Woodruff and others (Woodruff *et al.*, 2002) modelled the association between climate variables and epidemics of RRv disease in the Murray region, and found a strong relationship between heavy rainfall and outbreaks of disease. They concluded that early warning of weather conditions conducive to outbreaks of RRv disease was possible at the regional level with a high degree of accuracy. Rainfall, temperature and tides have been associated with monthly case incidence in Queensland (Tong *et al.*, 2002), and El Niño-Southern Oscillation has showed some promise as a predictor of RRv disease epidemics in south-eastern States (Maelzer *et al.*, 1999).

More frequent extreme rainfall events are predicted in future (even in regions where average annual rainfall may decrease by up to 5%). In relation to RRv disease, Russell has speculated that *Ochlerotatus* (previously included in the *Aedes* genus) populations in dry areas may be adversely affected by decreased winter rainfall, possibly delaying or precluding virus activity (Russell, 1998). Conversely, the predicted increase in summer rainfall may increase the availability of mosquito habitat that, combined with higher average temperatures, may lead to higher humidity, a lengthened season of abundance and greater transmission levels (Russell, 1998). Rising temperatures on their own, without an accompanying increase in rainfall in a region, are unlikely to lead to an increase of RRv disease in most parts of Australia.

In summary, rising temperatures and changing rainfall patterns are likely to have significant impacts on the transmission of RRv disease. These impacts would vary by geographical area. In view of the dynamics of transmission for this disease, more research is required at the regional level into the ecology of the virus, 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 (Tong *et al.*, 2002). Modelling of the relationship between climatic factors and disease outbreaks would help in the prediction of future potential consequences of climate change.

Increased exposure to solar ultraviolet radiation

Stratospheric ozone destruction is essentially a separate process to greenhouse gas accumulation. However, greenhouse gas warming of the troposphere appears to be linked to cooling of the stratosphere (Houghton *et al.*, 2001). Further, people's solar exposure behaviour may change as climatic conditions change. The former, physical, link with climate change, appreciated only recently, is that lower temperatures in the stratosphere may accelerate the destruction of ozone by chlorofluorocarbons (CFCs). Although emissions of ozone-depleting chemicals such as CFCs have fallen significantly because of international agreements, global climate change may delay recovery of the stratospheric ozone. High levels of solar ultraviolet (UV) radiation will continue to pass through to Earth's surface for longer than would occur without climate change.

The effects of UV radiation on skin cancer, skin ageing, and cataracts of the eye are important public health issues in Australia, which has one of the highest skin cancer rates in the world (Marks *et al.*, 1989). These high rates cannot be attributed to relatively recent phenomena such as ozone depletion or climate change because of the relatively long incubation time of serious skin cancer forms such as melanoma. Much of the risk is likely to be due to a predominantly pale-skinned population living in an environment with relatively low air pollution, plentiful sunlight and an outdoors-oriented lifestyle (Armstrong, 1994). In a warmer world, patterns of exposure to solar radiation can be expected to change (such as an increase in swimming and other outdoor activities, or conversely a retreat indoors to air conditioning).

These behaviours do signal a high degree of vulnerability to prolonged elevated levels of UV radiation (McKenzie and Elwood, 1990). The present levels of UV radiation have been increasing for the past 20 years (McKenzie *et al.*, 1999), and it is expected that the incidence of melanomas and other skin cancers will increase as a result of increasing UV radiation (Longstreth *et al.*, 1998). Preliminary evidence also suggests that higher environmental temperatures enhance UV carcinogenesis. If this were true, the effect of rising temperatures on skin cancer incidence may soon be greater than that of ozone depletion (Leun and Gruijl 2002). While recognising the adverse effects of increased exposure to ultraviolet radiation, Lucas and Ponsonby (2002) also point out that some exposure to ultraviolet radiation is needed to maintain healthy levels of vitamin D.

Respiratory diseases

Asthma is a major health concern in Australia, with the prevalence one of the highest in the world (AIHW, 2000). Asthma became the sixth National Priority Health Area in Australia in 1999. Studies of the prevalence of asthma in New Zealand have shown an association with average temperature (Hales *et al.*, 1998). Predicted changes to the Australian climate will certainly influence the life cycle of a range of plants and animals that have been linked to asthma occurrence (Curson, 1993). However, although there is a demonstrated relationship between many allergen-producing organisms such as plants, mould, house mites and cockroaches, and climatic factors such as humidity, rainfall, temperature and sunshine (Beggs, 2000), the mechanism for the relationship between climate and asthma is contradictory and not well understood (Koren, 1997). Because of the multi-causal nature of asthma initiation, it is not clear how climate change would affect this disease. Further research into general allergies and asthma, including their seasonal and geographic distribution, is required.

Outdoor air pollution

Climate change may influence the levels of several outdoor air pollutants. Ozone and other photochemical oxidants are a concern in several major Australian cities (Woodward *et al.*, 1995). In Brisbane, current levels of ozone and particulates have been associated with increased hospital admission rates (Petroeschevsky *et al.*, 1999) and daily mortality in persons aged 65 and over (Simpson *et al.*, 1999). Outdoor particulate pollution in the winter (largely generated by household fires) is common in some Australian cities such as Hobart and Canberra, and has been associated with increased daily mortality in Christchurch, New Zealand (Hales *et al.*, 2000). Formation of photochemical smog is promoted in warmer conditions, although there are many other climatic factors—such as windspeed and cloud cover—that are at least as important as temperature but more difficult to anticipate. A rise in overnight minimum temperatures may reduce the use of fires and hence emissions of particulates; but it is not known how this might affect pollution and population exposures.

Algal blooms

Toxic algal blooms may affect humans as a result of direct contact and indirectly through consumption of contaminated fish and other seafood. At present this is not a major public health threat in Australia, but it is an economic issue (because of effects on livestock and shellfish). It could affect very large numbers of people (Oshima *et al.*, 1987; Sim and Wilson, 1997). No work has been carried out in Australia relating the health effects of algal blooms to climate. Elsewhere in the Pacific, it has been reported that the incidence of fish poisoning (resulting from ingestion of fish contaminated with ciguatoxins) is associated with ocean warming in some eastern islands, but not elsewhere (Hales *et al.*, 1999). It is uncertain whether these conditions will become more common in Australia with projected climate change.

4.5.8 Vulnerability

Climate impacts are determined not just by the magnitude of environmental change but also by the vulnerability of exposed populations. Examples of biophysical vulnerability are the susceptibility of pale-skinned populations to the effects of UV radiation and the vulnerability of isolated island ecosystems such as Australia's to invasion by exotic species (including disease vectors).

Woodward *et al.* (1998) reviewed social determinants of vulnerability to health effects of climate change in the Pacific region. Australia is one of the wealthiest countries in the region, with relatively low population densities and well-developed social services. For these reasons, Australia is likely to be less vulnerable overall to many of the threats to health from climate change than many neighbouring countries. However, within Australia there are groups that are particularly susceptible to poor health. Sources of disadvantage include poverty, low housing standards, high-risk water supplies, lack of accessible health care, and lack of mobility. These factors tend to be concentrated in particular geographical locations and ethnic groups (Ewald and Hall, 2001; Gracey, 1997) and carry with them increased vulnerability to most of the hazards that are associated with climate variability and climate change.

Apart from McMichael *et al.* (2003), there have been no studies in Australia that have attempted to quantify vulnerability to disease and injury. Some work has been carried out on indices of environmental vulnerability in the South Pacific (e.g., Kaly *et al.*, 1999). These studies have focussed on measures of the resilience and integrity of ecosystems; with further development, they may assist in future forecasts of the impacts of climate change on human health. The number of people exposed to flooding due to sea level rise in Australia is predicted to approximately double in the next 50 years, although absolute numbers would still be low. For the rest of the Pacific region, however, the number of people who experience flooding by the 2050s could increase by a factor of more than 50, to between 60,000 and 90,000 in an average year. As well as the impact of flooding on settlements, the impact of sea level rise on freshwater quality and quantity is likely to be a critical threat to Pacific Island health and welfare (Hay and Beniston, 2001; Barnett and Adger, 2001). Vulnerability in the Pacific Islands could impinge indirectly on Australia, through our external relations and aid programs (Edwards, 1999).

Vulnerability of Aboriginal and Islander communities

In general, indigenous people in Australia (Aborigines and Torres Strait Islanders) are vulnerable to the effects of climate change because they tend to be under-represented in mainstream economic activity and modern technological education, and experience higher levels of poverty, lower rates of employment, and higher rates of incarceration than the overall population. These factors have widespread and long-term impacts on health (Braaf, 1999).

For example, Northern Territory health data for 1992–94 show that the mortality rate for indigenous people was 3.5-4 times greater than that for non-indigenous people. Life expectation at birth was 14–20 years lower for indigenous Australians than for non-indigenous Australians (Anderson *et al.*, 1996). The indigenous population displays diseases and health problems that are typical of developed and developing nations. These include high rates of circulatory diseases, obesity, and diabetes, as well as diarrheal diseases and meningococcal infections. High rates of chronic and infectious diseases affect individual and community well-being and reduce resilience to new health risks (Braaf, 1999). This is certainly the case in central Australia (Edwards and Hall, 2001) and Western Australia (Gracey, 1997).

As noted earlier, changing climate has implications for vector-borne and waterborne diseases in indigenous communities. In the "Top End" of the Northern Territory during the wet season, hot and humid conditions are conducive for vectors of infectious diseases endemic in the region. Vectors include flies, ticks, cockroaches, mites, and mosquitoes. Flies can spread scabies and other diseases. Mosquitoes are vectors for Australian encephalitis and endemic polyarthritis. Giardia and shigella are water-borne diseases that are common among indigenous children in the region. Both can be spread from infected people to others through consumption of infected food and untreated water. Existing and worsening overcrowded housing conditions, poor sanitation, and poor housing materials create breeding grounds for infection. Climate changes and sea level rise—which create conditions that are suitable for new vectors (such as malaria) or expand distributions of existing vectors—may expose such vulnerable populations to increased risks.

Impact assessments that consider only biophysical relationships between climate and health will be inadequate in evaluating indigenous health outcomes. The possibility, or indeed likelihood, that people may have very different views concerning what makes them vulnerable to climate change, which impacts may be significant, and what responses may be implemented also will need to be considered (Braaf, 1999).

The present social circumstances of indigenous peoples provide a poor basis on which to build adaptation responses to climate change threats. Thus, policies that aim to improve resilience to climate change impacts could encompass efforts to reduce relevant social liabilities such as poverty, poor education, unemployment, and incarceration, and support mechanisms that maintain cultural integrity. Adaptive strategies could pursue economic development of these communities while sustaining the environments on which these populations are dependent (Howitt, 1993). Strengthening communication between indigenous communities, scientists, health workers and decision-makers is essential (Baker *et al.*, 2001).

4.5.9 Adaptation

Climate change differs from many other environmental health problems because of its gradual onset, widespread as well as localised effects, and the fact that the most important effects will probably be indirect. These factors inevitably affect perceptions of the problem.

In particular, there is a danger that the problem will not be recognised until it is too late to respond effectively, or a substantial cost has already been incurred. Adaptative ability will be strongly influenced by the extent and rate of warming, as well as local environmental conditions and social behaviours, and the range of social, technological, institutional, and behavioural adaptations taken to reduce the threats.

The long causal chain between climate variation and most human health outcomes underlines the critical role of adaptation. It is noteworthy that, particularly in the work of the IPCC's Third Assessment Report (McCarthy *et al.*, 2001), there has been a substantial growth in the attention being paid to the question of adaptation. While mitigation of greenhouse gas emissions remains the primary need worldwide, it has become clear that the planet is committed to significant climatic change already. Greater emphasis is therefore being given to research evaluating the possibilities for planned and autonomous adaptations, and how impacts might be modulated by differing scenarios of independent non-climate change (e.g., in demography, urban design, technologies, information flows, trade and economic development). The impact on health of mitigation strategies has not been dealt with in this report. However, there could be appreciable health benefits in the short-term from many mitigation strategies. Transport policies to cut emissions from vehicles could potentially lead, for example, to lower levels of particulate and gaseous air pollution and increased physical activity.

Climate change may bring conditions that are more favourable for disease and other adverse health impacts, but that does not necessarily mean that such impacts will occur, as long as there is the capacity to adapt to changing circumstances. Nevertheless, many individuals and communities are likely to lack the resources required for adequate response (under assumptions of reasonable economic growth, technology change, etc. in the future). For example, not all Australians can afford to heatproof their houses as protection against increasing heatwaves. Even if this option was affordable for most, it may not be sustainable as a global strategy. The environmental costs of providing air-conditioning for the whole population of continental Asia, for example, would be overwhelming. (See also the earlier discussion in section 4.5.2.)

It would be short sighted to imagine that adaptation provides a complete answer to the problems of climate change. Nevertheless, adaptation must be part of the response. Studies of adaptation to climate change are still relatively few in Australia and New Zealand. Climate change pressures provide further reason for developing and sustaining effective quarantine and other biosecurity measures, which are already a high priority to protect Australia's future well-being, even in the absence of climate change.

Public health infrastructure

A major challenge in Australia is how to protect and improve public health systems that deal with threats to health such as those that will potentially accompany climate change. Examples include border controls to prevent introduction of pathogens (including those from livestock and animal imports), measures required to ensure safe food and clean water, and primary health care services that reach the most disadvantaged and vulnerable members of the community. Threats to these systems include restrictions on government spending, increasing demands, and fragmented systems of purchase and provision of services.

With vector-borne diseases, the major challenge in Australia will be to control the expansion and increased incidence of diseases that already are present in the country, such as Ross River virus and Murray Valley encephalitis—which are strongly influenced by climatic events. Introduction of new pathogens from close neighbours such as Papua New Guinea also is possible. Imported Japanese encephalitis and malaria remain serious threats, influenced principally by the numbers of people moving across the Torres Strait and the effectiveness of health services in the far north of Australia.

Design of human environments

Several measures can be taken to better design human environments to cope with potential health stresses resulting from climate change. These measures include:

- Air conditioning and other measures to reduce exposure to heat.
- Limiting exposure to disease vectors by measures such as use of screens on doors and windows and restriction of vector habitats (especially near waterways and urban wetlands).
- Land-use planning to minimise ecological factors that increase vulnerability to potential climate changes, such as deforestation (which increases runoff and the risk of flood-related injury and contamination of water supplies), animal stock pressures on water catchments, and settlement of marginal or hazardous areas such as semi-tropical coastal areas that are prone to storms and close to good vector breeding sites.

5

Adaptation Potential and Vulnerability

5. Adaptation Potential and Vulnerability

5.1 Adaptation Concepts and Strategies

As discussed in section 3.1, adaptation is an automatic or planned activity that minimises adverse effects of climate change and maximises advantages. It is one of the two possible means of coping with the impacts of human-induced climate change—the other is emissions mitigation, or reduction of the degree of climate change. Adaptation is essential to cope with the climate change we cannot avoid now and in the near future, while mitigation would limit the extent of the climate change over time.

The United Nations Environment Program has developed a handbook on methods for climate change impacts assessment and adaptation strategies (Feenstra *et al.*, 1998) which discusses the principles and strategies for adaptation. According to Burton *et al.* in Feenstra *et al.* (1998) these can be summarised in eight alternative but not exclusive strategies (slightly edited here):

1. Bear losses. All other adaptation measures may be compared with the baseline response of "doing nothing" except bearing or accepting the losses. Bearing loss occurs when those affected have no capacity to respond in any other ways (for example, in extremely poor communities) or where the costs of adaptation measures are considered to be high in relation to the risk or the expected damages.

2. Share losses. This involves sharing the losses among a wider community. Such actions take place in traditional societies and in the most complex, high-tech societies. In traditional societies, many mechanisms exist to share losses among a wider community, such as extended families and village-level or similar small-scale communities. In societies organised on a large-scale losses are shared through public relief, rehabilitation, and reconstruction paid for from public funds (usually government funds or public appeals). Sharing losses can also be achieved through private insurance (but usually only when the risk is considered random and uncertain for the individual insured).

3. Modify the threat. For some risks, it is possible to exercise a degree of control over the environmental threat itself. When this is a "natural" event such as a flood or a drought, possible measures include flood control works (dams, dikes, levees) or water storage. For climate change, the major modification possible is to slow the rate of climate change by reducing greenhouse gas emissions and eventually stabilising greenhouse concentrations in the atmosphere. In the language of the UNFCCC, such measures are referred to as mitigation of climate change and are considered to be in a different category of response from adaptation measures.

4. Prevent effects. A frequently used set of adaptation measures involves steps to prevent the effects of climate change and variability. Examples for agriculture would be changes in crop management practices such as increased irrigation, additional fertiliser, and pest and disease control.

5. Change use. Where the threat of climate change makes the continuation of an economic activity impossible or extremely risky, consideration can be given to changing the use. For example, a farmer may choose to substitute a more drought-tolerant crop or switch to varieties with lower moisture. Similarly, agricultural land may be returned to pasture or forest, or other uses may be found such as recreation, wildlife refuges, or national parks.

6. Change location. A more extreme response is to change the location of economic activities. For example, major crops and farming regions could be relocated away from areas of increased aridity and heat to areas that are currently cooler and which may become more attractive for some crops in the future.

7. Research. The process of adaptation can also be advanced by research into new technologies and new methods of adaptation.

8. Educate, inform, and encourage behavioural change. Another type of adaptation is the dissemination of knowledge through education and public information campaigns, leading to behavioural change. Such activities have been little recognised and given little priority in the past, but are likely to assume increased importance as the need to involve more communities, sectors, and regions in adaptation becomes apparent.
(Adapted from Burton et al., in Feenstra et al.,1998:5-5)

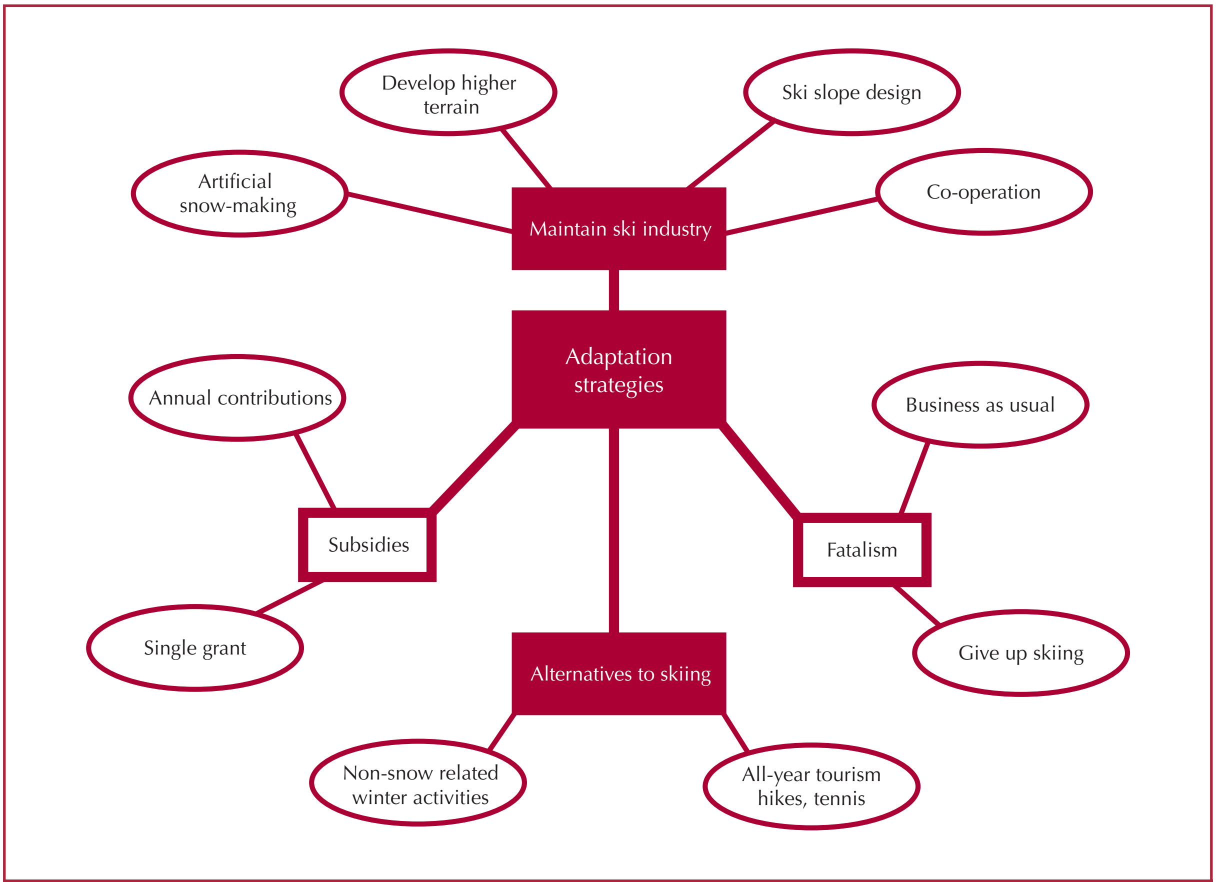


Figure 5.1.
Schematic diagram, adapted from Elsasser and Burki (2002), showing the choice of adaptive strategies for a ski industry faced with the threat of global warming. The choice that is actually made will depend on the resort location and features, nature of competing tourist resorts, rate of warming and the views and preferences of all stakeholders, including skiers, staff and resort owners. Cost and return on investments will be a major factor, and environmental considerations such as water supplies for artificial snow-making, power usage and visual impact will also be important. The situation of the Australian ski industry is discussed in section 4.4.5.

There are many examples of adaptation strategies and choices, and some Australian examples will be given below. **Figure 5.1**, adapted from a study of the threat of climate change to tourism in the European Alps (Elsasser and Burki, 2002), illustrates many of the above points from Feenstra *et al.* (1998). A similar schematic diagram could be drawn up for most affected sectors and activities.

Much more can be said about adaptation, drawn from the Handbook cited above, or the many other reports and papers on the subject, including especially chapter 18 of the TAR Working Group II Report (McCarthy *et al.*, 2001). Appropriate adaptation strategies will only be adopted if there is a degree of foresight as to what is likely to happen and how it will affect people. Confidence is also needed that the projected climate changes will occur, with understanding of possibilities and alternatives. Agreement is also required that the cost/benefit ratio for action is favourable, and the necessary human, economic and technical capacity to act must exist. If any of these conditions are not met, adaptation will at best be less than optimal.

In this connection it is interesting to reflect on the role of technology, and the common tendency to look for “either/or” solutions to problems. The problem of coping with climate change is so complex, especially as it interacts with other environmental and socioeconomic problems, that no single solution is sufficient. In particular, both adaptation and mitigation have essential roles to play, as indicated in section 3.3 and **Figure 3.2**. Yet there are some who argue that human inventiveness means that we can adapt to almost any climate change (and therefore do not need to reduce emissions), while others argue that we can reduce greenhouse gas emissions very rapidly if only we have the will, and so do not need to adapt. The fact is that both strategies are needed, and both require a good measure of technological innovation and resourcefulness.

5.2 Australian Adaptation Studies

The south-west of Western Australia has already experienced a multi-decadal climate change in the form of a roughly 10 to 20% decrease in rainfall in the 1970s, with a corresponding 40 to 50% reduction in inflow to Perth’s water supply, which has not returned to the previous ‘normal’ in the last three decades (see discussion in section 2.2.1). Whether or not this change is due to the enhanced greenhouse effect remains an open question, although the most likely answer is that it is partly natural, and partly of human origin (Sadler, 2002; Foster, 2003). However, the projections of climate change due to the enhanced greenhouse effect, as early as 1987, suggested that rainfall in the region would decline, although not until well into the 21st century (Pittock, 1988; Sadler *et al.*, 1987).

Following the recommendations out of the review paper by Sadler *et al.* (1987), the Water Authority of Western Australia announced a strategy of incremental water system adjustments effectively assuming that the rainfall and yield would track down a trend-line to a 20% decline in rainfall (and twice that amount in yield) relative to the pre-1970 average by 2040. In an initial adjustment, the water system yield was written down by some 13%. This response implied some earlier scheduling of future water source developments and continued promotion of demand management. Decisions would be reviewed from time to time based on experience and advances in climate science. Meanwhile, research into the causes of the rainfall decline were encouraged, and this resulted in the setting up of the Indian Ocean Climate Initiative (IOCI), which continues to investigate the reasons for the decline, methods of seasonal forecasting in the region, and the possible future implications of the enhanced greenhouse effect (Sadler, 2002). Also, the Western Australia government is in the process of adopting a greenhouse strategy to both mitigate and adapt to climate change (Greenhouse Task Force, 2002).

As Sadler (2003) states "This decision by water managers was controversial at the time and remained so for many years. However, against what has transpired, a decline of some 50% in streamflow by 2002, not 2040, the decision was far from extreme." It is a good example of what Sadler (2003) calls "informed adaptation", which is subject to adjustment as new information comes to light.

A major review of the adaptive capacity of the Australian agricultural sector to climate change was performed by Howden *et al.* (2003a). The study identified a number of potential options for Australian agriculture to adapt to climate change, and found that many were extensions or enhancements of existing activities that are aimed at managing the impacts of existing climate variability. It noted, however, that less than a dozen had been evaluated for their utility in reducing the risks or taking advantage of climate change impacts. Only a couple of adaptations had been evaluated for their costs and benefits. The Howden *et al.* (2003a) report notes that additional research and development is needed on specific adaptations, and that such research and development should yield high returns. A list of sector-specific but generic adaptation strategies are listed in section 4.3.11. Each would need to be investigated in relation to the location, industry and stakeholder concerns and capabilities, and costs and benefits in its local context.

Crimp *et al.* (2003) report on a scoping study for an integrated assessment of climate change impacts and options for adaptation in the Cairns and Great Barrier Reef region. This involves stakeholder consultations and aims to look at impacts and adaptations in relation to biodiversity, agriculture and water resources, pests, diseases and health, coastal regions, the Great Barrier Reef and tourism. Knowledge gaps were considered to be important barriers to understanding potential impacts and thus to developing adaptation strategies.

Various programs aimed at managing existing problems such as soil erosion, salinity and eutrophication (problems largely due to previous land use practices) are of course relevant to managing for climate change. An example is the National Eutrophication Management Program (Chudleigh *et al.*, 2000) that aims to understand the causes of algal blooms, which impose an annual cost estimated at A$200 million. Since increased storm runoff and higher water temperatures may make eutrophication a more serious problem under enhanced greenhouse conditions, such programs are a valuable preparation for action to minimise adverse effects.

Discussions on adaptation can also be found in sections above on ecosystems and conservation (section 4.2.9) and settlements and industry (section 4.4.6). What is clear from all these discussions is that at present most consideration of adaptation to climate change in Australia is generic, with only a small number of specific examples, and even fewer where costs and benefits have been assessed. Lack of stakeholder involvement and of fundamental knowledge about systems behaviour, co-benefits and possible adverse side-effects make assessment of adaptation strategies difficult and their adoption in many cases premature. Experience dealing with natural climatic variability is important, but where climate change exceeds previous limits of variability new thresholds may be crossed which require new forms of adaptation.

Internationally, the United Nations Development Program is developing an Adaptation Policy Framework, with Australian participation, mainly for use in developing countries, but relevant to Australia also. Details are available on the web at: <http://www.undp.org/cc/apf_outline.htm.>

While there are many approaches to developing adaptation strategies, some steps seem to be essential:

- Qualitatively identify vulnerability with stakeholder participation
- Make initial assessments and prioritise
- Identify key variables and thresholds for impacts, and identify gaps in knowledge
- Gather relevant data, commission research where necessary, and build models of affected systems
- Run models to assess impacts and identify possible adaptation strategies
- Identify co-benefits and possible adverse side-effects
- Do costings
- Discuss with stakeholders with regard to acceptability, levels of confidence, priorities, related context, and willingness to act
- Implement and assess results
- Reconsider and take account of any new information
- Modify strategies and act again.

This is a long and continuing process requiring integration across the community of stakeholders and related issues. It is clear that the process has only just begun in Australia.

5.3 Possible Benefits of Climate Change

Not all the impacts of climate change will be detrimental. Indeed, several studies have looked at possible benefits. Moreover, adaptation is a means of maximizing such gains as well as minimizing potential losses.

However, potential gains have not been well documented, in part because of lack of stakeholder concern in such cases and consequent lack of ear-marked funding. Examples that have not been fully documented include the possible spread of tropical and subtropical horticulture further poleward (there are some New Zealand studies, for example Salinger and Kenny, 1995; Hall and McPherson, 1997). In southern parts of Australia, notably Tasmania, there could be gains for the wine industry, increased comfort indices and thus tourism, and in some scenarios increased water for hydroelectric power generation.

Benefits may also occur from small sea level rise in some shallow access ports such as Fremantle, Geelong and Melbourne. Sea level rise would increase the permissible draught of ships entering or leaving port, thus increasing their payloads. However, larger sea level rises could threaten port infrastructure, especially during storm surge events.

Guest *et al.* (1999) have documented possible decreases in winter human mortality alongside possible increased summer mortality. However, more recent work (McMichael *et al.*, 2003) indicates that increasing mortality from heat in summer will far exceed any decreases in winter mortality in Australia (see section 4.5.2).

Howden *et al.* (1999f and g) have shown that Australian wheat yields may increase for a 1 °C or 2 °C warming, before showing declines at greater warmings (see section 4.3.3). A similar situation may apply to forestry (see section 4.3.4). Such studies take account of gains from increased carbon dioxide concentrations. Changes in overseas production and thus in markets in some cases also could lead to greater demand and higher prices for Australian primary products (see section 4.3.9), but only if such changes do not disrupt world trade in other ways (e.g., lower capacity to pay).

Some of these potential benefits from climate change will only be fully realised if they are understood and acted upon, e.g., a more pleasant climate for tourists in Tasmania may only attract more tourists if this is made known through marketing, and increased water supply for electricity generation is only useful if the generating capacity exists.

A good example of assessments aimed at taking advantage of climate change is the study by Hood *et al.* (2002) that mapped land suitability for a range of crops in East Gippsland, Victoria, under a number of climate change scenarios. Crops considered included Blue Gum plantations, pasture and varieties of wine grapes.

Vulnerability and adaptation to climate change must be considered in the context of the entire ecological and socioeconomic environment in which they will take place. Indeed, adaptations will be viable only if they have net social and economic benefits and are taken up by stakeholders. Adaptations should take account of any negative side effects, which would not only detract from their purpose but might lead to opposition to their implementation (PMSEIC, 1999).

Adaptation is the primary means for maximising gains and minimising losses. This is why it is important to include adaptation in impact and vulnerability studies, as well as in policy options. As discussed in McCarthy *et al.* (2001) chapter 18, adaptation is necessary to help cope with inevitable climate change, but it has limits; therefore, it would be unwise to rely solely on adaptation to solve the climate change problem.

In some cases adaptation may have co-benefits. For example, reforestation to lower water tables and reduce dryland salinisation, or to reduce storm runoff and erosion, may provide additional income and help with mitigation by sequestering carbon. However, other potential adaptations may be unattractive for other reasons (e.g., increased setbacks of development in coastal and riverine environments may adversely affect land values). These considerations have particular application in Australia. Studies of adaptation to climate change in Australia are still relatively few and far between, and include many assumptions and caveats. They are summarised in the remainder of this section.

5.4 Integrated Assessments and Thresholds

Over the past decade there have been several national and regional assessments of the possible impacts of climate change. A regional assessment for the Macquarie River basin was done by Hassall and Associates *et al.* (1998, reported in Basher *et al.*, 1998), and Howden *et al.* (1999g) made a national assessment for terrestrial ecosystems (see section 4.2).
Two other preliminary regional assessments cover the Hunter Valley in New South Wales (Hennessy and Jones, 1999) and the Australian Capital Territory (Baker *et al.*, 2000). The former was based on a stakeholder assessment of climate change impacts that identified heat stress in dairy cattle as a subject for a demonstration risk assessment. Thresholds for heat stress and the probability of their being exceeded were evaluated, as were the economic value of adaptation through installation of shade and sprinklers (see section 4.3.2; Jones and Hennessy, 2000). Baker *et al.* (2000) made a preliminary qualitative assessment of the impacts of scenarios on the basis of the CSIRO RCM at 60 km resolution (Hennessy *et al.*, 1998) on a wide range of sectors and activities.

However, most integrated studies in Australia have been "one-off" assessments, have lacked a time dimension, cannot readily be repeated to take account of advances in climate change science, and often have not placed the problem in its socioeconomic context. Several groups are collaborating on integrated modelling systems that overcome these drawbacks. An Australian system called OZCLIM (CSIRO, 1996b) based on the New Zealand CLIMPACTS program (Kenny *et al.*, 1995, 1999, 2000; Warrick *et al.*, 1996), has been developed to do integrated assessments. This integrated model system contains a climate change scenario generator, climate and land surface data, and sectoral impact models. It provides a capacity for time-dependent analyses, a flexible scenario approach, a capability for rapid updating of scenarios, and inclusion of models for different sectors. Studies using OZCLIM are reported in Hood *et al.* (2002); Herron *et al.* (2002); Jones and Page (2002) and Walsh *et al.* (2001).

OZCLIM contains regional climate patterns for monthly temperature and rainfall over Australia from several GCMs and the CSIRO RCM. They can be forced or scaled by the latest emission scenarios, and variables include potential evapotranspiration and relative humidity. It is being adapted to produce projected ranges of impact variables and to assess the risk of exceeding critical thresholds (CSIRO, 1996b; Jones, 2000a; Pittock and Jones, 2000).

There are different levels and styles of integration in impact and adaptation assessment, and several of these have been attempted in Australia. Bottom-up integration was done for a range of climate change scenarios in the water supply, pasture, crop, and environmental flow sectors for the Macquarie River basin study by Hassall and Associates *et al.* (1998). It also has been done in a more probabilistic way to take account of uncertainty, with a focus on the probability of exceeding a user-defined threshold for performance and the need for adaptation (Jones, 2000a).

Top-down integration has been attempted via the use of global impacts assessment models with some regional disaggregation—such as a regional analysis based on the Carnegie Mellon University ICAM model, which was used to examine adaptation strategies for the Australian agricultural sector (Graetz *et al.*, 1997). The principal conclusions were that climate matters and that the best strategy is to adapt better to climate variability.

Another top-down approach, based on an Australian regionalisation of the DICE model of Nordhaus (1994), is that of Islam (1995). An initial application of this model to quantifying the economic impact of climate change damages on the Australian economy gave only a small estimate, but the authors expressed reservations about model assumptions and the need to better quantify climate impacts (Islam *et al.*, 1997). Others have examined the structure and behaviour of the Integrated Model to Assess the Greenhouse Effect (IMAGE), but to date have not applied this to climate change impacts in Australia (Zapert *et al.*, 1998; Campolongo and Braddock, 1999).

A spatially explicit modelling system known as INSIGHT is being developed to evaluate a wide range of economic, social, environmental, and land-use impacts that could affect large areas (Walker *et al.*, 1996). It can map and summarise key social, economic, and environmental outcomes in annual steps to the year 2020. The need for such a system was identified through workshops involving potential stakeholders, and the system could factor in scenarios resulting from climate change.

As pointed out in PMSEIC (1999), much of Australia is subject to multiple environmental problems, of which climate change is only one. This leads to a logical emphasis on regional integrated assessments, which look for adaptations and policies that help to ameliorate more than one problem and have economic benefits.

5.5 Natural Systems

A large fraction of Australia is composed of unmodified or non-intensively managed ecosystems where adaptation will depend mostly on natural processes. Vulnerability will occur when the magnitude or rate of climate variations lies outside the range of past variations. In some cases, adaptation processes may be very accommodating, whereas in others adaptation may be very limited. Australian ecosystems handle a wide variety of climatic variability, in some cases with very large swings, but generally this variation occurs on short time scales—up to a few years. This does not necessarily confer adaptability to long-term changes of similar magnitude.

An important vulnerability identified by Basher *et al.* (1998) is the problem of temperatures in low to mid-latitudes that reach levels never before experienced and exceed the available tolerances of plants and animals with no options for migration. The south-west of Western Australia is a case in point (section 4.2.8). Another potential vulnerability arises from changes in the frequency of events. Examples include a climatic swing of duration exceeding a reproductive requirement (e.g., water birds in ephemeral lakes — Hassall and Associates *et al.*, 1998) and damaging events occurring too frequently to allow young organisms to mature and ecosystems to become re-established.

Vulnerability also is expected to exist where species or ecosystems already are stressed or marginal, such as with threatened species; remnant vegetation; significantly modified systems; ecosystems already invaded by exotic organisms; and areas where physical characteristics set constraints, such as atolls, low-lying islands, and mountain tops. Coral reefs, for instance, may be able to survive short periods of rising sea level in clear water but are less likely to do so in turbid or polluted water or if their growth rates are reduced by acidification of the ocean (Pittock, 1999). Vulnerability of coastal freshwater wetlands in northern Australia to salinisation resulting from increasing sea level and the inability of some of these wetlands to migrate upstream because of physical barriers in the landscape is described in section 4.2.7.

Unfortunately, there is relatively little specific information about the long-term capacity for and rates of adaptation of ecosystems in Australia that can be used to predict likely outcomes. Therefore, a large degree of uncertainty inevitably exists about the future of the Australian natural ecosystems under climate change.

5.6 Managed Systems

Most Australian farming systems respond rapidly to external changes in markets and technology, through changes in cultivars, crops, or farm systems. 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, at low latitudes, where temperatures increasingly will lie outside past bounds, there will be no pool of new plant or animal options to draw from, and the productivity of available systems is likely to decline.

Adaptation options will be more limited where a climatic element is marginal, such as low rainfall, or where physical circumstances dictate, such as restricted soil types. Even where adaptations are possible, they may be feasible only in response to short-term or small variations. At some point, a need may arise for major and costly reconfiguration, such as a shift from or to irrigation or in farming activity. Indeed, one adaptation process already being implemented in Australia to cope with existing competition for water is water pricing and trading, which is likely to lead to considerable restructuring of rural industries (see section 4.1.3).

Management of climate variability in Australia currently involves government subsidies in the form of drought or flood relief when a specific level of extreme that is classified as exceptional occurs (Stafford Smith and McKeon, 1998; see also section 4.3.6). One adaptive measure being applied in Australia is to improve seasonal forecasting and to help farmers optimise their management strategies (Stone and McKeon, 1992; Stone *et al.*, 1996a; White, 2000), including reducing farm inputs in potentially poor years.

However, if a trend toward more frequent extremes were to occur, such measures might not allow farmers to make viable long-term incomes because there may be fewer good years. The question arises whether this is merely a string of coincidental extremes, for which assistance is appropriate, or whether it is part of an ongoing trend resulting from climate change. An alternative policy response to the latter possibility may be to contribute to restructuring of the industry.

The PMSEIC (1999) report notes that there are opportunities for new sustainable production systems that simultaneously contribute to mitigation objectives through retention of vegetation and introduction of deeper rooted perennial pasture. Tree farming in the context of a carbon-trading scheme would provide additional opportunities, and this strategy could be linked to sustainability and alleviation of dryland salinity.

Nevertheless, the PMSEIC report recognises that totally new production systems may be required for sustainability. These systems will need to capture water and nutrients that otherwise would pass the root zone and cause degradation problems. The design of such systems will entail research into rotating and mixing configurations of plants; manipulating phenology; modifying current crops and pastures through plant breeding, including molecular genetics; and possibly commercialising wildlife species and endemic biological resources. The report concedes, however, that there probably still will be agricultural areas where attempts to restore environmental and economic health will meet with little success.

Vulnerability and the potential for adaptation can be investigated quantitatively if a system and the climate change impacts on that system can be modelled. This was done by Pittock and Jones (2000) and Jones (2000a) for climatically-induced changes in irrigation water demand on a farm in northern Victoria. Here a window of opportunity is opened for adaptation via identification of a future time when adaptation would be necessary to reduce the risk of demand exceeding irrigation supply.

Jones (2000a) used a model that was based on historical irrigation practice. Seasonal water use was used to estimate an annual farm cap of 12 Ml per ha, based on the annual allocated water right. Water demand in excess of this farm cap in 50% of the years was taken to represent a

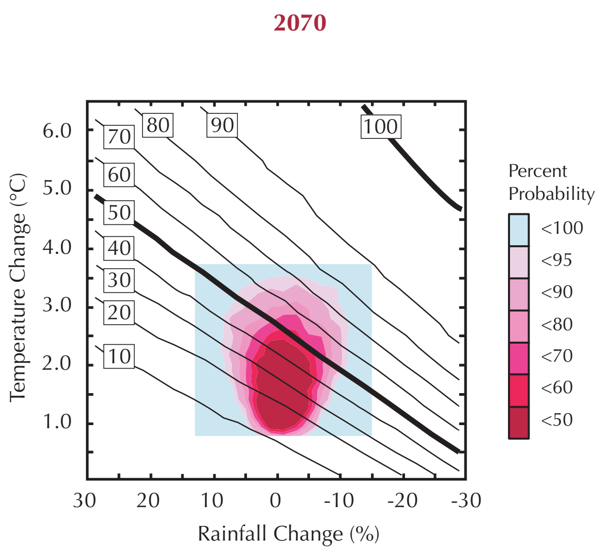


Figure 5.2
Risk response surface incorporating cumulative probability plots (in shaded box) for climate change magnitudes as indicated on the x- and y-axes. Indicated percentage probabilities are probabilities of climate change in northern Victoria in 2070 lying within each concentric shaded area (thus, there is a 100% probability of climate within the shaded square, and a 50% probability of climate lying within the innermost region). The probability (in percent) of irrigation water demand exceeding the farm supply cap in any one year, for indicated climate change, is indicated by the oblique lines. A critical threshold (heavy line) is set at a 50% chance of exceeding the cap (Jones, 2000a). Scenario used is CSIRO (1996a).

critical threshold beyond which the farmer cannot adapt. Conditional probabilities within projected ranges of regional rainfall and temperature change were utilised, combined with a sensitivity analysis, to construct risk response surfaces (see **Figure 5.2**). Monte Carlo sampling was used to calculate the probability of the annual farm cap being exceeded across ranges of temperature and rainfall change projected at intervals from 2000 to 2100. Some degree of adaptation was indicated as desirable by 2030, although the theoretical critical threshold was not approached until 2050, becoming probable by 2090 (see **Figure 5.3**).

In a full analysis, this example would need to be combined with an analysis of the likelihood of changes in water supply (e.g., Schreider *et al.*, 1997) affecting the allocated irrigation cap and an evaluation of possible adaptation measures.

Adaptation strategies for agriculture are listed in **Table 6** in section 4.3.11, and there are other discussions in section 4.4.6 (settlements and industry) and 4.2.9 (ecosystems and conservation).

5.7 Human Environments

The most vulnerable human environments in Australia are those that are subject to potential coastal or riverine flooding, landslides, or tropical cyclones and other intense storms. Adaptation to natural variability in these cases usually takes the form of planning zones, such as setbacks from coasts and flood levels of particular return periods, or engineering standards for buildings and infrastructure. Many of these settlements and structures have long lifetimes—comparable to that of anthropogenic climate change. This means that many planning zones and design standards may become inappropriate in a changing climate.

Adaptation in these circumstances depends on costs and benefits, the lifetime of the structures, and the acceptability of redesigned measures or structures (e.g., seawalls). Thus, responses will depend in part on aesthetic and economic considerations; poorer communities, such as many indigenous settlements, will be particularly vulnerable. Conflicts will arise between investors with short time horizons and local government or other bodies who think on

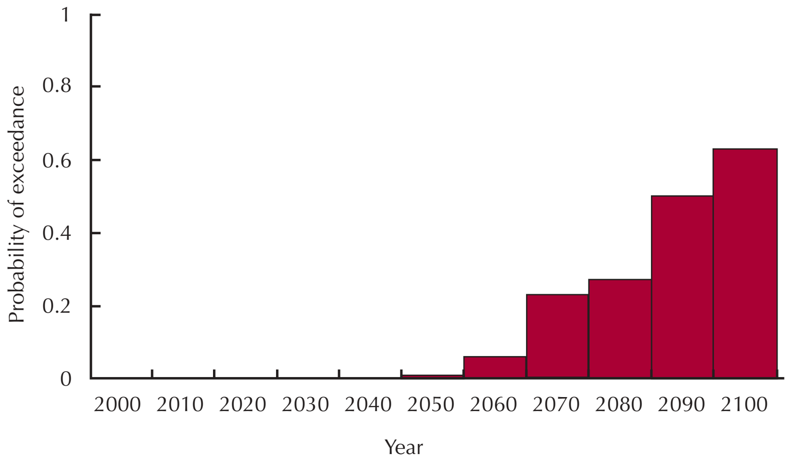


Figure 5.3. Change in probability of irrigation demand exceeding critical threshold (exceeding the irrigation supply cap in 50% of all years) over time. Note that if the farm cap were reduced through reductions in irrigation supply under climate change, the probability of the cap being exceeded would be increased (Jones, 2000a).

longer time scales and may bear responsibility for planning or emergency measures. Complex jurisdictional arrangements often will add to the difficulties of adopting rational adaptation measures (Waterman, 1996).

In an attempt to meet these problems for the Australian coastline, a guide has been developed for response to rising seas 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 identifying measures they could implement to adapt to climate change, for example in relation to coastal development, but such action has not been well documented. However, under the Far North Queensland Regional Plan, stakeholders in the Cairns Great Barrier Reef region are becoming involved in a study to identify climate sensitivities and to identify possible actions to deal with the impacts of climate change (Crimp *et al.*, 2003).

Australia's health infrastructure is quite strong, and numerous existing adaptations, such as quarantine and eradication of disease vectors, are available to deal with the main changes expected. However, there is concern that already disadvantaged communities, especially indigenous people, may not have equitable access to adaptation measures. Another issue is the question of adaptations to deal with a climatic impact that may cause secondary effects. Examples include adaptations that require more energy production or higher water use (e.g., air conditioning), and vector controls that result in reduced population immunity to the disease carried.

5.8 Indigenous People

Traditional indigenous societies in the region have lived in a close and conscious relationship with their environment (Tunks, 1997; Skertchly and Skertchly, 2000). Australian Aborigines have modified and managed the landscape through the controlled use of low-intensity fire (Kohen, 1995). They have lived in Australia for at least 40,000 years. Thus, they have a long history of adaptation to sea level rise, which amounted to 130 m from the last glacial maximum 18,000 years ago until the present level was reached 6,000 years ago. Memories of these traumatic events are found in oral traditions recorded by early European settlers (Mulvaney and Kamminga, 1999).

With the recognition of indigenous land rights, indigenous Australians are now major land managers (Coombs *et al.*, 1990; Langton, 1997) and hence are impacted by and responsible for managing climatic impacts. The importance and cross-cultural problems of their participation in land management is discussed in Baker *et al.* (2001). The involvement of indigenous people in development of policy and response strategies for climate change has been minimal to date. This is a result partly of greater emphasis in Australia and elsewhere on mitigation of climate change rather than adaptation (Cohen, 1997), lack of indigenous community involvement in climate change research, and the array of other more pressing social issues for such communities (Braaf, 1999).

5.9 Regional Vulnerabilities

The following is a short list of some key issues for vulnerability and adaptation by state or territory. This is a subjective choice, and is not in order of importance. There will be other issues of importance especially to affected people. Readers are referred to a longer list (**Table 10**) sorted by sector in Chapter 6.

Queensland

- Impacts of sea level rise and storm surges on coastal settlements
- Droughts, floods and water management
- Wind and water erosion inland, especially that ending on the Great Barrier Reef
- Coral bleaching and tourism

- Sea level rise and the low islands of the Torres Straits
- Tropical pests and diseases
- Crop responses to heat and drought

New South Wales

- Coastal erosion
- Floods and droughts
- Tropical pests and diseases on the north coast
- Fire in forests and near Sydney

Victoria

- Water supply for irrigation and towns
- Floods and droughts
- Sea level rise especially under storm tides in Port Phillip, Western Port and Gippsland Lakes
- Ski industry and biodiversity losses in Victorian Alps
- Fire
- Some vector-borne diseases

South Australia

- Water supply for Adelaide and irrigation
- Crops vulnerable to heat, including wine grapes and wheat
- Dust storms

Western Australia

- Water supply in south-west
- Tropical cyclones and floods affecting industry and settlements in north
- Wheat harvest
- Loss of biodiversity in south-west

Tasmania

- Fire
- Some opportunities (hydroelectricity, tourism, wine)?

Australian Capital Territory

- Fire
- Water supply

Northern Territory

- Tropical cyclones affecting settlements
- Sea level rise and coastal wetlands
- Fire
- Floods inland
- Adverse effects on tourism?

5.10 Extra-Regional Factors

Basher *et al.* (1998) draw attention to the vulnerability of the region to external influences arising from climate change—in particular, from likely changes in terms of trade (see also Stafford Smith *et al.*, 1999). Increased risk of invasion by exotic pests, weeds and diseases, and population pressures from neighbouring territories rendered less viable by rising sea level are other factors (Edwards, 1999; Barnett and Adger, 2001; Hay and Beniston, 2001). These issues exist independent of climate change but are likely to be exacerbated by climate change. A variety of adaptation measures to deal with each problem exists and can be strengthened, but the costs involved and remaining impacts could be considerable.

6

Synthesis

Synthesis

6.1 Introduction

Many activities and ecosystems in Australia are sensitive to climate change, with positive and negative effects. Much climate sensitivity information is still qualitative, and there are substantial uncertainties in predictions of regional- to local-scale climate changes—especially rainfall changes and changes in extreme events. Thus, comprehensive, quantitatively based cross-sectoral estimates of net Australasian costs of climate change impacts are not yet available. Confidence remains very low in the earlier impact estimate for Australia and New Zealand of –1.2 to –3.8% of GDP for an equivalent doubling of carbon dioxide concentrations (Basher *et al.*, 1998, citing Fankhauser and Tol, 1997). This estimate is based on climate change scenarios that are now outdated; does not include some potentially important impacts, including changes in weeds, pests and diseases, storm surges, and urban flooding; and does not account for possible adaptations to climate change.

Despite the uncertainties, there is a large body of knowledge and more agreement on changes than often is realised (e.g., between different coupled ocean-atmosphere climate models on the sign of the change in rainfall over large areas of Australia; see section 2.3.2). There is also qualitative agreement on reduced water supplies and more severe drought in large agricultural regions of Australia (see sections 2.3.2, 4.1.2 and 4.3.6).

Potential net impacts on grazing, crops, and forests critically depend on the balance between the competing effects of warming, positive or negative rainfall changes, direct physiological effects of higher carbon dioxide concentrations, and spatial and temporal variations in soil fertility. The beneficial physiological effects of higher carbon dioxide concentration will become less dominant with time and effects of warming will become more damaging, especially given the expected tendency toward greater aridity over much of Australia. Impacts (and thus climate change benefits or damages) will not vary in direct proportion to increasing greenhouse gas concentrations and temperature change, but may change abruptly as threshold effects are reached (section 2.1.4), and might even change sign.

The following subsections draw together material from this report that is pertinent to policy concerns in relation to climate change impacts, vulnerability and adaptation.

6.2 Observed Australian Sensitivity to Climate Variability

Consequences documented in this report from floods, droughts, and temperature changes associated with recent ENSO events include losses in the pastoral agriculture sector from droughts of about 1-2% of Gross Domestic Product (GDP) (section 4.3.6), and impacts on streamflow and water supply (section 4.1.2), stream ecology (section 4.2.6), horticulture, some commercial fisheries, and toxic algal blooms. Parts of the Great Barrier Reef have suffered mass coral bleaching from high sea surface temperatures (possibly related to ENSO and recent warming trends) and/or lowered salinity resulting from floods (section 4.2.7).

Extreme climatic events resulting from natural climatic variability in the past century have caused major damage and loss of life in Australia (section 4.5.2 and 4.5.3). These extremes are expected to change in intensity, location-specific frequency, and sequence as a result of climate change (see **Table 2**, and section 2.3.4), with major impacts on infrastructure and society unless strong adaptation measures are adopted (section 4.4).

6.3 Observed Changes in Australian Climate and Ecosystems

Observed changes in Australian climate include warming over the last half century consistent with climate change projections due to the enhanced greenhouse effect, and unlikely to be entirely natural in origin. At the same time there has been a drying trend notable in the south-west of Western Australia, and to a lesser degree across much of southern and extreme eastern Australia. Increased rain has occurred in the north-west since the 1950s. There has been an increase in surface atmospheric pressure over south-western and parts of eastern Australia at the same time, broadly consistent with the rainfall changes (section 2.2.1). There is some evidence that rainfall changes tend to occur abruptly. These changes appear to be partly natural, but may also reflect the influence of the enhanced greenhouse effect and stratospheric ozone depletion on the pressure pattern.

Whether or not the observed climate changes have been due to the enhanced greenhouse effect, there have been a number of changes in ecosystems over the same period, broadly consistent with the climate sensitivity of many species (section 2.2.2). Attribution of causes is complicated by other possible causes such as land clearing and fire management changes in some instances.

6.4 Factors Influencing Vulnerability

6.4.1 Abrupt or nonlinear changes in impacts

Several potential abrupt or nonlinear responses to climate change are listed in **Table 9**. In some cases, they involve a reversal of the sign of the effect with greater climate change; in others they result from the onset or acceleration of a biophysical or socioeconomic process that occurs or greatly accelerates beyond some threshold of climate change

Such thresholds can be quite location and system specific and need to be identified in collaboration between climatologists and stakeholders. The frequency with which thresholds are exceeded often is used in engineering in the form of design criteria to withstand an event with a certain "return period," or average time between occurrences. It also can manifest itself as a change from an average profit to an average loss for a given enterprise such as a farm.

6.4.2 Interactions with other environmental and social factors

Some of the region's ecosystems are extremely vulnerable to invasion by exotic animal and plant species because of relative isolation before European settlement. Land-use changes have left some systems and areas more vulnerable to added stresses from climate changes, as a result of salinisation or erosion, and because of ecosystem fragmentation, which lessens adaptation options for movement of species threatened by changing habitats (section 4.2.9).

Increasing human populations and development in coastal areas and on floodplains cause increasing vulnerability to tropical cyclones, storm surges, and riverine flooding episodes (sections 4.2.7 and 4.4.5), which may become more frequent with climatic change.

Table 9.

Nonlinear or rapid climate change responses identified in this book.

System	Description of Change	Certainty and Timing	Section
Great Barrier Reef	Reef death or damage from coral bleaching	Medium to high, next 20-50 years	4.2.7
Deep ocean	Chemical, dynamical, and biological changes from reduction in bottom-water formation	Low to medium, century time scale	2.1.4, 4.2.7
Rainfall regimes	Abrupt changes in Australian rainfall regimes happened before and may be stimulated by global warming	Uncertain impact of enhanced greenhouse effect on future occurrence and timing	2.2.1, 2.1.4
South-west of Western Australia	Rapid loss of species with narrow annual mean temperature ranges	High, next 20-50 years	4.2.8
Australian alpine ecosystems	Loss of species due to warming and reduced snow cover	Medium to high, next 50 years	4.2.4
Insect-borne disease spread	Conditions more favourable to mosquitoes and other disease vectors	High potential, growing vulnerability	4.5.4, 4.5.5, 4.5.7
Agriculture	Shift from net profit to loss as a result of increased frequency of bad years, especially droughts	High potential in some places, next 20–50 years	4.3.2, 5.4
Agriculture	Shift from positive to negative balance between benefits of increased CO_2 and losses from increasing aridity	High potential in parts of Australia, 50–100 years	4.3.2
Horticulture and viticulture	Reduced winter chill inhibits some fruiting, fewer frosts extend growing season, more high temperatures damage fruit	Highly likely next few decades, very variety-dependent	4.3.3
Built environment and infrastructure	Change in magnitude and frequency of extremes which exceed design criteria, leading to rapid increases in potential damages to existing infrastructure and shifts in hazard zones	Medium to high in tropical coastal and riverine situations, next 30–50 years	4.4.2

Development has reduced the area and water quality of many estuaries, increasing the vulnerability of their ecosystems to sea level rise and climate changes. Pressures on coral reefs including the Great Barrier Reef include increased coastal development, fisheries, tourism, and runoff of nutrients, chemicals, and sediment from land, as well as climate-related stresses such as rising sea level, rising temperatures, changes in tropical storm frequency, and acidification of the ocean from increasing carbon dioxide concentrations (section 4.2.7).

Poorer communities, including many indigenous settlements, are more vulnerable to climate-related natural hazards and stresses on health (section 4.5.8) because they are often in exposed areas and have less adequate housing, health, and other resources for adaptation.

Capacity to adapt is a function not only of the magnitude and critical nature of the climatic change but also of the demographics, economy, institutional capacity, and technology of a society. Thus, alternative socioeconomic futures (section 1.4.4) will lead to different capacities to adapt. This has hardly been explored to date in Australia in relation to climate change.

6.4.3 Regional-global interactions

Reliance on exports of agricultural and forest products makes the region sensitive to changes in commodity prices produced by changes in climate elsewhere (section 4.3.9) and to increases in global forests as a result of carbon sink policies. Other extra-regional factors include increased risks of invasion by exotic pests, weeds, and diseases (section 4.3.7); pressures from immigration from neighbouring low-lying Pacific island territories impacted by sea level rise (section 4.5.8); and international agreements that constrain net emissions of greenhouse gases. In an era of increasing globalisation, these issues may assume more importance, although this report hardly touches on them.

6.5 Impacts for Differing Emissions Scenarios and Stabilisation Pathways

Initial studies of the global impacts of emissions scenarios producing stabilisation of greenhouse gas concentrations indicate that stabilisation at 750 ppm of carbon dioxide would lead to reduced impacts compared to no-mitigation scenarios, while stabilisation at 450 ppm of carbon dioxide would lead to greater reductions in impacts. However, even with stabilisation at 450 ppm, some climate change effects would occur, requiring adaptation (section 3.5).

Quantitative cross-sectoral impact assessments for differing scenarios are not yet available for Australia. Regional impacts will vary nonlinearly with time before and after stabilisation of greenhouse gas concentrations. Warming will continue to increase after stabilisation of concentrations, but the beneficial effects of carbon dioxide on plants will no longer increase. Moreover, regional patterns of rainfall change, particularly in southern Australia, will tend to reverse after stabilisation of greenhouse gas concentrations (section 2.1.5). These complexities, together with the continuing post-stabilisation rise in sea level, mean that estimated impacts at the time of stabilisation of concentrations will not be sufficient to determine whether the level of stabilisation is a safe one.

6.6 Uncertainties and Risk Management

Given that some of the climate sensitivities listed in section 6.7, and especially in **Table 10**, already have been observed for natural climate variations (such as El Niño) and recent decades when warming has occurred (section 2.2.2), confidence is high that a range of impacts will occur in Australia as a result of climate change over the coming decades. This level of certainty, and the possibility that the early stages of greenhouse-related changes already may be occurring, justify prudent risk management through initiation of appropriate mitigation and adaptation strategies. Probabilistic assessments of risk, which account for the uncertainties, are regarded as a way forward. These assessments attempt to quantify the various sources of uncertainty to provide a conditional probability of climate change that would cause critical system performance thresholds to be exceeded and require adaptation or result in losses. Stakeholders may define their own subjective levels of acceptable risk and plan accordingly to adapt before or when the threshold is exceeded. Examples of risk assessment topics presented in this report include heat stress in dairy cattle (section 4.3.2), storm tides (section 4.4.2), reproduction of water birds (section 4.1.2), irrigation supply (section 4.1.2) and irrigation demand (section 5.4).

6.7 Vulnerability and Adaptability in Australia

Key regional concerns identified in this book regarding vulnerability to climate change impacts include ecosystem uniqueness, isolation, and vulnerability; agricultural commodities and terms of trade; droughts, floods, and water supply; increased coastal and tropical exposure to climate hazards; impacts on indigenous peoples and their involvement in adaptation planning; coral reefs; and Australian alpine areas.

Major expected impacts, vulnerability, and adaptability are summarised in **Table 10.** Note that although Australian farmers have adapted, at least in part, to existing El Niño-related droughts, they depend on good years for recovery. Thus, despite their adaptability, they are quite vulnerable to any increase in the frequency of drought or to a tendency for droughts to last for a longer period. This vulnerability flows through to the rural communities that service them (section 4.3.6).

Several of these vulnerabilities are likely to interact synergistically with each other and with other environmental stresses. Moreover, vulnerability is a result of exposure to hazard and is reduced by a 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.

No rigorous studies for Australia that have taken all of these variables into account have been reported. Thus, **Table 10** is based largely on studies that assume that the society that is being impacted is much like that of today. It should not be assumed, however, that socioeconomic changes in the future necessarily would reduce vulnerability. Indeed, many existing socioeconomic trends may exacerbate the problems. For instance, the bias toward population and economic growth in coastal areas, especially in the tropics and subtropics, by itself will increase exposure to sea level rise and more intense tropical cyclones. If such trends are not to increase vulnerability, they will need to be accompanied by a conscious process of planning to reduce vulnerability by other means (e.g., changes in zoning and engineering design criteria). Thus, vulnerability estimates are based on present knowledge and assumptions and can be changed by new developments, including planned adaptation.

Table 10.

Main areas of vulnerability and adaptability to climate change impacts in Australia. Degree of confidence that tabulated impacts will occur is indicated by a letter in the second column (VH = very high, H = high, M = medium, L = low, VL = very low). These confidence levels, and the assessments of vulnerability and adaptability, are based on information reviewed in this report and assume continuation of present population and investment growth patterns.

Sector	Impact	Vulnerability	Adaptation	Adaptability	Section
Hydrology and water supply	Irrigation and metropolitan supply constraints, increased salinisation **H**	High in some areas	Planning, water allocation, and pricing Conservation, recycling	Medium	4.1.2, 4.1.3
	Saltwater intrusion into some island and coastal aquifers **H**	High in limited areas	Alternative water supplies, retreat	Low	4.1.4
Terrestrial ecosystems	Increased salinisation of dryland farms and some streams **M**	High	Changes in land-use practices	Low	4.1.4
	Biodiversity loss, notably in fragmented regions, alpine areas, and the south-west of WA **H**	Medium to high in some areas	Landscape management; little possible in alpine areas	Medium to low	4.2.2, 4.2.4, 4.2.8, 4.2.9
	Increased risk of fires **M**	Medium	Land management, fire protection	Medium	2.3.2, 4.2.2, 4.3.10
	Weed invasion **M**	Medium	Landscape management	Medium	4.2.3, 4.3.7
Aquatic ecosystems	Salinisation of some coastal freshwater wetlands **H**	High	Physical intervention	Low	4.2.7

Table 10. continued

Sector	Impact	Vulnerability	Adaptation	Adaptability	Section
	River and inland wetland ecosystem changes **M**	Medium	Change water allocations	Medium to low	4.1.3, 4.2.5, 4.2.6
	Eutrophication **M**	Medium in inland Aus. waters	Increase environmental flows, reduce nutrient inflows	Medium to low	4.1.5
Coastal Ecosystems	Coral bleaching **H**	High	Seed coral? Reduce other stresses	Low	4.2.7
	More toxic algal blooms **L**	Medium, downstream of nutrient sources	Increase environmental flows	Medium	4.2.6, 4.2.7
Agriculture, grazing, and forestry	Increased drought & fire risk reduce productivity & increase stress on rural communities **M**	Location-dependent, worsens with time	Management and policy changes, fire prevention, seasonal forecasts	Medium	4.3.2, 4.3.3, 4.3.4
	Climate change effects on global markets, sign uncertain **H**	High, but sign uncertain	Marketing, planning, niche and fuel crops, carbon trading	Medium	4.3.9
	Increased spread of pests & diseases **H**	Medium	Exclusion spraying	Medium	4.3.7
	Increased soil erosion **M**	High during drought & heavy rain	Land management	High	4.2.9
	Initial benefit from increased CO_2, but later offset by climate change **L**	Changes with time	Change farm practices, change industry		4.3.3, 4.3.4

Table 10. continued

Sector	Impact	Vulnerability	Adaptation	Adaptability	Section
Horticulture	Mixed impacts, depends on species & location **H**	Low overall	Change management or crop, relocate	High	4.3.3
Fisheries	Recruitment changes (some species) **L**	Unknown net effect	Monitoring, management	—	4.3.5
Settlements and industry	Increased impacts of flood, storm, storm surge, sea level rise, fire, damage to buildings & infrastructure **M**	High in some places	Zoning, disaster planning, design standards	Moderate	4.4
	Decline of industries due to aridity, loss of attractions e.g., snow or coral **M**	Medium to high in some locations	Diversify?	Varies with location	4.4.1, 4.3.6, 4.4.5
Electricity generation	Increased peak capacity needed for air conditioning **H**	Medium to high	Shade, design, insulation, solar powered cooling	High	4.4.4
Tourism	Ski resorts, reef resorts, coastal wetlands (e.g., Kakadu) lose attractions **VH**	High in some locations	Diversify? Snowmaking	Medium to low	4.4.5, 4.2.5, 4.2.7
Insurance	Increasing losses from natural hazards **H**	High especially in low-lying coastal and riverine locations	Zoning, revise building codes, rate incentives, reduce cover	Medium to high	4.4.3
Human health	Potential expansion and spread of vector-borne diseases **H**	High	Quarantine, eradication, or control	Moderate to high	4.5.4, 4,5,5, 4.5.7, 4.5.9

7

Filling the Gaps

7. Filling the Gaps

Significant knowledge gaps continue to exist. These gaps mean that the net cost or benefit of unmitigated climate change in Australia is highly uncertain (section 6.1) and cannot be compared objectively with the cost of mitigation. Moreover, knowledge of impacts on particular systems in particular locations is very imprecise, as is the understanding of adaptation strategies to minimise harm and maximise any benefits. Without this knowledge base, policymaking regarding adaptation and mitigation cannot be soundly based on economic considerations and may not be effective in avoiding significant damages to the economy, ecology and people. Research priorities that might help to remedy this situation follow.

The IPCC TAR Synthesis Report (Watson and the Core Writing Team, 2002) presented a list of key uncertainties in answer to the final question the authors were asked by decision-makers. The list focussed on climate change and attribution, future emissions of greenhouse gases and aerosols based on the SRES and stabilisation range of socioeconomic scenarios, and future changes in global and regional climate. They also addressed uncertainties regarding regional and global impacts of changes in average climate and climatic extremes, and lastly, on the costs and benefits of mitigation and adaptation. The Synthesis Report can be viewed on the IPCC website at: <http://www.grida.no/climate/ipcc_tar/>

While all the gaps identified by the IPCC are important, here we will focus more on those that are of particular relevance to Australia.

7.1 Indicators of Climate Impacts

Although long-term monitoring programs are in place for physical indicators (such as climate variables and sea level), work is still desirable on designing and implementing long-term monitoring programs that cover vulnerable animals, plants and ecosystems, and systematically examine them for the effects of climate changes. Flora and fauna with presently restricted or marginal climatic ranges would be most appropriate (sections 2.2.2 and 4.2.8). (Candidate indicators for the UK are presented in Cannell *et al.*, 1999.) This need was discussed at a workshop organised by the Biological Diversity Advisory Committee where potential indicators of plant and animal physiological responses to climate and atmospheric carbon dioxide concentrations, changes in phenology and in distribution and abundance were identified (Howden *et al.*, 2003b). Recommendations for further action were adopted. See the BDAC website at: <http://www.ea.gov.au/biodiversity/science/bdac/>

7.2 Underpinning Physical Knowledge and Improved Scenarios

Improved impact assessments will depend on better understanding of how climate change may influence factors such as the frequency and intensity of El Niños and related droughts, the intensity and location-specific frequency of tropical cyclones, and return periods for heavy rainfalls, floods, high winds, and hail. A special need in Australia is to understand how these climatic changes will impact on fire frequency, spread and intensity, and on dust storms and water erosion that threaten the sustainability of our forests, agricultural land and also the riverine and coastal coral reef ecosystems.

Oceanic issues include understanding the mechanism and possible impacts on Australia of a slow-down or cessation of bottom-water formation (section 2.1.4), predicting the impact of warming of the oceans on the Antarctic ice shelves and determining the influence of greenhouse warming on currents, upwelling, and nutrient supply. More knowledge is needed about influences of greenhouse gas related cooling in the stratosphere on ozone depletion, regional UV radiation levels (section 4.5.7), and its possible impact on surface climate (section 2.2.1). Explanations are needed for observed sudden shifts in rainfall and other climate patterns (section 2.1.4) including the observed change in the south-west of Western Australia in the 1970s. All of this knowledge is needed to improve scenarios of regional climate (including ocean behaviour).

A better understanding of natural climatic and oceanic variability is needed, as these combine with climatic change to determine impacts.

7.3 Underpinning Biological Knowledge

The sensitivities of many Australian plant and animal species and ecosystems to climate changes, as well as the potential threats to biodiversity, are still unknown (section 4.2). Knowledge is required for assessment of potential impacts and for development of conservation strategies. This is important for marine and coastal environments, including coastal freshwater wetlands (section 4.2.7), as well as for terrestrial systems. Identification of relevant climatic thresholds for biological (and other) systems is needed (sections 2.1.4, 5.4 and 5.6). The effects of the time-varying balance between the beneficial physiological effects of increasing carbon dioxide concentrations and climate change on natural (indigenous) and managed ecosystems (section 4.3.3) needs to be better understood, especially in light of recent regional scenarios.

The role and climatic preferences of pests, parasites and pathogens (section 4.3.7) in Australia is particularly important, but needs far more work, despite a good basis in models. This applies particularly to knowledge of over-wintering success, interactions between species, modelling adaptations and their costs and benefits.

The role of fire, and soil erosion via dust storms and heavy rains, will almost certainly change with climate change in Australia (section 4.2.9), but the role of these phenomena in sustainable ecological and socioeconomic systems in Australia has not been adequately explored.

The IPCC Technical Paper on climate change and biodiversity (Gitay *et al.*, 2002) lists several information gaps, but they are in very general terms. They can be viewed on the IPCC website as above.

7.4 Underpinning Social Knowledge

Better knowledge is required about the vulnerability of particular population groups (including indigenous people), about how people and organisations have adapted to past climate variability and change, and about individual attitudes to adaptation and mitigation options. Work is needed to understand how different socioeconomic futures (demography, economic capacity, and technological change) (section 1.4.4) would affect vulnerability (sections 6.4.2 and 6.7) and on socioeconomic thresholds for change, such as economic non-viability and unacceptable risk.

7.5 Fisheries

There is insufficient information to enable confident predictions of changes in fisheries' productivity from climate change (section 4.3.5). This requires better knowledge of physical and biological processes in the ocean (as above) and improved information on the climate sensitivities of many species. Effects on estuarine fish-farming may be particularly important.

7.6 Health

Continuing work is needed on the potential for introduction and spread of significant disease vectors, including their sensitivity to climate, population shifts, and effectiveness of health services and biosecurity procedures (sections 4.3.7 and 4.5.9). Other health issues should be addressed, including potential effects of threats to water supply on remote communities (section 4.5.8), heat stress and adaptation to heat (section 4.5.2), and food and water-borne disease (section 4.5.6).

7.7 Regional Effects and Integration

Better quantitative sectoral knowledge is required about, for example, influences of climate change on water supply and demand (section 4.1.2), salinisation (section 4.1.4), and some crops and farming practices (sections 4.3.3 and 4.3.4). Because various sectors (e.g., agriculture, ecosystems, infrastructure, and hydrology) interact at the regional and national levels, continued work is needed on integrated assessment approaches and models that synthesise sectoral knowledge and draw on the social sciences (section 5.4), in rural and urban settings. Such models should include the impacts of other stresses, and of socioeconomic changes (section 1.4.4). Models of the physical economy that track fluxes and pools of materials, energy, land and water are required for national analyses.

Uncertainties need to be identified and dealt with in a risk assessment framework, where the probabilities of exceeding critical physical, biological or socioeconomic thresholds are quantified so that cost-benefit or other approaches can be applied to decision-making (sections 3.3 and 5.4).

7.8 Global Interactions

More understanding is needed of the interaction of global climate change impacts, and of mitigation policies, on Australian markets, sectoral change, and land use (sections 4.3.9 and 5.10). Another potential issue that has hardly been touched upon in Australian studies is the implications for Australia of increasing international inequity resulting from climate change impacts (see references in sections 2.1.4, 3.4, 4.5.8 and 5.10 and the discussion in Chapter 18 of McCarthy *et al.*, 2001).

7.9 Adaptation

Further objective studies are required, in close collaboration with stakeholders, on adaptation options and their acceptability, costs, co-benefits, side effects, and limits (chapter 5). Adaptation should be regarded as a means to maximise gains and minimise losses, with a greater exploration of opportunities (see section 5.3). Integrated studies are needed that cross sectoral boundaries, involve stakeholders, consider other stresses on communities and systems, and examine costs and benefits realistically. Adaptation to climate change and variability needs to be considered in the context of routine planning and decision-making as a necessary factor alongside other environmental and socioeconomic issues.

7.10 Costing

More comprehensive and realistic costings are needed for impacts and adaptation options, taking account of human behaviour and using up-to-date scenarios (section 6.1). Co-benefits and side effects need to be accounted for (chapter 5), as does the issue of discount rates and their uncertainty in considering delayed effects and inter-generational equity (sections 3.2 and 3.3).

7.11 Communication of Policy-Relevant Results

If climate change issues are to be addressed by decision-makers, there will need to be better communication of results from research. This will come partly from consultation with decision-makers and other stakeholders to ensure that the right policy-relevant questions are addressed (section 5.4) and partly from effective communication of what is known, as well as the uncertainties. A risk-assessment approach geared to particular stakeholders seems likely to be most effective (section 6.6).

Abbreviations

BMRC – Bureau of Meteorology Research Centre

CSIRO – Commonwealth Scientific and Industrial Research Organisation

CCHRA – Climate Change Health Risk Assessment

CRC – Cooperative Research Centre

EAC – East Australian Current

ENSO – El Niño-Southern Oscillation

GBR – Great Barrier Reef

GCM – Global Circulation Model

GIS – Geographic Information System

HDD – Heating degree days

IGBP – International Geosphere-Biosphere Programme

IOCI – Indian Ocean Climate Initiative

IPCC – Intergovernmental Panel on Climate Change

MDBC – Murray Darling Basin Commission

NAO – North Atlantic Oscillation

NPDO – North Pacific Decadal Oscillation

OECD – Organisation for Economic Cooperation and Development

PMSEIC – Prime Minister's Science and Engineering Innovation Council

SAR – Second Assessment Report (IPCC)

SCOPE – Scientific Committee on Problems of the Environment

SRES – Special Report on Emissions Scenarios (IPCC)

SST – sea surface temperature

TAR – Third Assessment Report (IPCC)

UNFCCC – United Nations Framework Convention on Climate Change

WAIS – West Antarctic Ice Sheet

WGI – Working Group I (IPCC TAR)

WGII – Working Group II (IPCC TAR)

Glossary

Note that many of these definitions are in a climate change context, and that more general definitions may apply in other fields.

Adaptation

Adjustment in natural or human systems in response to actual or expected climatic changes or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory or reactive adaptation, private or public adaptation, and autonomous or planned adaptation.

Adaptive capacity

The ability of a system to adjust to climate change (including changes in variability and extremes) so as to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Aerosols

A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 mm, which reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in two ways: directly through scattering and absorbing radiation, and indirectly through acting as condensation nuclei for cloud formation or modifying the optical properties and lifetime of clouds.

Algal bloom

The explosive growth of blue-green algae that deprives aquatic life of oxygen. Algal blooms can be toxic to animals and humans.

Antarctic Circumpolar Wave

A feature of the Antarctic Ocean circulation that affects the weather over the southern seas, as well as Australia, South America and southern Africa. The wave circles the globe every 8 to 9 years within the massive circumpolar current.

Antarctic vortex

See *Polar Vortex*.

Anthropogenic

Resulting from or produced by human activities, in particular, factors that affect the atmosphere due to the burning of fossil fuels, deforestation and other land use change.

Biodiversity

The numbers and relative abundances of different genes (genetic diversity), species, and ecosystems (biological communities) in a particular area.

Carbon dioxide (CO_2)

A colourless, odourless gas that occurs naturally and is also emitted by fossil fuel combustion and land clearing. The atmospheric concentration of carbon dioxide has increased by about 31% since the Industrial Revolution (about 1750 AD). It is the main anthropogenic-influenced greenhouse gas affecting climate change.

Carbon dioxide (CO_2) fertilisation

Increasing plant growth or yield by elevated concentrations of atmospheric carbon dioxide.
A plant's photosynthesis mechanism determines its sensitivity to carbon dioxide fertilisation. Most trees, most agricultural crops such as wheat and rice, and most cold climate plants are more sensitive to changes in atmospheric carbon dioxide than other plants such as tropical grasses and crops including maize and sugar cane.

Carbon sequestration

See *sequestration*.

Carbon sink

Natural or human activity or mechanism that removes carbon dioxide from the atmosphere, such as the absorption of carbon dioxide by growing trees.

Catastrophic event

A climate-related event having sudden onset and widely distributed and large magnitude impacts on human or natural systems, such as historically rapid sea level rise or sudden shifts (over a decade or less) in atmospheric or oceanic circulation patterns. Such events have occurred in the past due to natural causes. See also *discontinuity*.

CFCs

Chlorofluorocarbons, greenhouse gases used for refrigeration, aerosol propellants and other purposes. Observations from ice cores show there were no CFCs in the atmosphere before the 1950s. CFC concentrations increased for 50 years before peaking in 2000 but are now declining, as a result of adherence to the Montreal Protocol for the protection of the ozone layer. They are being replaced by other greenhouse gases such as *perfluorocarbons* q.v. that are addressed by the *Kyoto protocol*, q.v..

Climate

Climate in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change

Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines "climate change" as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." See also c*limate variability*.

Climate feedback

The influence of a climate-related process on another that in turn influences the original process. For example, a positive climate feedback is an increase in temperature leading to a decrease in ice cover, which in turn leads to a decrease of reflected radiation (resulting in an increase in temperature). An example of a negative climate feedback is an increase in the Earth's surface temperature, which may locally increase cloud cover, which may reduce the temperature of the surface.

Climate model

A mathematical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity (i.e., for any one component or combination of components a hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions; the extent to which physical, chemical, or biological processes are explicitly represented; or the level at which empirical parameterisations are involved. Coupled atmosphere/ocean/ sea-ice General Circulation Models (AOGCMs) provide a comprehensive representation of the climate system. There is an evolution towards more complex models with active chemistry and biology. Climate models are applied, as a research tool, to study and simulate the climate, but also for operational purposes, including monthly, seasonal, and interannual climate predictions.

Climate prediction

A climate prediction or climate forecast is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future (e.g., at seasonal, interannual, or long-term time scales. See also *climate projection, climate scenario* and *scenario*.

Climate projection

A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasise that climate projections depend upon the emission/ concentration/radiative forcing scenario used, which are based on assumptions, concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty.

Climate scenario

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A "climate change scenario" is the difference between a climate scenario and the current climate.

Climate system

The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the *cryosphere* q.v., the land surface, and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external *forcings* q.v. such as volcanic eruptions, solar variations and human-induced forcings such as the changing composition of the atmosphere and land use.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also *climate change*.

Critical threshold

The point at which an activity faces an unacceptable level of harm, such as a change from profit to loss on a farm due to decreased water availability, or coastal flooding exceeding present planning limits. It occurs when a *threshold* q.v. is reached at which ecological or socioeconomic change is damaging and requires a policy response.

Cryosphere

The component of the climate system consisting of all snow, ice, and permafrost on and beneath the surface of the earth and ocean.

Detection (and attribution)

Detection of climate change is the demonstration that climate has changed by identifying statistically significant trends or jumps in the long-term climate data. Attribution of such changes involves the identification to a defined level of confidence of the most likely causes.

Discontinuity

Relatively sudden and usually irreversible change in Earth systems caused by gradual changes in the climate system, such as a shutdown of the *thermohaline circulation* q.v. or the disintegration of the *West Antarctic Ice Sheet* (WAIS) q.v. Discontinuities occur when gradual changes to the climate system take it beyond some relevant point or *threshold* q.v., causing more rapid change.

Discount rate

This arises due to the need to compare present costs (or investments), e.g., for greenhouse gas mitigation, with future costs, e.g., of delayed impacts of climate change, in any cost/benefit analysis for greenhouse policy. In normal investments future gains due to investment now are discounted or reduced to allow for economic growth that might make it easier to deal with future costs. However, future economic growth rates are uncertain, especially over long timescales, and some climate change impacts (e.g., lives or species lost) cannot be readily assessed in purely monetary terms. Appropriate discount rates for use in regard to climate change are controversial, and IPCC (Metz et al., 2001) has suggested the use of multiple discount rates in assessments.

Diurnal temperature range

This is the difference between the daily maximum and minimum temperatures, which has been observed to be decreasing globally, especially in Australia.

Downscaling

Statistical or dynamical methods of deriving finer regional detail of climate parameters from global and regional climate models.

Drought

Droughts can be grouped into four types (Heim, 2002):

- Meteorological drought: a period of months to years when atmospheric conditions result in low rainfall. This can be exacerbated by high temperatures and evaporation, low humidity and desiccating winds.
- Agricultural drought: short-term dryness in the surface soil layers (root-zone) at a critical time in the growing season. The start and end may lag that of a meteorological drought, depending on the preceding soil moisture status.
- Hydrological drought: prolonged moisture deficits that affect surface or subsurface water supply, thereby reducing streamflow, groundwater, dam and lake levels. This may persist long after a meteorological drought has ended.
- Socioeconomic drought: the effect of elements of the above droughts on supply and demand of economic goods.

Drought exceptional circumstances (DEC)

If drought conditions are considered beyond the bounds of normal risk management practices a declaration can be made by the Federal government of ‘drought exceptional circumstances’ in particular regions. This involves six core criteria relating to the meteorology, farm conditions, water supplies, environment, economic impact and scale of the event. See <http://www.affa.gov.au/.>

EC

A unit of salinity measured by electrical conductivity.

Emission Scenario

A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. In 1992, the IPCC presented a set of emission scenarios that were used as a basis for the climate projections in the Second Assessment Report published in 1996. These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emission Scenarios (Nakicenovic et al., 2000), new emission scenarios—the so-called SRES scenarios—were published.

Endemic

Restricted to a particular region, people or country, such as a human disease prevalent in a population or locality.

Enhanced greenhouse effect

Increases in the concentration of greenhouse gases in the atmosphere leading to an increase in the amount of infrared or thermal radiation near the surface. Most scientists agree that the enhanced greenhouse effect is leading to rising temperatures, referred to as global warming, and other changes in the atmospheric environment, known as *climate change* (a term that in common usage also includes natural changes).

ENSO

El Niño – Southern Oscillation (ENSO) refers to widespread 2-7 year oscillations in atmospheric pressure, ocean temperatures and rainfall associated with El Niño (the warming of the oceans in the equatorial eastern and central Pacific) and its opposite, La Niña. Over much of Australia, La Niña brings above average rain, and El Niño brings drought. A common measure of ENSO is the Southern Oscillation Index (SOI) which is the normalised mean sea level pressure difference between Tahiti and Darwin. The SOI is positive during La Niña events and negative during El Niño events.

Epidemic

An outbreak, usually of an infectious disease, affecting an unusually large number of individuals within a population or region at the same time.

Equilibrium warming

The final amount of warming projected by a climate model once the oceans and atmosphere have fully adjusted to a change in radiative *forcing* q.v., for example a doubling of carbon dioxide. Equilibrium warming provides information about the magnitude of the change from current conditions. Equilibrium warming will be reached only decades to centuries after greenhouse gas concentrations in the atmosphere are stabilised, due to the large heat capacity of the oceans. See also *Transient warming*.

Equity

Equity is an ideal, grounded in philosophy, morality, or human nature, which corresponds closely to the Australian idea of a “fair go”. While concepts may vary, equity relates to a fair or even distribution of goods or opportunities. In the climate change context, spatial (regional or international) inequities may arise due to the uneven distribution of impacts, or of costs of adaptation or mitigation. Inter-generational inequities arise similarly, but between generations over time, for example if the present generation enjoys a living standard boosted by large greenhouse gas emissions which may have adverse effects on future generations. Complex economic and social questions arise in assessing international and inter-generational equity.

Eutrophication

The increase in dissolved nutrients and decrease in dissolved oxygen in a (usually shallow) body of water, caused by either natural processes or pollution.

Evaporation

The process by which a liquid becomes a gas; especially in the climate context, evaporation of water. Actual evaporation is the amount of water that evaporates from an actual surface, whatever the properties (wetness or dryness, surface cover) of that surface. Potential evaporation is the amount of water that would evaporate from a wet surface in a given climate. Actual evaporation will usually be less than potential evaporation, and could in fact be zero from a dry surface.

Extreme event

An extreme weather event refers to meteorological conditions that are rare for a particular place and/or time, such as an intense storm or heat wave. An extreme climate event is an unusual average over time of a number of weather events, for example heavy rainfall over a season.

Forcing

Forcing, or radiative forcing, is a measure of how internal or external factors affect climate. Internal forcing is part of the natural chaos of the climate system, for example ENSO. External forcing may be natural (for example, volcanic eruptions or solar fluctuations) or anthropogenic (for example, increasing greenhouse gases or aerosols). External forcing can change the Earth’s energy balance, and hence its climate patterns.

Global temperature

Usually referring to the surface temperature, this is an area-weighted average of temperatures recorded at ground- and sea-surface-based observation sites around the globe, supplemented by satellite-based or model-based records in remote regions.

Global warming
An increase in global average surface temperature due to natural or anthropogenic climate change. See *enhanced greenhouse effect* q.v..

Greenhouse effect
The natural greenhouse effect is the process where gases in the lower atmosphere such as carbon dioxide, methane and water vapour are warmed by radiation released by the Earth's surface after it has been warmed by solar energy. These gases then radiate heat back towards the ground—adding to the heat the ground receives from the Sun. Without the natural greenhouse effect the surface of the planet would be about 33 °C colder on average. See also *enhanced greenhouse effect*, q.v..

Greenhouse gases
Natural and anthropogenic gases in the atmosphere that absorb and emit infrared or heat radiation, causing the greenhouse effect. The main greenhouse gases are *water vapour* q.v., *carbon dioxide* q.v., *nitrous oxide* q.v. and *methane* q.v..

Greenhouse gas concentrations
A measure of the amount of each greenhouse gas in the atmosphere, usually the number of molecules of a chemical per million or billion molecules of the surrounding air, or the radiatively equivalent amount of carbon dioxide.

Greenhouse gas emissions
The release of greenhouse gases and aerosols into the atmosphere. Emissions are usually measured in tonnes. About 25% of carbon dioxide emissions are absorbed by the ocean and another 25% by the terrestrial biosphere, leaving about 50% in the atmosphere. Carbon dioxide emissions are mainly from the burning of fossil fuels and deforestation. These emissions have led to an increase in atmospheric greenhouse gas concentrations since the Industrial Revolution.

Hazard
A situation or condition with potential for loss or harm to the individual, community or environment.

Impact assessment
The analysis of positive and negative consequences of climate changes on natural systems and human societies, both with and without adaptation to such changes.

Integrated assessment
A consistent framework to analyse models that simulate climate (including physical and biological conditions) and socioeconomic conditions (including policy and behaviour) and the interactions and feedbacks between them. This integration can be performed over a range of spatial scales, increasing in complexity from farms or cities, to regions, to countries to global.

Interdecadal Pacific Oscillation (IPO)
An oscillation that reflects decadal changes in tropical Pacific Ocean temperatures, having an influence on ENSO behaviour and Australian rainfall patterns. When the IPO is negative, the correlation between the SOI and Australian rainfall is enhanced, and when the IPO is positive the correlation is reduced (see ENSO).

Intergenerational equity
See *equity*.

IOCI
The Indian Ocean Climate Initiative, a Western Australian State Government program that involves CSIRO and the Commonwealth Bureau of Meteorology. The IOCI aims to provide a greater understanding of the effects of the Indian and Southern Oceans on the climate of the south-west of Western Australian across seasons, years and decades to enhance climate predictability.

IPCC
The Intergovernmental Panel on Climate Change, set up in 1988 by the World Meteorological Organisation and the United Nations Environment Program to advise governments on the latest science of climate change, its impacts and possible adaptation and mitigation. It involves panels of climate and other relevant experts who write relevant reviews, which are then critically reviewed by many other researchers and governments from member countries around the world. Summaries for Policymakers are adopted in a plenary session of government delegates, typically from over 100 member countries including developed and developing countries. See <http://www.unep.ch/ipcc>.

Kyoto Protocol
A protocol adopted by the supreme body of the *UNFCCC* q.v. in Kyoto, Japan, in 1997, committing Annex B countries (most OECD and some others) to reduce anthropogenic greenhouse gas emissions relative to 1990 levels.
The Kyoto protocol deals with carbon dioxide, nitrous oxide, methane, sulfur hexafluoride, hydrofluorocarbons and perfluorocarbons.

Methane (CH_4)
A greenhouse gas produced through processes including decomposition of landfill waste in the absence of oxygen, digestion in animals such as cattle, production of coal, natural gas and oil, and rice growing. Atmospheric methane concentrations have increased by 151% since the Industrial Revolution (about 1750 AD).

Mitigation
Mitigation of climate change refers to those response strategies that reduce the sources of greenhouse gases or enhance their sinks, to subsequently reduce the probability of reaching a given level of climate change. Mitigation reduces the likelihood of exceeding the adaptive capacity of natural systems and human societies.

Moisture balance
Atmospheric moisture balance is the difference between rainfall and potential *evaporation* q.v.. When the balance is negative, evaporation exceeds rainfall. As this is common over most of Australia, water storage and irrigation is important.

Montreal Protocol
An international agreement adopted in Montreal, Canada, in 1987 to regulate the production and use of chemicals containing chlorine and bromine, which deplete stratospheric ozone.

Murray-Darling Basin
Catchment for the Murray and Darling Rivers and their many tributaries, extending from Queensland through New South Wales and Victoria, to South Australia. It has a population of nearly two million people, with another million people outside the region depending heavily on its resources. The Murray-Darling Basin generates about 40% of the national

income derived from agriculture and grazing. It supports onequarter of the nation's cattle herd, half of the sheep flock, half of the cropland and almost three-quarters of its irrigated land.

NAO

The North Atlantic Oscillation, a large-scale seesaw in atmospheric pressure and ocean temperatures, influencing weather and climate from central North America to Europe and much of Northern Asia.

Nitrous oxide (N_2O)

A greenhouse gas mainly produced by industrial processes, fertiliser use and other agricultural activities, including land clearing and biomass burning. Atmospheric nitrous oxide concentrations have increased by 17% since the Industrial Revolution (about 1750).

NPP

Net Primary Productivity is the increase in plant biomass or stored carbon in a unit area of land. It is equal to the amount of carbon absorbed from the atmosphere by photosynthesis minus the carbon lost through respiration.

Orbital variation

Three types of changes in the characteristics of the Earth’s orbit have an effect on climate, particularly glacial cycles or “ice-ages” which occur every 100,000 years or so. These orbital variations are: the obliquity or tilt of the Earth’s axis, which varies between 22° and 24.5° over a 41,000 year period and influences the latitudinal distribution of solar radiation; the eccentricity of the Earth’s orbit around the Sun, which becomes more and less circular over two main periods of approximately 96,000 and 413,000 years and influences the amount of solar radiation received by the Earth; and the precession of the equinoxes over two periods of 19,000 and 23,000 years, which affects the hemispheric distribution of radiation and hence the intensity of the seasons.

Ozone depletion

The reduction of ozone (O_3) in the upper atmosphere as a result of human-produced chemicals, such as CFCs. Ozone depletion is especially severe over Antarctica in September to November each year, causing the ozone ‘hole’. However, at all latitudes away from the equator, the layer of ozone that protects us from the Sun’s harmful radiation is thinner that it was in the late 1970s. Recent evidence suggests that ozone depletion in the upper atmosphere may affect climatic patterns at the Earth’s surface.

Paleoclimatology

The study of climate from past ages beyond the availability of thermometer measurements that provide a global temperature. Paleoclimate records are constructed from *proxy climate data* q.v..

Perfluorocarbons (PFCs)

Greenhouse gases that are used as replacements to CFCs in the manufacture of semiconductors and which are produced as a by-product of aluminium smelting and uranium enrichment. Their concentrations are increasing and they have a greater global warming potential and much longer atmospheric lifetime than carbon dioxide.

Photosynthesis

The production of chemical compounds in the chlorophyll-containing tissues of plants, in particular the formation of carbohydrates from the carbon in carbon dioxide and the hydrogen in water with the aid of sunlight, releasing oxygen in the process.

Polar vortex

The Antarctic and Arctic polar vortices are natural, continental-scale westerly wind circulations surrounding the poles especially in winter and spring. These circulations act like giant whirlpools and reach up to 200 km per hour in the upper atmosphere. In the upper atmosphere, these vortices largely confine *ozone depletion* q.v. to polar regions in late winter and spring but breakdown in late winter (Arctic) or spring (Antarctic). These strong westerly winds are due to the transport of westerly momentum polewards, driven by the temperature differences between the polar atmosphere and that at lower latitudes. The Antarctic polar vortex is associated with the mid-latitude westerlies that deliver rain to southern Australia in winter.

Pre-industrial

The Industrial Revolution was the rapid increase in industrial activity triggered by the invention of the steam engine in 18th century England. It marked the beginning of a large increase in the burning of fossil fuels around the world and consequent large increases in carbon dioxide emissions due to human activities. The pre-industrial period usually refers to years prior to 1750.

Proxy climate data

A localised substitute for thermometer-derived temperature measurements over the period prior to thermometer observations, usually from records of temperature-dependent indicators, such as tree rings, ice cores, corals, and marine sediments, as well as from historical documents. Proxy data can also provide information on past variations in other climate-related factors, including rainfall, aridity, glacial extent and river flows.

Radiative forcing

See *Forcing* q.v.

Reinsurance

Insurance for insurers. As with insurance, the basic function of reinsurance is to spread risks; that is, part of the liability accepted by an insurer is transferred to the reinsurance company.

Return period

A measure of risk used by engineers and insurers describing the average time between events of a given magnitude. For example, a one-in-100 year event has a 1% probability of occurring in any given year.

Riparian

Living or located on, or relating to, the bank of a natural watercourse such as a river.

Risk

Risk is the probability that a situation will produce harm under specified conditions. It is a combination of two factors: the probability that an adverse event will occur; and the consequences of the adverse event. Risk encompasses impacts on human and natural systems, and arises from exposure and hazard. Hazard is determined by whether a particular situation or event has the potential to cause harmful effects.

Risk management

The implementation of strategies to avoid unacceptable consequences. In the context of climate change adaptation and mitigation are the two broad categories of action that might be taken to avoid unacceptable consequences.

Ross River virus (RRv)

An arbovirus (a virus transmitted mainly by arthropods) widely distributed throughout Australia. The virus causes epidemic polyarthritis, which consists of arthritic symptoms that persist for several months and can be severe and debilitating.

Salinisation

The build up of salts in soils (dryland salinisation) or in water (riverine or groundwater salinisation).

Scenario

A climate scenario is a coherent, internally consistent and plausible description of a possible future state of the climate. Similarly, an *emissions scenario* is a possible storyline regarding future emissions of greenhouse gases. Scenarios are used to investigate the potential impacts of climate change: *emissions scenarios* q.v., serve as input to climate models; *climate scenarios* q.v., serve as input to impact assessments.

Sensitivity

The degree to which a system is affected, either adversely or beneficially, by climate related stimuli, including mean (i.e., average) climate characteristics, climate variability and the frequency and magnitude of extremes.

Sequestration

The uptake and storage of carbon. For example, trees and plants absorb carbon dioxide, release the oxygen and store the carbon in above ground organic matter or in the soil. In the context of climate change response strategies, sequestration usually refers to the process of increasing the storage of carbon, for example reforestation, increasing the carbon content of the soil, or removal of carbon dioxide from flue gases for storage below ground or in the deep ocean.

Sink

Any process, activity or mechanism that removes greenhouse gases or aerosols from the atmosphere, into a reservoir such as the ocean, a forest, soil or subterranean storage.

Solar output

Radiation emitted from the Sun in a range of wavelengths, exhibiting variation on time scales from minutes to millions of years.

SRES scenarios

A set of emissions scenarios from the IPCC Special Report on Emissions Scenarios, used as a basis for climate projections in the TAR. See *emissions scenarios* q.v.

Stochastic

Random. Having a probability distribution, usually with a finite variance, ie., varying randomly within limits.

Storm surge

A region of elevated sea level at the coast caused by the combined influence of low pressure and high winds associated with a severe storm such as a tropical cyclone.

Stratospheric ozone (O_3)

A triatomic form of oxygen formed by the interaction between solar ultraviolet (UV) radiation and O_2 in the stratosphere, the region of the atmosphere extending from the troposphere (at a height of between 9 to 16 km) to about 50 km. Depletion of the ozone layer in the stratosphere (see *ozone depletion*, q.v.) leads to increased levels of UV radiation at the ground, and cooling of the stratosphere (or upper atmosphere). Tropospheric (i.e., lower atmosphere) ozone, some of which is formed in photochemical smog, is a greenhouse gas (see also *ozone depletion*, q.v.).

Sulfur dioxide (SO_2)

A gas resulting largely from the burning of fossil fuels. It reacts in the atmosphere to form an *aerosol* q.v. that results in a localised cooling effect, taken into account in emissions scenarios and climate models.

Sustainability

Sustainable activities meet the needs of the present without having a negative impact on future generations. A concept associated with sustainability is triple bottom line accounting, taking into account environmental and social costs as well as economic costs.

TAR

The Third Assessment Report of the IPCC, published in 2001.

Thermohaline circulation

A global ocean circulation driven by differences in seawater density, which depends on temperature (thermo) and salinity (haline). A key feature of the thermohaline circulation is the Gulf Stream, which warms western Europe. There are also contributions to the global thermohaline circulation from deep-water formation associated with the formation of sea-ice around Antarctica. There are concerns the circulation may break down over several decades due to density changes resulting from warming and inflows of fresh water, particularly to the North Atlantic Ocean, and a decrease in sea-ice formation around Antarctica. Such a breakdown would lead to abrupt changes in the Earth's climate.

Threshold

Any level of a property of a natural or socioeconomic system beyond which a defined or marked change occurs. Gradual climate change may force a system beyond such a threshold. Biophysical thresholds represent a distinct change in conditions, such as the drying of a wetland, floods, breeding events. Climatic thresholds include frost, snow and monsoon onset. Ecological thresholds include breeding events, local to global extinction or the removal of specific conditions for survival. Socioeconomic thresholds are set by benchmarking a level of performance. Exceeding a socioeconomic threshold results in a change of legal, regulatory, economic or cultural behaviour. Examples of agricultural thresholds include the yield per unit area of a crop in weight, volume or gross income.
See also *critical thresholds* q.v.

Transient warming

The time-dependent response in temperature resulting from a change in greenhouse gas concentrations in the atmosphere, before a new equilibrium is reached. Compare *equilibrium warming*, q.v.. Transient warming may continue for centuries after greenhouse gas emissions, or even greenhouse gas concentrations, have been stabilised, due to delays or inertia in the climate system.

Uncertainty

The degree to which a value is unknown, expressed quantitatively (for example, a range of temperatures calculated by different models) or qualitatively (for example, the judgement by a team of experts on the likelihood of a collapse of the *West Antarctic Ice Sheet*, q.v.). Uncertainty in climate projections is primarily introduced by the range of projections of human behaviour which determine emissions of greenhouse gases, and the range of results from *climate models* for any given greenhouse gas *emission scenario*.

UNEP

The United Nations Environment Program, which encourages cooperation in caring for the environment while improving quality of life.

UNFCCC

The United Nations Framework Convention on Climate Change, signed by more than 150 countries, including Australia, at the 1992 Earth Summit in Rio de Janeiro, Brazil. Its aim is to stabilise atmospheric greenhouse gas concentrations at a level that would prevent dangerous levels of climate change.

Vulnerability

The extent to which a natural system or human society is unable to cope with the negative impacts of climate change, variability and extremes. It depends on changes in climate as well as the sensitivity and adaptive capacity of the system or society.

West Antarctic Ice Sheet (WAIS)

West Antarctic Ice Sheet, the world's largest ground-based body of ice. Located in western Antarctica, if melted, the WAIS could raise global sea level by six metres.

Water vapour

A gas formed by the evaporation of water or by combustion. It is a *greenhouse gas* q.v.. Its concentration in the atmosphere is part of the hydrological cycle of evaporation, condensation, rainfall and runoff. Its concentration is ultimately determined by the surface temperature of the Earth.

WMO

The United Nations World Meteorological Organisation, which coordinates global scientific activity in areas including weather prediction, air pollution, climate change and ozone layer depletion.

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