# Climate change

## Risk in Australia under alternative emissions futures

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**For the Australian Government**
**Department of Treasury**

Part of the study: Climate Change Impacts and Risks
Modelling of the macroeconomic, sectoral and distributional implications of long-term greenhouse-gas emissions reduction in Australia

# Contents

# Executive summary

The climate of the Earth is changing, affecting physical and biological systems across the globe. Almost certainly, the climate change of recent decades is attributable to rising greenhouse gas concentrations in the atmosphere caused by greenhouse gas emissions from human activity.

Warming has occurred across Australia and in our oceans. Evidence of impacts on our biological systems is growing. This warming may have contributed to the current extended drought in eastern and southern Australia but this remains uncertain.

Scientific understanding of all aspects of climate change has dramatically advanced in recent years, clarifying the ensuing risks. The magnitude of climate change and the potential vulnerability of systems to it may have been underestimated by earlier assessments. The remaining uncertainties need to be part of the risk management process.

Our knowledge of how the climate system will respond is imperfect. The way human societies develop over the coming decades will influence emissions levels. Ongoing warming of the planet may culminate in dire consequences for both human and natural ecosystems. The magnitude of these consequences will be a result of the scale of change, how quickly and effectively global emissions can be reduced and the capacity of human and natural systems to adapt.

This report qualitatively examines four possible scenarios of future change:

- global greenhouse-gas emissions reduce almost immediately to meet a stabilisation target of 450 ppmv (parts per million by volume) carbon dioxide equivalent concentration in the atmosphere
- equivalent carbon dioxide concentration stabilises at 550 ppmv
- equivalent concentrations stabilise at about 750 ppmv
- emissions continue to grow through this century, reflecting growth in demand for, and largely unconstrained use of, fossil fuels (a ‘reference’ case against which the other scenarios are compared).

For Australia, the most probable consequences of these scenarios in the twenty-first century are summarised in Table 1. Further change next century is projected for all scenarios, but is least for the 450 ppmv case.

Such changes will impact very differently on different parts of Australia and on other countries around the world, with the magnitude of the impact depending on the degree of global warming. A summary of likely impact areas for Australia is as follows:

**Table 1 Greenhouse gas emissions scenarios to 2100**

| Scenario | Annual and nationally averaged response by 2100 from pre-industrial conditions | | | | | |
|---|---|---|---|---|---|---|
| | Temperature increase, °C | Rainfall decrease, % | | Evaporation increase, % | | Sea-level rise, cm |
| 450 | 2.2 (1.5–3.3) | 5 | Little change in far north: 50% greater in southwest | 4 | Greatest in north and eastern regions | 40 (30–48) |
| 550 | 2.4 (1.7–3.5) | 7 | | 5 | | 43 (33–53) |
| 750 | 3.4 (2.3–5.0) | 10 | | 7 | | 50 (36–63) |
| Reference | 4.6 (3.0–7.0) | 15 | | 9 | | 58 (41–74) |

- Water availability—reduced availability due to the combined effects of rainfall losses across most of the continent, increased evaporation associated with higher temperatures, and changed seasonality and levels of rainfall intensity.
- Coastal communities—will face generally higher sea levels, but regionally modulated by temperature, ocean and atmosphere circulation patterns. They will be exposed to increased extreme storm events and sea-level variations.
- Energy security—will be affected by higher thermal loads and changed seasonal/diurnal demands for heating and cooling and impacts of water supply on power-plant cooling (these are independent of changes to energy futures resulting from mitigation actions).
- Major infrastructure—will bring changed demands for drainage infrastructure due to higher intensity precipitation and changed rainfall patterns and energy use due to increased thermal and wind stress.
- Health—increased exposure to disease-bearing vectors such as mosquitoes and thermal stress from a higher frequency of extreme temperatures, but with some reduction in low-temperature stress.
- Tourism—significant disruptive changes to ecosystems in vulnerable tourist areas, in particular the Great Barrier Reef, Kakadu and alpine regions, and direct effects of temperature and water supply.
- Agriculture and forestry—loss of productivity, mainly due to greater aridity across most of Australia, severe climatic events and increased fire risk. Agriculture and forestry operations will be affected by infrastructure stress. Changes to oceanic productivity and distribution of marine organisms will affect fisheries.
- Food security—domestic food security will be weakened, mainly as a result of reduced productivity, infrastructure stress and severe climatic events. Oceanic productivity and distribution of marine organisms will be affected. Decreased global food production will have an impact on exports.
- Natural ecosystems—will be affected by changes in temperature and water availability, as well as by inundation, storminess, extreme events and the acidification of oceans, resulting in the loss of species (biodiversity) and the resilience of ecosystems. Conservation and ecosystem services will be affected.

Each of these impacts creates risk, the magnitude of which depends on the rate, nature and size of the climate change, the sensitivity of the various systems to it, and the probability that changes will occur. Risk can be reduced through natural and planned adaptation.

Warming in Australia through to 2030 is approximately the same under the four scenarios considered in this document; that is, about 0.6°C greater than in 2000 or 1.2°C above pre-industrial temperatures. Warming is similar over this relatively short period because the emission scenarios do not differ greatly, reflecting the inertia of the climate system (the warming over this period results from emissions that have already happened). By 2050, warming paths begin to diverge and by 2100 differentiation between scenarios becomes clear.

By 2050, the 450 ppmv equilibrium scenario leads to a most probable temperature increase of almost 2°C above pre-industrial times. Water resources, coastal communities and natural ecosystems approach the vulnerable range at this time. By 2100, all other areas of impact remain within the adaptive capacity range. This scenario suggests limited increase of risk beyond 2100, except that ongoing sea-level rise and changes to ocean chemistry may lead to long-term impacts on coastal communities and marine-dependent industries.

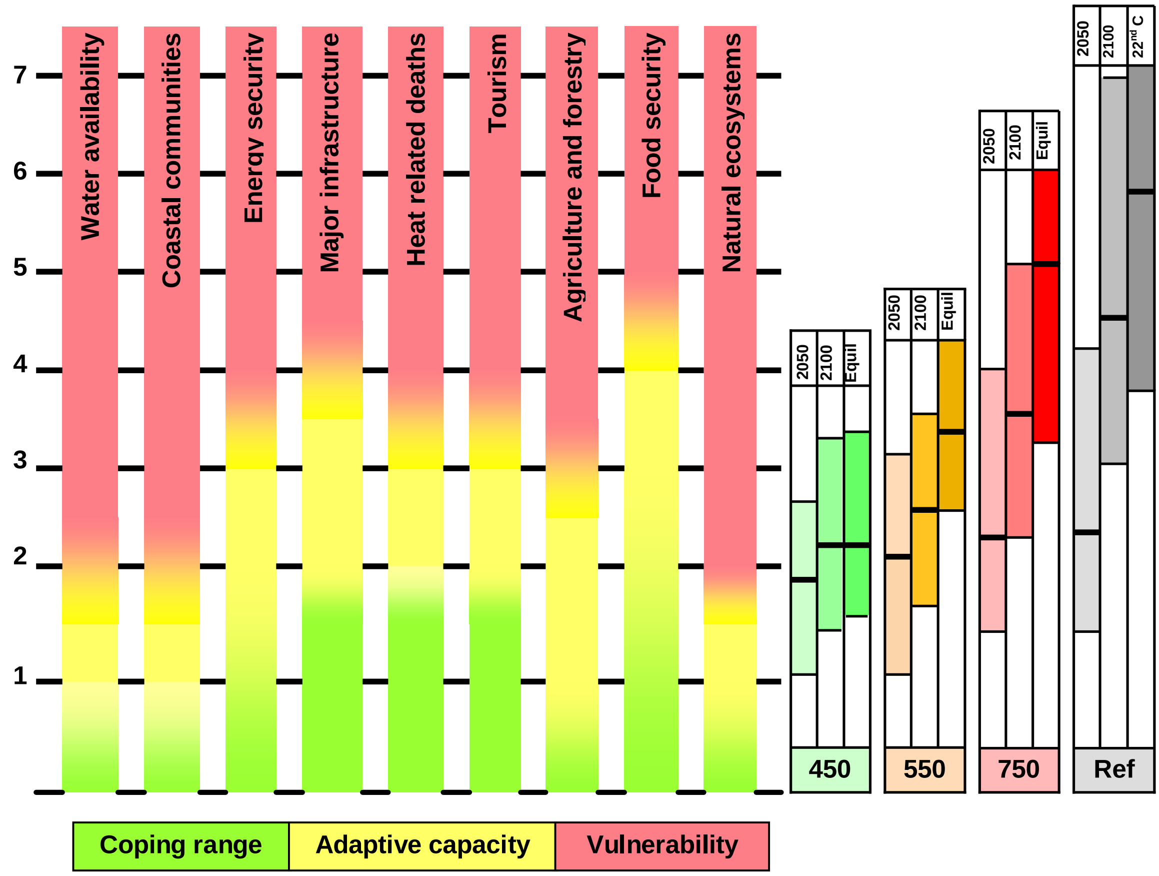
Figure 1 summarises the risk posed to areas of impact in Australia associated with various levels of warming above pre-industrial times, based on IPCC (2007b). The diagram provides a qualitative indication for each area of impact, the temperature range within which current coping strategies will operate, where adaptive capacity will be important, and where vulnerability is likely. The vertical bars on the right indicate the level of temperature change and the time at which warming will occur for each of the four scenarios, and the uncertainty bounds as defined by IPCC (2007d). For the 'reference' case, there is no anticipated equilibrium warming.

Under the 550 ppmv scenario, it is probable that temperatures will rise 2.4°C above pre-industrial levels by the end of this century. All areas of impact under this scenario will show increased exposure, requiring managed adaptation by 2050. However, water resources, coastal communities and natural ecosystems may become vulnerable by exceeding the limits of adaptive capacity. By 2100, these areas fall well within the vulnerable range. Unlike the 450 ppmv scenario, warming continues beyond 2100, with a very high likelihood that equilibrium temperatures will exceed 3°C above pre-industrial levels and most areas of impact will approach or enter the vulnerable range.

Under the 750 ppmv scenario, water availability, coastal communities and natural ecosystems become vulnerable by 2050, and all impacted areas in Australia, possibly excluding food security and major infrastructure, will approach or exceed their estimated adaptive capacity by 2100. All areas of impact become vulnerable when temperatures reach equilibrium at about 5°C above pre-industrial levels.

All areas of impact in Australia, with the possible exception of food security, fall well within the vulnerable range by the end of this century for the reference case. As concentrations continue to rise through the following century, all areas will move far into the vulnerable range.

**Figure 1 Affect of temperature rise on areas of impact in Australia**




Source: Based on IPCC (2007b).

By the end of this century, the 550, 750 and reference scenarios will most probably result in warming of 3°C or more. Such a major increase in temperature has not occurred since the mid-Pliocene three million years ago, when the Arctic Sea was free of ice, much of the Greenland ice sheet had melted and sea levels were between 13 metres and 37 metres higher than they are today.

Comparing the different scenarios provides clear, albeit qualitative, guidance on Australia's exposure to impact-related risks under different emissions futures. However, the projections are based on current views of the most probable future changes. Risk management strategies associated with climate change should recognise that:

- current knowledge is limited, and there is potential for climatic changes to occur more quickly or in ways not yet identified
- the climate system and many other systems dependent on climate are complex and will not necessarily respond in an incremental or linear fashion
- actual change may reflect extremes in the probability distribution of potential changes, rather than the more moderate estimates presented here
- current knowledge of how systems, particularly ecosystems, will respond to climate change is inadequate, limiting the ability to assess consequences.

Spontaneous adaptation to climate change has already begun, reflecting the normal coping capacity of human and natural systems. In some cases, adaptation is apparent, but in many cases—such as with the changing dynamics of ecosystem function or gene frequencies in gene pools—change has gone undetected. Planned adaptation will be required under all scenarios considered in this document. A wide range of responses is available, including behavioural change and the managed evolution from traditional to more appropriate sectoral activities. Government intervention will be necessary in some cases to aid markets and communities to adapt.

Australia will also be affected by the impacts of climate change around the world, such as:

- changed agricultural production capacity, which will vary nation by nation
- humanitarian issues related to the capacity of individual nations to adapt and to meet development goals.

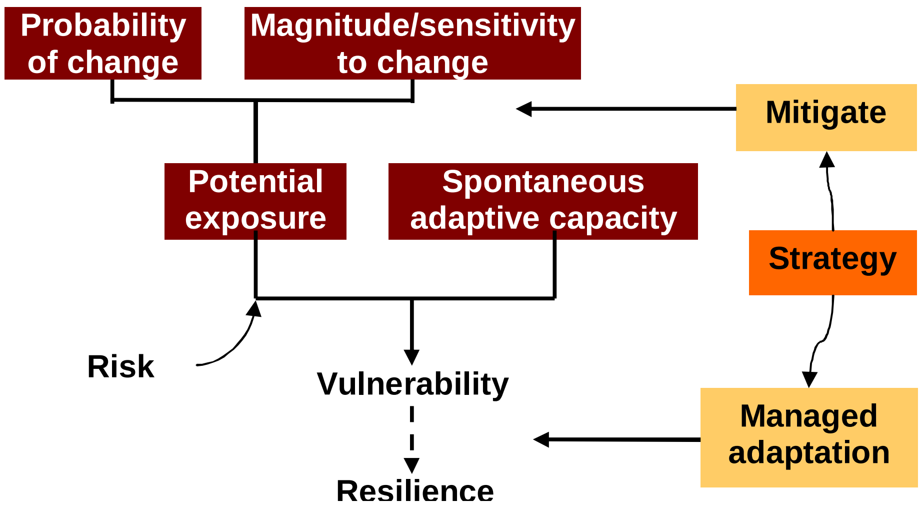
# 1 Introduction

The connection between the chemical composition of the atmosphere and global climate has been appreciated for well over a century. Direct observations of the changing levels of greenhouse gases in the atmosphere in the last third of the twentieth century, and improved knowledge of the climate system, led the climate science community in 1986 (WMO 1986) to strongly assert that climate change should no longer be considered as an academic issue alone, but as an issue for consideration by the whole community.

We now know that climate change is occurring as a result of the emissions of greenhouse gases from human activities. Further change in the next few decades may result in very significant impacts on the natural environment and on humans (IPCC 2007d; Brook 2008). Anticipating these future impacts with precision is problematic, given the complexity of the climate system and its wider relevance, and uncertainty about global responses to the issue. Nevertheless, the potential magnitude of these changes is such that responses need to reflect the implied risks.

Risk derives from the probability of a particular change occurring and the magnitude of the impact of the change if it does occur, leading to a potential exposure (see Figure 2). Both factors need to be evaluated. Climate change outcomes that may be highly improbable, yet devastating if they occur, require as much attention as those outcomes that will occur, but the impact of which is less severe. Climate-change risks cover the full spectrum of such possibilities.

**Figure 2 Risk and the relationship between probability and impact**

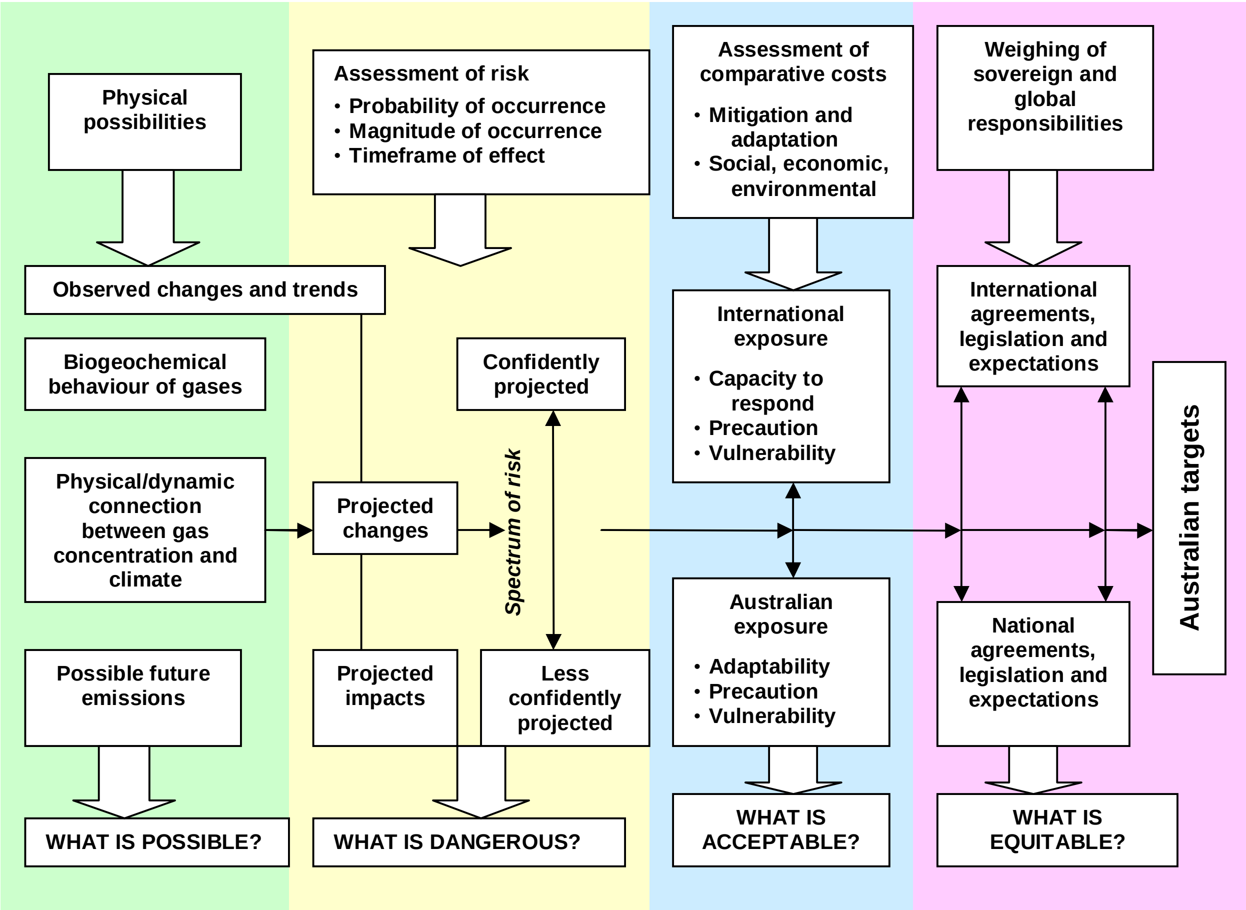



Note: Risk reflects the probability of an event occurring and its impact if it does occur. This leads to a potential exposure and vulnerability or loss of resilience.
Source: Modified from Allen Consulting (2005).

Natural and human systems have some spontaneous capacity to adapt to change, thereby removing or minimising risk. Beyond this capacity remains risk that leads to a state of vulnerability, which needs to be managed. This can be achieved by intervening to mitigate the magnitude of the event. In the case of climate change, this involves minimising greenhouse-gas emissions (mitigation)—the rationale for setting national and global emissions targets. Mitigation can also be achieved through managed adaptation to lessen vulnerability and enhance the resilience of systems.

The process for determining global and national targets for greenhouse gas emissions reductions is complex and involves a number of interdependent steps (summarised in Figure 3). It includes a range of decisions that will be based on scientific understanding couched in a risk-management framework, in which the consequences of action are weighed against the consequences of inaction. Those consequences are themselves as much related to changes to the physical environment as to changes in social and economic security.

**Figure 3 Steps in determining global and national targets for greenhouse-gas emissions**




The purpose of this study is to examine the first two phases of this process and to summarise the scientific basis for considering emissions-reduction targets in Australia by exploring what might be physically/dynamically possible under four alternative global emissions scenarios. The study considers the probability of changes resulting from climate change and the magnitude of their effects. Where the risk is high, this is what is referred to as ‘dangerous’ climate change in the United Nations Framework Convention on Climate Change. This study stresses that uncertainty about the outcomes of climate change exists and that, while lower levels of future emissions reduce risks, they do not eliminate them. The study does not consider the broader issues around which changes and responses are acceptable and equitable.

# 2 Connecting emissions to climatic consequences

Anticipating how climate will change through this century requires the interpretation of:

- alternative views on the level of future global greenhouse gas emissions from human activities
- the accumulation of those emissions in the atmosphere
- the sensitivity of global climate to future concentrations of greenhouse gases
- how feedbacks within the climate system reduce or amplify the effects of greenhouse gases
- how global climate changes lead to regional changes of significance around the world.

This complexity means that projections are largely qualitative. Nonetheless, they provide an informed basis for managing climate change risks.

## 2.1 Emissions and atmospheric greenhouse-gas concentrations

Many gases in the atmosphere have the capacity to influence global temperatures. The IPCC (2007a) examined about thirty of those gases and how they have influenced temperatures or may do so in the future. Table 2 lists the most significant of them. The potential for warming of individual greenhouse gases is related to their molecular structure (capacity to absorb infrared radiation) and to their retention in the atmosphere once released. To simplify calculations, all gases are converted to an equivalent amount of carbon dioxide in terms of their warming impact. The equilibrium scenarios in this document refer to the concentration of carbon dioxide (carbon dioxide equivalent) that would have the same warming effect as all greenhouse gases combined.

The fate of greenhouse gases released into the atmosphere is well understood (see for example Etheridge *et al.* 1996; Clerbaux *et al.* 2006; Lüthi *et al.* 2006; IPCC 2007a; Krummel *et al.* 2007). The 'residence' time of each gas (carbon dioxide, methane, nitrous oxide, chlorofluorocarbons and so on)—that is, how much of each gas is retained in the atmosphere after it is emitted, and for how long—depends on its chemical reaction times and propensity to be absorbed by the oceans and/or vegetation. Residence times are typically long (see Table 2), so once greenhouse gases are released into the atmosphere their climatic legacies endure.

Table 2 shows 2005 concentrations of significant greenhouse gases affected by human activity. The global warming potential (relative warming effect per unit concentration change over 100 years), effective residence time in the atmosphere and radiative forcing (the impact of changes so far on the imbalance of the global energy budget) for each gas are also shown.

### Table 2: Greenhouse gases and atmospheric residence

| Gas | Pre-industrial concentration | Concentration at 2005 | Warming potential relative to carbon dioxide | Effective atmospheric residence time (yr) | Radiative forcing ($W\ m^{-2}$) |
|---|---|---|---|---|---|
| **Carbon dioxide** | 278 ppmv | 379 ppmv | 1 | 80 | 1.66 |
| **Methane** | 715 ppbv | 1774 ppbv | 21 | 12 | 0.48 |
| **Nitrous oxide** | 279 ppbv | 319 ppbv | 310 | 114 | 0.16 |
| **CFC11** | 0 | 251 pptv | 3800 | 45 | 0.06 |
| **CFC12** | 0 | 538 pptv | 8100 | 100 | 0.17 |

Note: Different units of concentration for different gases: ppmv, ppbv and pptv refer to parts per million ($10^6$), billion ($10^9$) and trillion ($10^{12}$) by volume, respectively.

Source: IPCC (2007a).

Several decades of observations and research have led to a relatively well understood global carbon budget, reflecting how carbon flows between the atmosphere, oceans and biosphere and how this flow has changed over recent decades (Field and Raupach 2004). While global carbon budgets continue to operate as they have in recent decades, there is a high degree of scientific confidence in the relationship between emissions and concentrations of greenhouse gases in the atmosphere However, budgets may change in the future, in part due to the changing climate, and that level of certainty will no longer exist.

Conditions under which the *current* budgetary relationships for greenhouse gases could change, perhaps precipitously (thus invalidating future projections), are discussed in Appendix 1. In short, those conditions relate to:

- a reduced capacity of the oceans to absorb carbon dioxide due to changes in the chemistry of the water, changes in circulation patterns (as warming tends to stabilise the oceans and reduce mixing), and changes in biological uptake
- a reduced capacity of terrestrial plants to absorb carbon dioxide under conditions of higher temperature and, in some locations, reduced water availability
- carbon dioxide and methane from new sources, such as gases currently contained in reservoirs under frozen soils or trapped in the deep ocean being released into the atmosphere.

Any of those conditions would exacerbate global warming by reducing the capacity to remove carbon dioxide from the atmosphere. Current projections of warming, and emissions targets, which are based on conservative projections of change, may need to be tightened if the likelihood of those conditions increases.

For carbon dioxide, the relationship between emissions and greenhouse-gas concentration largely depends on how quickly excess carbon can be dissolved into the surface of the Earth's oceans and transported into the deep oceans (a potentially huge reservoir for emitted carbon). Current estimates are that this process, relating to both the chemical properties of the water and the dynamic mixing of that water (the ocean circulations), restricts this uptake to about 2 Gt (gigatonnes) of carbon per year (equivalent to 7 Gt of carbon dioxide per year). This compares with current emissions from human activities of around 8–9 Gt of carbon per year (Raupach *et al.* 2007). Therefore, the concentration of greenhouse gases can be stabilised, and further climate change averted, only once emissions reduce to about this level—providing the basis for calls to reduce global emissions by about 80 per cent.

We can estimate the level of atmospheric concentration that will result from particular emissions, but our knowledge of the level and type of future emissions is limited. Emission profiles will reflect the growth of global population and the global economy and future patterns of energy production, transport and development, as well as policy responses to climate change. The science community has responded to this uncertainty by establishing, modelling and analysing a number of emissions scenarios, each representing an alternative view on how the global economy and energy use will unfold through this century (IPCC 2000). These scenarios are not predictions, but they allow the comparison of levels of climate change derived from alternative global development pathways. They were originally intended to fully encompass the likely range of potential futures, although it now seems that many facets of development and its effects were underestimated. This study compares the relative risks and impacts for Australia of four different emissions scenarios.

Some consideration needs to be given to the possibility that the effective carbon dioxide concentration may initially exceed and then reduce to a target level—an overshoot scenario (see for example van Vuuren *et al.* 2007). This is relevant because:

- risk assessments undertaken now may conclude that an appropriate global stabilisation concentration is close to current levels (thus, with the inertia of emissions growth, it would be difficult to avoid some overshoot before reducing to a lower concentration)
- current assessments of what constitutes adequate stabilisation levels may turn out, as knowledge grows, to underestimate critical limits (if so, a lower ultimate concentration may be required, perhaps below that already reached, and so more rigorous reduction targets will be sought).

Atmospheric residence times of the greenhouse gases are relevant here. Long atmospheric residence times imply that concentrations will fall very slowly through the natural cycling of those gases, and that reduced concentrations will be possible only once emissions have been very substantially reduced. This will be critically affected by changing sink capacities over time.

An approach in which concentrations are exceeded for a time but with the intention of ultimately reducing them (overshoot) may be, for economic or societal reasons, an attractive management strategy. However, it is inherently more risky than approaching stabilisation levels from lower concentrations because:

- climatic impacts depend on the pathway of concentration change and warming, not just the final level—for example, once initiated, de-glacial processes might not be reversible for millennia and species forced to extinction will not be recoverable (den Elzen *et al.* 2007)
- it increases the likelihood that tipping points or points of non-reversible change might be met (see for example Hansen *et al.* 2007; just how likely this is will depend on by how much and for how long overshoot occurs; avoiding overshoot maximises the chance that advances in knowledge will enable risk to be assessed before exposure occurs)

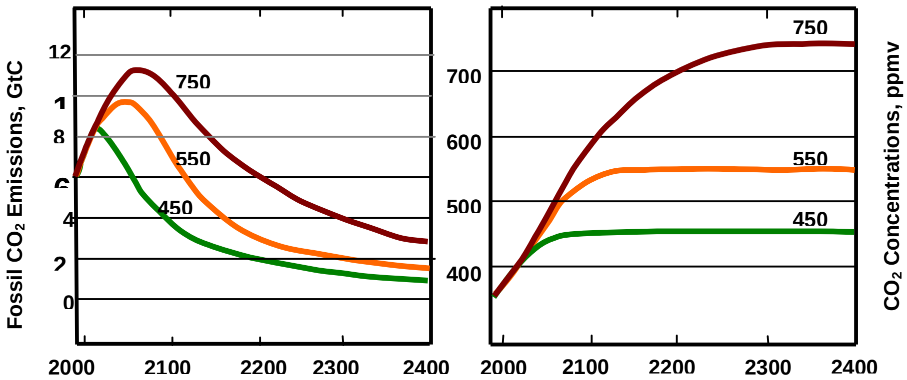
- the physical capacity to correct for an overshoot in a timely manner depends on uncertain options, such as whether it is possible
  - in the first instance, to reduce methane emissions (methane has a much shorter residence time) to reduce carbon dioxide equivalent levels
  - in a changing climate, to reduce emissions through changes to land-use practices, perhaps to the level where anthropogenic emissions are able to be offset for a time.

Limitations on just how quickly adjustment to emissions can be made in the future implies that “a practical transition path to a given stabilization target in the most commonly cited range can allow, at most, one or two decades delay” (Mignone *et al.* 2008).

## 2.2 Atmospheric concentrations and global warming

The response of the global climate to specific future concentrations of greenhouse gases can be determined using climate models such as those described in the IPCC Fourth Assessment Report (IPCC 2007a). Simple models allow assessments of the likely average changes to key aspects of the global climate system, such as temperature and sea level. More complex models allow for assessment of changes at the regional level, the consequent impact of those changes on each sector of the community, and the capacity to adapt and the cost of unavoidable impacts (see for example Hansen *et al.* 1997). Different models produce a range of estimates due to the sheer complexity of the climate system and their slightly different representation of the components of that system. Meinshausen *et al.* (2006) argue that the lack of a suitable method to deal with the complexities of this system has hindered the rigorous development of rationally determined emissions targets. But the qualitative nature of such determinations is unavoidable, given the uncertainties in the climate system and the complexities of other steps in the process (as outlined in Figure 3)—in particular, defining ‘dangerous’ climate change across jurisdictions (Dessai *et al.* 2004).

**Figure 4 Carbon dioxide emissions scenarios: stabilisation at three atmospheric concentrations**

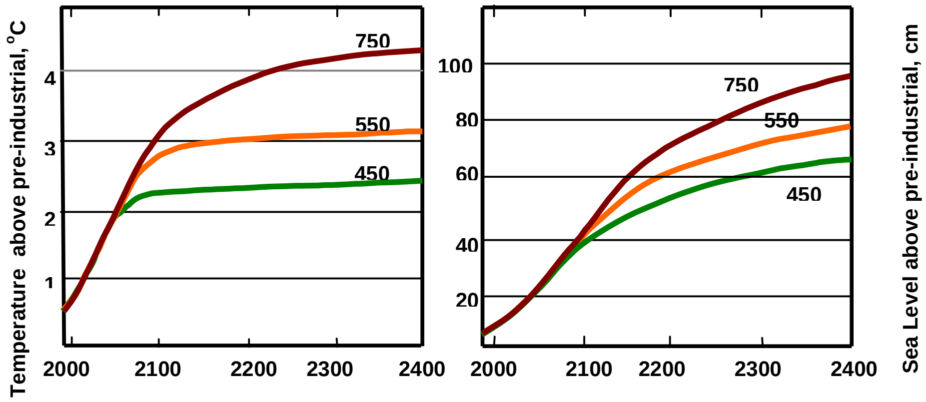



Note: Shown as illustrative examples only as they do not include the effects of non-$CO_2$ emissions, and the relationships are peculiar to the carbon cycle models used.
Source: Based on Meinshausen *et al.* (2006)

It is possible to produce a consistent set of relationships between emissions and ultimate climate change by using a single set of biogeochemical and climate models.

Figures 4 and 5 show such a set based on the work of Meinshausen et al. (2006). However, while this achieves comparability between alternative scenarios, it does not represent the range of uncertainty related to alternative models and modelling approaches.

**Figure 5 Carbon dioxide emissions scenarios: changes in mean temperatures and sea level**




Note: Changes in global mean temperatures and sea level relative to pre-industrial levels in response to the emissions scenarios and concentration changes in Figure 4. Again, these are shown as illustrative examples only as they are peculiar to the climate models used.

Source: Based on Meinshausen *et al.* (2006).

Twenty-three global climate models were used in the analysis of the IPCC Fourth Assessment Report (IPCC 2007a) to examine the response of global temperature to future concentrations. Table 3 shows the many possible future emissions scenarios, grouped into six ‘stabilisation categories’ (IPCC 2007d), with the corresponding temperature and sea-level changes projected to occur this century. The range reflects the different estimates from the different models.

This study examines four emissions scenarios. The three stabilisation scenarios are most closely represented by categories I, III, and V in Table 3 (shown as green, orange and dark red) reflecting stabilisation at approximately 450, 550 and 750 ppmv, respectively. The fourth scenario, the reference case, with ongoing emissions growth and warming, is best represented by category VI (grey).

In turn, three of the emissions scenarios broadly correspond to IPCC Special Report on Emission Scenarios (IPCC 2000) scenarios which have been extensively modelled and analysed in the scientific literature, including for Australia by the CSIRO and the Australian Bureau of Meteorology (CSIRO and BoM 2007). These scenarios are identified in Table 3. However, very little modelling is available for the 450 ppmv stabilisation scenario; so, for this case, risks and impacts have been interpolated from the 550 ppmv case, according to the smaller projected temperature change.

**Table 3 Stabilisation categories: IPCC Fourth Assessment Report**

| Category | Nominal IPCC emissions scenario[a] | $CO_2$ concentration ppmv | $CO_2$ equivalent concentration ppmv | Global $CO_2$ emissions peaking years | $CO_2$ emissions change 2050 (% of 2000) | Temperature °C above pre-industrial | Sea-level above pre-industrial (m)[b] |
|---|---|---|---|---|---|---|---|
| I | | 350–400 | 445–490 | 2000–2015 | –85 – –50 | 2.0–2.4 | 0.4–1.4 |
| II | | 400–440 | 490–535 | 2000–2020 | –60 – –30 | 2.4–2.8 | 0.5–1.7 |
| III | B1 | 440–485 | 535–590 | 2010–2030 | –30 – +5 | 2.8–3.2 | 0.6–1.9 |
| IV | | 485–570 | 590–710 | 2020–2060 | +10 – + 60 | 3.2–4.0 | 0.6–2.4 |
| V | A1B | 570–860 | 710–855 | 2050–2080 | +25 – +85 | 4.0–4.9 | 0.8–2.9 |
| VI | A1FI | 660–790 | 855–1130 | 2080–2090 | + 90 – +140 | 4.9–6.1 | 1.0–3.7 |

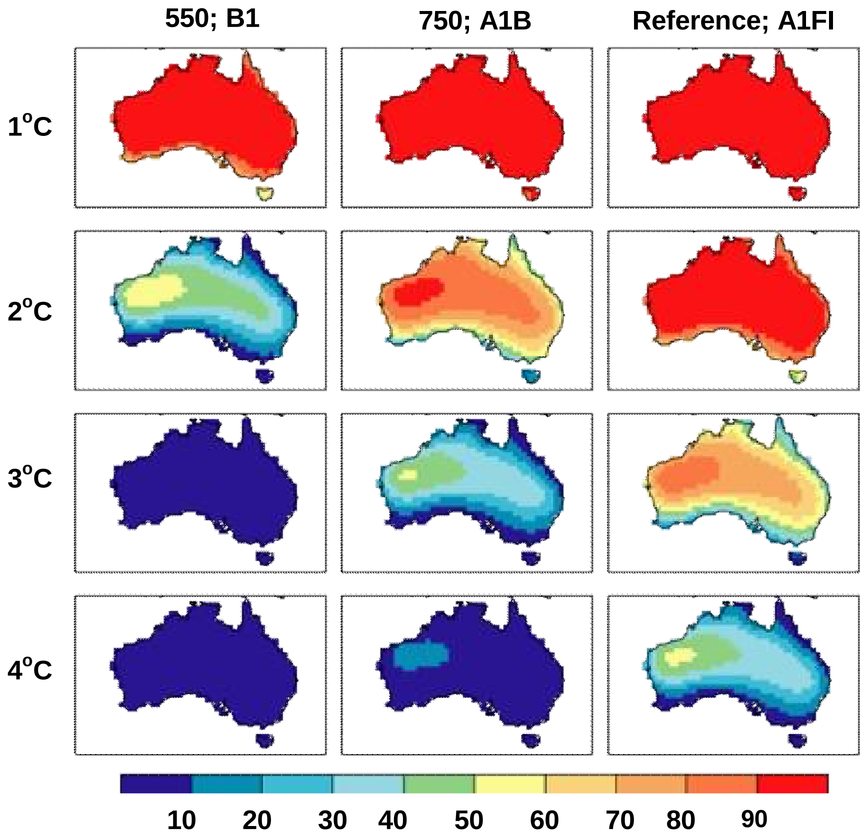
Note: Table 3 shows the six stabilisations categories of the IPCC Fourth Assessment Report (IPCC 2007d) showing the temperature and sea-level rise above pre-industrial levels calculated at equilibrium; the range of global emission reductions required globally at 2050; and the year at which emissions need to peak.

a These refer to emissions scenarios produced by the IPCC Special Report on Emission Scenarios (SRES; IPCC 2000). Those selected to be approximately equivalent to achieving the specified nominal future concentration are coloured. Category I does not coincide with a particular SRES scenario.

b Sea-level rise is calculated as the result of thermal expansion of water (primarily) and the net effects of melting and accumulation of ice. It ignores the potential for rapid de-glaciation of Greenland and parts of Antarctica and thus represents a conservative estimate of potential sea-level rise. See discussion in Appendix 1.

Any given scenario will lead to a range of projections, reflecting the uncertainties in future greenhouse-gas emissions, global gas budgets, and model estimates of the sensitivity of the climate system to increased levels of greenhouse gases. To represent this uncertainty, CSIRO and the Australian Bureau of Meteorology (CSIRO and BoM 2007) established probability density functions that pool the results of all 23 models and alternative emission scenarios. While this approach is not perfect, and alternative probability distributions are possible, it is by far the best representation available. While this document focuses on the most probable futures, it is important to note that there will always be a range of probable outcomes. For example, Figure 6 shows how a 550 ppmv stabilisation gives a very high likelihood of at least 1°C warming by 2070 (above the 1990 figure), about a 30-40 per cent chance of a 2°C rise, and a small chance of a 3°C rise by 2070. In contrast, a 750 ppmv stabilisation gives a very high likelihood of at least a 2°C rise and about a 30 per cent chance of 4°C rise. Similarly, in considering sea-surface temperature changes, Figure 7 shows how by 2030 temperature will most probably increase above 1990 levels by about 1°C, whereas changes of less than about 0.5°C or greater than 1°C are much less likely.

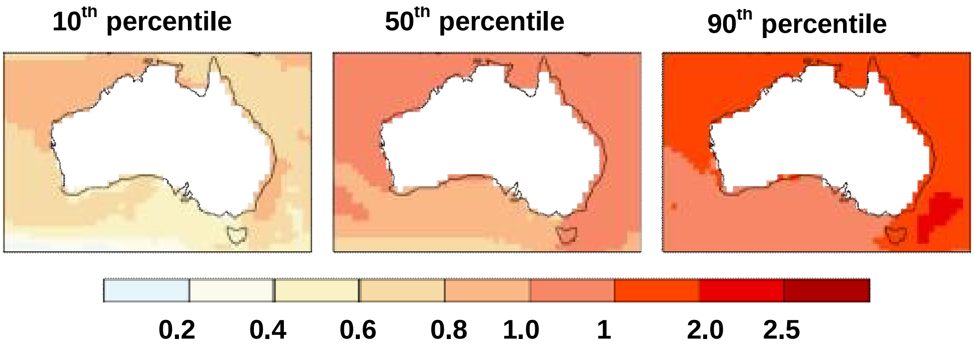
## Figure 6 Probability of exceeding thresholds for annual warming




Note: Probability of exceeding thresholds in the annual warming above 1990 by 2070 for three scenarios (colour code in %).

Source: CSIRO and BoM 2007, Figure 5.8.

## Figure 7 Annual change in sea-surface temperature, 1990 to 2030




Note: Annual change in sea-surface temperature (colour code in °C) from 1990 by 2030 using the 750 ppmv stabilisation (A1B) emission scenario. The 50th percentile indicates that there is a 50% chance that at least this amount of warming will occur by 2030. The 10th and 90th percentiles represent where it is very likely or very unlikely that the indicated warming will occur, respectively

Source: CSIRO and BoM 2007, Figure 5.48.

## 2.3 Global warming and impacts

Risks associated with global warming will vary from region to region due to changes in the circulation of the oceans and atmosphere. Warming will be greatest at high latitudes, greater over land than water and generally greater at night-time than daytime. Sea-level rise is a global phenomenon, but will also vary from place to place due to changes in the general circulation of the oceans, different levels of regional heating, changes of atmospheric pressure and the isostatic motions of local land masses. For example, impacts may be very different between low-lying island states and mountainous ones.

Some impacts may be effectively irreversible, meaning that the risk associated with them is high even though the probability of occurrence might be low or currently uncertain. In general, higher future concentrations bring bigger impacts and risks, as do more rapid concentration rises—faster growth is riskier and allows less time for adaptation. Inertia in the climate system means that temperatures will continue to increase long after concentrations are stabilised.

The level of certainty associated with the impacts will depend on the degree to which projections of relevant components of the climate system are accepted as accurate. For example, it is likely that impacts related to temperature change will be more certain than those related to rainfall change. This is partly because the physical processes that determine temperature change are less complex and better represented in the climate models than those for rainfall. Furthermore, because of the dynamics involved, some climatic changes appear to be more robustly determined by the modelling processes than others. For example, the projections of rainfall loss across southern Australia, mainly related to the progression of winter frontal storms, are more confidently projected than losses in northern Australia associated with changes to the monsoon system.

The main global impacts of various degrees of warming are summarised in Table 4 (based on Stern 2006), demonstrating the multiple sectors impacted by climate change and the nonlinear escalation of risks beyond temperature changes of a few degrees.

Section 3 looks at Australia as it might appear under conditions commensurate with the four alternative emissions scenarios. We base the description of these futures for Australia, in the first instance, on the best or mean estimates developed by the CSIRO and the Australian Bureau of Meteorology (CSIRO and BoM 2007).

## Table 4 Possible climate impacts in the global context for various levels of mean annual warming

<table>
<tr><th>ΔT</th><th>Water</th><th>Food</th><th>Health</th><th>Land</th><th>Environment</th><th>Abrupt & large-scale impacts</th></tr>
<tr><td>1°C</td><td>Small glaciers in the Andes disappear completely, threatening water supplies for 50 million people</td><td>Modest increases in cereal yields in temperate regions</td><td>At least 300,000 people each year die from climate-related diseases. Reduction in winter mortality in high latitudes (northern Europe, USA)</td><td>Permafrost thawing damages buildings and roads in parts of Canada and Russia</td><td>At least 10% of land species facing extinction (according to one estimate).<br><br>80% bleaching of coral reefs, including Great Barrier Reef</td><td>Atlantic thermohaline circulation starts to weaken</td></tr>
<tr><td>2°C</td><td>Potentially 20–30% decrease in water availability in some vulnerable regions (e.g. South Africa and Mediterranean)</td><td>Sharp declines in crop yield in tropical regions (5-10% in Africa</td><td>40–60 million more people exposed to malaria in Africa</td><td>Up to 10 million more people affected by coastal flooding each year</td><td>15–40% of species facing extinction, according to one estimate. High risk of extinction of Arctic species, including polar bear and caribou</td><td rowspan="4">Potential for Greenland ice sheet to begin melting irreversibly, accelerating sea-level rise and committing world to an eventual 7 m sea-level rise<br><br>Rising risk of abrupt changes to atmospheric circulation is e.g. the monsoon<br><br>A rising risk of collapse of West Antarctica ice sheet<br><br>A rising risk of collapse of Atlantic thermohaline circulation</td></tr>
<tr><td>3°C</td><td>Serious droughts occur in southern Europe once every 10 years. 1–4 billion more people suffer water shortages, while 1–5 million gain water, which may increase flood risk</td><td>150–550 additional millions at risk of hunger (if carbon fertilisation weak). Agricultural yields in higher latitudes likely to peak</td><td>1–3 million more people die from malnutrition (if carbon fertilisation weak)</td><td>1–170 million more people affected by coastal flooding each year</td><td>20–50% of species facing extinction (according to one estimate), including 25–60% of mammals, 30–40% birds and 15–-70% of butterflies in South Africa. Onset of Amazon forest collapse (some models only)</td></tr>
<tr><td>4°C</td><td>Potentially 30–50% decrease in water availability in Southern Africa and Mediterranean</td><td>Agricultural yields declined by 15–35% in Africa, and entire regions lose production (parts of Australia)</td><td>Up to 80 million more people exposed to malaria in Africa</td><td>7–300 million more people affected by coastal flooding each year</td><td>Loss of around half Arctic tundra. Around half of all world's nature reserves cannot fulfil objectives</td></tr>
<tr><td>5°C</td><td>Possible disappearance of large glaciers in Himalayas, affecting quarter of China's population and hundreds of millions in India</td><td>Continued increase in ocean acidity that parallels temperature increase seriously disrupting marine ecosystems and fisheries</td><td></td><td>Sea-level rise threatens small islands, low coastal areas (Florida) and major world cities such as New York, London and Tokyo</td><td></td></tr>
<tr><td>>5°C</td><td colspan="6">The latest signs suggest that the Earth's average temperature will rise by even more than 5°C or 6°C if emissions continue to grow and positive feedback amplifies the warming effect of greenhouse gases (e.g. release of carbon dioxide from soils or methane from permafrost). This level of global temperature rise would be equivalent to the amount of warming that occurred between the last ice age and today and is likely to lead to major disruption and large-scale movement of population. Such 'socially contingent' effects could be catastrophic but are currently very hard to capture with current models, as temperatures would be so far outside of human experience.</td></tr>
</table>

Source: Summary of possible climate impacts in the global context for various levels of mean annual warming based on Stern (2006), Part 3, p. 75.

# 3 Projection of climate change in Australia under alternative emissions scenarios

This Section describes the four emissions scenarios, weighing the magnitude of potential impacts under different future conditions against their likelihood of occurrence; that is, the components of a risk assessment. Undoubtedly, as time progresses, scientific knowledge will improve both the descriptions of the impacts and estimations of their probability of occurrence, although some uncertainties will remain.

## 3.1 Stabilisation at 450 ppmv

The 450 ppmv scenario would require urgent and strong mitigation action. Global emissions will need to peak within the next decade (recall stabilisation scenario I in Table 3 reducing through the remainder of the century. This is likely to involve overshooting of 450 ppmv before the concentration reduces and stabilises (see, for example, Knutti *et al.* 2005) because the current levels of long-lived greenhouse gases in the atmosphere are already around 455 ppmv (IPCC 2007d). The warming effect of these gases is offset somewhat by current levels of aerosols in the atmosphere, but expected reduction of aerosols over time leaves little room for further emissions growth of these gases if a 450 ppmv target is to be met.

This is the only scenario considered that gives a reasonable chance of limiting the increase in global average temperature to 2°C—the temperature threshold most frequently spoken of in the scientific literature as representing the limit beyond which 'dangerous' climate change may occur (see, for example, Hansen *et al.* 2007). IPCC (2007a) gives a best estimate of warming for 450 ppmv equilibrium as 2.2°C. Avoidance of the consequences of exceeding such a limit cannot be guaranteed under conditions where an overshoot of concentration occurs, even if this level of ultimate concentration stabilisation is achieved, as discussed in Section 2.1.

### Australia at 450 ppmv

Through the twenty-first century, Australia will experience substantial environmental change. The change is approximately equivalent to moving the climatic zones in Australia southwards by 200 km (see Appendix 1). This is only qualitatively indicative, but illustrates the importance of spatially and temporally averaged changes of this amount. As a consequence, by the end of the century both natural and agricultural production systems will show little resemblance to current systems. While the emphasis here is on changes related to global warming, these should be seen as concomitant with other stresses associated with population growth and land-use change. The combined effects of higher temperatures, reaching as high as 2°C above pre-industrial levels, and a general loss of rainfall of 4 per cent or more across much of the nation will significantly reduce water availability, with implications for both natural and agricultural production systems.

### Natural ecosystems

Significant loss of species is possible through this century, perhaps 10 per cent or more by 2100. Climate change is likely to lead to substantial reshaping of natural ecosystems and loss of resilience and viability in some cases. Factors such as a higher frequency and intensity of bushfires across the nation have the potential to adversely impact on ecosystems. Such changes will affect the provision of ecosystem services (timber, aesthetics, water harvesting, soil protection, tourism and so on), with specific ecosystems at greatest risk being the Great Barrier Reef, the southwest of Western Australia, the Murray–Darling Basin, eastern Australian alpine systems, eastern Queensland, Kakadu, the Queensland wet tropics and the sub-Antarctic islands.

These risks will require significant adaptive responses, such as for the conventional ski industries and the most important ecotourism icons across the nation. They will create challenges for the provision and suitability of national reserves and of corridors for migration of species, and for the preservation of species endangered by climate change.

### Water availability

Significant adaptation will be required in water management. The continued decline in water available to our major cities will require both behavioural change and technical intervention to ensure that reliable supplies are maintained (see Section 4).

### Coastal communities

Coastal inundation by seawater will impact on salt-intolerant natural vegetation, and on the maintenance of sandy beaches and coastal fish nurseries. It will affect freshwater aquifers and wetlands in coastal regions. In some areas, combined with the changing frequency of extreme storminess, sea-level rise will mean that some coastal settlements will need to be abandoned or substantially redeveloped.

### Agriculture

The productive capacity of agriculture systems will be reduced, principally due to reduced water availability (changes in rainfall and evaporation), if substantial adaptation is not achieved by improvements to or innovation in agricultural methods, such as shifting to alternative cultivars, geographically shifting production systems, or both. Very significant impacts on rural communities are likely, even with a relatively low emissions scenario. Less frequent extreme low temperatures will reduce the setting of stonefruit and affect the distribution of pest species and disease vectors.

### Human health

Direct temperature and weather effects will include more extremely hot days and high-precipitation events, with consequences for human and animal health. Changes will be generally within the coping capacity of public health services, but at some additional cost.

### Major infrastructure

Bushfires and extreme storminess will pose a greater threat to built infrastructure in coastal and rural regions.

### International pressure

This report cannot examine global environmental changes region by region (see IPCC 2007b for such an analysis), but in some cases risks and opportunities for Australia will derive from the impacts of climate change elsewhere. Major examples of such risks and opportunities are as follows:

- changed production capacity of nations competing or trading with Australia in the provision of food, fibre and energy, where these are influenced by water availability and temperature change
- humanitarian issues, particularly in developing countries, related to incapacity to cope with change that in turn leads to political challenges such as:
  - human stress/mortality from food and water deficiencies and extreme events
  - calls for humanitarian aid
  - failure of governments, increased vulnerability to military or extremist activities, breakdown of societies and national population movements
  - migration and environmental refugees.

## 3.2 Stabilisation at 550 ppmv

This scenario describes a world in which global emissions peak within the next two decades and then decline.

### Australia at 550 ppmv

The changes listed under the 450 ppmv scenario will, through the twenty-first century, occur sooner and become more extreme under the 550 ppmv concentration scenario. Conditions encountered in 2100 under the 450 ppmv scenario would be reached as early as 2050 under the 550 ppmv scenario. For Australia, changes under this scenario are equivalent to temperature belts shifting southwards by 200–300 km (see Appendix 1).

Temperatures are expected to reach about 2°C above pre-industrial levels by 2050, 3.1°C by 2100 and a little more than 3.3°C at equilibrium. Compared with the 450 ppmv scenario, Australian temperatures would be about 1°C warmer by 2100.

### Natural ecosystems

The IPCC (2007b) attributes a 50 per cent probability of loss of between 20 and 30 per cent of all species with this level of temperature change. This would involve the total realignment of ecosystems across Australia. The particular species that might be permanently lost, the kinds of functioning ecosystems that might develop, and whether they could deliver the ecosystem services and tourism opportunities currently available, are not possible to predict.

### Water availability

Rainfall is projected to decline by a little less than 5 per cent by 2050 and around 7 per cent by 2100 for the central and eastern regions of Australia, and by more than 10 per cent in the southwest. Little or no change through the century is projected across the northern coastal regions. Evaporation is expected to increase by 3 per cent by 2050, with increases in the range of 4 per cent to 8 per cent in the eastern and northern regions by 2100.

#### Coastal communities

Sea levels are expected to rise by at least 43 cm by 2100, with additional increases through the following century. This will result in frequent or permanent coastal inundation and erosion for parts of the Australian coastline, and will require the abandonment of some coastal developments or the construction of sea walls.

#### Agriculture

It is highly likely that substantial restructuring of the rural sector will result, through relocation, land abandonment and changed production methods and crop types.

#### Human health

There will be significant risk to human life associated with extreme events of fire, flooding, heatwaves and new geographical ranges for disease-bearing vectors.

#### Major infrastructure

Storminess will be likely to increase substantially across the nation, with effects on the delivery of rain and consequences for flooding, soil and river erosion, silting of reservoirs and the destruction of infrastructure and the loss of livestock, crops and human life. The combination of higher sea levels and increased storminess under this scenario greatly increases the probability of major storm surges, with concomitant infrastructure destruction and risks to human life.

#### International pressure

A world subjected to global warming of 3°C by the end of this century is likely to be vastly different from that of today. This warming could lead to almost half of the world's population being at risk of water shortage, as many as a quarter of a billion people exposed to potential health problems associated with the warming, and hundreds of millions facing food shortages and coastal inundation (see Parry *et al.* 2001). This is a world in which international cooperation and security might be jeopardised and in which the potential for militancy and conflict over resources is substantially increased.

## 3.3 Stabilisation at 750 ppmv

In the 750 ppmv scenario, emissions continue to grow in the first half of the century, then peak and subsequently decline. Anticipated global average warming through this century is approximately 3.5°C and, at climatic stabilisation, 4°C to 6°C above pre-industrial levels. Temperatures are expected to reach 2.3°C above pre-industrial levels by 2050, 4°C by 2100 and more than 5°C at equilibrium. Relative to the 450 ppmv scenario, warming would be about 2°C greater by the end of the century and 3°C greater at equilibrium.

### Australia at 750 ppmv

From a regional perspective, an approximate indication of the magnitude of this effect is that it is equivalent to moving the climatic zones in Australia southwards by as much as 1000 km (see Appendix 1). Under this scenario, Australia's climate will bear little resemblance to that of today. With the poleward movement of climate systems, the intensity of storms will increase. The scale and likelihood of changes to monsoon and tropical cyclone intensity, location and frequency are uncertain.

### Natural ecosystems

There will be significant loss of life from bushfires, heatwaves, invasive diseases and loss of capacity to supply hydroelectricity and water for power-plant cooling. Higher temperatures and low water availability will result in massive loss of species in the Australian and global contexts. Most ecosystems and ecosystem services will be at risk of complete breakdown. Most alpine ecosystems will have disappeared well before 2100. Australia's ability to meet its food demands would be stretched.

### Water availability

Rainfall is projected to decline by a little less than 5 per cent by 2050 and by around 7 per cent by 2100 for the central and western regions of Australia, and by more than 10 per cent in the western coastal area. Little or no change is projected through the century across the northern coastal regions. Evaporation is projected to increase by up to 4 per cent in the western regions and more than 4 per cent in the eastern and northern regions by 2050, and reach 4 per cent to 8 per cent across the whole nation by 2100. Water availability problems under the 750 ppmv scenario will reach conditions likely by the end of the century in the 550 ppmv scenario by as early as 2050. Water capture and delivery infrastructure will need to evolve dramatically to meet changed demand and the demise of existing structures, such as geographically inappropriate dams and reservoirs. The provision of energy to meet cooling and pumping demands will be limited by higher energy prices and efforts to reduce emissions, and by competition for funds to meet other climate change needs.

### Coastal communities

Sea levels are expected to rise by 50 cm by 2100, with massive consequences for coastlines. This will be likely to have substantial impacts on the breeding grounds and habits of fish and other marine organisms and to result in the destruction of coastal infrastructure, the flooding of wetlands, and the salination of freshwater reserves and otherwise non-saline environments. The interaction of these higher sea levels with increased storminess, flooding events and low-pressure systems strongly suggests a world exposed to high levels of damage, with substantial impacts on the wellbeing and survival of coastal cities in Australia and around the world. There is a significant probability of rapid de-glaciation exceeding simple proportional changes in temperature, resulting in much greater sea-level rises through this and subsequent centuries.

### Agriculture

Despite a global food shortage, Australia's trade in food may be limited by both our capacity to produce and the world's economic capacity to purchase. Food shortages around the world will reverse the current trend in alleviating hunger globally.

### Human health

Loss of life from bushfires, heatwaves, and invasive diseases will be exacerbated by the impact of limited water and food supplies. Together with mental health problems arising from social change and human dislocation, this will place an enormous burden on public and private health services.

### Major infrastructure

In some instances, it will no longer be possible to provide insurance cover for coastal communities exposed to inundation and extreme weather events.

### International pressure

The global environment will be radically changed. Shorelines will change, coastal settlement inundated and low-lying island nations, human health, food supplies and global peace compromised. Serious societal disruptions in other countries are likely as a result of water shortages, hunger and international disasters. The development of nations will be impeded, demand for aid increased and, in some cases, the breakdown of social order will result. Each has the potential to impact on Australia.

## 3.4 Reference case

The reference case scenario involves strong global emissions growth in the coming decades, with growth slowing in the second half of the century but emissions continuing to rise. This corresponds to a fossil-fuel intensive development path and is best represented by the IPCC emissions scenario A1FI. It does not lead to greenhouse-gas concentration stabilisation or climate stabilisation, but in warming of between 5°C and 6°C this century and substantially more warming in the following centuries.

Under the reference case, Australian temperatures are likely to increase by more than 4.6°C above pre-industrial levels by the end of this century, placing all impacted areas beyond their coping range and, in most cases, beyond the expected limits of adaptive capacity. This scenario all but guarantees, even at the lower limits of the probability range, that by the end of this century Australia will experience the following effects.

### Natural ecosystems

Major loss of complete ecosystems (coral reefs, alpine ecosystems and many others) will occur, and the resilience of remaining assemblages of species will be seriously compromised. Major problems will emerge from the impact of invasive species (terrestrial and marine). Ecosystem services, such as timber, water production, tourism and genetic diversity, will be seriously jeopardised.

#### Water availability

Dangerous water availability problems will emerge by as early as 2050 and will compound, seriously limiting the viability of human occupation, agriculture and natural ecosystems.

#### Coastal communities

Large areas of Australia’s coastline will be permanently or periodically inundated, with destruction of infrastructure, salination of water supplies, and major loss of amenity for recreation, tourism and fish nurseries. There will also be a very high probability that global de-glaciation will have been triggered, with unavoidable longer term sea-level rises that will flood most coastal cities.

#### Agriculture

Food shortages in Australia will become significant and there will be widespread starvation globally.

#### Human health

Australian human habitation will be highly vulnerable as a result of inundation, limited water supplies, poor diet, changed distribution and frequencies of diseases, and social disruption.

#### Major infrastructure

Huge infrastructure costs will be associated with the protection of assets (for example, construction of sea walls), their replacement (for example, new water capture and transportation and power distribution infrastructure) and/or relocation, resulting from a much higher frequency of storminess, bushfires and flooding.

#### International pressure

There will be massive human misery and dislocation, particularly in the developing world, that will compromise international markets and security and create severe humanitarian problems.

## 3.5 Summary

The subsections above provide an overview of the risks associated with various degrees of future warming or with the alternative emissions scenarios. The intention is to provide a qualitative description of risk under these scenarios and to emphasis the broad scope of risk exposure and the uncertainties related to these projections. Table 5 summarises these risks. More specific examples are presented by Brereton *et al.* (1995); Beaumont and Hughes (2002); Hennessy *et al.* (2003); Newell *et al.* (2003); Church *et al.* (2006, 2007a); IOCI (2006); Preston and Jones (2006, 2008a and b); IPCC (2007c); Pearman (2007); Taylor and Figgis (2007); Hoegh-Guldberg *et al.* (2008); Jones *et al.* (2008).

# 4 Opportunities for adaptation in Australia

Figure 2 showed how adaptation is an essential component for managing climate change, as it allows for the minimisation of vulnerability to risk. This is especially the case as some level of change and related risk is locked in with future warming, which is a legacy of changes to greenhouse-gas concentrations that have already occurred. Also, inertia in our energy and other societal activities means that it will take time to bring about substantial mitigative actions and the stabilisation of concentrations.

However, adaptive actions might not be economically, socially or environmentally cost free. Assessing such actions and their costs is necessary as part of the decision-making process in which the level of effort devoted to mitigation through the setting of emissions targets and related interventions can be established. The costs of adaptive action will rise with the degree of climate change and thus risk exposure, but the cost of mitigation will also rise depending on the rate at which emissions are to be reduced. Furthermore, different areas of risk exposure are likely to have different levels of capacity to adapt. Understanding those actions and risks will enable the most reasoned expenditure of resources and effort on adaptation actions. The economic assessment of alternative adaptive strategies is beyond the scope of this study. What is discussed in this Section is the range and complexity of options that exist.

Natural (physical and biological) and human systems will respond to change by changing themselves—by adapting. Initially, this kind of adaptation is spontaneous; that is, it is consequential rather than planned, deliberative or anticipatory. For example, in biological systems (individual species or ecosystems) it can take place by genetic change. In the short term, this may include modification of the gene frequencies within gene pools, favouring different phenotypic forms more appropriate for the changed conditions. An example is the shift of gene frequency in *Drosophila* fruit flies down the east coast of Australia, believed to be in response to the warming that has occurred to date (Umina *et al.* 2005).

## Table 5 Qualitative assessment of risks to Australia with different degrees of global warming

| | Natural ecosystems | Water availability | Coastal communities | Agriculture | Human health | Major infrastructure | International pressures |
|---|---|---|---|---|---|---|---|
| 450 ppmv(~2 °C) | **Significant loss of species and resilience**. At high risk are the Great Barrier Reef, SW Western Australia, the Murray–Darling Basin, Alpine systems, Eastern Queensland, Kakadu, Queensland wet tropics and sub-Antarctic Islands. Natural coping capacity exceeded. | **Significant water shortages** impacting on natural and agricultural systems, use of water for agriculture, human consumption, power generation and ecosystem survival. Natural coping capacity exceeded. | **Coastal inundation and erosion** affecting parts of the Australian coastline, resulting in the abandonment of some coastal developments and/or the construction of sea walls. Changes in fishery or ecosystem distributions or health, affect on local economies. | **Reduced production** requiring improved/innovative agricultural methods, alternative cultivars and/or geographical shifts. Significant impacts on rural communities. Adaptive responses prop up some sectors, but some become marginal. | **Increased frequency of costly extreme weather events**. Consequences for human and animal health.<br><br>Coping capacity adequate, with public heath investment. | **Key tourism icons**. Threatened national reserves become problematic as repositories for genetic diversity and as tourist attractions. Bushfires become a significant human and economic cost. Coping capacity adequate, with some adjustments necessary. | **Foreign trade and national security**. Changes in weathe and sea-levels around the world impact on Australia's trading opportunities and demand for humanitarian aid and disaster response. |
| 550 ppmv, (~3 °C) | **30% of all species at risk of extinction.** Total realignment of ecosystems across Australia, with risks to ecosystem services. Total loss of alpine environments, major incursions of pests, weeds and diseases. Adaptive capacity exceeded. | **Dangerous water shortages**. Provision of water becomes a serious limiting factor in population growth, production of food and protection of natural ecosystems. | **Coastal inundation and erosion** requires abandonment of some coastal developments or the construction of sea walls. Impacts are significant for low-lying regions (e.g. Cairns, Gold Coast), Torres Strait, South Pacific and Indian Ocean islands. | **Substantially reduced production capacity**. Natural and agricultural systems will show little resemblance to current systems, with some serious risks. Coping capacity may be tested in a number of regions or sectors. | **Risks to human life** from flooding, disease, storms. Coping capacity severely tested in some areas, with some public health interventions essential. | **Infrastructure destruction** from flooding, soil erosion, siltation, inappropriate infrastructure, loss of livestock, crops, and human life. Requires enhanced emergency services, insurance and building regulation. | **International militancy and conflict**. Water shortage for half the world's people, healt problems for 250 million, and hundreds of millions facing food shortages and coastal inundation. Humanitarian aid grows and regional security i jeopardised. |
| 750 ppmv,(~4-5 °C) | **Massive loss of species** in Australia and globally, with little chance of any ecosystem maintaining resilience, and loss of ecosystem services. Alpine environments disappear well before the end of the century. Loss of ecosystem integrity. Adaptive capacity exceeded. | **Dangerous water availability problems** affecting water capture and delivery services, with changed demand, behaviour and population growth, industrial innovation, stranded assets (inappropriate dams/reservoirs). Adaptive capacity exceeded. | **Massive consequences for coastlines**. Some shorelines relocated, coastal settlements and wetlands inundated, and island nations compromised. Impacts on fisheries and marine organisms, coastal structures, cities, salination of freshwater reserves and non-saline environs. Likely de-glaciation of Greenland. | **Australia's ability to meet its food demands would be stretched**. Its trade in food, despite a global shortage, may be limited by capacity to produce and the world economic capacity to purchase. Coping capacity in serious doubt. | **Loss of life from bushfires, heatwaves, and invasive diseases** related to lack of water and food supplies, redistribution of disease and animal vectors, and thermal stress. Coping capacity in serious doubt. | **Serious exposure of infrastructure inappropriate for the climate**. Loss of water for hydroelectricity and power-plant cooling. Capacity for public and private investment in the infrastructure is limited. Coastal cities exposed to major costs in infrastructure protection. Adaptive capacity in serious doubt. | **Potential for serious breakdown of global systems**. Trade and monetar systems disrupted (by aridity, hunger and weather) impedin development, and the emergence of democracies. Increased aid needed as social order breaks down. Global peace highly compromised. |
| Reference Case (>5°C) | **Major loss of complete ecosystems** and serious resilience and structural problems for remaining assemblages of species. Adaptive capacity exceeded. | **Dangerous water availability problems** by as early as 2050 and compounding beyond. Adaptive capacity exceeded. | **Dangerous sea-level rise and storm surges**. High probability of non-linear additional sea-level rise and long-tem commitment to change. Melting of the Greenland ice sheet is likely. | **Food shortages** in a world with significant levels of starvation. Adaptive capacity exceeded. | **Health impacts exceed adaptive capacity**. | **Highly vulnerable Australian human habitation** resulting from inundation, insufficient water supply, human health problems, storminess, bushfires, inadequate power supply, invasive pests. | **Compromised international markets and security** resulting in severe humanitarian problems: starvation, displacement, migration, environmental refugees and wars. |

However, given the huge number of species and the lack of comprehensive genetic information about them, it is unlikely that most changes will ever be documented and it is uncertain how much change can be anticipated. Much longer time scales may involve the selection of new genetic material, which would contribute to species evolution.

Behavioural change might include changes to breeding, flowering or mating seasons, migration or invasion of new geographic environments. Such changes have been observed in Australia (see, for example, Howden *et al.* 2003, Lough 2000, Evans et al. 2003, Hughes 2003, Chambers *et al.* 2005 and Beaumont *et al.* 2006).

For human systems, spontaneous adaptation can take place through:

- *Modification of the built or societal environment*. Where the time scales of change are long compared with the lifetimes of built structures, infrastructure replacement may incorporate allowance for change (a response that may be quite subconscious, but nevertheless important). For example, the changing frequency of extreme high water levels in Fremantle and Sydney (Church *et al.* 2006) went largely unnoticed as normal development hid the changing level of vulnerability. Social change, culturally acceptable practices and norms may modify what are deemed to be acceptable social frameworks.
- *Behavioural change*, which might include shifts in farming practices, such as direct stubble ploughing, which are consciously designed to improve productivity yet also improve capacity to deal with declining water availability. Similarly, many of the actions now taking place across Australia involving city water supplies (new pipelines, desalination, behavioural changes) might ultimately be viewed as responses to climate change if it turns out that current water scarcity is indeed part of the climate-change impact.

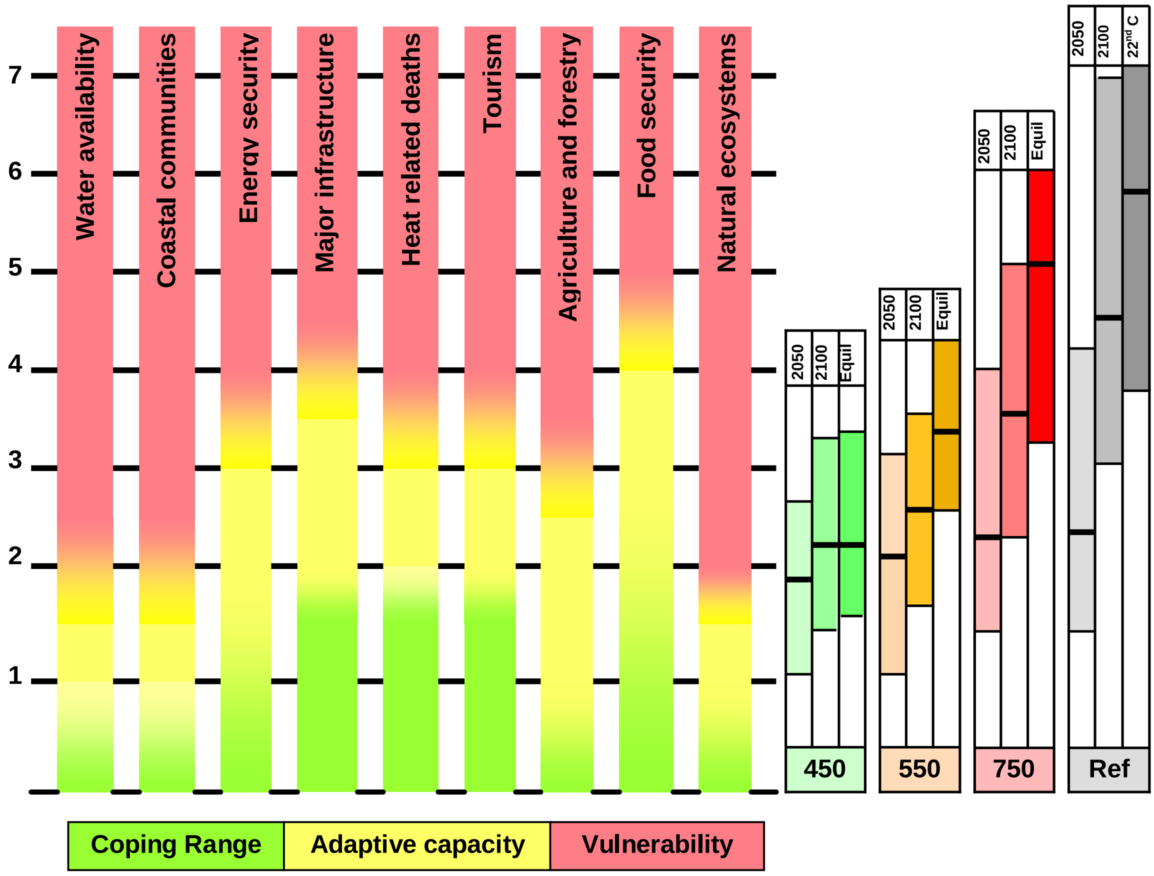
Such spontaneous adaptation lessens the vulnerability that might otherwise occur with climate change. By and large, this form of adaptation is dominating observed changes around the world that can be attributed to climate change (see, for example, Rosenzweig *et al.* 2008). The extent of such adaptation is what is referred to as the ‘coping range’ (based on IPCC 2007b), meaning that within the human and natural systems there is an existing adaptive capacity to limit vulnerability to climate change and thus maximise the resilience of those systems.

A second level of adaptation is planned, deliberative and/or anticipatory. All four scenarios in Section 3 suggested that the coping range will be exceeded in all areas of impact in the Australian economy (see Figure 8) at least by the end of this century. For some areas, this range may be exceeded by 2050. A strong program of planned or managed adaptation is necessary to defer or reduce vulnerability and to overcome exposure that relates to rates of change and the absence of early intervention.

As these are strategic, planned and targeted actions, it is possible that additional social benefits might be able to be obtained. This is important, as managed adaptation is likely to have economic, social and environmental costs. Nor is it independent of simultaneous exposure to changes related to the evolution of a carbon-constrained world and Australian economy. It is clear that both managed adaptation and mitigative actions will be needed in the face of climate change. An understanding of these costs is therefore part of the process of deciding how to weigh the level of investment in both approaches.

Figure 8 summarises the risk associated with various levels of warming in Australia above pre-industrial times and is based on IPCC (2007b). The diagram qualitatively assesses changes for which there is inherent capacity to cope, where adaptive capacity will be important, and where vulnerability is likely.

**Figure 8 Coping capacity associated with levels of warming in Australia**




Note: The vertical bars on the right indicate the time at which given warming occurs for each of the scenarios discussed in this document, together with the uncertainty limits as defined by IPCC (2007d).

Source: Qualitative assessment based on IPCC (2007d).

As incentives for planned adaptive action are necessary (often, perhaps unfortunately, when crises are emerging rather than just anticipated), action is likely to occur gradually as climatic patterns shift, and will occur at a local level in light of the particular climate change impacts occurring at that place and time. For every sector, adaptation options are multifaceted, complex and require research and planning. Although it is not possible in this report to examine all of the options for adaptation in Australia, we will consider adaptive options in the water availability area.

Table 6 shows how lower water availability leads to loss of moisture in soils in productive and natural ecosystems, lower levels of stream flow, and less resilient rural communities. In each case, a range of adaptive options could be part of a planned adaptation strategy. However, in considering each of those options, the technological feasibility, economic costs, societal impacts and/or acceptability and collateral environmental impacts must be considered.

The adaptation options for dealing with a loss of water availability are illustrated in Table 6 highlighting a number of factors common to adaptation in other areas of impact:

- Adaptive options do exist, and could allow for the maintenance of resilience in a warming world, at least to some degree.
- Options are diverse and complex and often at this stage poorly examined, underlining the need, in many cases, for serious research and holistic strategic planning.
- There will be costs associated with such adaptation, although, given the diversity and complexity of options, they are generally poorly evaluated at present.
- In some cases, government intervention could ensure strategic investment and encourage market responses to contribute to better outcomes.

**Table 6 Adaptive options for water availability impact area**

| Sector | Exposure | Adaptive options | |
|---|---|---|---|
| Water availability | Low soil moisture | Land- use management change | • Improved soil moisture retention<br>• Improved soil carbon retention<br>• New drought tolerant cultivars<br>• Shift of regional land use |
| | Reduced stream flow | Catchment capacity improved | • Managed catchment vegetation cover<br>• Evaporation limitation |
| | | Water management | • Targets and pricing in a water market<br>• Clear targets for simultaneous management of water, production, biodiversity, energy, possible supply<br>• Improved storage and pipelines to reduce loss<br>• Public education on need for and appropriateness of recycling |
| | | New water supplies | • New dams/reservoirs<br>• Ground water pumping/storage<br>• Pipelines and geographic sharing<br>• Recycling<br>• Desalination |
| | Rural society resilience | Societal relief | • Enhanced funding of rehabilitation of a rural communities and exposure in extreme events<br>• Enhanced value of rural land management for combined production, biodiversity, carbon storage, water collection<br>• Education and training for resilience<br>• Governmental support for mobility in marginalised areas<br>• Relocation and exit strategies |

Tables 7 and 8 illustrate adaptation options for other impact areas in the Australian economy. These Tables are not intended to be comprehensive; nor do they represent judgments about the best options available.

**Table 7 Availability options for food security and coastal communities impact area**

| Sector | Exposure | Adaptive options | |
|---|---|---|---|
| Food security | Reduced productivity | New genotypes | • Research, development and application of plant/animal breeding and genetic modification |
| | | Improved farm management | • Better use of available water<br>• Improved weather and seasonal climate forecasting<br>• Improved incorporation of forecasts into management practices<br>• Avoidance of extreme temperature and/or rainfall events<br>• Redistribution of wealth generated across the food value-chain |
| | | Modified fisheries practices | • Alternative fishing ports and regions<br>• Alternative fish species<br>• Greater reliance on aquaculture |
| | | Trade | • Greater dependence on imported foods, cognisant of the so-called food miles issue<br>• Greater opportunities for expansion into some more exposed countries<br>• Improved consumer awareness of the energy and environmental consequences of production |
| | Changed exposure to pest species | Quarantining processes | • Improved methods for limiting importation and/or spread of vectors/diseases |
| | | Insecticides/control | • Improved use of insecticides and/or genetically resistant cultivars |
| | Infrastructure exposure | Improved weather and seasonal climate forecasting | • Improved forecasting skills and observational networks (weather, climate, water, pests)<br>• Management of transport and storage facilities |
| | | Refurbishment and replacement | • More resilient dams/reservoirs, buildings, flood protection, drainage systems for extreme events |
| Coastal communities | Sea-level rise erosion | Sea wall protection | • New or higher sea walls<br>• Groynes/breakwaters to limit/control beach erosion |
| | | Remediation | • Beach sand replenishment |
| | | Land abandonment | • Infrastructure relocation with potential community support in cases of incapacity/failure of insurance industry support<br>• Landholder assistance/compensation |
| | Inundation | Levy bank construction | • Construction, new designs of protective barriers or upgrading of existing infrastructure |
| | | Land abandonment | • Compensation paid for abandonment of land infrastructure, beachside, estuarine and canal estates |
| | Infrastructure protection | Protection of infrastructure, ports and estuaries | • Construction of locks<br>• Construction of new and remediation of old wharves, marinas, canals estates, coastal roads, homes, etc |
| | Emergencies | Upgrading emergency services to meet storm surge, extreme weather and inundation risks | • Improved emergency communications with regards to tsunamis, tropical cyclones, extreme low-pressure systems, high tides, high winds<br>• Boat/aircraft availability in case of extreme events<br>• Sanctuary buildings/sites in the case of extreme events and infrastructure failure |

**Table 8 Availability options for the agriculture and forestry, sustainability and national security impact areas**

| Sector | Exposure | Adaptive options | |
|---|---|---|---|
| Tourism | Alpine | Manage reduced level of snow cover | • Greater use of snowmaking equipment, cognisant of energy and water<br>• Improved use of natural resources/infrastructure in the off-season |
| | Coastal | Reefs | • Targeting of least damaged reef resource<br>• Diversification of regional businesses |
| | | Beaches | • Replenishment of beach sands<br>• Geographical shift of industry |
| | | Estuaries | • Lower dependency on particular fish species and changed seasonality<br>• New infrastructure less vulnerable to extreme events |
| | Forests | Response to loss of biodiversity | • Realign enterprises around new ecosystem structures and opportunities<br>• Contribute to conservation programs for biodiversity |
| | | Response to exposure to fire risk | • Improved fire monitoring, fighting and remediation processes<br>• Improved emergency services around fire response and rehabilitation |
| Biodiversity | Loss of habitat | Live with loss of biodiversity | • Acceptance of the loss of significant numbers of species, especially in the coral reefs and alpine communities<br>• Plan for capturing genetic resources contained within endangered species for rehabilitation and/or pharmaceutical purposes |
| | Loss of ecosystem integrity | Understand and manage new ecosystem structures | • Research ecosystem resilience to changed species composition<br>• Monitoring of the stability of ecosystems<br>• Prop up specific species with management to extend resilience<br>• Reduce other, compounding factors such as pest or feral species, physical interventions such are the river sedimentation, land clearing, fire frequency |
| | Migration | | • Provide access pathways for species migration where soil conditions and interrelated species allow |
| | Extinction | | • Preservation and genetic material |
| | Conservation | | • Revamping of existing state and national park systems, zoos and species conservation programs |
| Agriculture and Forestry | Increased aridity | Improved management | • See 'water availability' sector |
| | | New species | • New cultivars/species that are water and temperature tolerant<br>• New water management processes |
| | Reduced production | | • Flexibilities in forest/agricultural land use to meet land-use challenges |
| | Land-use alteration | | • Re-evaluation of value of land-use for multiple community purposes and market intervention for all alternatives |
| | Changed markets | Connection with carbon storage | • New system for evaluation and recompense for carbon storage and protection of all ecosystem services |
| | | Changes trading opportunities | • Positioning crop production in light of changing national and international demands and production capacities |
| | Increased fire risk | Investment and management actions | • Improved prevention, fighting and compensation processes |
| Sustainability and national security | National carrying capacity | Adjust to regionally capacity | • Review and modify current population growth and geographic distributions to match emerging environmental limits |
| | Decreasing production and food security | Humanitarian action | • Humanitarian aid through enhanced aid budget |
| | | Use of carbon trading for joint outcomes | • Trading in carbon as a mechanism for timely emissions reduction and wealth transference to developing and/or vulnerable communities |
| | Regional instability | Diplomatic action | • Through aid, education, diplomacy, anticipate conflicts arising from environmental threats |
| | | Military/policing action | • Increase military/policing support for neighbouring nations where social disruption is threatening |
| | Environmental refugees | Dislocation of regional communities | • Foreign assistance to deal with dislocation due to sea level, food security, extreme climate events |
| | | Refugees to Australia | • Legislation to allow for selective migration of the dislocated people resulting from climate change |

# 5 Additional reading

For more information on climate change, particularly the underpinning science and physical drivers, see the following publications.


AAS (2008), Australian Academy of Science web site *Nova* for links to items on climate change and biodiversity, human health, sea level rise, coral reefs, emissions trading, carbon credits and so on, available at: http://www.science.org.au/nova/envir.htm.

ABM (2005), *The Greenhouse Effect and Climate Change*, Australian Bureau of Meteorology, Melbourne. 78pp available at: http://www.bom.gov.au/info/GreenhouseEffectAndClimateChange.pdf.

CSIRO (2008), *Greenhouse: Questions and Answers*, available at: http://www.cmar.csiro.au/e-print/open/gh_faq.htm#gh1.

DCC (2008), *Climate Change Science: Frequently Asked Questions*. Australian Government Department of Climate Change, available at: http://www.greenhouse.gov.au/science/faq/index.html.

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UCSUSA (2007), Frequently Asked Questions about Global Warming, Union of Concerned Scientists, available at: http://www.ucsusa.org/global_warming/science/global-warming-faq.html.

# Appendix 1: Elements of climate-change risk

Managing the risks posed by climate change requires an assessment of the probability of impacts occurring, the magnitude of their potential consequences, and the timeframe over which they operate. The urgency for action and research has increased in recent years, partly because:

- observations have confirmed that the climate is changing
- improved scientific understanding has:
  - directly linked these changes to the growth of greenhouse gases from human activities in the atmosphere
  - highlighted the fact that otherwise incremental changes to the climate may manifest in abrupt and irreversible changes in aspects of the climate system
- the potential impacts of what were regarded as ‘small’ climatic changes on many sectors of the economy have become better understood
- governments and large companies are increasingly including climate change risks in their strategic planning
- extreme climatic events have been interpreted, correctly or not, as impacts of the general warming of the planet.

In this Appendix, we examine how recent research has indicated that current projections may underestimate the risks because:

- the importance of small changes to mean global temperatures has been downplayed
- potential nonlinear responses or tipping points in the climate system and/or those systems dependent on climate may not have been identified
- current modes of assessing existing knowledge have led to conservative views of what might eventuate.

## Importance of ‘small’ changes

The magnitude of the impacts possible with ‘small’ changes of temperature relative to the variations we experience from day to day and season to season are widely underestimated. The potential importance of such ‘small’ changes when they are averaged over wide regions and long time frames is misunderstood. This is the crux of the climate change issue. Some physical and biological systems are sensitive to small changes in temperature, water availability or other climatic factors. Furthermore, there is growing evidence that a range of critical thresholds are likely to be exceeded with relatively small amounts of climate change. Those critical thresholds are likely to be relevant to coral reefs, heat stressed cool climate areas, sea ice, permafrost, glacial lakes, alpine ecosystems, and cool-water marine ecosystems. But they also include the potential for small changes in climate to multiply into major changes socially or economically (for example, small changes in rainfall and evaporation combine to have substantial social and economic effects).

The importance of small changes can be put into perspective by comparing them with the total change in global mean temperature over the past one million years, as the Earth oscillated between ice-age and interglacial conditions. That variation, globally averaged, was just 5°C but led to massive changes in the global distribution of biota and sea levels (see, for example, Overpeck *et al.* 2003). On longer time-scales, three million years ago, during the mid-Pliocene, average global temperatures were between 2°C and 3°C warmer than at present, with sea levels between 13 metres and 37 metres higher.

For Australia, changes of 2°C–4°C through this century (the approximate magnitude of changes associated with the scenarios examined in this report) are equivalent to temperature belts shifting southwards by between a few hundred kilometres and more than 1000 km, as illustrated in Figure A1. This is, of course, only indicative because the capacity for ecosystems and human activities to shift geographically depends on soil conditions, social innovation and cultures, and other factors. However, such shifts are already being observed in biological systems; for example, the frequency of specific genes in fruit flies has shifted southwards down the east coast of Australia by 400 km in response to warming that has occurred thus far (Umina *et al.* 2005).

Perhaps the most telling indication of global sensitivity to ‘small’ mean temperature changes comes from the IPCC Fourth Assessment Report (IPCC 2007b), which concluded that a 2°C warming has a 50 per cent probability of leading to the loss of 20–30 per cent of all species.

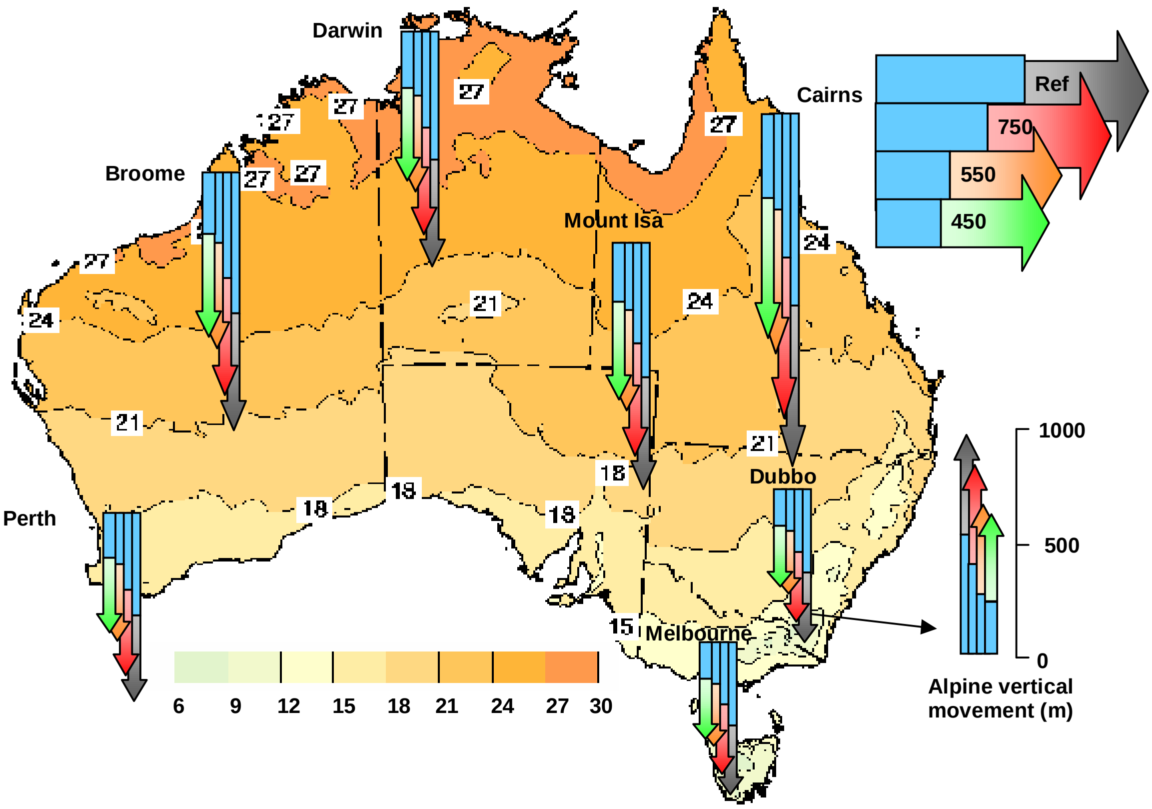
Figure A1 shows approximate meridional and vertical movements of temperature zones by 2100 for selected sites in Australia under the four scenarios—450 ppmv (green), 550 ppmv (orange), 750 ppmv (red) and the reference case (grey). Mean temperature contours (in °C) are based on the average of maximum and minimum temperatures over the period 1958 to 2005 (P.Hope, *personal communication*). Vertical changes are based on an adiabatic lapse rate of 9.8°C/km.

## Are there wild cards?

There are limits to our current understanding of climate processes and the potential consequences of changes currently underway. Nonlinear changes are particularly poorly understood, and are typically not included in projections; however, those processes could lead to a more rapid breakdown in the integrity of physical and/or biological systems. Dupont and Pearman (2006) have referred to these as ‘wild cards’—changes that have a low or unknown probability of occurrence, but which would have large impacts if they were to eventuate. Further examples of possible wild cards are shown in Table A1.

For example, it is possible that rising temperatures may trigger the rapid global loss of land-based glaciers. Because de-glaciation rates—particularly for Greenland and Antarctica—are poorly understood, the IPCC Fourth Assessment Report (IPCC 2007a) excluded this effect in developing its projections of global sea-level rise.

**Figure A1** **Approximate meridional and vertical movements of temperature zones by 2100**




Note: Approximate meridional and vertical movements of temperature zones (°C) by 2100 for selected sites across Australia under all four scenarios considered in this document. Vertical changes based on an adiabatic lapse rate of 9.8°C/km.

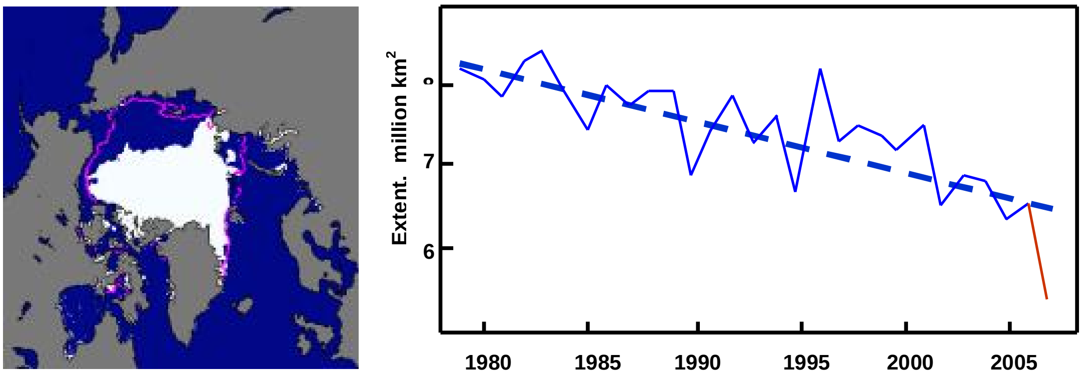
Source: Temperature contours are climatological averages from P.Hope, *personal communication*.

However, recent observations have suggested that de-glaciation may be accelerating, as evidenced by:

- satellite observations of glacial melt (Thomas *et al.* 2004; Velecogna and Wahr 2006)
- increased seismic activity in Greenland (Ekstrom *et al.* 2006)
- gravitational satellite evidence of changes in Greenland (Velicogna and Wahr 2005; Luthcke *et al.* 2006)
- recent loss of Arctic polar ice (National Snow and Ice Data Center, University of Colorado, http://nsidc.org/; Figure A2)
- recent satellite imagery showing the collapse of 13 680 km$^2$ of the Wilkins Ice Shelf in Antarctica (http://nsidc.org/news/press/20080325_Wilkins.html).

Figure A2, left panel, shows the areal extent of the Arctic polar ice for the month of August (16 August 2007). Figure A2, right panel, shows the extent of Arctic ice for the month of August over the past three decades, revealing the general decline, but the particularly large decrease that occurred in 2007. The pink line represents the average extent for that month averaged over the past two decades.

**Figure A2  Decline in the areal extent of Arctic ice over past three decades**




Note: Left Panel: Areal extent of the Arctic Polar ice for the month of August (16 August, 2007). Right Panel: extent of Arctic ice for the month of August over the past 3 decades showing the general decline, but the particularly large decrease during this year. The pink line represents the average extent for that month averaged over the past 2 decades.

Source: .National Ice and Snow Laboratory, Boulder, Colorado.

**Table A1  Possible climatic wild cards in global warming**

| Physical/dynamic phenomenon | Impact | Consequence |
|---|---|---|
| **De-glaciation of land-based ice, particularly in Greenland and Antarctica** | Sea-level rise | Coastal exposure to infrastructure damage and human dislocation |
| | Local flooding in spring | Threats to life and infrastructure, saltation of rivers and dams, impacts on ecosystems |
| | Reduced availability of water, particularly of major water sources (Andes and Tibet) | Impacts on agriculture, hydro-electricity production and supply of potable water |
| **Slowing of bottom water formation (the global thermohaline circulation)** | Change to chemical and dynamical features of carbon cycle. Reduced capacity of the oceans to absorb part of the released carbon dioxide | Faster accumulation in the atmosphere and warming |
| | Significant regional climate change, particularly in western Europe | Changes to agriculture, forestry, water availability, natural ecosystems |
| | De-oxygenation of the deep ocean | Loss of capacity to support life |
| **Loss of capacity to take up carbon—biosphere** | Terrestrial ecosystems reverse from a net uptake of fossil-fuel carbon dioxide to a net release | Speed-up of rate of atmospheric accumulation of emissions |
| **Loss of capacity to take up carbon—oceans** | Temperature and physiochemical changes, together with circulation changes, reduce capacity of oceans to remove carbon dioxide form the surface oceans into the large reservoirs of the deep ocean | Enhanced rate of global warming |
| **Outgassing from permafrost** | Release of trapped greenhouse gases | Enhanced rate of global warming |

Source: Based on Dupont and Pearman (2006).

Closer examination of the satellite observations of the Arctic sea ice not only show this demise of sea-ice extent, but also reveal that much of the areal extent is now occupied by recent ice—ice that is often only one year old and much more susceptible to melting. The United States National Center for Snow and Ice Data (Boulder Colorado http://nsidc.org/, 21 May 2008) has made a number of observations:

- April extent has not fallen below the lowest April extent on record, but it is still below the long-term average.
- given that the North Pole region is currently covered with first-year ice, we can not dismiss the possibility that the region may be ice-free this melt season.

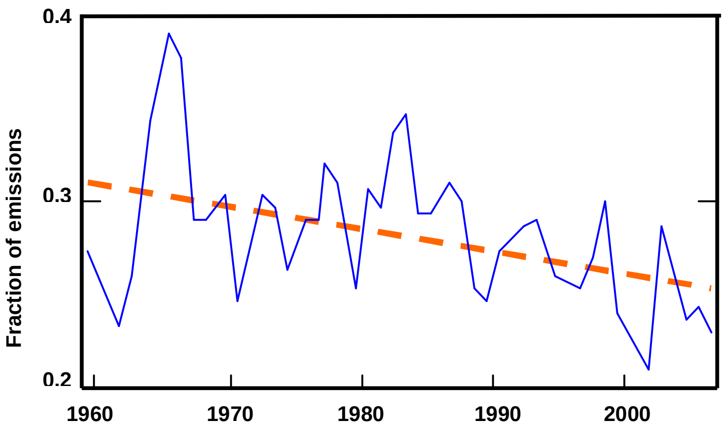
The significance of these changes and their rapidity has been assessed to have positive economic value in terms of high-latitude northern hemisphere trade and access to resources, but also to bring the possibility of political and economic instability in the region (Borgerson 2008).

## Have we underestimated how much change will occur?

Other changes that have been observed since the IPCC Fourth Assessment Report was published raise the question of whether the scale of change has been underestimated because some aspects of the behaviour of systems are not represented well enough by the models. These changes include:

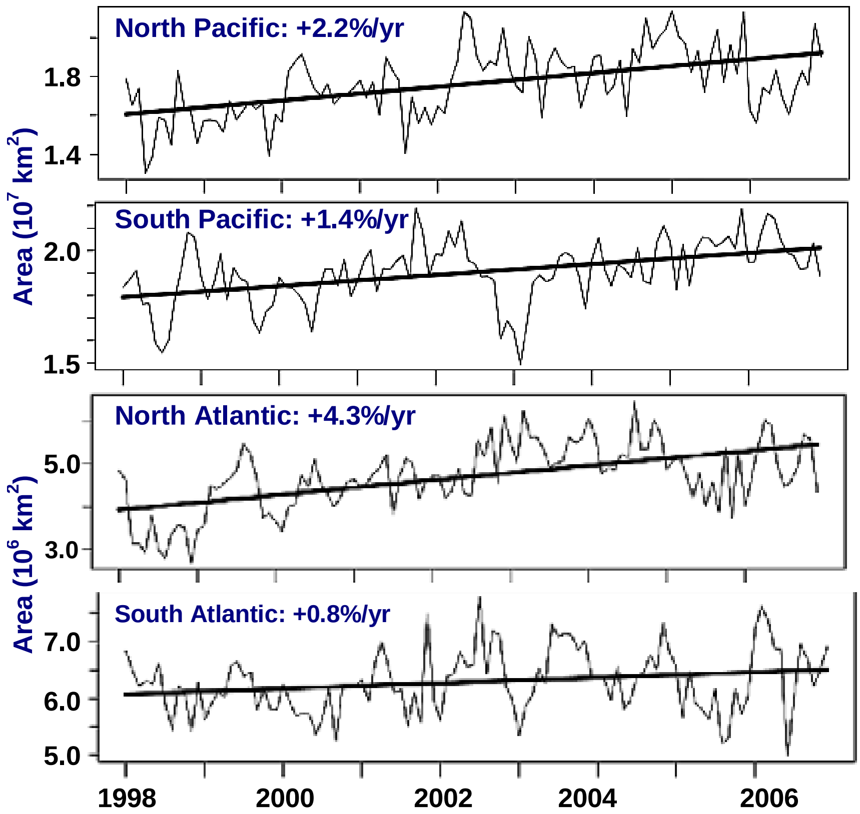
- numerous observations of changes to biological systems (migration, breeding and flowering times, behaviour, fecundity and genetics) that appear to have been responses to the changed climate (see, for example, Rosenzweig *et al.* 2008)
- apparent decreases in the capacity of the oceans to absorb carbon dioxide (Figure A3) over the past two decades (Le Quéré *et al.* 2007; Canadell *et al.* 2007)—expected for the future (IPCC 2007a) but not previously recognised as already occurring. This finding is disputed (Law *et al.* 2007), but it reminds us that a greater proportion of emitted carbon dioxide may stay in the atmosphere in the coming years
- apparent increases in the low-productivity regions of the oceans (Figure A4) in the north and south Atlantic and Pacific oceans (Polovina *et al.* 2008), consistent with greater stability of the warmer ocean surface and lower nutrient levels to support biological activity. The increasing area of the major ocean basins in which productive activity (chlorophyll levels) is low is consistent with reduced levels of vertical mixing of nutrients in the surface waters.

**Figure A3 Capacity of the oceans to absorb carbon dioxide as a fraction of total emissions**




Source: Canadell *et al.* (2007).

**Figure A4 Area in major ocean basins in which chlorophyll levels are low (low productivity), is increasing**



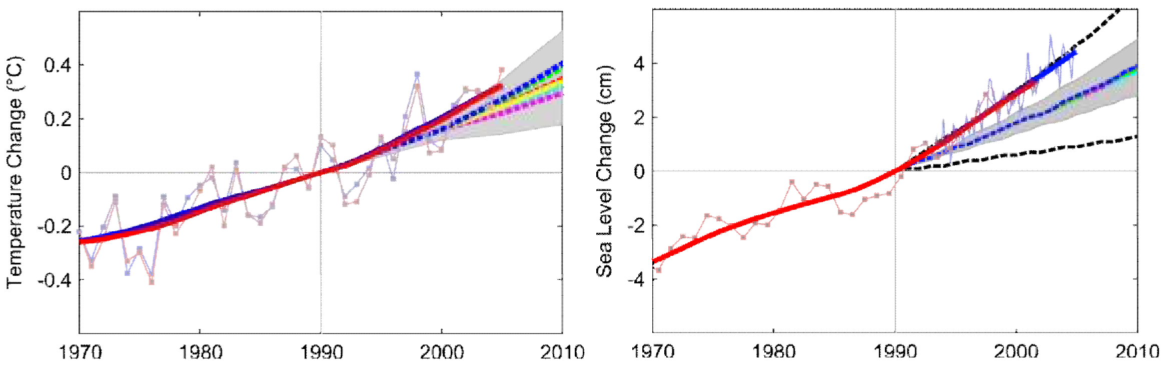

Source: Based on Polovina et al. (2008). (For comparison, the area of Australia = 7.7 x $10^6$ $km^2$.)

Since the completion of the IPCC Fourth Assessment Report, a number of publications (see for example, Pittock 2007, 2008; MacCracken 2008) have also directly questioned whether the IPCC's assessment process is inherently conservative and has therefore underestimated the scale of future change and the rate at which change is occurring. Some observational evidence suggests that changes in the climate system appear to be more rapid than projected:

- Rates of change of temperature and sea level, projected in earlier IPCC analyses, were lower than are now observed, as shown in Figure A5 (Rahmstorf *et al.* 2007).
- Global emissions are growing at a rate that is at the high end of projections (Raupach *et al.* 2007) despite current mitigation efforts, suggesting that projections may have underestimated the inertia in the world's energy systems, the growth of emissions from emerging economies and therefore the potential for future warming (see Figure A6).
- Changes to the melting rates detected in recent years suggest that ice-sheet sensitivity to warming and therefore sea-level rises may be greater than previously considered (Alley *et al.* 2005). Church *et al.* (2007b) have shown that recent rates of sea-level rise exceed IPCC projections and suggest that this clearly indicates a growing contribution to the rise from de-glaciation.

- Recent emissions and projections of change to 2030 suggest that the scenarios in the IPCC Special Report on Emission Scenarios are no longer a reliable guide to emissions over the next several decades (Sheehan, in press).

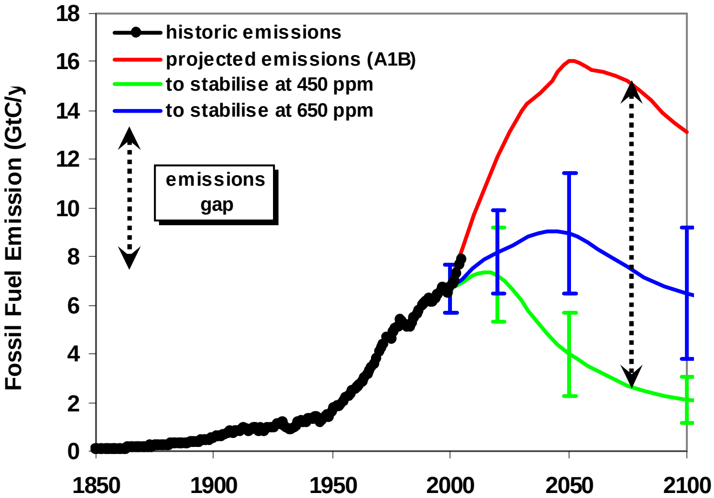
**Figure A5 Rates of change of temperature and sea level**




Note: Projections of temperature and sea-levels made previously by the IPCC (various scenarios represented by the shaded areas and dotted lines), showing how they generally fall below the changes that have since been observed.
Source: Rahmstorf *et al.* 2007.

These possibilities are not introduced to create undue concern, but rather to emphasise that a very wide range of potential impacts—some of them poorly understood—are relevant to climate change risk management. Both adaptation and mitigation responses to global warming may need to be accelerated substantially in the next few years. Policies that fail to build in contingency for these possibilities carry a risk that the resilience of economic and social systems will be undermined.

**Figure A6 Growth in global emissions**




Note: Recent assessment of global carbon dioxide emissions compared with scenarios of future emissions from the IPCC showing that the emissions are tracking the upper level (more like a ‘business as usual’ trajectory) and provide no indication that the rate of growth of emissions is moderating.
Source: Raupach *et al.* 2007.

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