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Climate Change Impacts, Risk and the Benefits of Mitigation

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Important Notice

Use of this Report

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CONTENTS

EXECUTIVE SUMMARY

Assessments of the costs of mitigating climate change rarely address the benefits of avoided damages, because doing so is a very difficult task. This report describes work undertaken for the Energy Futures Forum (EFF), which assesses the benefits of avoided damages for a range of greenhouse gas emission scenarios developed by the EFF.

The costs associated with reducing greenhouse gas (abatement and sequestration) are incurred in the relatively near future, whereas the benefits of avoided damage are experienced much later because of delays in the climate system. Furthermore, precise estimates of both climate damages and the benefits of avoided damages are highly uncertain. Because of this, the debate surrounding climate change mitigation compares the costs of moving from the familiar and understood situation of abundant supply of cheap fossil-fuel energy, to one where the outcomes are very unclear.

The successful management of climate risks through the reduction of greenhouse gases can be achieved in cases where the benefits of avoided damages outweigh the costs of mitigation. The costs of greenhouse gas abatement to 2050 are compared with the benefits of avoided climate damages in 2100. This is done by comparing the climate damages associated with a reference greenhouse gas emission scenario with those from a set of mitigation scenarios. Damages are assessed using both monetary and non-monetary measures. The benefit of avoided damages is the difference between the reference case damages – the so-called "costs of inaction" – and mitigation scenario damages. The major scientific uncertainties affecting the assessment of climate change and its impacts are accounted for by calculating risk-weighted damages.

Based on the results from these particular scenarios, when contrasted with the costs of acting, the risks of not acting on climate change clearly outweigh those associated with acting.

The report is in three parts:

Chapter 1 outlines a risk framework for contrasting climate and policy-related risks designed to assess the benefits of responding to human-induced climate change.

Chapter 2 summarises the major uncertainties affecting the projection of climate change, and then quantifies sectoral impacts affecting Australia and four key global-scale vulnerabilities constructed for further analysis.

Chapter 3 applies the emission scenarios produced as part of the project to assess risk-weighted outcomes for a set of monetary and non-monetary criteria.

ADAPTATION V MITIGATION

Risks associated with climate change can be managed either by reducing greenhouse gas emissions (mitigation) or adapting to climate change impacts.

Mitigation reduces climate change impacts by reducing the rate and magnitude of global warming. This increases the chance that the remaining risks can be adapted to. Adaptation increases the ability of a system to cope with a changing climate, including variability and extreme events.

Adaptation and mitigation reduce risks from opposite extremes of the projected range of climate change (Figure 1). The range of mean global warming under the Special Report on Emission Scenarios (SRES) is shown in the chart, while likelihood and consequences are shown on its right.

Adaptation will be required to manage climate change risks that are already committed to by historical emissions and those expected in the near future. Adaptation is most urgent for risks that are already being experienced and those that are sensitive to only small changes. Adaptation to higher levels of warming will be difficult and costly, requiring a great deal of accepted loss. Mitigation reduces the uppermost possibilities of climate change by reducing the potential volume of accumulated future emissions. Where the limits of adaptation are exceeded e.g. because adaptation is too expensive, impractical, or unfeasible; mitigation may be the only realistic risk treatment.

The right hand side of Figure 1 relates the consequences of climate change to the likelihood of exceeding a specific level of global warming. High levels of warming are less likely to be exceeded, but the negative consequences are *very likely*[†] to be widespread and severe. The risk-weighted damages mentioned above are calculated from this combination of probability and consequence.

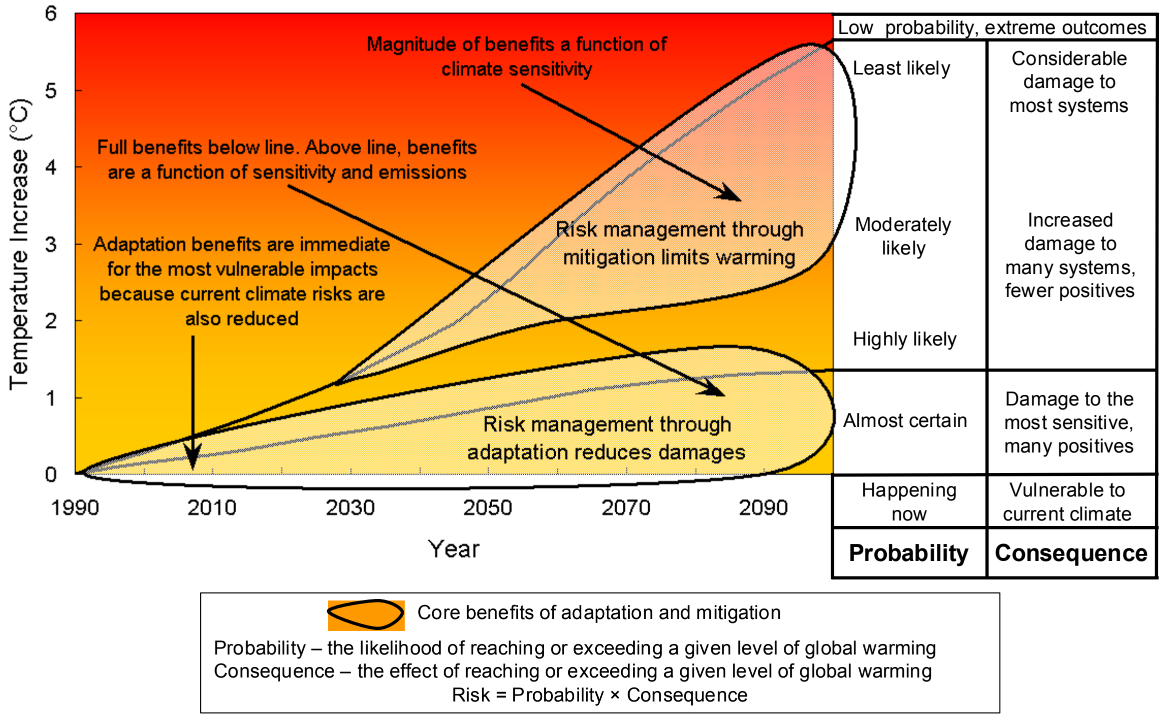

Figure 1. Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on the six SRES greenhouse gas emission marker scenarios with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold exceedance as a function of global warming and the consequences of global warming (Jones, 2004a).

Adaptation and mitigation can be related in the following ways:

1. They manage different parts of risk: mitigation reduces the likelihood and magnitude of climate-related hazards and their resultant impacts; adaptation reduces the consequences of those impacts.
2. They manage risk in different parts of the potential climate change envelope: mitigation reduces the likelihood of climate change at the upper defined limit of the plausible range; adaptation manages the experienced or more probable changes occurring at the lower limit of the plausible range.

3. They are effective over different timescales: most adaptations will have benefits in the short to medium term, especially if designed to manage current climate risks; mitigation benefits are long-term because of the delayed response of climate change.
4. They are effective at different scales: mitigation reduces climate change at the global scale because greenhouse gases are well mixed in the atmosphere; adaptation is specific to local conditions.

UNBALANCED RISKS

Weighing anticipated economic losses in the short term against uncertain gains in the long term creates an unbalanced debate on whether to act, or to not act, on climate change. For example, an aversion to economic loss focuses on the damage that action on climate change may cause to the economy in the short term. This may include the perceived risk of growing the economy at anything less than the optimal rate. Those averse to environmental loss are highly sensitive to long-term threats to natural and human systems, believing that significant economic intervention is warranted to prevent such losses.

These views are difficult to balance because of their asymmetrical nature (Figure 2). By framing the issue differently with respect to which side of the issue the notion of loss and gain is attached to, proponents of either view have different burdens of proof. The economically risk averse prefer quantified economic estimates, most often based on cost-benefit analysis (CBA), which aims to show whether the benefits outweigh the costs. The loss side of the ledger is attached to the economy. The environmentally risk averse will rely most on scientific advice that assesses the possibility of critical environmental or socio-economic thresholds being exceeded at some time in the future. The loss side of the ledger is attached to the environment.

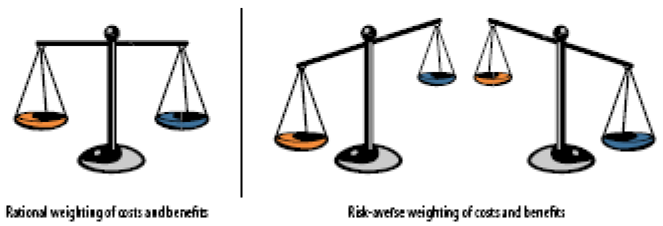

Figure 2. An illustration of the risk-neutral weighting of costs and benefits empahsising impacts known with greatest certainty and risk-averse weighting of costs and benefits with opposing precautionary approaches to uncertainty.

Cost-benefit analysis is not well suited to decision-making on climate change because:

- CBA requires both cost and benefits to be quantified using a single (monetary) measure. However, because damages such as loss of life and loss of species do not have a single market value they cannot easily be monetised. Overlooking such impacts or reducing them to a single value (for example, the statistical value of a human life, which is different between a developed and a developing country) is generally considered unsatisfactory.
- The long delay between emissions and response (and thus, to the costs and the benefits) makes conventional discounting controversial because of varying rate-of-time preferences and risk-aversion.
- The large uncertainties make the possibility of damages being non-marginal (i.e. by producing negative growth or critical outcomes, which are both infinite in a CBA analysis).

- Because of different risk-averse attitudes to perceived damages to the economy and to the environment, it is concluded that the questions, "*Can we afford to act on climate change?*" and "*Can we afford to <u>not</u> act on climate change?* "are not the same, and must be treated separately within a risk management framework before being addressed together.

TURNING UP THE HEAT

The first step in such an assessment is to assess the climate changes and impacts resulting from a reference case and set of mitigation greenhouse gas emission scenarios (EFF scenarios 1 and 2a–d). Impacts are expressed in both economic and biophysical terms allowing the comparison of market and non-market damages. The EFF reference case represents a world in which technological development and government policies progress along their known paths, with significantly reduced trade barriers, and no implementation of any significant greenhouse gas emission reduction policies. The EFF scenarios (1 and 2a–d) as quantified by the Australian Bureau of Agricultural and Resource Economics (ABARE; Ahammad et al., 2006) represent a set of technologies and policies that reduce emissions from the reference case by 35 per cent and 39 per cent by 2050, ultimately stabilising at around 575 ppm CO_2.

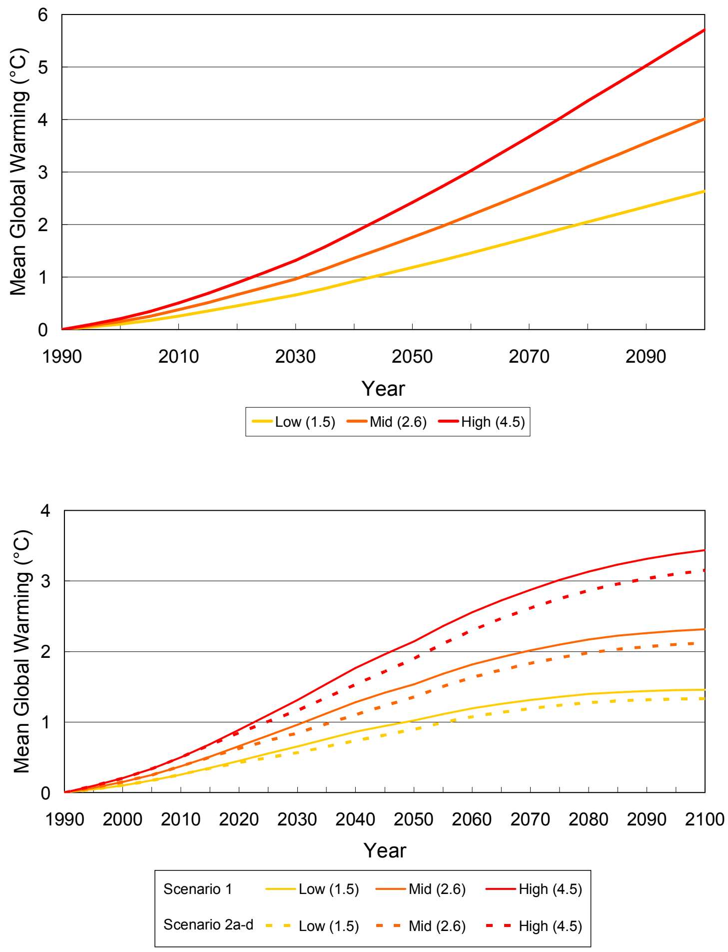

Figure 3. Mean global warming projected for the EFF reference scenario (upper) and scenarios 2a-d (lower) for climate sensitivities of 1.5, 2.6 and 4.5°C.

The EFF reference case and scenario 1 and 2a–d emissions produced by ABARE were extended to 2100 and loaded into a simple climate model. The EFF scenarios were extended in two ways: (1) constant emissions from 2050 and reducing along the lines of the IPCC A1T marker scenario. The latter stabilises CO_2 in the range 550–575 ppm CO_2. Mean global warming to 2100 was then estimated for both the reference case and scenarios 1 and 2a–d.

For the reference scenario, mean global warming in 2100 is in the range of 2.6 to 5.7 degrees Celsius (°C) with a mid-range warming of 4.0°C (Figure 3).

The small differences between the reference case and scenarios 1 and 2a–d beyond 2050 (Figure 3) show that most of the reduction in 2100 is due to relative changes in greenhouse gases and sulphate aerosols (which produce warming and cooling, respectively), cancelling each other out. Much of the reduction in warming by 2100 is due to the reductions in emission before 2050. This is due to the inertia of the Earth’s climate system, where most greenhouse gases remain for many years in the atmosphere and radiative changes take some time to warm the atmosphere and especially, the oceans.

AUSTRALIAN IMPACTS

A number of Australian sectors were assessed for the impact of varying levels of global warming. The sectors assessed were natural ecosystems, cropping, forestry, and livestock, water resources, public health, settlements and infrastructure and extreme weather events (Table 1).

Table 1. Summary of risks to a range of sectors in Australia, rated low, moderate or high. The risks are judged subjectively based on a broad literature (summarised in the report) associated with the range of mean global warming of 2.6°C and 5.7°C in 2100, projected from the reference scenario. Low risks imply that damages are relatively minor after adaptation, moderate risks imply significant damages after adaptation and high risks imply severe damages after adaptation.

System	Sensitivity	Adaptive Capacity	Risk
Natural Systems			
Coral Reefs	High	Low	High
Alpine Ecosystems	High	Low	High
Endemic Species	Moderate to high	Unknown (limited?)	Moderate to high
Cropping, forestry and livestock			
Cropping	Low to High	High	Moderate
Livestock	Moderate to high	Moderate	Moderate to high
Forestry	Low to moderate	Moderate	Moderate
Water Resources			
Urban Water Supply	High	High	Moderate to high
Irrigated agriculture	High	Moderate	Moderate to high
Industry (inc hydro)	Moderate	High	Moderate
Wetlands	High	Moderate	High
Public Health			
Heat stress	Moderate	High	Low to moderate
Disease vectors	Moderate	High	Low
Indigenous health	High	Low to moderate	High
Settlements and Infrastructure			
Energy	Low to moderate	Moderate to high	Low to moderate
Coastal Settlements	Low to high	Moderate to high	Moderate to high
Extreme weather events			
Floods	Moderate	Moderate to high	Moderate
Fire	High	Moderate	Moderate to high
Tropical cyclones	Moderate	Moderate	Moderate
Extreme hot days	Moderate to high	Moderate	Moderate

The risks to natural systems and water resources are generally rated as high, whereas most systems with a strong socio-economic component face more moderate risks due to capacity to adapt. However, risks to food and fibre production depend greatly changes to rainfall patterns in different regions. With favourable rainfall, higher atmospheric CO_2 could also lead to net improvements in yield, if temperature increases can be constrained.

Although few studies have extensively surveyed climate change impacts at higher levels of global warming, warming in the range of 2.6°C to 5.7°C by 2100 would severely damage Australia's ecosystems, exceed adaptive capacity in a range of primary industries, lead to substantial sea level rise along the coast and greatly increase the magnitude and frequency of extreme events. Unfortunately, due to the paucity of national studies, it is difficult to provide more than a qualitative assessment.

GLOBAL IMPACTS

To further assess the non-monetary benefits of climate change mitigation on a global scale, four key biophysical indicators were chosen: coral reefs, species extinction risk, North Atlantic thermohaline circulation (THC) and melting of the Greenland ice sheet. Each are valued natural resources with a limited adaptive capacity, and are thus largely dependent on mitigation. Damage curves for each of these impacts, relating levels of damage or the likelihood of exceeding a "tipping point" to global warming have been constructed.

The impacts of large-scale damage to these four indicators are:

- Coral reefs: critical rates of bleaching and coral mortality, resulting in replacement by seaweeds, with a cascade of subsequent changes in fish and other populations. Changes in appearance affect tourism.
- Species extinction risk: endemic species and those with limited ranges and/or high specialisation are most at risk. Although the exact relationship between the risk and extinction rates is unknown, high rates will result in extinction rates unprecedented in human history and the highest for millions of years.
- North Atlantic thermohaline circulation: northern Europe cools or ceases to warm by as much, more severe winters, long-term lack of oxygen in ocean depths, detailed impacts unknown. Large-scale dislocation of regional environments possible.
- Greenland ice sheet: most or all of Greenland ice sheet melts taking hundreds to thousands of years depending on the subsequent rate of warming and ice sheet stability, producing a rise in sea level of up to 7 m.

There are large uncertainties in estimating global economic damages. A recent review (Downing et al., 2005) showed that existing estimates of economic damages addressed a limited range of climate change phenomena and largely omitted indirect and non-market values. There is a great deal of evidence from individual studies to show that the costs in Table 3 increase along both axes, but most of the estimates of global costs are restricted to the part of the matrix bounded by the red line.

On balance, the literature probably under-estimates the costs of climate change (Stern et al., 2006). Some guided sensitivity analyses of economic damages informed by estimates from the literature were therefore developed. The biophysical curves also relate to Table 2 because Greenland and THC represent thresholds and singularities, and the coral reef and species at risk curves represent damages to indirect use and options, and to existence and bequest values. This provides a framework within which both monetary and non-monetary damages can be examined.

Table 2. Major uncertainties in estimating the costs of climate change (Downing et al., 2005), showing the breadth of most integrated assessment studies. The red boundary and background represents how well costs have been quantified in economic terms. WTP stands for willingness to pay methods of valuation.

Valuation uncertainties

Increasing costs →

Quantified economic costs

Climate uncertainties

Increasing costs ↓

	Market (direct) value	Non-market (indirect use and options)	Existence and bequest value
Mean climate	Global studies	Some global studies (as WTP)	None
Variability & extremes	Regional studies, some allowance in global studies	Some local and regional studies	None
Thresholds & singularities	Few sensitivity studies	None	None

Four exploratory economic damage curves expressed as a reduction in gross domestic product (GDP) were assessed: a straight line representing one per cent decrease in GDP per °C of global warming, two lines of differing curvature and a line representing a global economic response to a large-scale tipping point or major event. These curves allow us show the response to different rates of economic damages. Although temperatures above 5°C are possible but unlikely, the likely costs associated with this magnitude of climate change are unknown. What if a large-scale biophysical system ceased to function adequately? The shape of the resulting economic damage curve is likely to be highly non-linear, but its magnitude and degree of non-linearity is unknown. The biophysical and monetary damage curves are shown in Figures 4 and 5.

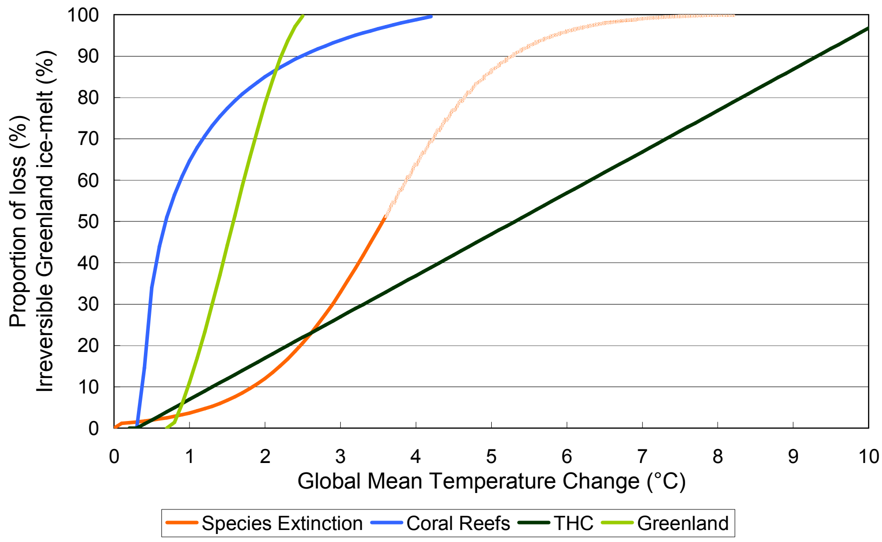

Figure 4. Damage curves for four key biophysical vulnerabilities: risk of species extinction, proportion of loss of coral reefs due to thermal bleaching, slowdown in North Atlantic thermohaline circulation and the probability of commencement of irreversible melting of the Greenland ice-sheet.

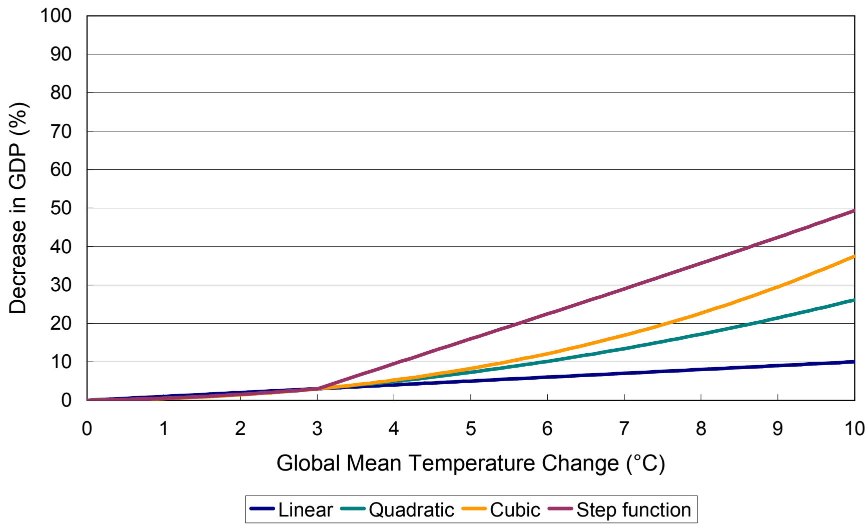

Figure 5. Different conceptual damage curves for global impacts expressed as percentage loss in global Gross Domestic Product (GDP) compared to a reference case. Note that economic damage curve is positive, going against economic convention – this is to allow comparisons between the economic and biophysical damage curves.

THE COST OF INACTION

For the reference case, mean global warming in 2100 ranges between 2.6 and 5.7°C with a mid-range warming of 4.0°C. These levels of warming are in higher part of the IPCC (2001) range of 1.5–5.8°C and are projected to result in significant impacts. Clearly, warming in the range projected by the reference case by 2100 would critically impair coral reefs, commence irreversible melting of the Greenland ice sheet, substantially slow the THC and place a great proportion of species at risk. Economic damages would likely be above three per cent of GDP for the linear damage curve and be higher for all the others. These changes would exceed the capacity of many systems to adapt, including some of these rated as having moderate to high capacity in Table 1.

These findings are consistent with the wider literature such as the studies reviewed by Stern at el. (2006), for increases in temperature to around 4°C. This literature does not generally analyse increases at the higher end of the current estimated range of climate change, however.

THE BENEFITS OF MITIGATION

The benefits of avoiding climate-related damage through the application of risk-weighted damages to both the reference case and scenarios 1 and 2a–d were estimated for 2100. Risk-weighted damages were calculated by multiplying the likelihood of a given level of warming multiplied by the consequence level of damage. The benefits of mitigation actions in 2100 are measured as the difference in risk-weighted damages associated with the reference case and the mitigation scenarios (1 and 2a–d). The risk-weighted estimates for the biophysical damages are shown in Figure 6 while the risk-weighted estimates for the economic damages are shown in Figure 7.

The benefits of avoided damage for both biophysical and economic damages are substantial.

For both THC and species at risk, the benefits are greater than half, as are all the non-linear economic damage functions. The benefits for coral reefs and Greenland ice sheet are less as they are likely to be critically damaged with temperatures even lower than those projected from the scenarios 1 and 2a to 2d. However, consistent with the discussion about targets for atmospheric concentration of CO_2 in Section 5, significant impacts still remain under these scenarios, so the levels set by these emission scenarios are not endorsed as mitigation targets.

MINIMUM ECONOMIC BENEFITS OF MITIGATION

The above analysis shows there are significant benefits to be gained by 2100 in moving from the reference to the mitigation scenarios for all four types of biophysical damages assessed, with slightly larger gross benefits for the mitigation 2a–d scenarios. There are greater economic benefits the more non-linear the economic damage curve becomes.

However, because the economic damage curves described above only allow sensitivity analyses to be carried out, the minimum economic damage curves required to balance avoided damage costs (that is, benefits) in 2100 with mitigation costs to 2050 were assessed. Both costs and benefits were assessed in Net Present Value using UK Treasury Greenbook discount rates, which occupy the mid-range of long-term discount rate estimates from the literature. The analysis showed that the minimum damage curves required to balance the costs to 2050 for Scenario 1 are lower than three out of four well-known cost curves from the literature. The minimum damage curve for Scenario 2a is in the middle of the range from the literature and is slightly higher for Scenarios 2b–d. Furthermore, this “minimum economic benefit” analysis does not account for economic benefits after 2100, or for social and environmental benefits not included in the economic cost curves.

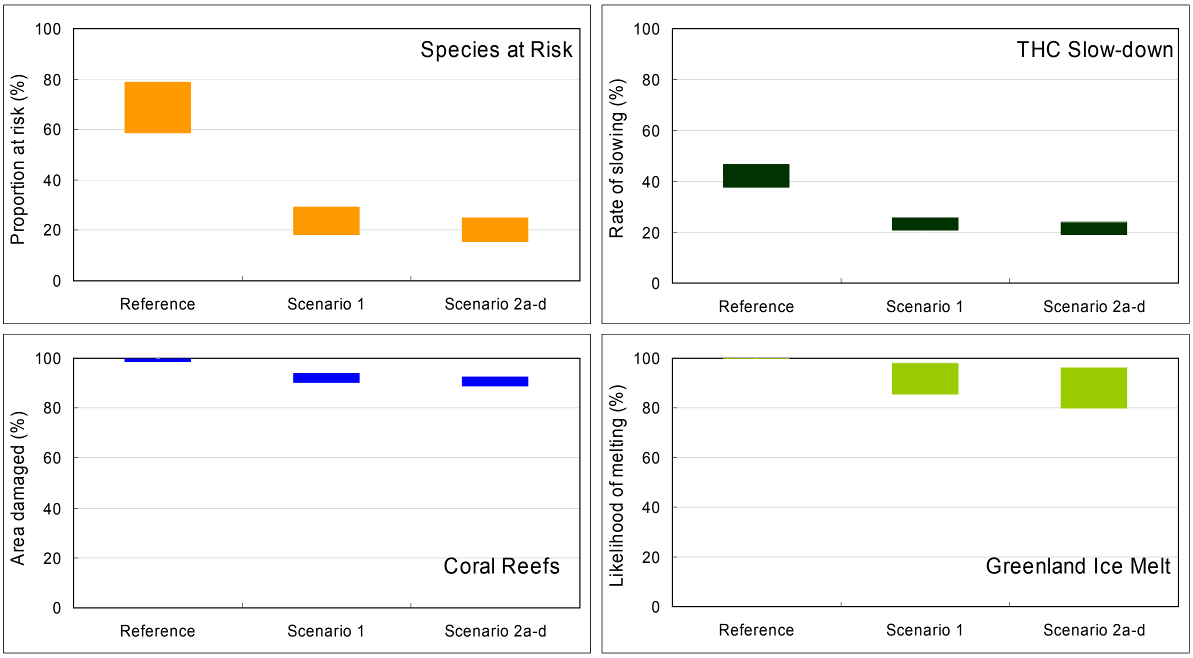

Figure 6. Risk-weighted damages for four key biophysical measures: species at risk, area of coral reefs critically damaged, THC slowdown and melting of the Greenland ice sheet showing the benefits of mitigation. The reference scenario represents no policy action, scenario 1represents a 35% reduction in greenhouse gases by 2050 and stabilisation at 575 ppm CO_2 and scenario 2 represents a 39% reduction in greenhouse gases by 2050 and stabilisation at 550 ppm CO_2. The spread of damages represented by the bars allows for different estimates of climate sensitivity in estimating the risk-weighted damage.

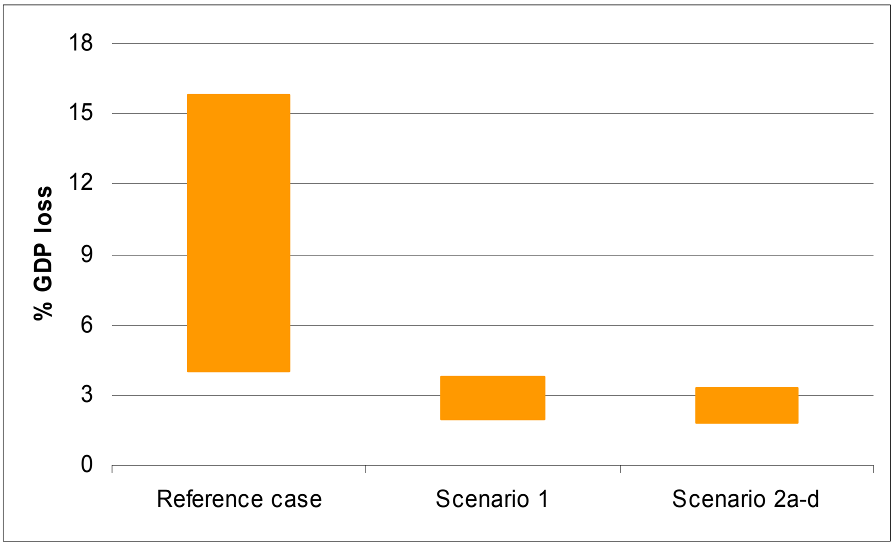

Figure 7. The range of risk-weighted damages for four different postulated economic damage curves expressed as percentage loss in global gross domestic product (GDP).

If the risk-weighted outcomes are disaggregated into individual scenarios explicitly allowing for scientific uncertainties in estimating global warming, using this "minimum economic benefit" approach, about two-thirds show a positive economic benefit and one-third are negative (based on Net Present Value in 2100). Thus, the risk-weighting approach also leads to positive benefits for the larger part of the range of possible outcomes. The optimised solutions for the scenarios 1 and 2a compared with those used in the assessment of economic damages are shown in Figure 10.

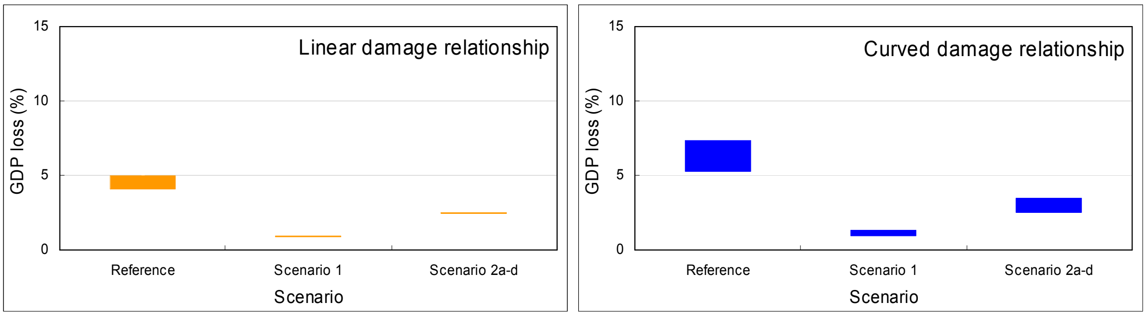

Figure 10. Optimised risk-weighted damages (scenario 1and scenario 2) representing the minimum damage in 2100 required to balance the costs of mitigation incurred to 2050 for linear and non-linear damage functions expressed in percentage loss in global GDP. These are compared with the reference linear and quadratic damage curves in Figure 9. The spread of damages represented by the bars allows for different estimates of climate sensitivity in estimating the risk-weighted average damage

Therefore, in conclusion:

1. The "minimum economic benefit" for Scenario 1 in 2100 is at the low end of estimates from the literature showing that, even after allowing for uncertainty, most outcomes are *very likely* to be positive. In other words, regrets due to over-expenditure on mitigation are *very unlikely*[*] for this scenario. A high value placed on accompanying environmental and social benefits will strengthen this conclusion.

2. The "minimum economic benefit" for Scenarios 2a–d in 2100 is near the middle of the range of estimates from the literature showing that, even after allowing for uncertainty, most outcomes are *likely* to be positive. In other words, regrets due to over-expenditure on mitigation are *unlikely* for this scenario (less than one-third probability). A high value placed on accompanying environmental and social benefits will strengthen this conclusion.

The analytic framework used here will apply to any set of reference and mitigation scenarios. The likelihood of ensuring there is a positive benefit due to mitigation depends on the cost of mitigation, damages associated with the reference scenario and how likely the minimum benefit required will fall below the real, but difficult to assess, damage curve. The successful management of climate risks through the reduction of greenhouse gases can be achieved when the benefits of avoided damages outweigh the costs of mitigation. For this set of scenarios, success is rated as being likely to very likely.

1. CONTEXT

This report to the Energy Future Forum (EFF) examines how the risk analysis of climate impacts can be used to assess the benefits of mitigating climate change. Climate change mitigation is represented by contrasting a reference greenhouse gas (GHG) emission scenario with a set of mitigation scenarios developed by the EFF. Global warming projections to 2100 produced from these scenarios are used to assess Australian and global impacts. Reductions in warming represented by the mitigation scenarios are then used to assess both the monetary and non-monetary benefits of reducing greenhouse gas emissions. An assessment of the minimum damage to the global economy in 2100 required to balance the mitigation costs is carried out using expected-value cost-benefit analysis (CBA). The CBA is only partial, however and is part of a larger multi-criteria analysis. The risk-weighting techniques applied to economic impacts are also used to assess the benefits of avoiding biophysical impacts that have not been monetized. This approach allows conventional economic analysis to be contrasted with precautionary approaches to climate policy.

The reference scenario used in this study applies a range of business as usual assumptions, including population growth and energy forecasts consistent with projections from the International Energy Agency, which utilise a set of new technologies that make no special allowance for climate change. The mitigation scenarios apply a carbon tax sufficient to achieve a target compatible with achieving stabilisation of atmospheric CO_2 at 550–575 ppm by applying different mixes of energy technologies as prescribed in a series of storylines developed by the EFF. Greenhouse gas emissions for those scenarios were quantified by ABARE using their GTEM economic and technology model (Ahammad et al., 2006).

Most assessments of climate change mitigation have so far concentrated on the direct costs of abating[†] and sequestering greenhouse gases. Although such studies acknowledge that the purpose of mitigation is to reduce climate change damages, they usually do not directly account for the benefits of reducing those damages (Corfee-Morlot and Agrawala, 2004a). Indeed, how that should be done is much debated in the policy arena (Corfee-Morlot and Agrawala, 2004b; Downing et al., 2005). For example, the following assessment approaches are all reflected in policy positions:

- Integrated assessments that concentrate on monetary costs and benefits. Formal cost-benefit analysis then assesses quantified economic estimates based on optimised short-term costs justifying the long-term benefits (e.g. Manne et al., 1995; Manne and Richels, 1998; Nordhaus and Boyer, 2000; Tol, 1999, 2003). Both total and marginal costs are required in such approaches.
- Integrated assessments that integrate biophysical earth systems, assessing critical thresholds and safe minimum standards. Precautionary approaches set stabilisation and/or warming targets based on assessments of dangerous levels of anthropogenic interference (DAI). Targets for emissions consistent with these aims can then be calculated. Economic analysis may or

[*] Here, terms used to communicate uncertainty are consistent with those used in the IPCC Third Assessment Report (IPCC, 2001), where *likely* is >66% probability and *very likely* is >90% probability. *Very unlikely* is <10% and *unlikely* is <33%.

[†] Abatement is the reduction of emissions and sequestration is the removal of gases from the atmosphere into some form of storage.

may not be included (e.g. Mastrandrea and Schneider, 2004; Toth et al., 1997; Petschel-Held, 1999; Yohe, 1999).

- Assessments that suggest taking only actions known to have a positive outcome in any eventuality (i.e., actions suited to a wide range of outcomes), until outcomes can be better predicted (e.g. Lempert at al., 2003; Lempert and Schlesinger, 2000).

Much of the policy debate centres on how a restricted set of risks are framed and perceived without formally assessing a comprehensive range of risks surrounding climate change and policy. Internationally, there is little agreement about which blend of methods offers the most appropriate way forward and there is no single assessment method available that satisfies all knowledge needs.

The two major areas of contested risk in these debates are climate- and policy-related risks. Climate-related risks are those resulting from the impacts of climate change. Policy-related risks are those that arise as the result of applying particular policies to adapt to, or mitigate, climate change. Climate risks include primary risks that ensue from changes in climate, secondary risks from climate acting on the environment and contributing risks where climate combines with another stress to produce a negative outcome. Policy risks emanate from the setting and implementation of both public and private policy. They are usually considered to be economic risks but can include legal, sovereign, social and environmental risks. Such risks include misdirected processes such as maladaptation to climate change (actions that have consequences opposite to those intended).

In this three-part report, we describe how climate risks are assessed (Chapter 1), and summarise climate risks for Australia (Chapter 2) in order to assess the benefits of a set of policy GHG emission scenarios compared to a reference scenario (Chapter 3). Chapter 1 describes the framing of climate and policy-related risks and discusses how they may be better integrated. Chapter 2 summaries the major uncertainties affecting climate change, then quantifies a series of impacts affecting Australia and the planet as a whole. Finally, we apply the emission scenarios produced as part of the project to assess risk-weighted outcomes for a small set of national and global risks, showing the benefits of mitigation when policy greenhouse gas emission scenarios are contrasted with a reference scenario.

1.1 Risk management frameworks

Managing risk is about decision-making under conditions of uncertainty. Risk can be formally defined as the combination of the likelihood of an event and its consequences. The event is known as a hazard if it is associated with a propensity to cause harm. There may be more than one event, consequences can range from positive to negative and the interaction between likelihood and consequences can be measured qualitatively or quantitatively, depending upon available information and the needs of stakeholders (ISO/IEC, 2000). Risk management is defined as the culture, processes and structures directed towards realising potential opportunities whilst managing adverse affects (AS/NZS, 2004).

Methods developed for climate change risk management also follow this path. Adaptation frameworks that utilise risk management approaches have been produced by Jones (2001), the United Kingdom Climate Impacts Program (Willows and Connell, 2003), and the United Nations Development Programme (UNDP, 2005). In Australia, the Australian and New Zealand Risk Management Standard (AS/NZS, 2004) is the primary cross-sectoral guidance framework for risk management activities. The Australian Greenhouse Office recently released an Australian guide for implementing the Standard in adapting to climate change impacts (AGO, 2006).

Risk management frameworks apply scientific and technical analyses, guided by the subjective interests and priorities of stakeholders to estimate the likelihood of different outcomes. Different decisions for reducing the risk of adverse outcomes and/or enhancing the likelihood of benefits are then evaluated and prioritised. Decision-making on climate risks is dominated by uncertainty, so specialised methods developed to manage climate uncertainty are incorporated with more conventional risk management methods. The decision-making context mainly covers strategic, or longer-term planning horizons. Mitigation and adaptation to climate change commonly applies foresight about potential long-term changes to actions being taken over much shorter time-scales spanning several years to decades.

The relationship between consequence and likelihood is shown in Figure 1.1. Risk is low when a consequence and its likelihood of occurrence are relatively small. Risk is high when critical outcomes are judged to have a sufficiently high likelihood of occurrence. When low frequency or unique events have catastrophic consequences, their risk may be assessed as high even though their likelihood may be very low. Climate change is associated both with impacts of moderate frequency and consequence, low frequency events that may become more common, and unique events (singularities) of assumed low probability that may have catastrophic consequences (e.g. irreversible melting of large ice-sheets).

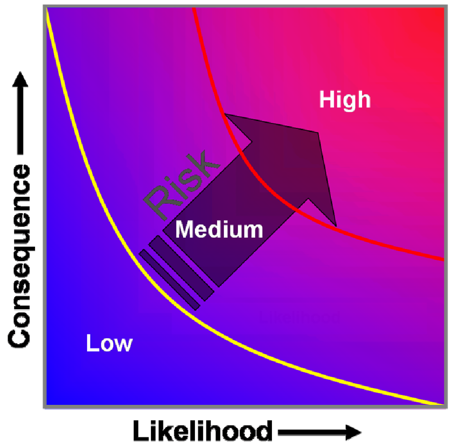

Figure 1.1 Conceptual model of risk.

The two main approaches to the likelihood–consequence relationship used in climate change risk assessment are (1) predictive and (2) diagnostic (Jones and Mearns, 2005):

1. Identify the most likely range of climate change and focus management efforts on its impacts. Less likely climate changes (which may be more severe) are monitored to ensure they remain insignificant. This is a largely predictive, or exploratory, approach that begins with the stress, assesses the impact, then assesses the appropriate response. The formula for risk is usually the likelihood of the climate hazard multiplied by consequence.
2. Focus on a key outcome, say a critical system threshold or desired policy outcome, and then determine how that outcome could be avoided, or achieved, under climate change. This is a diagnostic, or normative, approach that works in reverse to the above method. For example, sustainable development under climate change is a desirable outcome and the loss of a coral reef or large ice-sheet is an undesirable outcome. The formula for this type of assessment is usually the likelihood of attaining (positive outcome) or exceeding (negative outcome) a given threshold.

1.2 The structure of climate change risks

Climate change risks may result from climate hazards acting on their own or together with other factors. Consequences arise from the impacts of climate change and, based on a value judgement, can be assessed as positive or negative. Climate change risks can be treated either by mitigating climate change by reducing greenhouse gas emissions or adapting to climate change impacts. Because adaptation and mitigation manage different components of climate risk, at the policy level they are largely complementary rather than competing actions. Mitigation reduces climate hazards by reducing the rate and magnitude of global warming. This increases the chance that the remaining risks can be adapted to. Adaptation increases the ability of a system to cope with a changing range of climate variability, including extreme events (Jones, 2004b).

Adaptation and mitigation reduce risks from opposite extremes of the projected range of climate change (Figure 1.2). The range of mean global warming under the non-greenhouse gas policy SRES scenarios (IPCC, 2001a) is shown in the chart, while likelihood and consequences are shown on its right. Adaptation will be required to manage climate change risks that are already committed to. Committed risks cover those caused by historical emissions and those expected in the near future driven by existing demand and supply of energy sourced from fossil fuels, and from ongoing land-use and industrial activities. Adaptation is most urgent for risks that are already experienced under current climate, especially those that may worsen under climate change, and those that may not be currently threatened but may be sensitive to only small changes. Adaptations to higher levels of warming will be difficult and costly, needing to cover a large number of activities and large rates and magnitudes of change in any single activity (Smith et al., 2001). Such adaptation would be difficult and expensive, requiring a great deal of triage and accepted loss.

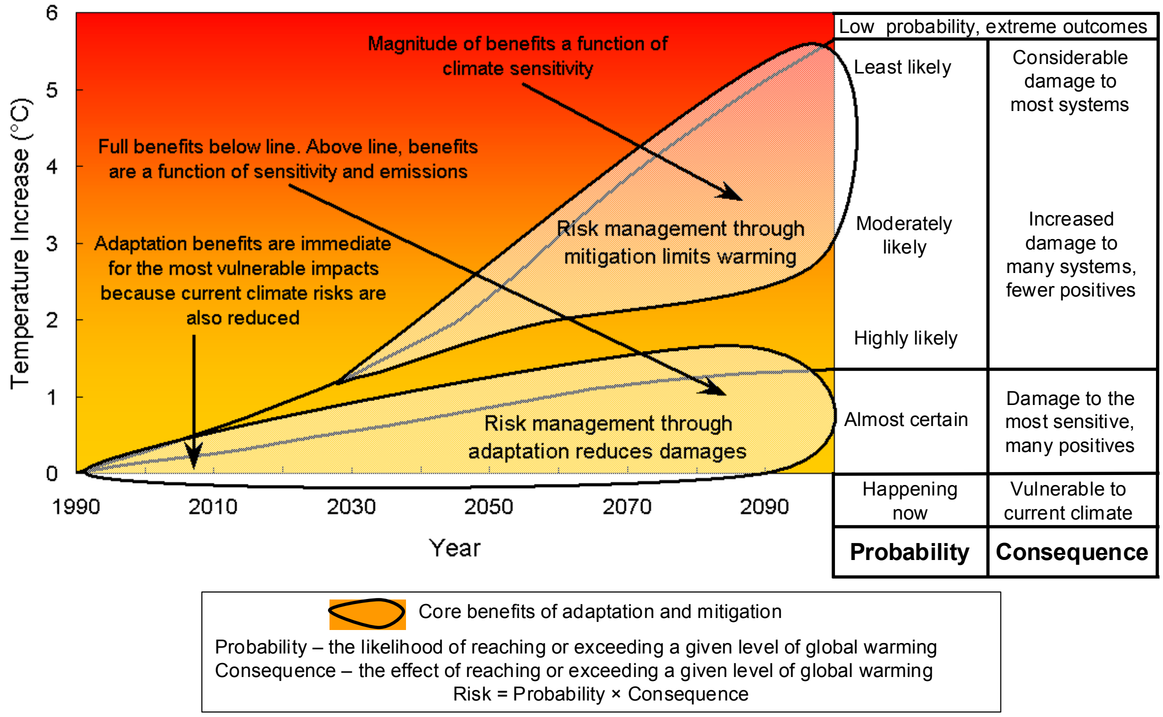

Figure 1.2 Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on the six SRES greenhouse gas emission marker scenarios with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold exceedance as a function of global warming and the consequences of global warming (Jones, 2004a).

Mitigation reduces the uppermost possibilities of climate change by reducing the potential volume of accumulated future emissions. Where the limits of adaptation are exceeded e.g. because adaptation is too expensive or impractical, mitigation may be the only realistic risk treatment.

However, because warming is not likely to be as high as for a world with no emission controls, future climate risks are reduced, irrespective of scientific uncertainties associated with climate change (Jones, 2004a). This has many implications for assessing the benefits of climate policy, as will be shown later.

The right hand side of the figure relates the consequences of climate change to the likelihood of exceeding a specific level of global warming, showing that low levels of climate change are most likely to be exceeded. However, impacts will only be negative in only some cases. For example, in regions and/or activities where the benefits of warmer winters outweigh warmer summers this will be the case. High levels of warming are less likely to be exceeded, but the negative consequences are likely to be widespread and severe. This conclusion remains sound under a wide range of uncertainties affecting the magnitude of climate change.

The following complementary and opposing effects of adaptation and mitigation need to be accounted for within a risk assessment framework:

1. They manage different parts of the risk: mitigation reduces the likelihood and magnitude of specific climate-related hazards and their resultant impacts; adaptation reduces the consequences of those impacts.
2. They manage risk in different parts of the potential climate change envelope: mitigation reduces the likelihood of changes at the upper defined limit of the plausible range of change; adaptation manages the experienced or likely changes occurring at the lower limit of the plausible range of change.
3. They are effective over different timescales: adaptations are put in place and will have an effect when the conditions they are designed for ensue, usually within a specific planning period; the benefits of mitigation are delayed as climate change responses take decades to centuries to cascade through the biophysical earth systems
4. They are effective at different spatial scales: mitigation reduces climate change at the global scale because greenhouse gases are well-mixed in the atmosphere and changes in radiative forcing are expressed globally; adaptation is usually locally specific in terms of climate, impacts, the activity in question and people engaging in/with that activity.

The common metric used to measure impacts for the purposes of assessing the benefits of mitigation is as a function of global warming (Smith et al., 2001). This allows widely varying impacts to be compared and also creates a link between emissions, climate change and levels of impact. Risk are assessed risks for a increasing levels of global mean warming, extending from 1°C or 2°C up to increases of >5°C, which are possible this century and more likely next century if emissions are not sufficiently curtailed. This structure is used to assess climate risks in Chapter 2.

1.3 Benefits of avoided impacts

The benefits of climate policy depend on the ability of adaptation and mitigation to manage risks stemming from climate change impacts. At the international policy level, this requires the avoidance of dangerous anthropogenic interference with the climate system as outlined in the United Nations Convention on Climate Change (UNFCCC). At the local level, this may result in accentuating the positive outcomes and reducing the negative outcomes for any activity, organisation, locality or sector. Due to the commitment to climate change from past emissions, and those inevitable in the near future (e.g. Wigley, 2005), it is no longer possible to prevent all the adverse impacts of global climate change. These will require some level of adaptation if risks are to be managed (AGO, 2006). Because mitigation generally reduces the upper limit for future temperature change, the primary benefit of mitigation is the minimization or elimination of climate change impacts associated with high magnitudes of warming. However, even systems that are adversely affected at low levels of warming would still benefit from mitigation (Jones, 2004a).

Figure 1.3 shows how adaptation and mitigation relate. Every activity has a range of climate phenomena under which it can thrive or at least cope. Risk increases from left to the right in the figure. Adaptation will be needed for climate change already committed to. Adaptive capacity is the ability to respond to climate changes, either anticipated or experienced, and covers both natural (e.g. biological) and socio-economic capacity. Every activity has a different adaptive capacity. In some cases, as for many unmanaged ecosystems sensitive to climate change, this capacity may be small. For other activities such as agriculture, where there is a long history of adaptation to climate phenomena, this capacity may be large (e.g. Brooks and Adger, 2005). If the limits of adaptation may be exceeded by climate change, then that risk can only be avoided by mitigation.

For systems sensitive to climate change, whether residual risk exists after adaptation and mitigation takes place depends on the rate and magnitude of the change. In this project, we are unable to investigate adaptive capacity, so restrict ourselves to assessing risk in systems where adaptive capacity is low; for such systems, mitigation is the principle form of risk treatment. Therefore, the following discussion on the policy benefits of avoiding climate change impacts mainly deals with the policy benefits of mitigation.

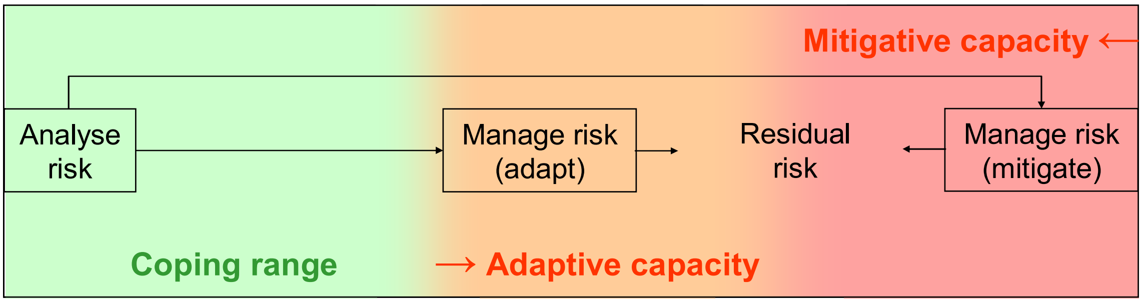

Figure 1.3 Schematic representing the complementary relationship between mitigation and adaptation (Jones, 2004b).

1.4 Relating climate and policy risks

The two major sets of risks that need to be assessed at the national and international policy level are climate- and policy-related risks. Policy-related risks are most often associated with the economic impacts of policy decisions and are generally expressed through the costs of mitigation[‡]. These two sets of risks are exceedingly difficult to assess within a common framework, in part due to the uncertainties surrounding climate change and the different time-scales over which these risks are expressed (Schneider and Lane, 2005), and how different risks may be perceived (e.g. Tversky and Kahneman, 1992). Rather than being rational according to description invariance, experiments assessing the perception of gains and losses under risk and uncertainty show significant asymmetry, where losses loom larger than gains (Kahneman and Tversky, 1984).

[‡] Policy-related risks associated with implementing adaptation measures are less prominent. Little is known about the economics of adaptation, particularly the macro-economic effects. Properly applied adaptation is expected to provide a realisable return, whether monetary or non-monetary, in the short to medium term.

As a rationally-weighted assessment, the application of climate policy (mitigation) is seen as incurring a cost that needs to be balanced by equal or greater gains in the benefits of reduced climate damages (e.g. Downing et al., 2005). However, this is very difficult to show, because not enough is known about climate damages to assure that the utility surrounding decisions to mitigate are being maximised. If we are averse with regard to environmental risks and apply the precautionary principle[§], then specific actions can be justified where they can be shown to be cost-effective (Hansson, 1999). However, when climate policy actions are seen as posing the threat of serious or irreversible damage to the economy, short-term losses on the one hand are confronting long-term social and environmental losses on the other.

Thus, there are two poles of risk-averse attitudes with regard to climate change; one is highly risk-averse to perceived damages to the economy and has a fast rate of time preference (short-term outlook), the other is risk-averse to perceived damages to the environment and has a slow rate of time preference (long-term outlook). Figure 1.4 shows the tension between these two precautionary approaches with regard to climate change. The upright axis shows increasing costs of mitigation and the horizontal axis shows the increasing costs of impacts and an increasing likelihood of encountering dangerous anthropogenic interference (DAI) with the climate system. Both axes are associated with significant uncertainties.

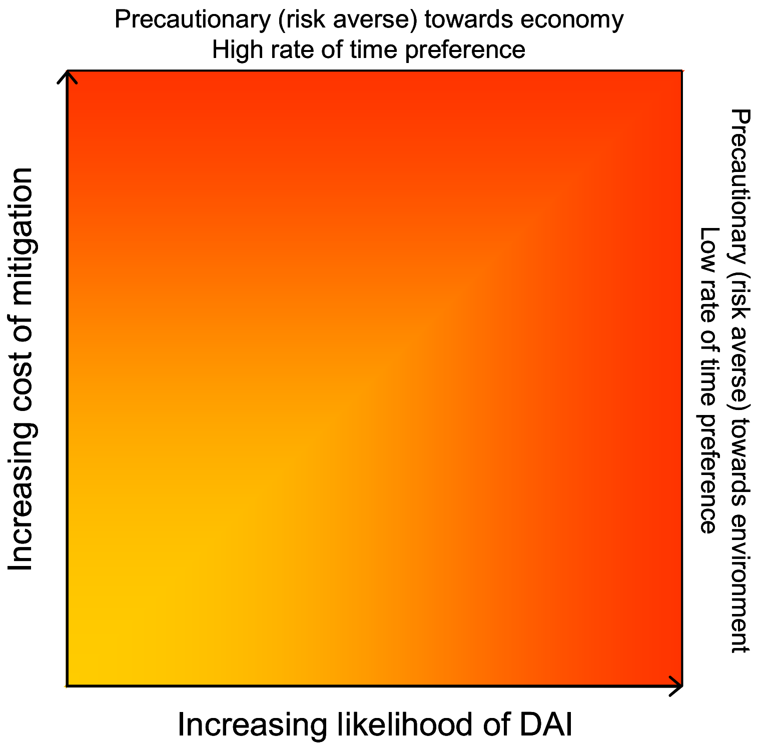

Figure 1.4 Simple risk matrix linking increasing costs of mitigation and increasing likelihood of dangerous anthropogenic interference (DAI) to two poles of risk aversion, economic and environmental risks, respectively.

[§] In the Rio Declaration (Principle 15), the Precautionary Principle was expressed as follows: *Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*. Here, precautionary approaches do not apply solely to the environment but refer to any area that a person believes more important than any other, and thus requires greater protection. Therefore, for that person, a greater weight of evidence is required to deviate from what they see as an optimal course of action, and a lesser weight of evidence is required to justify maintaining or adopting that particular course of action.

Aversion to economic loss may extend to including the perceived risk of growing the economy at anything less than the optimal rate. This stance expresses itself in an opposition to any action unless there is clear and compelling economic evidence that climate risks, properly discounted, will exceed the risks of taking action (i.e. mitigation). Threats to the natural and human systems over the longer term are uppermost in the minds of those averse to environmental loss who believe that the risk of DAI occurring warrants intervention in prevailing economic and industrial trends to prevent such an outcome.

It is difficult to balance these views because the decision space is not symmetrical (Figure 1.5). By framing the issue differently with respect to which side of the issue loss and gain is attached to, proponents of either view have different burdens of proof. The economically risk averse prefer quantified economic evidence, most often based on cost-benefit analyses, that aim to show whether the benefits outweigh the costs. The loss side of the ledger is attached to the economy. The environmentally risk averse will rely most on scientific advice that assesses the possibility of critical environmental or socio-economic thresholds being exceeded at some time in the future. The loss side of the ledger is attached to the environment.

Figure 1.5 An illustration of the risk-neutral weighting of costs and benefits empahsising impacts known with greatest certainty and risk-averse weighting of costs and benefits with opposing precautionary approaches to uncertainty.

These two poles are expressed in the following policy positions:

1. Market-based and technology-driven strategies initiated with a wait and see approach as to how serious climate change may become before applying any irreversible actions to the economy (averse to economic risks).
2. Targets for warming and atmospheric CO_2 concentrations being set with pathways towards those targets, designed to minimise the risk of DAI occurring (averse to environmental risks).

The precautionary approaches expressed by these two positions are that:

1. Deep cuts may visit harmful and irreversible impacts on the economy. Such cuts may limit society's capacity to adapt and mitigate at later stages and would be mistaken if impacts were less than anticipated.
2. Insufficient action may deliver the earth beyond a tipping point (DAI) causing environment and society (particularly future generations) to suffer irreversible and preventable levels of harm. The consequences of DAI are so severe that immediate and deep cuts in greenhouse gas emissions are required.

This dichotomy points to a variant of Type I / Type II errors, where a hypothesis is thought to be true but is in fact false (Type I) or thought to be false but is in fact true (Type II). If the science surrounding greenhouse warming is contested, then engaging in false positive, or Type I actions is posited as a significant policy risk. However, if the science is accepted, the risk of committing a

Type I error becomes negligible, and the argument is not about whether to take action but when and how much.

It is now recognised that DAI may be breached within the range of warming projected for 2100 (e.g. Mastandrea and Schneider, 2004; Kerr, 2004; Wigley, 2004). Estimates range from DAI being already committed to by past emissions, to DAI occurring at several °C warming or more (Dessai et al., 2004). Such estimates need at least to consider two major uncertainties: the climate sensitivity to radiative forcing and the sensitivity of key vulnerabilities to the resultant warming. Within the resulting broad range of uncertainty, a Type II error (false negative) is possible if DAI is preventable but too little is done too late. However, the fear remains that early action may be regretted if DAI turns out to be less likely than thought, if there is a technological "magical bullet" developed by mid-century that can drastically reduce emissions in time to avoid DAI or that early actions serve to reduce future mitigative and adaptive capacity.

In this assessment, we address both sides of this issue through the following questions:

1. The economically risk-averse decision maker: "*Can we afford to act on climate change?*"
2. The environmentally risk-averse decision maker: "*Can we afford to <u>not</u> act on climate change?*"

1.5 Existing integrated assessment

Although current research is dominated by dis-integrated approaches, integration is being pursued through assessment models (IAMs) that link climate damages with the costs of mitigation (Figure 1.6). For a comprehensive review of different IAM approaches see Schneider and Lane (2005). The most sophisticated examples undertaking cost-benefit analysis contain simple climate and greenhouse gas mixing models, allowing the progression of emissions and warming over time to be assessed and an economic model. Usually a computable general equilibrium (CGE) model is used, but dynamic models are becoming more common. If damages are not incorporated and a target for abatement set *a priori*, the costs of abatement can be assessed by:

- Prescribing a particular target for atmospheric concentration, a mitigation policy (e.g. carbon tax, emission trading) and allowing a price to be optimised over time; or
- Setting a price for carbon and letting that dictate the energy and technology mix, allowing the estimation of emission rates.

However, if damages are incorporated, the costs of mitigation are assessed by:

- Estimating the damages due to climate change and optimising the model to determine the relevant carbon price.

Optimised assessments imply a level of foreknowledge of damages that is unattainable and thus, ignore the role of risk in decision-making (e.g., Downing et al., 2005). Therefore, such assessments are of academic interest but unsuited to decision analysis. Where damages are incorporated, they often consist of a monotonic cost curve that makes a wide range of assumptions about sectoral and regional climate-impact-cost relationships. Even models that aggregate regional costs are subject to a wide range of assumptions that are limited by uneven coverage of underlying research into the socio-economic impacts of climate change (Tol, 2005).

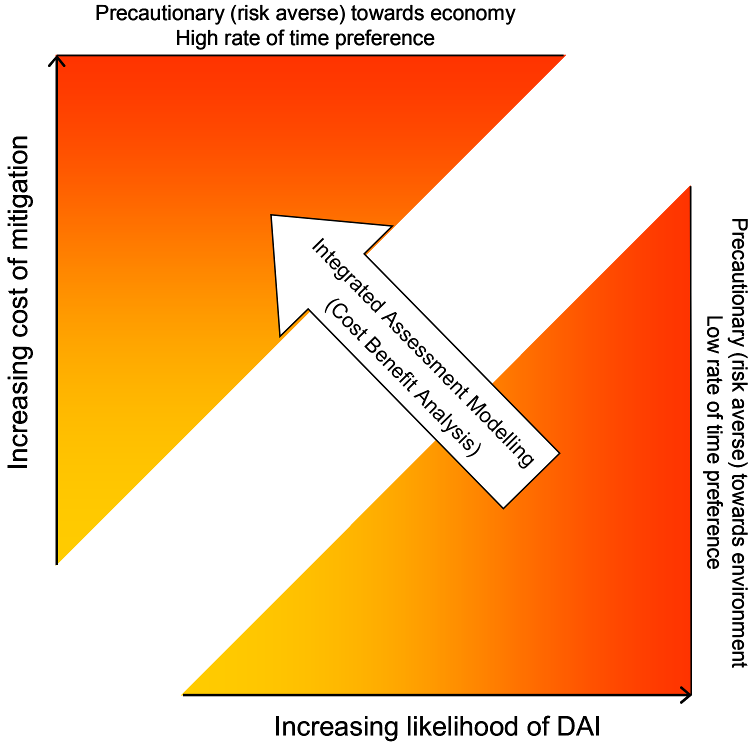

Figure 1.6 Divided nature of policy-related and climate-related risks showing the current set of tools used to links these risks.

The reliability of formal cost-benefit analysis applied by such models has been widely critiqued (e.g., Yohe, 2003) because:

- Uncertainty is too high for cost benefit analysis to be used reliably
- Traditional discounting is unsuited to long time frames as any marginal damage becomes negligible
- Some forms of damage are infinite, therefore a proportion of such damages is also infinite (analytic failure)
- Different damages are incommensurate in that all damages cannot be monetised or otherwise be couched within a common metric
- Cost analyses of damage are incomplete (see next section).

Therefore, because of the asymmetry in the perception of different risks outlined in the last section and the analytic limitations of cost-benefit analysis, we have developed a risk management approach that utilises cost-effectiveness analysis and multi criteria analysis. Because it sets a carbon tax based on a particular combination of technologies needed to reach a pre-ordained reduction of greenhouse gases by 2050, the ABARE analysis (Ahammad et al., 2006) qualifies as a cost-effectiveness analysis. We then apply a multi-criteria analysis to assess the benefits of those GHG reductions.

1.6 Estimating damage costs

The estimation of monetary damage/benefits[**] is one of the weakest aspects of integrated assessment modelling. The extent to which IAMs have been used to represent valuation uncertainties and climate uncertainties in estimating the costs of climate damages (or the social cost of carbon) is shown in Table 1 (Downing et al., 2005). The earliest estimates of damages were developed from impacts assessment developed from climate model simulations run at 2×CO_2 forcing (Pearce et al., 1996). Later assessments at a range of temperatures have created regional estimates and allowed for continuous damage curves measuring damage GDP as a function of global warming to be created (Figure 3.12, Figure 3.13; Nordhaus and Boyer, 2000; Tol, 2002a and b; Nordhaus, 2006).

Most studies have only assessed costs for mean changes in climate without specifically accounting for change in variability, extremes and large scale critical thresholds (Downing et al., 2005; Table 1.1). Abundant evidence from local and regional studies shows that when climate variability and extremes are explicitly accounted for in damage models economic costs can increase substantially (IPCC, 2001b). This is also the case for system changes and singularities. For example, what are the costs of a 5 m sea level rise if the Greenland ice sheet melts, or a substantial change in European climate if the North Atlantic Ocean thermohaline circulation is disrupted? Therefore, from Table 1.1, costs would increase along both axes if climate variability and critical thresholds were accounted for and if indirect and existence values were accounted for.

Marginal damage costs, taking into account both direct and indirect costs, can be measured as per tonne of carbon emitted, known as the social cost of carbon (SCC). The SCC is used as a policy instrument to estimate how carbon emissions should be costed into existing and new policies and can include direct and indirect costs (Watkiss et al., 2005). Estimates vary widely, as do the calculation methods and how inclusive such costs should be. A recent review estimated a mean of $65 (US$ in 2000) per tonne of carbon emitted in the year 2000 with 5% and 95% figures of $13 and $185 within a range of -$71 to >$285, established from a broader literature review, modelling exercise and expert assessment (Downing et al., 2005; note that the range in the literature is even larger). The spread of estimates is subject to the level of emissions, climate sensitivity, equity considerations, comprehensiveness of costing, discount rates and other factors. Therefore the range of uncertainty for the cost of carbon due to climate damages, which can be expressed along the horizontal axis of Figure 1.4 and Figure 1.6, is very large.

Monetizing all levels of climate impacts is problematic – for example, should existence and bequest value be costed, or should non-monetary values be used as separate measures along with monetary cost (Jacoby, 2004)? The IPCC Second Assessment Report summarised a number of global estimates of economic damages derived from assessments based on 2×CO2 scenarios (Pearce et al., 1996), but the Third Assessment Report stepped back from such estimates. Criticisms that monetisation did not capture all aspects of climate-related damages adequately, resulted in the creation and assessment of five areas of concern that concentrated on non-monetised damages (Smith et al., 2001).

[**] Here damage costs are assumed to include both damages and benefits, however research points to a very high likelihood of net damages at higher temperatures, across all metrics.

Table 1.1 Major uncertainties in estimating the costs of climate change (Downing et al., 2005), showing the breadth of most integrated assessment studies. The red boundary and background represents how well costs have been quantified in economic terms. WTP stands for willingness to pay methods of valuation.

Valuation uncertainties

Increasing costs →

Quantified economic costs

Climate uncertainties

Increasing costs ↓

	Market (direct) value	Non-market (indirect use and options)	Existence and bequest value
Mean climate	Global studies	Some global studies (as WTP)	None
Variability & extremes	Regional studies, some allowance in global studies	Some local and regional studies	None
Thresholds & singularities	Few sensitivity studies	None	None

This change in approach creates a problem for integrated assessment modelling, which relies on monetised regional and global damage estimates, because there is no accepted substitute measure against which to contrast the costs of mitigation. Therefore, such studies have continued to rely on globally aggregated monetary damages but the methods of calculating damages have progressed only slowly (Downing et al., 2005). Thus, a tension exists between the practical and ethical dimensions of trying to monetise everything and the perceived need to provide damage costs against which to balance the economic impacts of mitigation (Jacoby, 2004). The problems associated with estimating a single number for globally aggregated costs and benefits has justified the use of the precautionary approach to justify strong reductions in greenhouse gas emissions (e.g. WBGU, 2003), but as mentioned earlier, this approach is often rejected by those who are highly averse to economic risks.

The aggregated costs and benefits for adaptation are also difficult to estimate. Only a few IAMs specifically account for adaptation and, when they do, often assume constant levels of adaptation that extend across sectors and regions. Early estimates either had no adaptation or assumed that full adaptation assessed for countries such as the USA, extended worldwide (Tol et al., 1998). More recent studies link adaptation to levels of economic development, and vary it accordingly throughout an assessment (e.g. Tol, 2002; Mendelsohn and Williams, 2004; Downing et al., 2005; Hope, 2006).

The scope for adaptive capacity is a critical factor in calculating damage costs but has not yet been very well accounted for. Adaptive capacity, measured as the potential of people and institutions to reduce the consequences of climate change impacts, is largely a product of socio-economic factors. Estimates of such factors therefore require an understanding of how the economy, technology and society may change, and how the resulting adaptive capacity could reduce the net costs of climate change impacts (Yohe and Tol, 2002; Adger et al., 2004). Some sectors will be very highly influenced by the economy acting on adaptive capacity (e.g. agriculture, the built environment) whereas for others, the capacity to adapt is much more limited. Therefore, adaptation to climate change in these sectors is dependent on the underlying development pathway in the emissions scenarios from which climate change and impacts are assessed. Adaptive capacity also varies widely from region to region (Adger and Vincent, 2005).

Therefore, if non-monetary estimates of damage expressed per degree of global warming are required, critical bio-physical thresholds measuring significant vulnerabilities for systems with low adaptive capacity are the most suitable measures to use. Because the resulting vulnerability is largely independent of the underlying development pathway, it is almost entirely a product of climate change. Systems and sectors where this assumption can be applied include damages to key ecosystems (e.g., alpine and coral reefs), melting of large ice-sheets and changes to the carbonate geochemistry in the oceans due to higher atmospheric CO_2. Many of these significant biophysically expressed damages are reflected in Table 1.1 as system changes and singularities, so are likely to result in significant non-market damages and/or have large existence and bequest values. Estimates of critical threshold exceedance can be factored into a multi-criteria analysis that focuses on how much climate change should be avoided.

1.7 Estimating mitigation costs

Assessments of mitigation costs often choose either a target concentration or level of global warming then optimise the costs to meet that particular target. Mitigation costs are usually simulated as a carbon tax, or a price of carbon within a permit trading scheme. If mitigation costs are optimised to damage costs, a single value on the vertical axis of Figure 1.4 is produced but only by selecting a single point on the horizontal axis.

But as described above, the uncertainty surrounding climate damages is significant, and choosing a single point overlooks this uncertainty. In reality when trying to balance costs and benefits, the uncertainty along the horizontal axis propagates with the uncertainty inherent in estimating mitigation costs. Therefore, optimising mitigation costs based on single-value damage costs deals very poorly with the underlying uncertainty.

Mitigation costs are also influenced by assumptions about technology development and costs. Top-down macroeconomic models are forced to make assumptions about levels of technology and how that technology is costed over time and transferred between regions. Such information is obtained by bottom-up models of technology diffusion and learning curves. Demographic information about technology use is also critical to this process. Costs curves denoting technological learning, the influence of normative approaches to "push" technological solutions and long-term change in social norms are all aspects of bottom-up processes that will affect the costs of abatement (e.g. Grubb et al., 1994; Barker et al., 2005).

Although it is possible to deal with uncertainty by varying the input parameters and running a large number of simulations, to date the uncertainties within Figure 1.4 and Figure 1.6 have not been very well explored. Several studies have explored this space (Tol, 2005; Hope, 2006), either by varying a range of key input parameters (e.g. sensitivity, degrees of damage, underlying economic growth, technology vast and type), or by running multiple scenarios that represent different values of such parameters. However, there are plausible futures under climate change where cost-benefit analysis fails – when this failure is due to large damages, collapse in regional economies and the like (Tol, 2003; Yohe, 2003). Therefore, some combinations of climate damages and mitigation with non-marginal costs are possible. In such cases, a risk management approach would deem that sufficient measures be taken to avoid such an outcome (Yohe, 2003; Jones and Yohe, 2006).

Fixing emission or stabilisation targets independently of mitigation costs is rejected as a policy option by those who are economically risk averse because it does not answer the question asked in Chapter 1.4: “Can we afford to act on climate change?” However, a range of assessments have been carried out based on a target approach and many of these suggest that mitigation costs can be contained. For example a recent summary of mitigation costs suggests that that even stringent stabilisation targets can be met without materially affecting world GDP growth, at low carbon tax rates or permit prices, at least by 2030 (in $US(2000), less than $15/t CO_2 for 550ppmv and $50/t CO_2 for 450ppmv for CO_2; Barker et al., 2006). In a project undertaken for the Australian Business Roundtable on Climate Change, early action by developing countries to reach a target of 60% reduction by 2050 (commencing 2013) produced a cost of almost $200/t CO_2 (in $A(2002)) compared to a cost of ~$600/t CO_2 for delayed action beginning in 2022 (Allen Consulting Group, 2006). The difference is due to the steeper cuts required beyond 2030 in the delayed case.

This project has assessed mitigation costs by comparing several policy emission scenarios with a reference emission scenario. The reference scenario is exploratory, in that it projects changes due to existing and anticipated energy, technology and population trends to 2050. The reference scenarios project different combinations of energy and technology development to assess pathways to a scenario that approximate a stabilisation of CO_2-e in the atmosphere of about 550–575 ppm (Ahammad et al., 2006).

1.8 Integrating damages and costs

Deciding how to address climate change is not a simple either/or situation balancing the costs of mitigation against damages – aggregated climate change risks may range from mild to severe and it is possible that DAI may be achieved within the range of global warming projected to 2100 (Dessai et al, 2004; Mastrandrea and Schneider, 2004), as projected from the IPCC SRES scenarios (IPCC, 2001). Figure 1.7 links the increasing costs and mitigation and increasing likelihood of DAI to four possible strategies for managing those risks. These strategies range from “Do a little, wait and see”, which is most applicable when the penalties for inaction are low, to the highly precautionary “Act early and learn fast” strategy, most applicable when the penalties of inaction are high. To estimate which of those strategies may be the most likely to be successful requires the ability to assess the joint likelihood of DAI at some time in the future in response to implementing the costs of mitigating climate change.

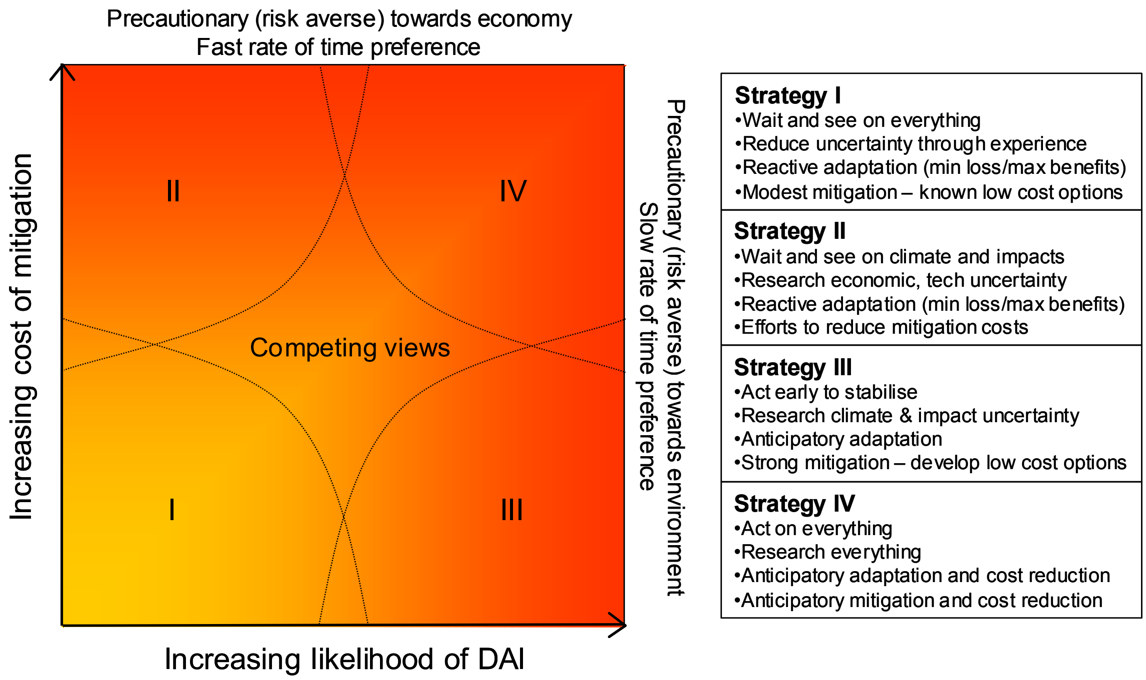

Figure 1.7 Matrix linking increasing costs and mitigation and increasing likelihood of dangerous anthropogenic interference (DAI) to four possible strategies for managing those risks.

However, few such assessments have been attempted and even fewer where the uncertainties in mitigation and damage costs have been contrasted (See Downing et al., 2005 for a review and recent analyses). For this reason, it is not yet possible to estimate the relative likelihoods of success for Strategies I–IV in Figure 1.7 or to articulate the outcomes if one particular strategy is followed and another eventuates (a variant of a Type II error). Furthermore, strategies that suggest taking actions that meet a wide range of outcomes, may not produce a satisfactory outcome either – it is possible that the adoption of such a strategy may not sufficiently lower the risk of reaching DAI.

Table 1.1 indicates that analyses based on monetized costs from existing studies are likely to significantly under-estimate costs. Some studies have assumed larger damage profiles to account for the lack of such information but such assumptions are very imprecise and will have low confidence attached.

1.9 Risk-weighted analysis of policy benefits

Risk-weighted climate impacts account for the most likely and low probability–high consequences of climate in a better way than consensus (maximum likelihood), averaging and scenario methods. The probabilistic methods of impact estimation applied in this report are developed from those outlined in Jones (2000, 2001, 2004a&b) and Jones and Mearns (2005). Risk-weighted estimates of climate impacts are created by multiplying the probability of mean global warming with the likelihood of a specific impact at a given date. The use of risk-weighted climate damages has the following aims:

- To account for as much of the plausible range of climate and impact uncertainties as possible and practicable.
- To account for both monetary and non-monetary damages within the same framework.

The policy benefits of reducing greenhouse gas emissions are measured as the change in risk-weighted damages from a reference to a policy emission scenario. This application is similar to that applied in the recently released Stern Review (Stern et al., 2006).

Because of the relationship between mitigation, adaptation and climate risk, policy benefits are not accounted for in the same way as climate damages. The marginal damage of climate change is accrued over time as the sum of the impacts resulting from climate changes per unit time (e.g. per year), so build up over time. The projected marginal damage of one tonne of an emitted GHG is the potential damage that may occur as long as that gas remains in the atmosphere. For example, if one tonne of CO_2 is emitted at a location it will become well mixed in the atmosphere; some will be absorbed by vegetation, some into soil and some into the ocean. The amount of gas remaining in the atmosphere will continue to affect the balance of radiative forcing. Other greenhouse gases are absorbed or broken down at different rates. Residence times range for different gases range from about 10 years for CH_4, to 100–150 years for CO_2, to thousands of years for some halogen compounds (IPCC, 2001a).

The benefits of mitigation are the damages prevented at some time in the future by not emitting GHGs that otherwise would have been emitted or removing GHGs from the atmosphere that would otherwise not have been removed. A reference emission scenario is a scenario that accounts for the sum of gases that would be expected to be emitted over time if anthropogenic climate change was not an issue. A mitigation scenario is one where specific actions to reduce emissions over time are proposed. The benefit of mitigation at year*(n)* is the difference in damages between a reference and mitigation scenario leading up to that date. The benefits for adaptation under the mitigation scenario are that adaptation is now needed for a lesser rate and magnitude of climate change. Therefore, adaptation will become easier and cheaper than it otherwise would have been under the mitigation scenario. The number of situations where the limits of adaptation (the amount of damage beyond which adaptation is no longer feasible) are exceeded are also reduced.

The delay in the climate system is important to the assessment of damages and benefits (IPCC, 2001c). For example, the climate change currently being observed is caused by past emissions and current emissions will affect the climate for a period into the future. Thus, reductions in emissions from a reference scenario will be delayed as the atmosphere, ice masses and oceans respond over time. The response time of the atmosphere is years to decades, of ice is years to decades (small glaciers) years to thousands of years (ice sheets), of the biosphere is years to centuries and of the oceans is decades to centuries (IPCC, 2001c).

Therefore, even if greenhouse gas concentrations are stabilised in the atmosphere, global systems will continue to respond for decades to centuries before their rate of change returns to natural or background levels (IPCC, 2001c). This does not necessarily mean that the Earth reaches a stable equilibrium – it is rather that humans are no longer a strong driver of de-stabilising influences on the Earth's climate. To assess the full benefits of climate policy requires integrated assessments to simulate changes for several centuries at least, which needs projections of climate change, the systems that respond to climate and the economy.

If there was no uncertainty, the benefits of mitigation would be a single sum taking the difference between damages associated with a reference and mitigation scenario. The economically averse decision maker would prefer that uncertainty reduce to such an extent (as yet unspecified) that policy risks become negligible. However, much of the uncertainty surrounding climate change may be untractable. The risk that DAI may be committed to before certainty can be reached, requires an approach that can contrast climate and policy-related risks. Risk-weighted damage functions aggregate the spectrum of plausible climate-related damage for a particular future date as a function of global warming. Two set of probabilities need to be assessed, the likelihood of damage at a specific level of global warming and the likelihood of global warming itself. The latter is mainly a function of greenhouse gas emissions and climate sensitivity and can be probabilistically assessed using simple models. Damage itself is more difficult to assess, as detailed earlier in the chapter.

A range of different types of damage function are possible. One type measures the degree of damage for a particular sector, activity or region (exposure unit), often tallied from zero to 100%. Another type measures the likelihood of exceeding a critical threshold. In this context, a critical threshold may either be a system threshold representing a fundamental change in system properties or behaviour, or a critical value threshold where a level of tolerable loss has been exceeded (Jones, 2001). Thresholds can be measured in biophysical, social or economic terms. Damage relationships for a range of sectors are summarised by Hitz and Smith (2004).

The most difficult damage curves to assess are those where adaptive capacity may be large. Such capacity is dependent on economic, social, environmental and political development pathways. Biophysical thresholds can be assessed largely independently of accompanying socio-economic changes, but thresholds where socio-economic factors are significant, require an integrated biophysical and socio-economic understanding of change processes. The need for this link has been relatively well understood by integrated modellers but the integration itself is difficult to carry out. Few integrated assessments allow a comprehensive understanding of how different combinations of climate and adaptive capacity may affect agriculture, access to water, the coastal zone and damage to settlements (Tol., 2005). The possibility that sectors with a degree of adaptive capacity (e.g., agriculture, water) faced significant risks has convinced many who are environmentally risk-averse, of the need for action. However, many who are economically risk-averse, may not be convinced of such a need, because of the possibility that people can adapt to even large changes.

In the next chapter we summarise the major uncertainties affecting the risk analysis of climate change damages, the major impacts for Australia as a function of global warming in order to assess the benefits of mitigation in Chapter 3.

2. ASSESSING CLIMATE CHANGE RISKS

2.1 Climate risk analysis

Climate risk analysis is developed from climate change impact analysis but adds two important factors. The exposure of a system to changing climate impacts needs to be assessed as does the consequences of that exposure. Table 2.1 shows the major uncertainties affecting risk analysis in order from the precursors of the stress, through the factors involved in climate change itself, to impacts. The major uncertainties are shaded orange.

Table 2.1 Major uncertainties affecting the assessment of climate change impacts. Key outputs treated in this assessment are shaded orange.

Subject	Current state of knowledge	Relative uncertainty
Social and Economic Futures	Improved integrated models combine a range of social and environmental changes (Population, demographics, economy), better knowledge of trends out to 2030, large uncertainties beyond	Major
Technological Futures	Improved bottom-up models, better knowledge of cost curves, but novel technologies and synergies still poorly understood, large uncertainties beyond 2030	Moderate
Emissions Futures	Improved integrated models combine a range of social and environmental changes, better knowledge of trends out to 2030, For reference scenarios, large uncertainties beyond 2030. Ability to calculate mitigation scenarios not well developed	Major – KEY OUTPUT
Atmospheric composition	Good models available, being incorporated into climate and earth system models.	Minor
Atmospheric forcing	Good models available, being incorporated into climate and earth system models. Dependent on atmospheric chemistry.	Minor for GHGs, Moderate for aerosols
Climate sensitivity	Increase in total range since the IPCC TAR, some concentration of mode in 2.5–3.5°C range. Range beginning to decrease but appears to exceed previous "best guess" range of 1.5–4.5°C	Major
Global climate change	Larger number of models with increased no. of drivers; ensemble representation of current climate is better that any single model; possible feedback with biosphere, cryosphere remain largest uncertainties. Consensus increasing but feedbacks and system thresholds remain a concern.	Major – KEY OUTPUT
Regional climate change	Increasing number of models, beginning to look at most likely outcomes. Increased sophistication of downscaling getting a better handle on variability and extremes. Poor handle on regional variability.	Moderate – KEY OUTPUT
Local climate change	Difficult to predict but can carry out sensitivity analysis of projected trends on variability and extreme events.	Moderate to major (variable and location dependent)
Biophysical impacts	Some areas narrowing (crop systems, hydrology), some expanding as models are improved (e.g. infrastructure damage), integrated assessment developing cross-sectoral impacts and feedbacks. Single issue assessments becoming mature and amenable to probabilistic analysis, integrated assessment linking models "new science"	Moderate – KEY OUTPUT
Socio-economic impacts	Not well developed. Ok for agriculture and some built systems, but the economic impacts of climate change remain poorly understood.	Major

Because these uncertainties are cumulative, this relationship has been called the ‘cascade of uncertainties’ or the ‘uncertainty explosion’ (Figure 2.1). Risk analytic methods for managing these uncertainties have been developed by CSIRO and applied to assess a variety of climate risks. These risks span the ranges of the most significant uncertainties that can be quantified with some degree of plausibility (Table 2.1). As mentioned above, if they are expressed as a function of global warming, allows emissions, radiative forcing in the atmosphere, the climate response and impacts can all be interrelated probabilistically.

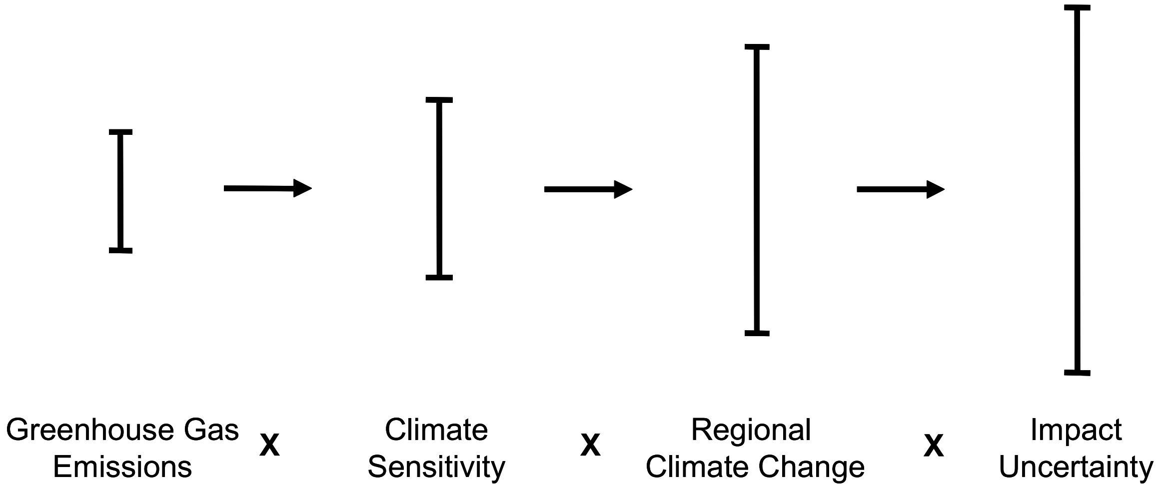

Figure 2.1 Schematic depiction of the uncertainty explosion (after Jones. 2000).

The next section summarises current knowledge about the major uncertainties in Table 2.1 with information about how they may be applied in an analysis.

2.2 Major climate uncertainties

2.2.1 Greenhouse gas emissions

Since the industrial revolution, atmospheric concentrations of CO_2 have increased by over 30% (from 280 to 370 parts per million), while concentrations of nitrous oxide and methane have increased by 17% and 151%, respectively. These emissions commit the world to a certain level of warming and accompanying climate change. The exact number is difficult to assess, but maintaining current forcing rates produces an estimated 0.5–1.0°C of committed warming (Wigley, 2005).

As mentioned earlier, the two major types of greenhouse gas scenario are reference and mitigation scenarios. Reference scenarios are those with no specific policies to reduce greenhouse gas emissions and mitigation scenarios represent policies to reduce emissions, whether explicit or implicit. The major reference scenarios produced by the IPCC are the Special Report on Emission Scenarios (SRES; Nakiçenovic and Swart, 2000). The SRES scenarios were constructed using four narrative storylines, labelled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents a set of demographic, social, economic, technological, and environmental developments that diverge over the course of this century resulting in very different levels of greenhouse gas emissions.

Emissions of greenhouse gases and sulphate aerosols were used to calculate changes in atmospheric greenhouse gas and aerosol concentrations, radiative forcing of the climate, effects on regional climate, and climatic effects on global sea level presented in the IPCC Third Assessment Report (IPCCa, 2001). Six marker scenarios and a total of forty-two scenarios were produced by the SRES and they fill about as wide a space as a larger set of scenarios from the literature (Nakiçenovic and Swart, 2000). The projected a range of CO_2 emissions of 3.3 to 36.8 GtC/year by 2100 relative to 1990 levels of 7.1 GtC/year. The resulting range of CO_2 concentrations in 2100 is 540 to 960 ppm (IPCCa, 2001).

There has been some controversy surrounding the SRES scenarios and their plausibility, involving possible differences between use of market exchange rates and purchasing power parity in forward projections. However, there is no compelling reason to suggest that the range of forcing produced by the SRES scenarios should be substantially revised upwards or downwards (IEA, 2003). In fact, the reference scenario produced by ABARE for this project is in the upper part of the SRES range, producing similar forcing to the A2 scenario.

Mitigation scenarios include:
- stabilisation scenarios, that represent stabilised concentration of GHGs in the atmosphere;
- target scenarios that aim to reach a given level of emissions or atmospheric concentration of gases by a particular date or
- scenarios that extrapolate from a set of specific policy initiatives.

The IPCC has used a set of stabilisation scenarios (IPCCa, 2001), WRE450 to 1000 (Wigley et al., 1996), which have been optimised to provide pathways towards GHG stabilisation in the atmosphere. However, these do not have detailed storylines or sufficient underlying information that can be used in integrated assessment, so the need for a new generation of scenarios has recently been recognised and the IPCC has commenced a process for the development of new scenarios.

Guided by the Energy Futures Forum, ABARE have produced one reference scenario and two sets of mitigation scenarios, which represent a change from a world where emissions are increasing beyond the 21st century to one where stabilisation in the range ~600 to 650 ppm of CO_2-equivalent concentrations of greenhouse gases in the atmosphere (Ahammad et al., 2006). Emissions were provided to CSIRO for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the halide compounds CF_4, HFC134a and SF_6. Details of how these have been converted into temperature will be given later.

2.2.2 Global climate change

Global climate change from Table 2.1 incorporates uncertainties due to atmospheric composition, atmospheric forcing and change in global climate. Atmospheric composition is calculated using models of sources and sinks in the Earth system, incorporating both natural and artificial components. Aspects taken into account are atmospheric chemistry that accounts for changing composition of different chemical species and their residence times in the atmosphere, and the 'breathing' biosphere on land and in the ocean. This is a reasonably minor uncertainty, expanding the resulting range of global warming in the order of 5%.

Atmospheric forcing models calculate the balance of absorption and emission of electromagnetic radiation in the atmosphere, converting it into changes in the radiative balance, measured in Watts per m^2 (Wm^{-2}). Each type of greenhouse gas has a different residence time in the atmosphere and global warming potential (GWP). Residence time is measured in half life and global warming potential as a factor of the GWP of CO_2. Although GWP and residence times are affected by the mix of gases in the atmosphere they are generally assumed to be constant, except for the reducing flux of CO_2 absorbed into the ocean over time. Net uncertainties are small.

However, sulphate aerosols also alter the radiative balance of the atmosphere both directly and indirectly, the latter mainly in their influence on cloud formation and composition. This also includes black carbon, dust and a range of minor particulate emissions. The uncertainties surrounding the radiative forcing of these species are high, but not cumulative, so because of their relative modest quantities in the atmosphere uncertainty is moderate at the global scale. There is one proviso and that is the role of direct and indirect forcing of sulphate aerosols on regional rainfall change, which has been implicated in rainfall reductions over Australia (Rotstayn, pers. comm.).

The current generation of coupled atmosphere-ocean global climate models utilise inputs of radiative forcing from GHGs and aerosols. Climate change is projected as the response of climate to changes in radiative forcing, historical to about the year 2000, then projected beyond 2000. The results are highly influenced by the resolution of the model, which runs in sub-daily time steps but has a spatial resolution ranging from about ~100 to 300 km. This resolution affects the simulation of sub-grid scale processes, so restricts emergent behaviour in the model and also the response of highly localised phenomena such as extreme rainfall.

The major uncertainty affecting the global response of climate is climate sensitivity, which is measured as the mean annual temperature response of the model to a given unit of radiative forcing. Estimates from the IPCC of sensitivity for double preindustrial CO_2 at climate equilibrium of 1.5–4.5°C remained constant from 1990 through to the Third Assessment Report (IPCC, 2001). Recent estimates of sensitivity have varied a great deal from these estimates, because a number of probability distribution functions for sensitivity have been published (Dessai and Hulme, 2003). These estimates are based on explorations of input model parameters in uncertainty space; palaeoclimatic change, especially following the last ice-age and; 20th century increases in temperature. New estimates resulted in an increase in the range beyond 1.5–4.5°C, although estimates surrounding the lower limit have become better constrained, and sensitivities <1.5°C are though to be unlikely. The estimated median sensitivity is slightly higher than the earlier 2.5 or 2.6°C, and now estimated to be around 3°C for a doubling of atmospheric CO_2 (Kerr, 2004). If reference emissions are high, then a climate sensitivity of this magnitude will result in significant climate risks.

Climate change beyond 1990 is additional to historical increases in temperature and sea level rise. Over the 20th century, average air temperatures at the Earth's surface increased by approximately 0.6°C (IPCC, 2001; Figure 2.2). The 1990s were the warmest decade since the beginning of instrumental records. These temperature increases have also influenced the global hydrological cycle. Precipitation in the northern hemisphere increased 5–10% over the 20th century, with most of this increase manifesting as extreme rainfall events (IPCC, 2001a).

In Australia, average temperatures have increased by about 0.7°C since 1910. Precipitation has also changed in some regions but this is difficult to attribute in full or even part, to global warming. In Western Australia and along Australia's east coast, rainfall has declined steadily since the mid-20th century, while it has increased in the northwest (Pittock, 2003). Extreme rainfall events have also increased in many areas, particularly during winter.

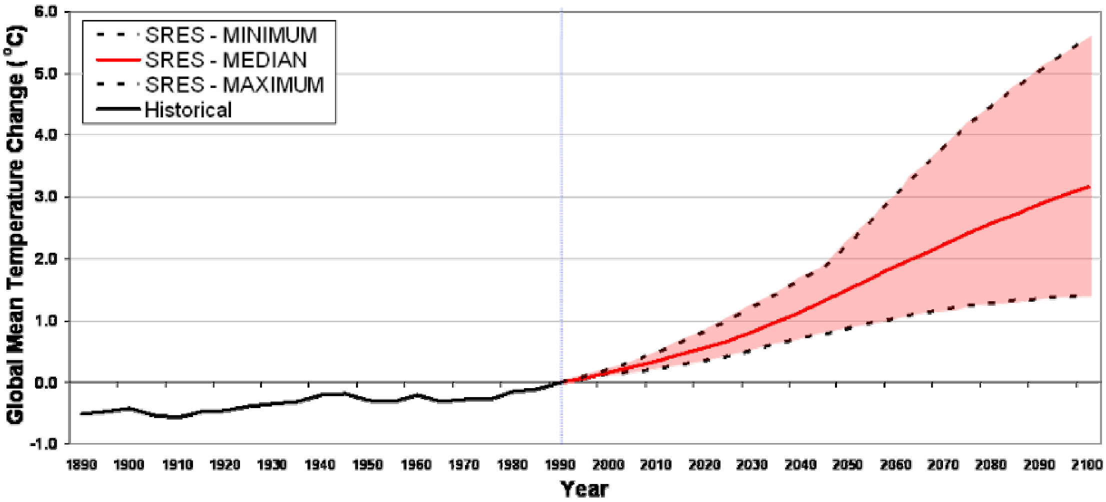

Figure 2.2 Projections of 21st century temperature increases (relative to 1990) from the MAGICC (v.4.2) simple climate model tuned to seven different global climate models with climate sensitivities ranging from 1.7–4.2°C. The lower and upper bounds represent the minimum warming resulting from the SRES B1 scenario and the maximum warming from the SRES A1C scenario, respectively, for the seven climate models. The median estimate is based on the median emissions scenario of the SRES set. Historical temperature anomalies are based upon a 5-year moving average of the NASA Goddard Institute for Space Studies analysis, normalised to 1990.

Without significant mitigation efforts, global mean temperatures are likely to increase by 1.4–5.8°C above 1990 levels by 2100 (Figure 2.2), accompanied by an increase in sea level of 8–88cm. These projections are in addition to the approximate 0.6°C of warming and 10–20 cm of sea-level rise that occurred over the 20th century. Unchecked, global warming will not cease in 2100, but continue into subsequent centuries. All projected changes in climate referred to in this report, such as changes in temperature, are relative to 1990 unless otherwise stated.

2.2.3 Regional climate change

Regional changes in mean climate are constructed from a range of climate models run with a consistent set of emission scenarios. For Australia, GCM runs submitted to the IPCC are downloaded and checked for how they perform in simulating the mean climate from 1961–1990. Those passing a subjective assessment of a "reasonable" reproduction of climate are then used to construct ranges of change for variables such as temperature and rainfall (McInnes et al., 2005).

Over most of Australia, annual average temperatures are projected to increase by 0.4–2.0°C from 1990 levels by the year 2030 and by 1–6°C by 2070 (Figure 2.3, CSIRO, 2001) Inland areas are likely to warm faster than the global average, while coastal areas and the tropics will warm at around the global average. The average number of days over 35°C may rise 10–100% by 2030 while the average number of days below 0°C may fall 20–80%. Annual average rainfall may decrease in the southwest and in the southeast. In other areas, including parts of eastern Australia, projected rainfall changes are uncertain. Where average rainfall increases, there is likely to be more extremely wet years, and where average rainfall decreases more droughts are anticipated.

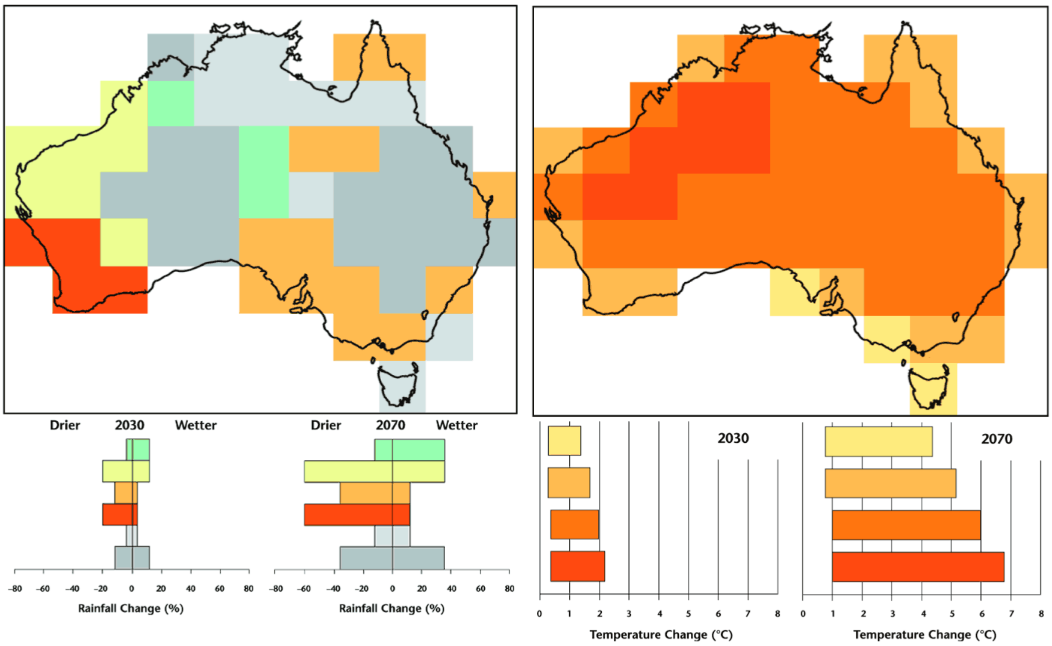

Figure 2.3 Spatial distribution of projected changes in Australian precipitation (left) and temperature (right) in 2030 and 2070 (CSIRO, 2001).

For a range of more detailed and recent state and regional reports, readers are directed to the following website: http://www.cmar.csiro.au/climatesearch/.

2.2.4 Impact assessments

The IPCC carries out the major global assessment every five years or so, which provides the most authoritative information on climate change impacts (IPCCb, 2001). The key conclusions from the Third Assessment Report include the statements *natural systems are vulnerable to climate change, and some will be irreversibly damaged*, *many human systems are sensitive to climate change, and some are vulnerable*, and *the potential for large-scale and possibly irreversible impacts poses risks that have yet to be reliably quantified*. One of the key outputs of that report was the five major reasons for concern shown in graphic form. These provide a subjective assessment of vulnerability of major systems to climate change, summarised from the many studies described in the report (Figure 2.4).

The key output is the relationship between vulnerability and global warming, where vulnerability increases with climate change, where global warming is used as a proxy for climate change. Although the relationship between impacts is more complex than this when looked at more closely the broad relationship between the magnitude of climate change and vulnerability is robust.

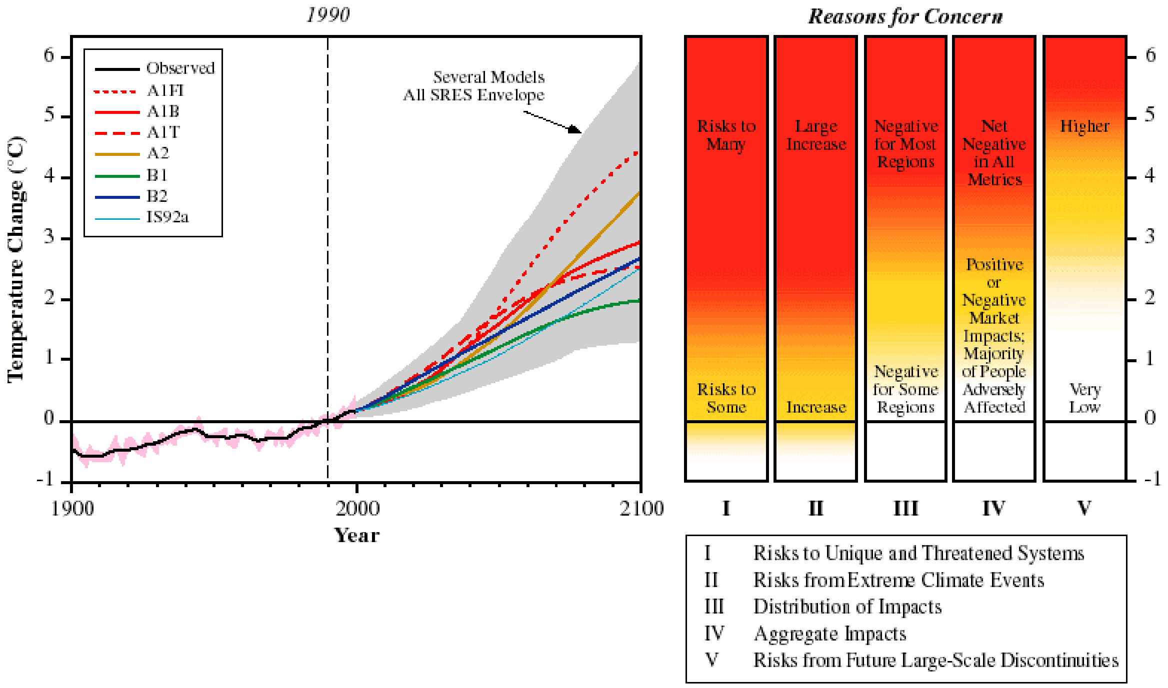

Figure 2.4 Reasons for concern about projected climate change impacts. The risks of adverse impacts from climate change increase with the magnitude of climate change. The left part of the figure displays the observed temperature increase relative to 1990 and the range of projected temperature increase after 1990 (IPCC, 2001c). The right panel displays conceptualizations of five reasons for concern regarding climate change risks evolving through 2100. White indicates neutral or small negative or positive impacts or risks, yellow indicates negative impacts for some systems or low risks, and red means negative impacts or risks that are more widespread and/or greater in magnitude. The assessment of impacts or risks takes into account only the magnitude of change and not the rate of change. Global mean annual temperature change is used in the figure as a proxy for the magnitude of climate change, but projected impacts will be a function of, among other factors, the magnitude and rate of global and regional changes in mean climate, climate variability and extreme climate phenomena, social and economic conditions, and adaptation.

The next section describes a range of Australian and global scale impacts described as a function of global warming, either with the level of vulnerability described or in a biophysical measure which is commonly linked to aspects of vulnerability. The degree to which different impacts can be linked directly to global warming as a proxy for climate change varies. Impacts such as snowfall, coral bleaching, most bioclimatic envelopes (but not necessarily risks to the species concerned), heat and cold stress-related impacts all are closely related to warming. Impacts to crops, pastures and forests are affected more by higher CO_2 and rainfall change than temperature change. Water resources are mostly affected by rainfall change and very little by warming, except for water demand. A number of impacts are affected by changes in extreme events. They include storm damage, flooding, climate-driven disease outbreaks and drought. In some situations, climate variables may interact, where the magnitude of change in one variable affects the response of the system to the other. For example, the impacts associated with a large temperature increases may be quite high if precipitation declines, but more modest if precipitation keeps pace with temperature. Thus, in communicating the risks of climate change, it is important to acknowledge these complex interactions.

2.3 Climate change and Australian impacts

Over the next century and beyond, climate change will result in a broad range of consequences for Australia (Pittock, 2003). Some of these impacts will be large, others small, and some surprises will likely occur. In assessing the impacts of climate change, one can refer to a system's *vulnerability* to climate, meaning a system's ability to experience adverse consequences from climate change. For example, the range of climate conditions that different systems can cope with before experiencing adverse effects varies significantly. Coral reef ecosystems are already experiencing adverse affects due to historical warming (Wilkinson, 2000). In contrast, economic studies of Australian agriculture suggest economic benefits may occur for warming as high as 3–4°C, given sufficient rainfall (Howden and Jones, 2001). A major factor affecting a system's vulnerability is the availability of mechanisms to manage or adjust to change, also referred to as *adaptive capacity*. Recent studies have indicated that corals may acclimatise to warming by 0–1.5°C, depending on location allowing them to expand their coping range over time, thus reducing their vulnerability to future temperature anomalies (Berkelmans and van Oppen, 2006). Agriculture has a relatively high adaptive capacity and has the potential to turn negative impacts positive. Limited adaptive capacity among populations or nations with financial, education, and technological constraints largely account for the regional variability in vulnerability to current climate conditions, as well as future climate change.

This section summarizes a range of climate change impacts, divided into five core sectors: natural ecosystems; crop agriculture, forestry, and livestock; water resources; public health; and human settlements and infrastructure. The general factors that affect the vulnerability of these sectors are discussed. This is followed by a summary of results from impact assessments specific to Australia, presented as a gradient over a range of 21st century temperature changes from ~1°C to 5°C. Two types of extreme events are discussed further: the potential for climate extremes and large-scale singularities.

2.3.1 Natural ecosystems

Natural ecosystems are considered vulnerable to climate change because of their sensitivity to climate change combined with human dominance of ecological processes at the global scale (Thomas et al., 2004). Patterns of temperature and precipitation are key factors affecting the distribution and abundance of species, and are used to describe the climatic envelope of each species or community. The climatic envelope in which most of a specie's population is found is termed core habitat; impact modelling of climate change assesses how climatically-defined core habitat may change. How this translates into risk to most species is unknown, therefore ecological assessment requires that a precautionary approach be taken to prevent irreversible consequences such as extinction.

Projected changes in climate will have diverse ecological implications (IPCC, 2002). Habitat for some species will expand, contract, and/or shift with the changing climate, resulting in habitat losses or gains, which could prove challenging, particularly for species that are already threatened or endangered. Species within ecosystems have an inherent capacity (behavioural, physiological, and genetic) to cope with some degree of climate variability, provided variability is maintained within a certain range. Yet this coping range can be relatively narrow for many species, and may be exceeded by short-term changes in climate extremes or long-term changes in average climate conditions. Recent studies indicate that globally, natural ecosystems are already responding to climate change (Parmesan and Yohe, 2003; Hughes, 2003). For some species, these responses appear to part of coping strategies, for others adverse effects including localized population extinctions have been observed (Parmesan and Galbraith, 2004). Both increases in atmospheric CO_2 influencing vegetation responses and animal-plant interactions, and invasive species dynamics will also change under climate change, but the nature of such changes remains unclear.

The two major types of response of individual species and ecosystems to climate change can be grouped under acclimatisation and adaptation. Acclimatisation covers generally more short-term responses to environmental change that include behavioural change, change in growth and response rates to factors such as temperature and rainfall and, in the case of communities, shift in population balances. For example, in the past many weeds and pests have acclimatised to climatic conditions different to those in their original habitat, and such responses may be available to some species if climate changes. However, this is more likely for generalist species that have a broad genetic variation, than for specialist species with a limited genetic range.

Biological adaptation is a slower, evolutionary process that involves change at the genetic level over generations in response to environmental change. The evolutionary capacity of species and ecosystems is an intergenerational, much slower process than acclimatisation. Adaptation by humans includes protection, better integration with other activities (e.g. agriculture), relocation, captive breeding and long-term storage of genetic material. Adaptation for all unmanaged systems is thought to be prohibitively expensive, hence the requirement of the UNFCCC for emissions to be maintained at a level that would allow ecosystems to adapt naturally to climate change. For more sensitive ecosystems, such as coral reefs, this level of "dangerous anthropogenic interference" may already have been breached.

Therefore, for natural ecosystems, adaptive capacity includes acclimatisation, the genetic capacity of species to evolve in response to a changing environment, the capacity for ecological communities to evolve in response to a changing environment and the ability of humans to respond through management actions.

A number of Australia's ecosystems are vulnerable to changes in temperature and precipitation and thus significant adverse consequences from climate change are projected, even for relatively small shifts in climate conditions (Pittock, 2003). The Great Barrier Reef, a UNESCO World Heritage area, is particularly vulnerable to climate change, given the narrow coping range and limited adaptive capacity of corals. Historically unprecedented rates of bleaching have occurred over the past two decades and considerable losses or contractions of species associated with coral communities are projected for a further warming of only 1°C (Table 2.2). Similarly, high altitude montane ecosystems are sensitive to climate change-induced reductions in winter snow cover, and the highland rainforests of northern Australia are projected to decrease by 50% for just a 1°C increase in temperature. Given higher magnitudes of warming, adverse effects for certain groups of species are expected to become progressively worse. Annual damage to the Great Barrier Reef increases to the point of catastrophic failure, snow cover and duration decreases substantially, and species from vertebrate and invertebrate communities in northern and southeast Australia are under threat of extinction.

Table 2.2. *Projected Impacts to Australian Ecosystems (Adapted from Preston and Jones, 2006; note 'core habitat' refers to climatically defined habitat)*

ΔT (°C)	Projected Impact
<1	10–40% shrinkage of snow-covered area in the Australian Alps[1]
	18–60% decline in 60-day snow cover in the Australian Alps[1]
	Bleaching and damage to the Great Barrier Reef equivalent to 1998 and 2002 in up to 50% of years[2]
	60% of the Great Barrier Reef is regularly bleached[3]
	Habitat is lost for 14% of Victoria's marine invertebrates[4]
	50% decrease in habitat for vertebrates in northern Australia tropics[5,6]
	<5% loss of core habitat for Victorian and montane tropical vertebrate species[5,7]
	28% of Dryandra species' core habitat is significantly reduced in SW Australia[8]
	4% of Acacia species' core habitat is significantly reduced in SW Australia[8]
	63% decrease in Golden Bowerbird habitat in N Australia[9]
	Habitat for 3 frog and 15 threatened/endangered mammals in W Australia is lost or restricted[8]
	50% decrease in montane tropical rainforest area in N Australia[10]
1–2	Up to 58–81% of the Great Barrier Reef is bleached every year[2]
	Hard coral reef communities are widely replaced by algal communities[11]
	90% decrease in core habitat for vertebrates in northern Australia tropics[5,6]
	5–10% loss of core habitat for Victorian and montane tropical vertebrate species[5,7]
	88% of butterfly species' core habitat decreases[12]
	66% of core habitat for Dryandra species is significantly reduced in SW Australia[8]
	100% of core habitat for 40 Acacia species tested eliminated in SW Australia[8]
2–3	97% of the Great Barrier Reef is bleached every year[3]
	10–40% loss of core habitat for Victoria and montane tropical vertebrate species[5,7]
	92% of butterfly species' core habitat decreases[12]
	98% decrease in Bowerbird habitat in N Australia[9]
	80% loss of freshwater wetlands in Kakadu (30 cm sea level rise)[13]
3–4	Catastrophic mortality of coral species annually[2,3]
	95% decrease in distribution of Great Barrier Reef species[3]
	65% loss of Great Barrier Reef species in the Cairns region[14]
	20–85% shrinkage of total snow-covered area in the Australian Alps[1]
	38–96% decline in 60-day snow cover in the Australian Alps[1]
	30–70% loss of core habitat for Victoria and montane tropical vertebrate species[5,7]
4–5	60–90% loss of core habitat for Victoria and montane tropical vertebrate species[5,7]
>5	90–100% of core habitat lost for most endemic Australian vertebrates[5,7]
References	[1]Hennessy et al., 2003 [2]Berkelmans et al., 2004 [3]Jones, 2004b [4]O'Hara, 2002 [5]Williams et al., 2003 [6]Williams and Hilbert, 2004 [7]Brereton et al., 2005 [8]Pouliquen-Young & Newman, 2000 [9]Hilbert et al., 2004 [10]Hilbert et al., 2001 [11]Wooldridge et al., 2005 [12]Beaumont & Hughes, 2002 [13]Hare, 2003 [14]Crimp et al., 2004

2.3.2 Cropping, forestry, and livestock

The cropping, forestry, and livestock sectors are influenced by changes in climatic conditions and also by increases in atmospheric CO_2 (Howden et al., 2003). The productivity of crop agriculture and forestry is dependent upon temperatures, the length of the growing season, available soil moisture, atmospheric CO_2 and climate extremes such as droughts and storms. Livestock are sensitive to temperature, water availability and access to food. Intensive management of these sectors can reduce their vulnerability to climate relative to extensive production ecosystems, but failure can be much more expensive if critical thresholds are exceeded in such systems. Over time, people have expanded the coping range of agriculture and livestock by breeding high-yielding strains tolerant of a wider range of climate conditions. Resource-intensive practices such as irrigation and pest control further expand the resilience of these sectors to climate conditions. Nevertheless, climate extremes are still capable of inflicting substantial damages on agriculture, forestry, and livestock. For example, prolonged droughts reduce agricultural productivity, while wildfires can significantly affect forestry operations.

Climate change will pose mixed consequences for Australian agriculture, forestry, and livestock, depending upon interactions between temperature, precipitation and the response of vegetation to the so-called "CO_2 fertilization" effect. Given sufficient increases in precipitation, wheat yields are projected to increase for warming of up to at least 3–4°C (Table 2.3). Under less favourable precipitation scenarios such increases in productivity may not be realized. Large reductions in precipitation and increases in drought could severely impact agriculture, especially rangeland grazing. In addition, despite domestic increases in wheat productivity, exports are projected to decline due to increased demand (Howden and Jones, 2001). Agricultural pests, such as the Queensland fruit fly and cattle ticks are also projected to increase. Warmer temperatures will increase the total pest load, affecting net changes in economic welfare; although some temperate pests, such as the light brown apple moth, may decrease.

Net timber production is also tied to precipitation – increased precipitation results in increased yield, while decreased precipitation results in decreased yields (Table 2.3). Impacts to the timber industry also vary with the type of timber and geographic location. For example, warming of just 1°C has been projected to exceed the core habitat of 25% of *Eucalyptus* species, though these are likely to be less commercial species of limited geographical extent. Despite this, most tree species will grow in a larger bioclimatic envelope than realised in their natural habitat, but whether they would regenerate after disturbance remains unknown. For higher magnitudes of warming, lowered productivity is projected for "average" forestry production in northern Australia, while southern Australia forest productivity increases. However, studies that explicitly factor in fire and drought have not yet been carried out.

Temperature increases will stress livestock, leading to reductions in milk production even for warming of just 1°C (Table 2.3). Decreases in precipitation will lower the quality of pasture land, resulting in reduced productivity of pasture land for grazing livestock. Meanwhile, like crop agriculture, pests such as ticks may reduce cattle productivity.

The adaptive capacity of most Australian agriculture and forestry is high, and will change with ongoing research, development and management innovations, therefore the impacts are not just a product of climate but are dependent on the development pathway undertaken. Impacts on international trade will also be a factor. This, and the dependency of agricultural impacts on the direction of rainfall change mean that the relationship between global warming and impacts is not as direct as it is for some other sectors. However, the net impacts may be positive or negative at low temperatures without adaptation but will become increasingly negative as temperature increases. The potential net effect of adaptation across activities and whole sectors remains unknown but may be considerable.

Table 2.3. *Projected impacts to Australian Agriculture, Forestry, Livestock (Adapted from Preston and Jones, 2006)*

ΔT (°C)	Projected Impact		
<1	$4.4 million/year to manage with southward spread of Queensland fruit fly[1]		
	$1.1 million/year benefit with contraction in range of Light brown apple moth[2]		
	Increase in "generic" timber yields (under wet scenarios) [3]		
	Decrease in "generic" timber yields (under dry scenarios)[3]		
	25% of core habitat lost for total Eucalyptus species numbers [4]		
	250–310 litre annual decline in milk production per cow in Hunter Valley[5]		
	8% reduction in pasture growth (11% precipitation decrease)[6]		
	13% reduction in livestock carrying capacity (11% precipitation decrease)[6]		
1–2	12% chance of decreased wheat production (without adaptation) [7]		
	32% chance of wheat crop value below current level (without adaptation)[7]		
	91% chance of wheat exports being below current level (without adaptation)[7]		
	$12.4 million/year to manage with southward spread of Queensland fruit fly[1]		
	$5.7 million/year benefit due to reduction of Light brown apple moth[2]		
	40% of core habitat lost for total Eucalyptus species numbers[4]		
	38% increase in tick-related losses in net cattle production weight [8]		
2–3	31% reduction in pasture growth (32% precipitation decrease)[6]		
	40% reduction in livestock carrying capacity of pastures (for 32% precipitation decrease) [6]		
3–4	32% chance of decreased wheat production (without adaptation)[7]		
	45% chance of wheat crop value being below current level (without adaptation)[7]		
	55% of core habitat lost for total Eucalyptus species numbers [4]		
	25-50% increase in "generic" timber yield in S Australia[3]		
	25-50% decrease in "generic" timber yield in N Queensland and Top End[3]		
	6% decline in Australian net primary production (20% precipitation decrease)[6]		
	128% increase in tick-related losses in net cattle production weight [8]		
References	[1]Sutherst et al., 2000	[4]Hughes et al., 1996	[7]Howden and Jones, 2001
	[2]Sutherst, 2000	[5]Jones and Hennessy 2000	[8]White et al., 2003
	[3]Kirschbaum, 1999	[6]Crimp et al., 2002	

2.3.3 Water resources

Water resources are increasingly a core issue for both the developed and, particularly the developing world due to limited resources and a growing global population. Water resources supply a broad range of goods and services, including drinking water, waste management, hydroelectric generation, irrigation, recreation and tourism opportunities, and habitat for wildlife. Past experience in Australia shows that climate variability and change has a powerful influence on water management. Extreme events are a particular challenge. For example, prolonged droughts reduce water availability, and periodic extreme rainfall events, can produce extensive run-off, increasing flood risk. Patterns of the El Niño–Southern Oscillation affecting Australia mean that the incidence of floods following droughts is higher than just a random pattern may suggest.

Australia is currently facing extensive water management challenges, particularly in the southwest, where current precipitation, run-off, and stream flows have dropped to levels well below long-term average. Water storages are currently well below capacity throughout much of West and South Australia, Victoria, and Queensland. These pressures are indicative of their general high vulnerability to further climatic change.

Projected climate change impacts on water resources are highly dependent upon the magnitude and direction of changes in rainfall regimes during the time of year when storages are generally filling. However, CSIRO projections generally indicate rainfall, particularly in winter, may decrease substantially in Victoria, S Australia, and W Australia over the 21st century. Changes are more uncertain for other regions, where water resources could either increase or decrease.

Until recently, impact studies have only been carried out on a catchment by catchment basis. For example, inflows to reservoirs in the Macquarie River catchment, NSW have been projected to decrease by up to 15% for just a 1°C increase in temperature (Table 2.4). However, a recently developed simple model that provides first order estimates of percentage change in average annual runoff has been developed and used to generate estimates for broader regions. Median estimates of change for 2030 (~ 1°C warming) for Australia are shown in Figure 2.5 along with the variation in estimates from eleven different climate models. These estimates need to be updated with the newer IPCC models to reflect improvements in model estimates of rainfall change but show that decreases dominate over much of Australia. A similar study for Victoria produced only negative changes over most of the state except for far eastern Gippsland (Jones and Durack, 2005). Changes such as those shown in Figure 2.5 will grow in magnitude with higher warming (Table 2.4).

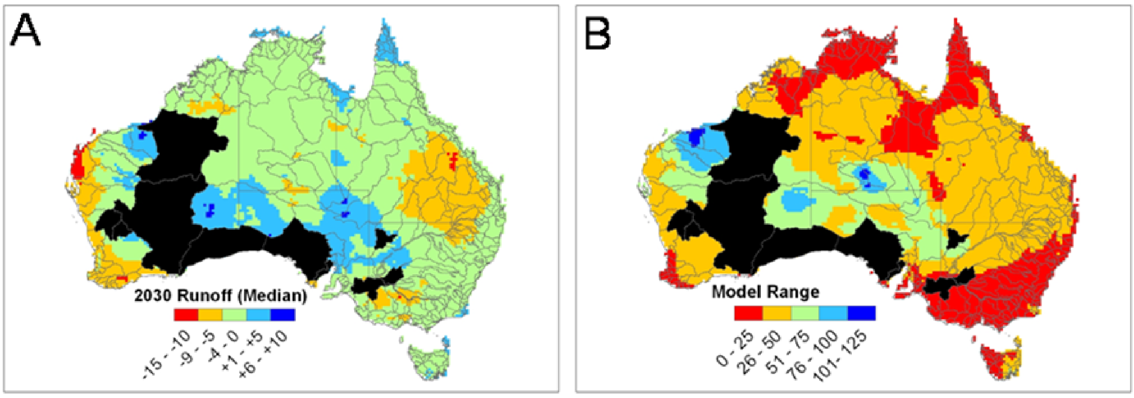

Figure 2.5. Estimated changes in Australian runoff in 2030 based upon application of a simple hydrological model. A) Median estimates based upon a series of 66 simulations using 11 different climate models, three different emissions scenarios, with both low and high climate sensitivities. 5th and 95th percentiles were calculated from the mean and standard deviations assuming the data were normally distributed. B) Range between minimum and maximum result for the 66 simulations. Catchments in black represent those with zero recorded runoff.

Projected decreases in runoff coincide with many of Australia's major cities and irrigation areas including the Murray Darling Basin. These will decreases will coincide with increases in water demand, and therefore will need to be adapted to. Although the adaptive capacity of water management bodies is generally high, increased competition for water including higher standards for environmental flows and the need to maintain water quality will increase adaptation needs as water becomes more scarce. Projected decreases in streamflow also have important ecological implications, by affecting wetlands important for bird breeding as well as other wildlife. For example, critical thresholds for bird breeding in the Macquarie Marshes of New South Wales, projected as having a 30% of exceedance by 2030 if drought-dominated rainfall conditions were present (Jones and Page, 2001) have already been exceeded, after ten years without a significant breeding event.

Table 2.4. *Projected impacts to Australian Water Resources (Adapted from Preston and Jones, 2006)*

ΔT (°C)	Projected Impact		
<1	0–15% likely decrease in flow to Burrendong Dam and Macquarie Marshes in Macquarie River Basin (NSW)[1,2]		
	3–11% decrease in Melbourne's water supply[3]		
1–2	0–25% decrease in flow in the Murray Darling Basin[4,5]		
	7–35% decrease in Melbourne's water supply[3]		
	5–30% decrease in southwest Western Australia[5]		
2–3	5–35% likely decrease in flow to Burrendong Dam and Macquarie Marshes in Macquarie River Basin (NSW)[2]		
3–4	50% chance critical bird breeding threshold exceeded in Macquarie Marshes[2]		
	16–48% decrease in flow in the Murray Darling Basin[4]		
References	[1]Hassall & Associates, 1998	[3]CSIRO & Melbourne Water, 2005	[5]Jones, pers. comm.
	[2]Jones & Page, 2001	[4]Beare and Heaney, 2002	

2.3.4 Public health

Assessing the implications of climate change for public health is challenging because of complex interactions among climate, the environment, and socioeconomic factors. The direct effects of climate change include the potential for increases in temperature to increase heat-related, and reduce cold-related, illness and death (McMichael et al., 2003). The former largely occurs in extreme heat events, such as that associated with the 2003 mass casualty event in Europe (Schär et al., 2004). Increases in winter temperatures may reduce illness and mortality, but it is unclear the extent to which seasonal patterns of infectious disease are in fact temperature dependent, and thus how much higher temperatures may alleviate cold-weather illness and mortality. Other extreme weather events such as severe storms, wind, and flooding directly cause injury and death.

In addition to the direct health effects of climate, there are a range of indirect consequences. Higher temperatures have been linked with higher levels of tropospheric ozone, particularly in urban areas, which can induce respiratory and cardiovascular illness and death. The risk of vector borne disease is influenced by climate, due to the effects of temperature and precipitation on disease vectors in the environment (e.g., mosquitoes, ticks). Temperature and precipitation extremes have also been associated with increases in food and water-borne illness (McMichael et al., 2003).

Due to its relatively high adaptive capacity, the vulnerability of Australia's population to the health impacts of climate change is relatively low, although some demographic groups, such as Australia's aboriginal population, are much more vulnerable because of limited access to financial and public health resources. Increases in temperature combined with population growth may result in an increase in heat-related deaths over the next century after adjusting for decreases in cold- and ozone-related mortality (Table 2.5). Climate change could cause large increases in flooding deaths and injuries, depending upon future changes in precipitation extremes. Climate change could cause the range of mosquito vectors for dengue and malaria to expand southward. However, public health interventions targeting malaria during the 1960s have largely eliminated the risk of transmission and reintroduction of the disease is unlikely. In contrast, the transmission of dengue continues in Australia, although cases are largely confined to northern Queensland. Proper public health interventions may prevent substantive increases in dengue transmission. Some studies have also suggested that climate change could increase transmission of Ross River virus in regions of Australia, but less is known about the epidemiology of this disease. Climate change could increase the risk of food and water-borne illnesses, yet again these can be addressed through appropriate infrastructure management and food handling.

Table 2.5. *Projected Impacts to Australian Public Health*

ΔT (°C)	Projected Impact	
<1	1185–1385 more deaths in 65-year age group in temperate Australian cities[1]	
	4–12 more deaths in 65-year age group in N tropical cities[1]	
	No increase in population at risk of dengue[1]	
1–2	Southward spread of malaria receptive zones[1]	
	Population at risk of dengue increases from 0.17 million to 0.75–1.6 million[1]	
	10% increase in diarrhoeal diseases among Aboriginal children in central Australia[1]	
	100% increase in number of people exposed to flooding in Australia and New Zealand[1]	
	Increased influx of refugees from Pacific Islands[1]	
2–3	Further southward spread of malaria receptive zones[1]	
	Temperature related mortality among people 65+ years in Australian capital cities increases by 89–123%[1]	
	Southward expansion of dengue transmission zone as far as Mackay[1]	
3-4	Temperature related mortality among people 65+ years in Australian capital cities increases by 144–200% Based on data from 1	
	Southward expansion of dengue transmission zone as far as Brisbane[2]	
References	[1]McMichael et al., 2003	[2]Hales et al. (2003)

2.3.5 Settlements and infrastructure

Aspects of human settlements that have been assessed for climate impacts include energy, the built environment of the coastal zone, transportation, and recreation/tourism. Human settlements, particularly those in developed countries, tend to have a fairly broad coping capacity and are generally resilient to daily and seasonal variability in the climate system. Thus, a particular concern for settlements is the potential for changes in the frequency of climate extremes (see below) – more frequent heat waves, more frequent or intense storm events including hail storms, more frequent floods. All of these may require adaptive responses, although their implications for communities have in many cases not yet been quantified. This is largely because future extreme climate events are difficult to model, and also because the impacts on people, buildings and infrastructure require a great deal of data.

Australia's settlements are moderately vulnerable to climate change, largely due to the potential impacts posed by extremes of temperature and precipitation, and their proximity to the coast. Australia's energy sector may be one of the first components of Australian settlements to respond to climate changes. Impact assessments indicate that just a 1°C increase in average temperatures would be sufficient to increase peak demand in Adelaide and Brisbane, and reduce transmission efficiency (Table 2.6). Yet, these increases may be offset by initial decreases in electricity demand in Melbourne and Sydney and reduced demand for natural gas in Melbourne. For higher levels of warming, electricity demand in Brisbane, Melbourne, and Adelaide increases, while demand in Sydney remains at slightly lower levels than present. Temperature increases of 2–3°C are projected to increase maintenance costs for transportation infrastructure.

Australia's coastal zone is of particular concern, due to its thousands of kilometres of coastline and the concentration of most of Australia's population, commerce, and industry in the coastal zone. Climate modelling has suggested that storm winds, including those associated with tropical cyclones, may become more intense with a warming of 1–2°C (Table 2.6). Combined with sea-level rise, this would result in higher storm surges on both temperate and tropical coastlines and a greater area flooded. Higher wind speeds would also increase storm damages to buildings disproportionately because of the highly non-linear relationship between peak wind speed and damage. Sea-level rise and storm events also contribute to coastal inundation and beach erosion, which may affect popular tourism and recreation areas. At higher levels of warming, coastal impacts become more severe with higher storm winds and sea levels.

Table 2.6. *Projected impacts to Australian Settlements*

ΔT (°C)	Projected Impact		
<1	3% decreases in thermal efficiency of electricity transmission infrastructure[1]		
	Decrease in demand for natural gas for heating in Melbourne[2]		
	Peak electricity demand in Melbourne and Sydney decreases up to 1%[3]		
	Peak electricity demand in Adelaide and Brisbane increases 2–5%[3]		
1–2	100 year storm surge height around Cairns increases 22%; area flooded doubles[4]		
	Peak electricity demand in Melbourne and Sydney decreases 1%[3]		
	Peak electricity demand in Adelaide and Brisbane increases 4–10%[3]		
2–3	17% increase in road maintenance costs over most of Australia[5]		
	Decreases in road maintenance costs in S Australia[5]		
	Peak electricity demand in Adelaide, Brisbane and Melbourne increases 3–15%[3]		
	Peak electricity demand in Sydney decreases 1%[3]		
3–4	Oceania experiences net loss of GDP[6]		
	Peak electricity demand in Adelaide, Brisbane and Melbourne increases 5–20%[3]		
	Peak electricity demand in Sydney decreases 1%[3]		
4–5	Peak electricity demand in Adelaide, Brisbane and Melbourne increases 9–25%[3]		
	Peak electricity demand in Sydney decreases 0.5%[3]		
>5	Peak electricity demand in Sydney decreases 0%[3]		
	Peak electricity demand in Adelaide, Brisbane and Melbourne increases 10–25%[3]		
References	[1]Thomas, 2002	[3]Howden & Crimp, 2001	[5]Austroads, 2004
	[2]Suppiah et al., 2001	[4]McInnes et al., 2003	[6]Mendelsohn & Williams, 2004

2.3.6 Extreme weather events

Extreme weather events are associated with significant impacts across multiple sectors. A large, extreme event can also cause a disaster if the damage is sufficiently severe and widespread. Extreme events tend to inflict large environmental and economic costs, which is exacerbated by the fact that they can be difficult to adequately manage through adaptive processes. Globally, the

World Meteorological Organization has claimed that extreme events are on the rise as a result of anthropogenic perturbation of the climate system (WMO, 2003), and climate models indicate the potential for increases in extremes of temperature, precipitation, droughts, storms, and floods (Hulme and Mearns, 2001).

Climate studies from Australia indicate that for a warming of just 1°C, both drought and extreme rainfall in NSW increase substantially (Table 2.7). Extreme rainfall increases in Victoria as do the number of days experiencing temperatures above 35°C in South Australia and the Northern Territory. For higher magnitudes of warming, cyclone wind speeds, rainfall, and storm surges become more intense (see also Settlements and Infrastructure, above), and increases in fire risk are also projected. These increases in Australian extremes must also be considered in the context of changes in Australia's socioeconomic context. Steady growth in Australia's population combined with the concentration of Australia's population within 50 km of the coast has exposed greater numbers of people, wealth and infrastructure to extreme weather events. These socioeconomic trends are projected to continue for at least the next half century, and thus Australia's vulnerability to extreme events will continue to increase.

Table 2.7. *Climate Change and Extreme Weather Events*

ΔT (°C)	Projected Impact
<1	-35 to 70% change in droughts in New South Wales[1]
	10–20% increase in the intensity of extreme daily rainfall in New South Wales[1]
	18% increase in annual days above 35°C in South Australia[2]
	25% increase in annual days above 35°C in Northern Territory[3]
	6% decrease in extreme daily rainfall in Victoria[4]
1-2	100 year storm surge height around Cairns increases 22%; area flooded doubles[5]
	25% increase in 100-year storm tides along eastern Victoria coast[6]
2–3	5–10% increase in tropical cyclone wind speeds[5]
	20–30% increase in tropical cyclone rainfall[5]
	12–16% increase in 100-year storm tides along eastern Victoria's coast[6]
	10% increase in forest fire danger index in N, SW, and W Australia[7,8]
	More than 10% increase in forest fire danger index in S, central, and NE Australia[7,8]
>5	30% increase in 100-year storm tides along eastern Victoria coast[6]
	25% increase in extreme rainfall in Victoria[4]
	173% increase in annual days above 35°C in Northern Territory[3]
	150% increase in annual days above 35°C in South Australia[2]
References	[1]Hennessy et al., 2004a; [2]McInnes et al., 2002; [3]Hennessy et al., 2004b; [4]Suppiah et al., 2004; [5]McInnes et al., 2003; [6]McInnes et al., 2005; [7]Williams et al., 2001; [8]Cary, 2002

2.3.7 Large-scale singularities

Large-scale singularities, are complex non-linear responses where systems switch from one state to another. They are implicated in a range of potential direct and indirect consequences to many regions of the world, including Australia. Historical and palaeological data provide ample evidence that singularities and abrupt changes in the climate system have occurred repeatedly in the past. Perhaps the singularity of most immediate relevance to Australia is the collapse (regional or even global) of coral reef ecosystems, which appear to change quite rapidly (i.e., over a narrow temperature range) from being healthy to being stressed, bleached, or eliminated (Done et al., 2003). Ecosystem changes further afield may also ultimately have affects on climate change in Australia. For example, carbon cycle modelling as suggested that forest dieback in tropical regions could ultimately transform the terrestrial biosphere from a sink for carbon to a source – increasing the net concentration of CO_2 in the atmosphere (e.g. Cox et al., 2004).

Scientists have expressed concern about the potential for climate change to destabilize the large ice sheets of Greenland and West Antarctica. Global warming as well as the melting of glaciers and ice sheets (which increases the flux of freshwater to the oceans), could destabilize the global ocean thermohaline circulation (THC). Such destabilisation could slow its circulation, potentially to the point of complete collapse, causing regional climate shifts with significant environmental and economic consequences. Melting of glaciers and ice sheets also contributes to sea-level rise. Vast quantities of ice are locked away in the ice sheets of West Antarctica and Greenland, collectively equivalent to approximately 12 meters of sea-level rise. Destabilisation or collapse of these ice sheets would lead to centuries of irreversible sea-level rise and coastal inundation around the world.

Palaeological data indicate that abrupt climate shifts have occurred in the past as a result of catastrophic release of GHGs, primarily methane, from methane hydrates in the ocean's sediments. There has been some investigation of the causes of this release, and speculation regarding the potential for anthropogenic climate change to once again destabilize this reservoir, resulting in a large-scale release of methane.

Although such singularities are potential consequences of a changing climate, the probability of specific events and the time scales over which they would occur (or even whether they would occur at all) is quite uncertain. Yet, the consequences of such events, should they occur, would be large and global. As such, much of the interest in defining DAI under the UNFCCC's Article II has emphasized the importance of mitigating GHG emissions to ensure such singularities are avoided. However, the climate thresholds for some of these singularities may be quite low. For example, Hansen (2005) recently suggested that the threshold for an irreversible loss of the Greenland ice sheet may be as low as 1°C. We quantify estimates for a few singularities in the next section.

2.4 Quantifying key damages

In this section, we construct damage relationships for four large-scale climate impacts: coral reefs, risk of large-scale species extinction, slow-down of the north Atlantic thermohaline circulation and melting of the Greenland Ice-sheet. Each of these relationships has been constructed from estimates of critical thresholds that have been published in the literature. For more detail see Sheehan et al. (2006).

2.4.1 Coral reef systems

Two sets of information were used to project critical damage due to thermal bleaching and mortality to the coral reef communities of the Great Barrier Reef (GBR). Because the model is based on temperature anomalies acting on the world's largest single reef system and one of the healthiest, we assume that extensive damage affecting the GBR will affect most other reef systems world-wide in a similar manner.

The two major aspects to the model involve:

Spatial bleaching risk across the GBR based on bleaching events in 1998 and 2002. Sea surface temperatures (SST) at Magnetic Island an inshore location reached about 1.2°C above the bleaching threshold during these events (Maximum 3-day SST; "*max3day*"). Averaged across the 1988 and 2002 events, bleaching affected approximately 50% of the GBR and moderate to severe bleaching affected 18% (Berkelmans et al., 2004). Based on observations and experiment, moderate to severe bleaching is estimated to occur at ≥0.5°C above the bleaching threshold and widespread mortality to sensitive corals occurs at ≥1°C above the bleaching threshold. A simple regression model based on *max3day* and areal extent of bleaching suggests that 82% of the GBR will bleach at ≥2°C, 97% at ≥3°C and 100% at ≥4°C anomalies above the bleaching threshold, respectively (Berkelmans et al., 2004). This model, because it uses anomalies, allows for the range of bleaching thresholds on the reef that vary from highest to lowest in a north to south direction and inshore to offshore (Berkelmans, 2002).

Temporal bleaching risk expressed as the frequency of events above a given threshold. These were estimated using the ReefClim model (Done et al. 2003; Jones, 2004) to calculate the frequency of bleaching and mortality risks for two sites, Magnetic Island (close to shore) and Davies Reef (outer reef), on the GBR under warming. This model reproduces bleaching events observed between 1990 and 2002 for three sites (Done et al., 2003). Sensitivity analysis of bleaching using an artificially weather-generated record of SST shows that the probability of bleaching threshold exceedance under rising SST at a site is sigmoidal (Jones, 2004).

Both bleaching frequency at a particular site and the spatial extent of bleaching can be expressed as a function of increasing local SST. We combine these two relationships by constructing three critical thresholds based on bleaching and mortality frequency then link them to the spatial extent model data above. The damage function is initialised using bleaching observations (e.g. Berkelmans and Willis, 1999) and models developed for both onshore and offshore sites (Done et al., 2003) and extends to yet to be affected sites. The joint relationship was quantified using a Weibull function.

The critical thresholds are:

CT1. Non-lethal bleaching every second year (p_{ann}=0.5), affecting coral health by reducing spawning rates and resistance to other stresses (e.g. disease). Threshold exceedance is likely to result in low resilience to stress.

CT2. Widespread mortality of sensitive, fast growing corals (e.g. *Acropora*) on a frequency of ≥10 years (p_{ann}=0.1), preventing sufficient time for recovery to a state of ecological viability. The local temperature anomaly is exceeded at bleaching +1°C. Such a reef will have an altered mix of coral species, favouring slow growing species.

CT3. Widespread mortality of tolerant, slow growing species (e.g. *Porites*) on a frequency of ≥25 years (p_{ann}=0.04), allowing sufficient time for the community to recover to a state of ecological viability (note that full cover will not be achieved in this time because critical threshold 2 is being exceeded on a frequency of >10 years making fast growing species unviable). The local temperature is set at bleaching +2°C. A reef in this state will have few, or no, live corals, depending on the viability of recruiting species and frequency of thermal extremes.

Each critical threshold was linked to bleaching and mortality model results for Magnetic Island (close to shore) and Davies Reef (outer reef), averaged between the two. CT1 reaches its 50% threshold at +0.4°C above current warming, CT2 reaches its 10% frequency at +0.5°C and CT3 reaches its 4% frequency at +1.1°C. Note that the 1998 and 2002 events killed sensitive species at some sites (Wooldridge and Done, 2004). By linking each anomaly to the spatial model at its zero point, it was then possible to estimate the extent of the GBR that would be exceeded by each of the critical thresholds for any estimate of local warming. This was converted into estimates of global mean temperature by assuming that SST in the GBR region will rise at 0.8 of the rate of global mean temperature, which approximates the mid-range of the estimates per degree of global mean temperature of 8 models from four modelling groups for the GBR (Done et al., 2003). The bleaching/area relationship is assumed to rise extremely rapidly from zero to 50% (the area affected in 1998 and 2002) because bleaching events were not commonly observed prior to 1980 (Lough, 2001).

The relationship between the three critical thresholds spans ≤1°C, with CT1 and CT2 occurring very close together (Figure 2.6). More than 50% of the reef area is exceeded CT1 and CT2 under <1°C global warming and CT3 by about 1.5°C. Only an estimated 15% of the GBR region is free of critical damage at >2°C.

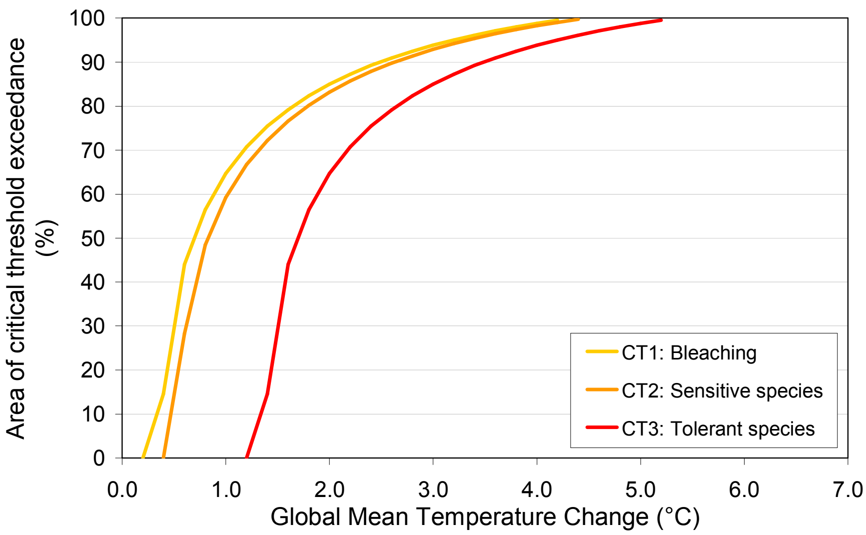

Figure 2.6 Global warming/areal relationships for the exceedance of three Critical Thresholds: CT1: Bleaching in ≥50% of years; CT2: widespread mortality of sensitive coral species in ≥10% of years; CT3: widespread mortality of tolerant coral species in ≥4% of years.

The consequences of substantial or total loss of coral reef ecosystems to Australia has not been looked at in significant detail but is thought to be severe (Crimp et al., 2003; Hoegh-Guldberg and Hoegh-Guldberg, 2003). Based on the costing uncertainties in Table 1.1, this would involve direct and indirect costs to the economy (e.g. fishing, tourism) in addition to substantial existence values and bequest values. Current international tourism value on the Great Barrier Reef is estimated to be between US$700 million and US$1.4 billion with a domestic value of US$400 million (Carr and Mendelsohn, 2003). Gross regional product produced from the reef and its resources was estimated by Hoegh-Guldberg and Hoegh-Guldberg (2003) to be A$1.4 billion. Clearly, substantial economic as well as ecological values are under threat.

2.4.2 Species extinction

The risk of species extinction was based on data used in the global analysis by Thomas et al. (2004) with data points for global mean temperature change >3°C added from two Australian studies (Brereton et al. 1995; Williams et al., 2003). Thomas et al. (2004) used climate scenarios to assess potential shifts in species' bioclimatic envelopes to assess extinction risks. They used sample regions that cover some 20% of the Earth's land surface. Three approaches of estimating the probability of extinction showed a power-law relationship with geographical range size.

We used estimates from Thomas et al.'s (2004) dispersal scenarios, as opposed to non-dispersal scenarios to create a relationship between global mean temperature change and extinction risk, measured by the total dislocation of current and future habitat, and exceeding reasonable estimates of dispersal. Because those estimates only extended to an increase of +3.5°C, we used data from two studies, where a relationship between closure of the climatic envelope and local increase in temperature for over 40 vertebrate Australian endemic species each has been created; by Williams et al. (2003) and by us based on data from Brereton et al. (1995).

The resulting distribution is sigmoidal (Figure 2.7), reflective of a normally distributed sample, and chosen because individual studies for a range of species show this pattern, both across an individual specie's range and between species. The upper limit is highly uncertain because it is based on only two studies both involving endemic vertebrates.

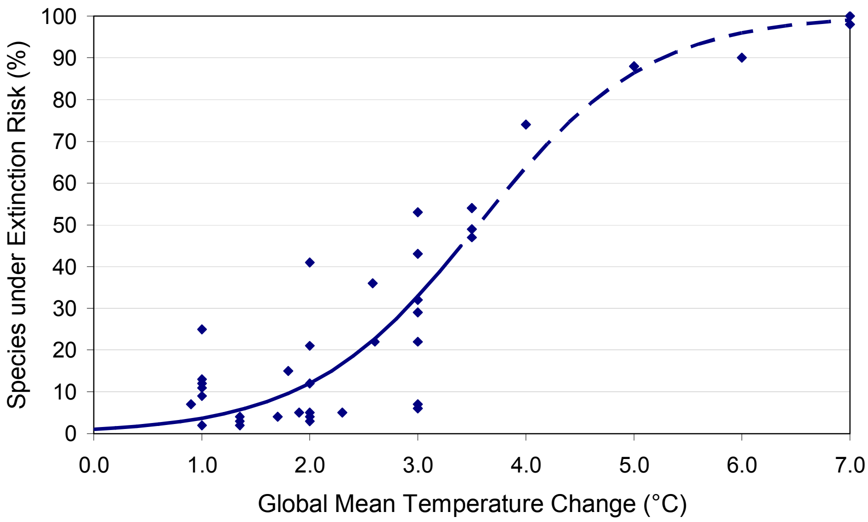

Figure 2.7. Relationship between global mean temperature change and extinction risk based on studies carried out for Latin/South America, Europe, South Africa and Australia.

Australia has a high degree of endemism in its native species and has already lost a significant number of vertebrate species in the past two centuries since Europeans arrived. Global warming has the potential to introduce a second wave of extinctions that may reduce vertebrate species to a much diminished group of generalist species that have shown themselves able to occupy a wide range of habitats, i.e. so-called 'weedy' species. As for coral reefs, the direct costs are unknown, but significant ecological values are at stake. Certainly, there is an element of moral hazard in a country not endeavouring to protect values that it has agreed to in a range of international treaties.

2.4.3 Greenland ice sheet

The function describing the threshold for the collapse of the Greenland ice sheet was based upon four estimates appearing in the literature. Hansen (2005) proposed a threshold for the collapse of the Greenland ice sheet of 1°C increase in global mean temperature, based upon an analysis of Earth's energy imbalance from anthropogenic greenhouse gas emissions and global mean temperature change during recent interglacial periods. Huybrechts et al. (1991) and Greve (2000), proposed thresholds of 2.7 and 3.0°C increase in Greenland surface air temperatures based upon the response of ice sheet models to climate forcing. The final estimate of 2.2°C comes from Huybrechts and de Wolde (1999), and represents the threshold global mean temperature change that would limit the loss of the Greenland ice sheet to 10% of its present volume over 1,000 years. This was assumed to represent a tolerable loss rate, and thus an upper temperature limit on the long-term stability of the ice sheet.

As the threshold temperatures for Huybrechts et al. (1991), Huybrechts and de Wolde (1999) , and Greve (2000) represent warming over Greenland, they were subsequently converted to global mean temperature changes, based upon estimated polar amplification (e.g., the ratio of Greenland temperature change to the global mean). Values for Greenland polar amplification were obtained from estimates reported in Huybrechts et al. (2004) for nine different climate models (ranging from 1.3–3.1°C). To account for model uncertainty in polar amplification, the three thresholds for Huybrechts et al. (1991), Huybrechts and de Wolde (1999), and Greve (2000) were divided by the polar amplification values from each of the nine climate models. With the addition of the Hansen (2004) threshold, this resulted in a total of 28 estimates of the threshold for Greenland ice sheet collapse, indicating a range of uncertainty in global mean temperature change causing the loss of the Greenland ice sheet of approximately 0.75–2.5°C.

These thresholds were converted to a percentile scale, and a third-order polynomial regression (r^2=0.99) was used to construct a cumulative probability distribution for the sensitivity of the Greenland ice sheet to climate-induced irreversible loss (Figure 2.8). Assuming this distribution is representative of the true uncertainty in the global temperature threshold for collapse of the ice sheet, responses indicate the likelihood of exceeding said threshold for a given magnitude of climate change.

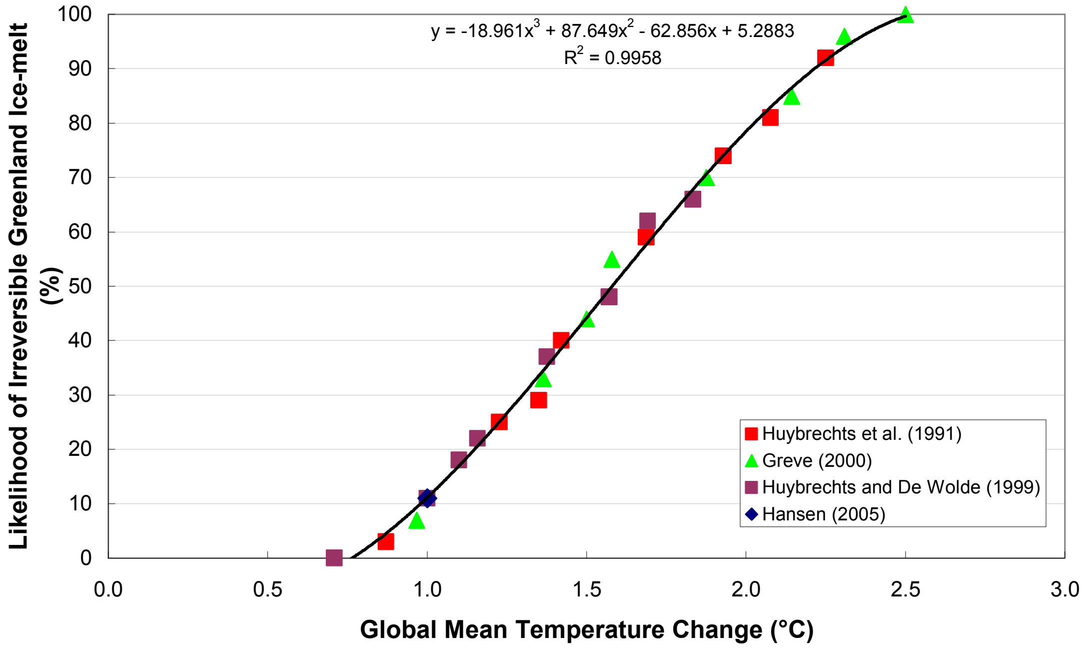

Figure 2.8. Estimated probabilistic sensitivity distribution for irreversible loss of the Greenland ice sheet. Values for Huybrechts et al. (1991), Huybrechts and de Wolde (1999), and Greve (2000) have been converted from Greenland temperature changes using estimates of polar amplification over Greenland from nine climate models.

This threshold is assumed to represent the point where melting and runoff of the Greenland ice sheet exceeds accumulation. Here it is assumed that one this threshold is exceeded, the ice sheet is effectively lost, although the rate of loss and what constitutes a "collapse" are undefined. Simulations by Huybrechts et al. (1991) indicate that it is possible that the ice sheet may reach a new steady state equilibrium, but only after losing approximately 50% of its current mass. Though this avoids a total loss of the ice sheet, losses of this magnitude are still consistent with substantial magnitudes of future sea-level rise and downstream consequences for natural and human systems.

The consequences of melting the Greenland ice sheet involve accelerated rates of sea level rise and injections of fresh meltwater into the north Atlantic that has the potential to turn off the North Atlantic thermohaline circulation (see below). The rates of sea level rise may be up to 1 metre per century for a total of 5 m, depending on the rate of warming in the Greenland region. Few studies have addressed the consequences of such studies on the coastal zone, but 5 m of sea level rise would have significant impacts on the Australian coastline. Even if property could be protected in an ordered retreat, there is still the issue of natural assets such as beaches, wetlands and estuaries.

2.4.4 Thermohaline circulation

Estimates of the response of North Atlantic thermohaline circulation (THC) to increases in global mean temperature were derived from a number of sources summarised below. For each study, the maximum THC reduction and associated global mean temperature change were recorded. A number of studies reported transient runs over multiple centuries. However, the current analysis was confined to 21st century responses (e.g., transient model runs <100 years).

Wood et al. (1999) reported reductions in THC using the HADCM3 coupled model and the IS92a emissions scenario. Washington et al. (1999) and Hu et al. (2004) reported responses of the PCM coupled model to CO_2 increases of 1% per year until a doubling and quadrupling of the preindustrial concentration. With the same model, Dai et al. (2005) applied a "business-as-usual" scenario for anthropogenic forcing analogous to the mean of the IPCC's SRES scenarios (interpreted here as a 2.2°C increase in global mean temperature in 2100 based upon simulations with the MAGICC simple climate model: Wigley et al., 1994). Boer et al. (2000) reported THC responses for the Canadian Climate Model given an increase in CO_2 emissions of 1% per year over the 21st century. Voss and Milkolajewicz (2001) reported reductions in THC using the ECHAM3 coupled model driven by CO_2 increases of 1% per year until a doubling and quadrupling of the preindustrial concentration. Raper et al. (2001) reported the global mean temperature and THC responses of eight different coupled climate models from the CMIP2 experiments.

A similar set of results were reported in the IPCC's Third Assessment Report (TAR) (IPCCa, 2001). Absolute reductions in 2100 from the IPCC TAR were compared with baseline overturning for the models reported in Raper et al. (2001) to estimate percent reductions. Kammenkovich et al. (2003) reported estimated THC responses from a model of intermediate complexity tuned to the NASA GISS coupled climate model, with CO_2 increasing at 1% per year until it reached double the preindustrial concentration. Zickfeld et al. (2004) developed a box model of the THC, based upon the CLIMBER-2 climate model, and reported THC responses for the box model and CLIMBER-2 for a forcing scenario resembling a 1% per year increase in CO_2 up to a quadrupling of the preindustrial concentration. Schmittner et al. (2005) reported global mean temperature and THC responses for a suite of models used for the IPCC's Fourth Assessment Report in response to forcing from the SRES A1B scenario (see also Gregory et al., 2005).

However, several modelling studies have found no significant change in THC in response to anthropogenic climate change. Sun and Bleck (2001) and Bleck and Sun (2004) reported no significant change in the THC using the GISS atmospheric model coupled to the HYCOM ocean model, with CO_2 increasing at 1% per year until it reached double the preindustrial concentration. Gent (2001) also reported no significant change in the THC using the CSM model with forcing specified by the IPCC SRES A1 scenario over the 21st century. These results have been mirrored by Latif et al. (2000) using the MPI coupled model with greenhouse gases increasing according to the IS92a scenario, although this study was not included in the current analysis. In addition, a number of model simulations indicate that slowing of the THC is reversible.

A least-squares linear regression (r^2=0.61) was performed on the data from the above studies to develop a relationship between THC response and global warming (Figure 2.9). Significant uncertainty about the general form of this relationship remains. For example, Gregory et al. (2005) reported transient THC responses from a more recent range of coupled model simulations, with THC reductions from 10–50% for a quadrupling of atmospheric CO_2. Nevertheless, assuming a mid-range estimate of global mean temperature change in 2100 of 2.9°C (median warming for SRES A1B scenario; IPCC, 2001), the response function calculated for the current study suggests a slowing in the THC of approximately 26%, consistent with the recent ensemble study of Schmittner et al. (2005).

In addition, this response function suggests warming on the order of 10°C would be required to induce a complete shutdown of the THC. This falls well within the range of global mean temperature change (5.0–25.0°C) required by various models to force a collapse of the THC (IPCCa, 2001). However, some recent studies have assessed the possibility that the North Atlantic THC may shut down due to the injection of freshwater from melting ice, possibly at warming levels that may be encountered by 2100 (Schlesinger et al., 2006; Zickfield et al., in press). Such assessments account for a wider range of physical phenomena than allowed for in coupled climate model simulations.

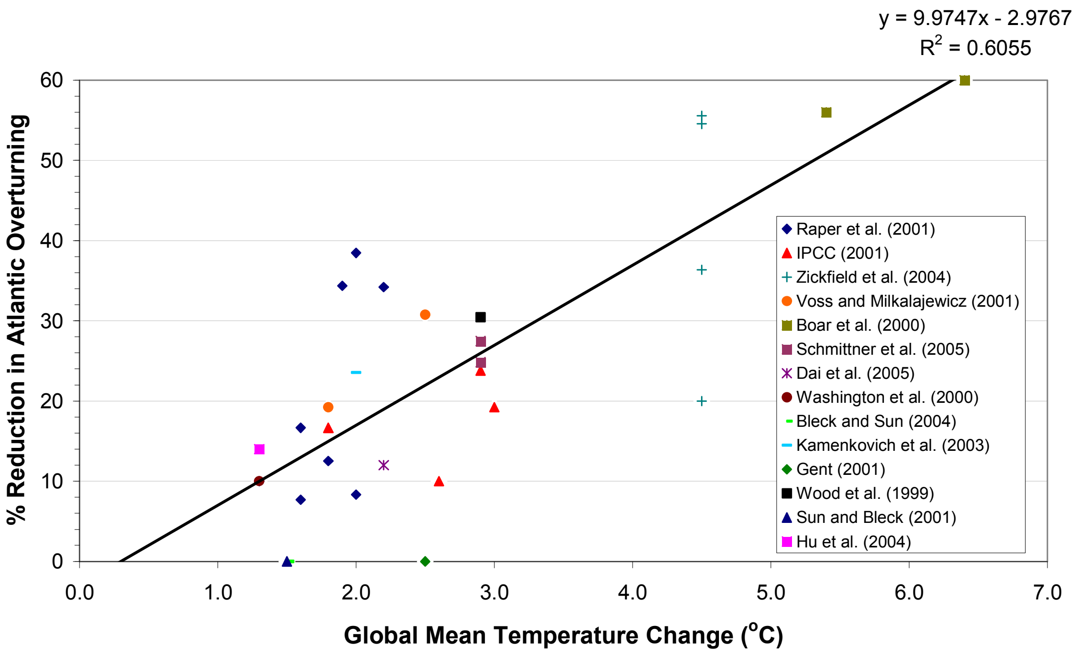

Figure 2.9. Estimated responses of thermohaline circulation to increasing global mean temperature over the 21st century from a range of studies.

THC slowdown is thought to affect the climate of northern Europe, which would cool substantially if the Gulf Stream were to weaken significantly or was prevented from reaching high northern latitudes. Cessation of the Gulf stream would curtail warming in Europe while the rest of the world continued to warm. The long-term ventilation of the ocean is at risk. If oxygen was no longer ventilated into the deep ocean this would significantly alter the biology of deep ocean waters.

3. BENEFITS OF CLIMATE CHANGE MITIGATION

3.1 Mitigation and reference scenarios

As part of Energy Futures Forum work ABARE produced a reference scenario and set of mitigation scenarios using the GTEM general equilibrium model (Ahammad et al., 2006). These scenarios were constructed under the guidance of the Energy Futures Forum, who outlined the structure of the mitigation scenarios and provided data on energy technology and use. In this section, we construct input emission scenarios for input into MAGICC, the simple climate used by the IPCC (Wigley, 1994) to estimate mean global warming to 2100. The results are analysed probabilistically and used to estimate risk-weighted damages of unmitigated climate change and benefits of applying mitigation actions.

The GTEM version 6.1 model and database produces estimates of seven anthropogenic greenhouse gases — combustion and non-combustion carbon dioxide, methane, nitrous oxide, HFCs, PFCs, SF_6 and CFC emissions. Most major emissions sources and sectors are represented in GTEM. Emissions from agricultural residues, and methane and nitrous oxide from combustion and some industrial processes are not modelled, but nitrous oxide emissions from transport are.

Emissions commence in 2001 and are constructed according to the methodology described in Hester and Ahammad (2002). Additional data on high GWP gases were sourced from the US Environmental Protection Agency through the Energy Modelling Forum (EMF) 21 modelling group on non-CO_2 greenhouse gases. Assumptions about growth of the population and economy and how they are expressed in terms of energy and technology use and ultimately, emissions, are detailed in Ahammad et al. (2006). Data for all scenarios was produced to 2050, but to assess the benefits of mitigation needed to take into account the delays in the climate system, so have been extended to 2100.

The reference scenario is an economically optimistic scenario that projects continuing demand for energy consistent with projections from the International Energy Agency. Trade liberalisation, removing 70% of tariffs from 2025 is assumed, leading to small growth increases that would otherwise not exist. Details are in Matysek et al. (2006) and Ahammad et al. (2006).

The mitigation scenarios, five scenarios in two groups, are detailed in Table 3.1. They are all target scenarios, where a target scenario for 2050 is set and a globally harmonised carbon tax is applied to a set of underlying assumptions about technology price and combination. The main variations are in how widely the tax is applied, when abatement commences and combinations of technology use. The two technologies that vary are carbon capture and storage (CCS) globally and nuclear energy in Australia.

Mitigation scenario 1. This scenario is similar to the A1T SRES scenario. It is a delayed action scenario where abatement only starts in earnest from 2030 and there is a target of 35% below the 2050 reference emissions. CCS is available globally but nuclear power is not available in Australia.

Mitigation scenarios 2a–d. These scenarios begin abatement from 2010 and have a target of 40% below the 2050 reference emissions. Several combinations of energy technologies are available. The first three alternate CCS and nuclear energy and the fourth assesses a separate target for Australia of a 50% reduction from 1990 emissions. Because of only very slight differences in these scenarios, results from scenario 2a are used to illustrate results from 2a–d.

CO_2 emissions from fossil fuel consumption are contrasted with the SRES A2 and A1T marker scenarios in Figure 3.1 for the years 2000–2050. Key differences are higher emissions in the reference compared to A2 scenario after 2030 and the earlier departure of the Mitigation 2a–d scenarios compared to A1T.

Table 3.1 Summary of greenhouse emission scenarios produced by ABARE for the EFF (Ahammad et al., 2006). Renewable energy generation is modelled as a single energy source with costs averaged across a range of technologies (water, solar, wind).

Scenario	Reference	Scenario 1	Scenario 2a	Scenario 2b	Scenario 2c	Scenario 2d
Global abatement target for CO_2 at 2050	0%	35%	40%	40%	40%	40%
Introduction of mitigation actions	No action	Late action beginning in 2030	Early action beginning in 2010	Early action beginning in 2010	Early action beginning in 2010	Early action beginning in 2010
Differentiation of Australian action	No	No	No	No	No	50% below 1990 CO_2-e by 2050
Technologies available	Business as usual	CCS (global)	No CCS	No CCS	CCS (global), nuclear (Australia)	CCS (global), nuclear (Australia)
SRES reference scenario for gases not modelled by GTEM	A2	B2 (constant) A1T (stab)	B2 (constant) A1T (stab)	B2 (constant) A1T (stab)	B2 (constant) A1T (stab)	B2 (constant) A1T (stab)

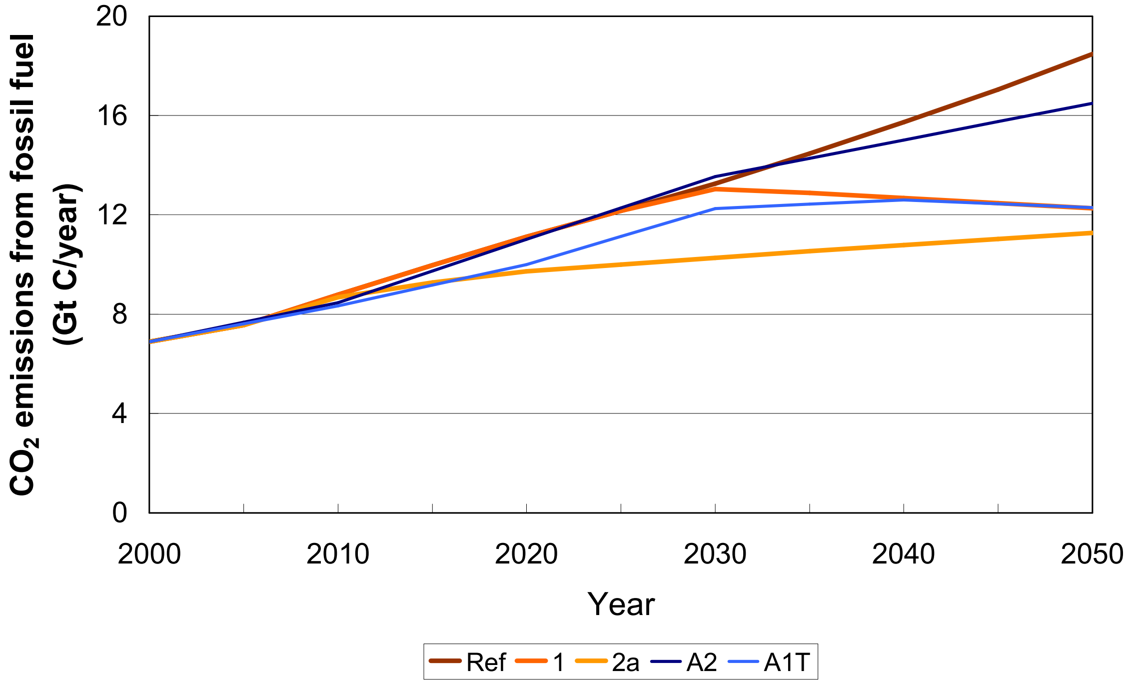

Figure 3.1 CO_2 emissions 2000–2050 from fossil fuel consumption from the EFF reference and mitigation 1 and 2a scenarios contrasted with the SRES A2 and A1T marker scenarios. The mitigation 2a–d scenarios all follow the same pathway.

3.1.1 Post 2050 emissions

To estimate changes in mean global warming using MAGICC and assess the benefits of warming, the scenarios were extended from 2050 to 2100. This required assumptions about emission rates beyond 2050. Because this was not part of the formal scenario description and analysis, implicit assumptions about the post-2050 economy are made in choosing any particular path. For example, emissions continuing on their existing path at 2050 would assume that abatement is keeping pace with growth in demand without significant new technology development, but deep cuts would assume that new technologies are introduced. These alternatives would have very different economic implications, so care is needed to ensure that the results are interpreted appropriately. The existing emissions for 1990 and 1995 used by IPCC (2001a) were used to extend the data set from 1990 to 2000.

Several more species of GHGs were required to run the MAGICC model: CO_2 due to deforestation, nitrous oxides, volatile organic carbon and carbon monoxide. Sulphate aerosol emissions were also altered with assumptions as to how aerosol pollution may be managed in the future. The deforestation pathway follows SRES unchanged, irrespective of the fossil fuel pathway and does not respond to climate change (positive atmospheric feedback leading to increased emissions is anticipated with higher levels of warming as vegetation changes from a sink to a source). Nitrous oxides, volatile organic carbon and carbon monoxide and were all scaled from fossil fuel CO_2 emissions using the A2 scenario as a baseline. Sulphate aerosol emissions rise in the early part of the century but fall well below 1990 levels by the latter half of the century, consistent with the expectation from Ahammad et al. (2006) that they would be curtailed to meet health objectives. Because sulphate aerosols have a net cooling effect on climate, this will increase the relative rate and magnitude of warming that would otherwise be suppressed.

All halogen gases included in the Montreal Protocol are part of the MAGICC inputs. The ABARE modelling used CO_2-equivalent assumptions of emissions for CF_4, HFC134a and SF_6. In the input scenarios for MAGGICC, the CF_4 input was assumed to include both CF_4 and C_2F_6; HFC134a input was assumed to include HFC125, HFC143a, HFC227ea and HFC245ca; lastly, SF_6 was multiplied by 2.2 to include all sources, consistent with Nakiçenovic and Swart (2000). The impact of these assumptions on total forcing is relatively small, although the emissions themselves are long-lived and the stratospheric ozone layer would also be affected.

Therefore, in this analysis, we look at two post-2050 constructions. The first assumes that emissions are stabilised in 2050 and continue unchanged to 2100; the second follows a similar pathway to A1T, which assumes significant cuts in emissions post-2050. The latter is most consistent with the EFF assumption that the mitigation scenarios be on target to meeting stabilisation at 550–575 ppm CO_2.

For emissions not projected by GTEM and for post-2050 emissions, we used SRES marker scenarios as a reference. Ratios for non-CO_2 emissions to CO_2 were calculated. These ratios were then multiplied with CO_2 for the EFF scenarios. The use of ratios assumes a roughly equivalent technological mix with reference to fossil fuel use but does not account for differences in other emission sources, such as agriculture for nitrous oxides. The SRES A2 scenario was used as the scaling reference for the EFF reference scenario, the SRES B2 scenario was used as the scaling reference for the 1 and 2a–d scenarios that maintained their 2050 trend and the SRES A1T scenario was used as the scaling reference for the 1 and 2a–d scenarios that moved towards stabilisation at 550–575 ppm CO_2. Emissions for the reference, and 1 and 2a scenarios are shown in Figure 3.2 and compared with the above-mentioned SRES scenarios. Note that here we are only comparing the emissions from the EFF and SRES scenarios for comparison in how they affect radiative change and global warming. They are governed by very different storylines, so similarity in emissions does not mean that the two sets of scenarios come from like futures.

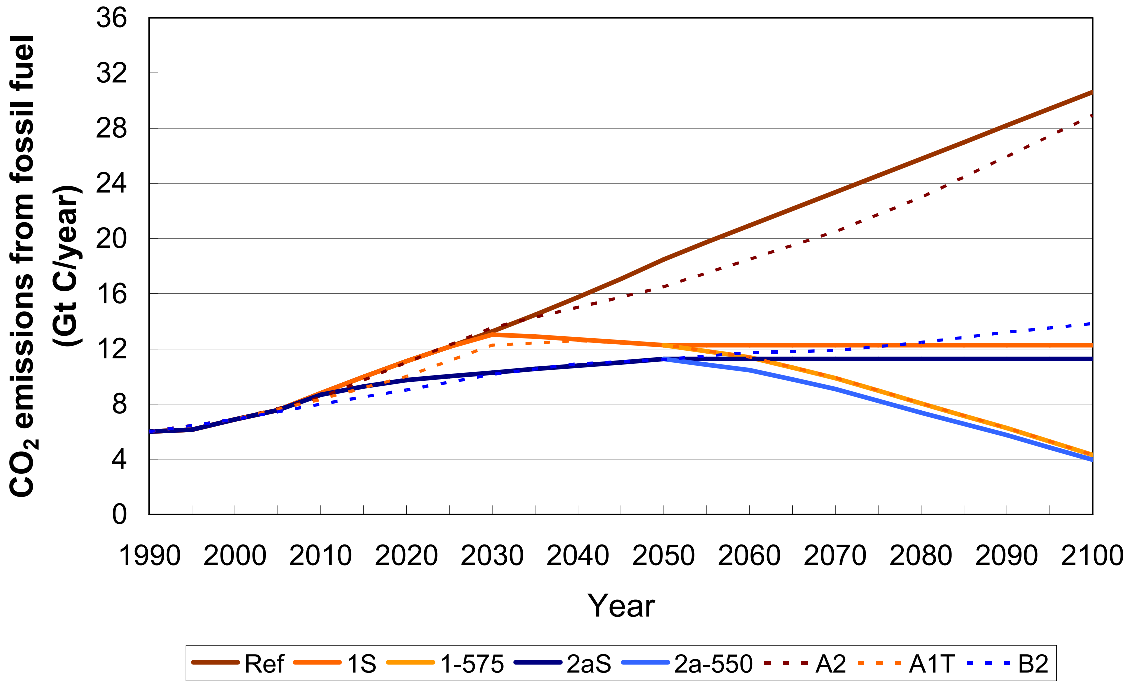

Figure 3.2 CO_2 emissions for the reference, mitigation 1 and 2a scenarios to 2050, bifurcating into stabilisation of emissions (1S and 2aS) and concentrations at 575 and 550 ppm CO_2 pathways. Also shown are CO_2 emissions for the SRES A2, A1T and B2 marker scenarios.

3.1.2 Atmospheric and climate change

Emissions from 1990–2100 input into MAGICC project atmospheric concentrations of CO_2 and other major greenhouse gases, changes in radiative forcing and mean global temperature and sea level rise. Changes in atmospheric CO_2 are produced from a simple atmospheric mixing model taking account of major sources and sinks but not accounting for changes in biophysical sources and sinks due to climate. The reference scenario results in about 540 ppm CO_2 by 2050 ppm and 900 ppm by 2100 (Figure 3.3). The difference by 2050 between all scenarios is only 50 ppm but by 2100, the different constructions of the mitigation scenarios range between about 550 ppm and 630 ppm. This is a substantial difference of about one-third. Compared with concentrations from the SRES marker scenarios, the reference case is slightly higher than A2, scenarios 1 and 2a–d held at 2050 trends are slightly higher than B2 and the mitigation scenarios aiming towards stabilisation are similar to A1T.

The reference scenario projects warming in a world that follows a business-as-usual pathway that projects changes in energy demand. Resulting emissions are influenced by changing efficiency trends based on past learning and anticipated technological improvements, with a small level of abatement from existing policies (Ahammad et al., 2006). Figure 3.4 shows the range of warming projected for climate sensitivities of 1.5, 2.6 and 4.5°C. Mean global warming in 2100 ranges between 2.6°C and 5.7°C with a mid-range (as measured for climate sensitivity) warming of 4.0°C. All of these temperature rises would result in significant impacts, those above 4°C resulting in severe impacts for both Australia and the world.

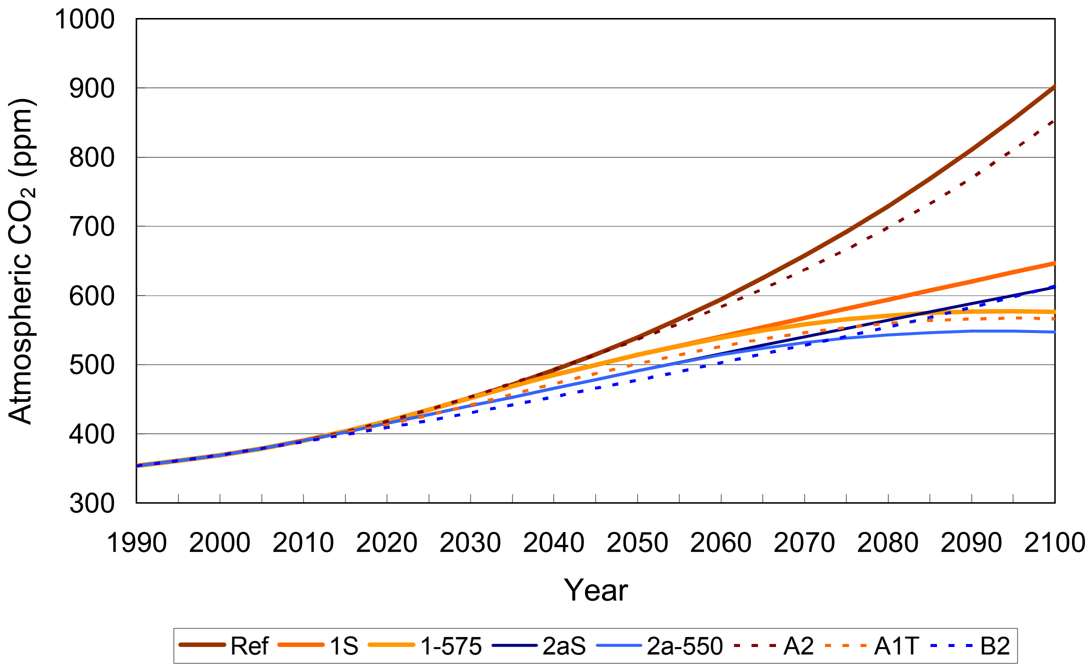

Figure 3.3 CO_2 concentrations for the reference, mitigation 1 and 2a scenarios to 2050, bifurcating into continuing trend and stabilisation at 575 ppm CO_2 pathways. Also shown are CO_2 emissions for the SRES A2, A1T and B2 marker scenarios.

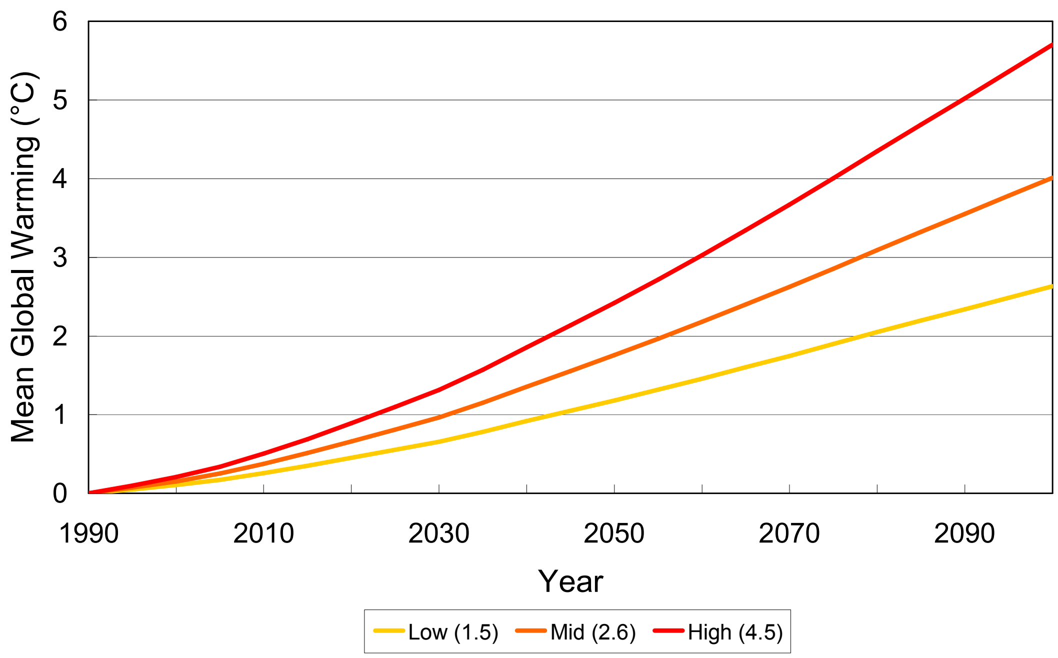

Figure 3.4 Mean global warming projected for the EFF reference scenario using the MAGICC simple climate model for climate sensitivities of 1.5, 2.6 and 4.5°C.

The mitigation scenarios produce lower levels of warming. Figure 3.5 compares the reference scenario with both representations of the mitigation 1 scenario. Large differences in global warming are produced, reducing warming by about 1.1°C to 2.2°C across the range of climate sensitivity of 1.5°C to 4.5°C. Interestingly, the lower emission scenario stabilising at about 575 ppm CO_2 (1–575) is slightly warmer than the 1S scenario from 2055 to 2085. This is because sulphate aerosol reductions due to lower fossil fuel emissions produce an immediate warming whereas the effect of lowered CO_2 emissions is delayed by several decades.

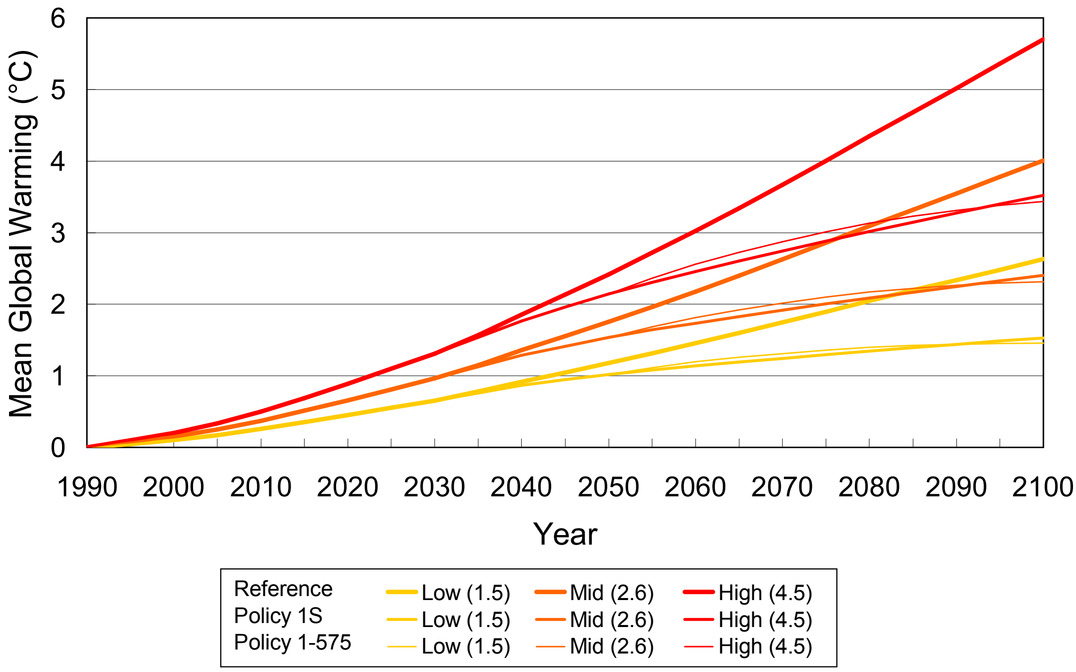

Figure 3.5 Mean global warming projected for the EFF reference and mitigation 1 and 1-575 scenarios using the MAGICC simple climate model for climate sensitivities of 1.5, 2.6 and 4.5°C. The mitigation 1 scenario results in a concentration of 623 ppm CO_2 in 2100 whereas the 1-575 scenario results in a concentration of 576 ppm CO_2.

Results are similar for the Mitigation 2a–d scenarios, which by 2100 project warming 0.1°C to 0.3°C lower than the mitigation 1 scenario. This reduced warming is due to an earlier departure from the reference scenario and decreases 5% larger by 2050 than the Mitigation 1 scenario (Figure 3.6). The 2a–dS scenarios also show a similar relationship with the stabilisation versions, as for the Mitigation 1 scenarios, where the scenarios with the lower emissions produce slightly higher temperatures after 2050.

This analysis illustrates several key points:

- When comparing a reference and mitigation scenario, there is a delay between the abatement of emissions and the resulting temperature response of several decades.
- Changes in the cooling effects of sulphate aerosol emissions occur immediately, whereas warming from GHGs may be delayed for several decades. Therefore, a mitigation scenario

that cuts both sulphate aerosols and fossil fuel emissions will experience a relative warming due to the sulphate cuts long before the benefits of the GHG cuts are realised.

- This delay in GHG response necessitated the construction of emission scenarios post 2050. Note that these post 2050 abatement paths have not been costed as part of this study. The small differences in warming by 2050 and the larger gaps by 2100 between the reference and mitigation scenarios show that the greatest benefit in the latter half of this century must come from the cuts made in the first half of this century.

- Early emissions cuts can have a long-term beneficial effect in reducing warming but will need to be sustained by continued future abatement.

- The benefits of cuts made during the 21st century will continue long after the 21st century is complete.

- The stabilisation of CO_2 at levels of 575 ppm or below will require that global emissions in the 21st century fall below the emission levels of the latter part of the 20th century.

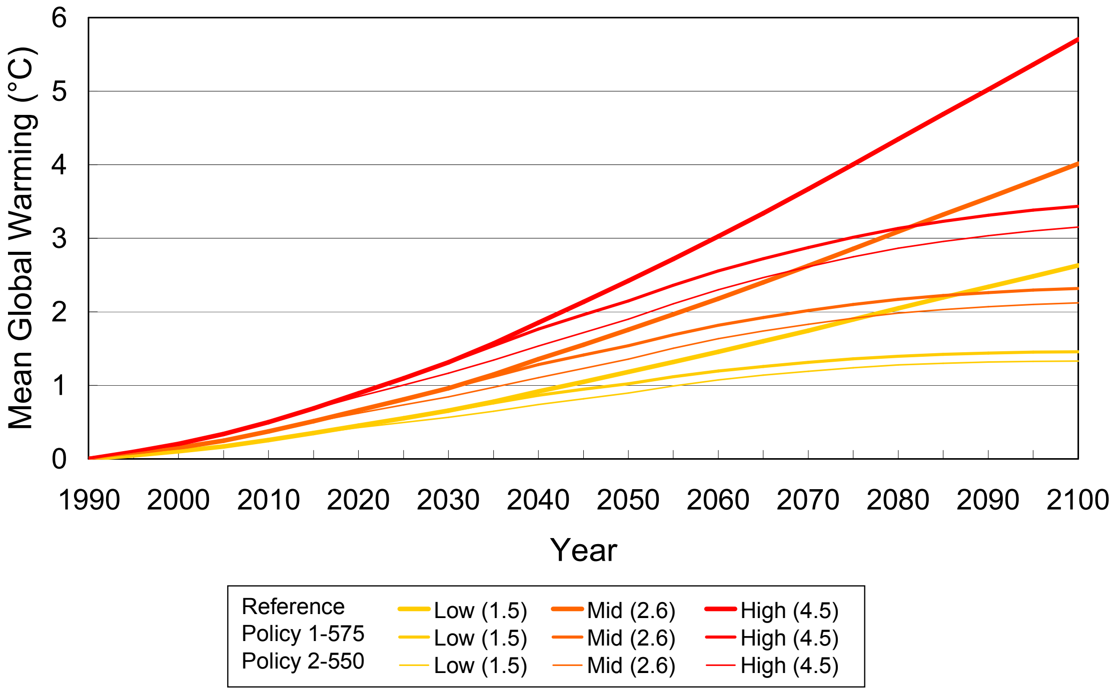

Figure 3.6 Mean global warming projected for the EFF reference and mitigation 1-575 and 2a-550 scenarios using the MAGICC simple climate model for climate sensitivities of 1.5, 2.6 and 4.5°C. The mitigation 1-575 scenario results in a concentration of 576 ppm CO_2 in 2100 whereas the 2a-550 scenario results in a concentration of 547 ppm CO_2.

3.2 Risk analysis

As outlined in the first part of the report, estimating the benefits of climate policy by comparing a reference with a mitigation scenario requires estimating the likelihood of global warming itself and of estimating a range of impacts as a function of global warming. In the next few sections we describe how this is done and present the results.

3.2.1 Global warming probabilities

Once having gained an estimate of radiative forcing changes for a particular scenario, the largest remaining uncertainty is climate sensitivity. Since the IPCC Third Assessment Report was published, there has been a great deal of attention paid to the value of climate sensitivity, and a number of attempts have been made to quantify it probabilistically (Dessai and Hulme, 2003). These estimates have produced a wide range of values, some of which are very large (Figure 3.7), exceeding 10°C. Such large values are thought to be implausible, based on evidence of warming following the last ice-age between 20,000 and 10,000 years ago, and from historical record of warming since the industrial revolution.

However, recent estimates suggest that the median climate sensitivity may be higher than that implied in the IPCC TAR, perhaps as much as 3.0 to 3.5°C and right-skewed towards higher temperatures (IPCC WGI, 2004). Most quantified ranges contain values that exceed the previous upper limit quantified as 4.5°C by IPCC (2001a). Given that the reference scenario with a sensitivity of 2.6°C produces a warming of 4°C by 2100, the possibility that the median climate sensitivity lies above this, must be treated very seriously. In this assessment, we rely on two expert probability distributions of climate sensitivity. Wigley and Raper (2001) have produced a probabilistic distribution with a median of 2.6°C and Murphy et al. (2004) a right-skewed distribution with a median temperature of 3.5°C (Figure 3.7). Two others distributions, one constructed from the GCMs used in the IPCC Third Assessment Report (IPCC, 2001a) and Andronova and Schlesinger (2001) are also used.

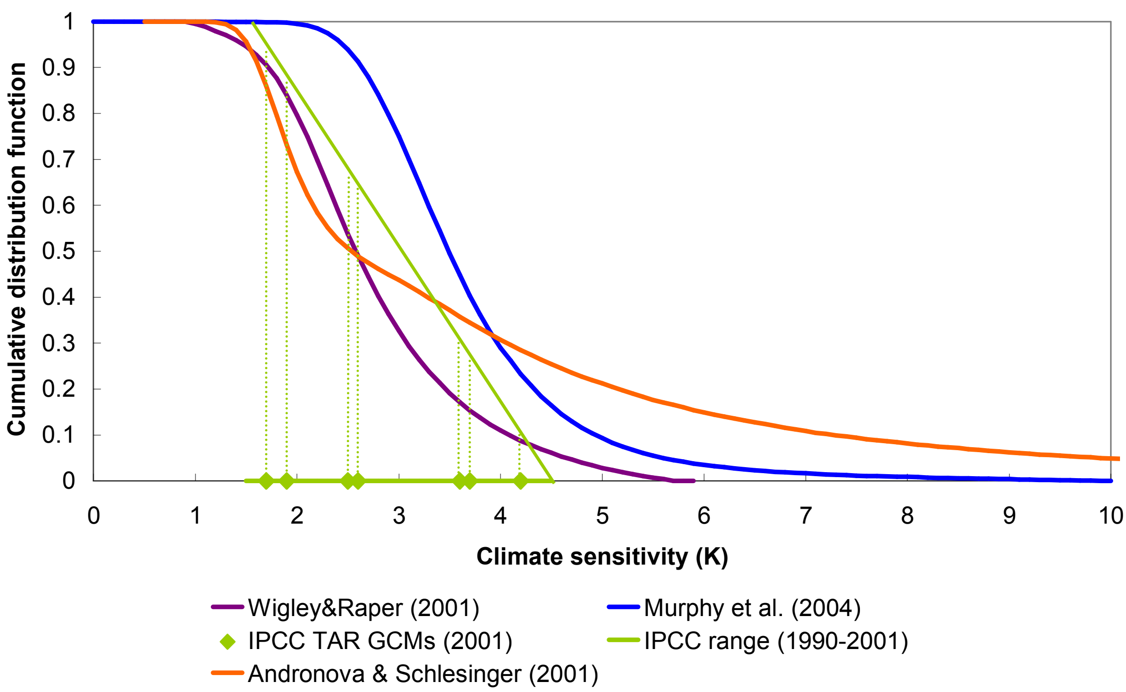

Figure 3.7 Cumulative probability distributions for a range of climate sensitivity estimates from the literature (based on Dessai and Hulme, 2003).

The probability of warming in 2100 was created from two factors: GHG and sulphate aerosol forcing (F), and climate sensitivity. Sensitivity (T_s) is represented by the factor λ, which is multiplied with radiative forcing from 1990 (F), using a method similar to that applied by

Schneider (2001). The factors a and b in equation 1 are constants calculated from a total of fifteen scenario runs (five GHG scenarios at three sensitivities: 1.5, 2.6 and 4.5°C). GHG forcing is derived using the MAGICC simple climate model (Wigley, 1994) and global warming (T) is projected using Equation (2).

$$\lambda = \boldsymbol{a}\boldsymbol{T_s} + \boldsymbol{b} \qquad (1)$$

$$\boldsymbol{T} = \boldsymbol{F}\lambda \qquad (2)$$

Because climate sensitivity is so uncertain, we tested the effects of several probability distributions on temperature. The ranges of uncertainty are:

1. Murphy et al. (2004) calculated using model parameter analysis. The results have a 5/50/95 percentile distribution of 2.4/3.5/5.4°C for 2×pCO_2.
2. Wigley and Raper (2001) produced a gaussian distribution similar to the IPCC 1.4–4.5 °C range, which has a 5/50/95 percentile distribution of 1.5/2.6/4.5°C for 2×pCO_2.
3. Global climate models used in the IPCC TAR (IPCC, 2001a) with sensitivities of 1.7, 1.9, 2.6, 2.5, 3.0, 3.7 and 4.2°C, distributed assuming equal likelihood.
4. Andronova and Schlesinger (2001), calculated from a Monte Carlo analysis of different climate drivers (natural and anthropogenic) contributing to the 20th century temperature increase. Although the upper levels of sensitivity are though to be implausible, this distribution is used to show the impact of a skewed distribution with long tail.

Average forcing in Wm^{-2} in 2100 was applied as a single number (ignoring the underlying uncertainties in estimating radiative forcing that the are described in previous sections) and Monte Carlo sampling according to the four distributions above used to sample $\boldsymbol{T_s}$. Equations 1 and 2 were then applied to estimate probability distributions for warming in 2100 for a given GHG scenario. The results were compiled from >60,000 random samples.

The four different sensitivities applied to the reference scenario are shown in Figure 3.8. These estimates show a clearly broader range than that shown in Figure 3.4, and are generally trending to warmer temperatures. The main part of the range is around 3–5.5°C, though both greater and lesser temperature rises are possible. There is a debate surrounding the plausibility of the higher sensitivities, but even a sensitivity of 4°C, which is thought plausible by most experts, would produce a warming of 5°C.

Probabilities of exceedance for the mitigation scenarios, 1S and 1-575 are shown in Figure 3.9 and for the scenarios 2 and 2a-550 are shown in Figure 3.10. Both the Murphy et al. (2004) and Wigley and Raper (2001) estimates of climate sensitivity are shown. They show that the main part of the range is around 2–3.5 °C for the stabilisation scenarios. These estimates are considerably lower than for the reference scenario.

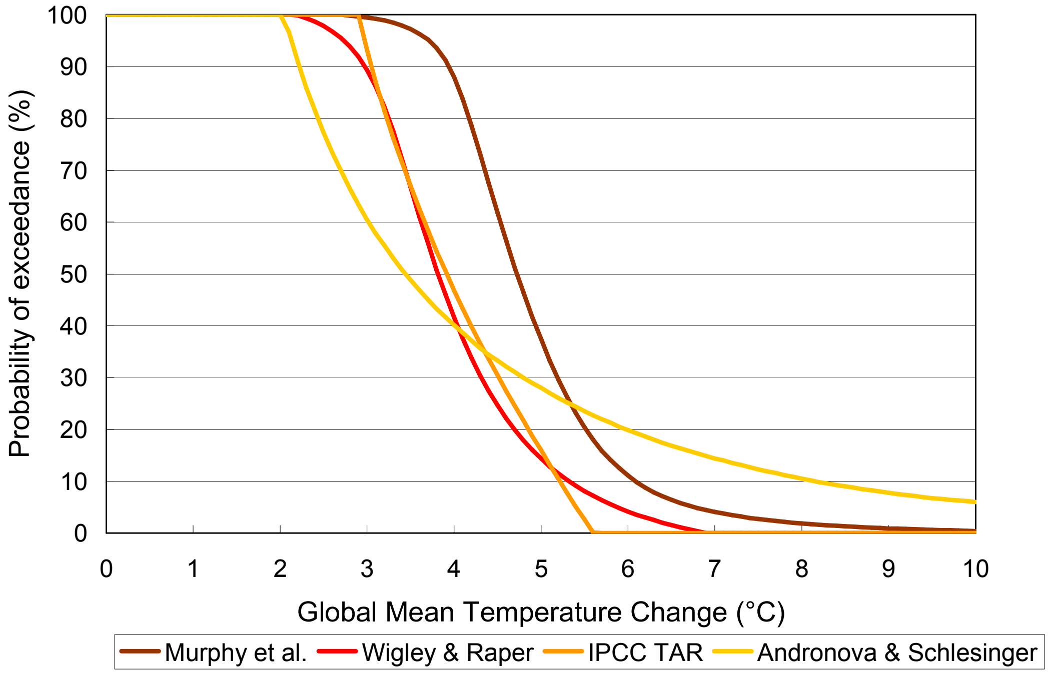

Figure 3.8 Cumulative probability distributions (probability of exceedance) for global warming in 2100 for the reference scenario according to four different estimates of climate sensitivity.

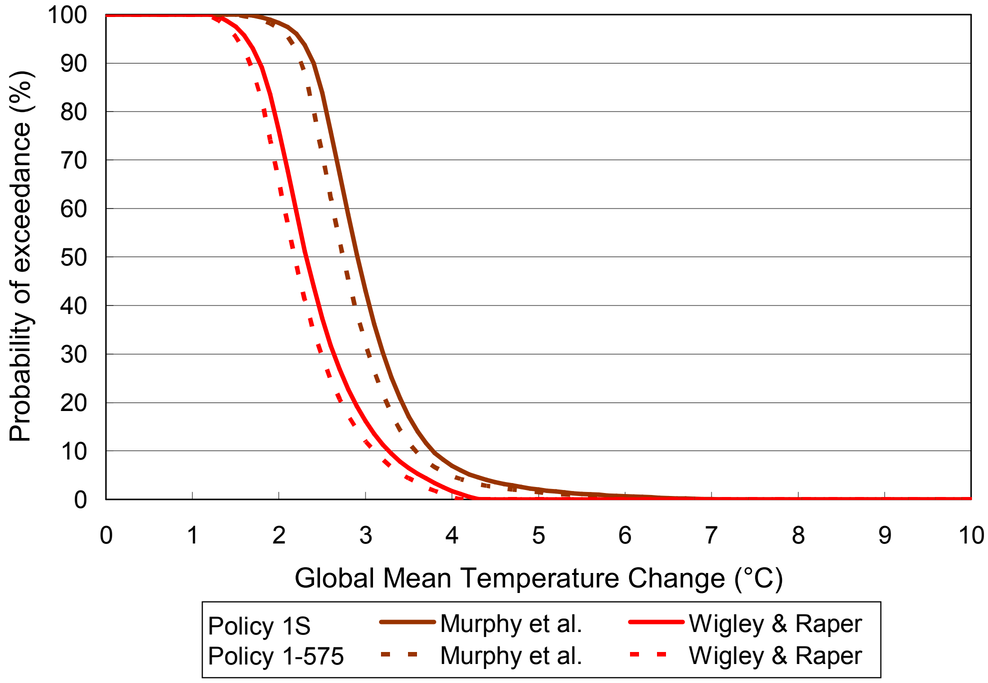

Figure 3.9 Cumulative probability distributions (probability of exceedance) for global warming in 2100 for the mitigation scenarios 1 and 1-575 according to Murphy et al. (2004) and Wigley and Raper (2001) estimates of climate sensitivity.

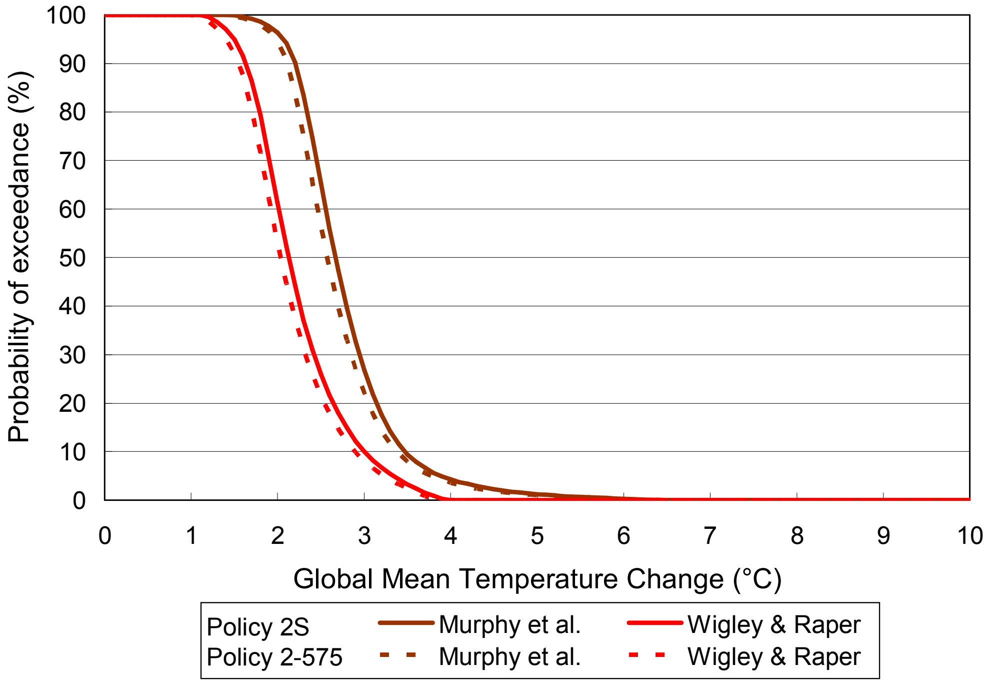

Figure 3.10 Cumulative probability distributions (probability of exceedance) for global warming in 2100 for the mitigation scenarios 2S and 2a-550 according to Murphy et al. (2004) and Wigley and Raper (2001) estimates of climate sensitivity.

3.2.2 Risk-weighted damage functions

This section introduces risk-weighted damage estimates for four biophysical impacts detailed in Chapter 2 of this report and four economic cost curves. The biophysical curves cover damage as a function of global warming for critical thresholds of coral reef bleaching, risk of species extinction, slowdown in North Atlantic thermohaline circulation and the commencement of irreversible melting of the Greenland ice-sheet (Figure 3.11). They were described in detail in Chapter 2.4.

The threshold for coral reef bleaching measures the proportion of the Great Barrier Reef affected by thermal bleaching in 50% of all years. The species extinction curve denotes the number of species at risk of extinction because their bioclimatic envelope is likely to be completely separate from their current range; the upper part of the curve >3°C warming relates to two studies in Australia, so is likely to be too sensitive to account for all species and should only be related to endemic species with limited distribution. The THC curve relates to the slowdown in North Atlantic Thermohaline Circulation from the range of climate models described in IPCC (2001a; Chapter 9). More recent estimates suggest that freshwater ice-melt and/or freshwater from increased continental runoff may render THC shut-down more sensitive than estimated by AOGCMs (Schlesinger et al., 2006; Zickfield, in press), but we have not tried to quantify this here. The Greenland Ice-sheet curve relates to different estimates in the literature as to when the Greenland ice-sheet is likely to commence irreversible melting – and the most recent estimates indicate a greater sensitivity than those published previously (e.g. Hansen, 2005; Joughin, 2006). Complete melting of the ice sheet would produce about 5–6 m average sea level rise. The rate of sea level rise is uncertain, since it will depend on the rate of local warming, consequent melting and ice sheet balance.

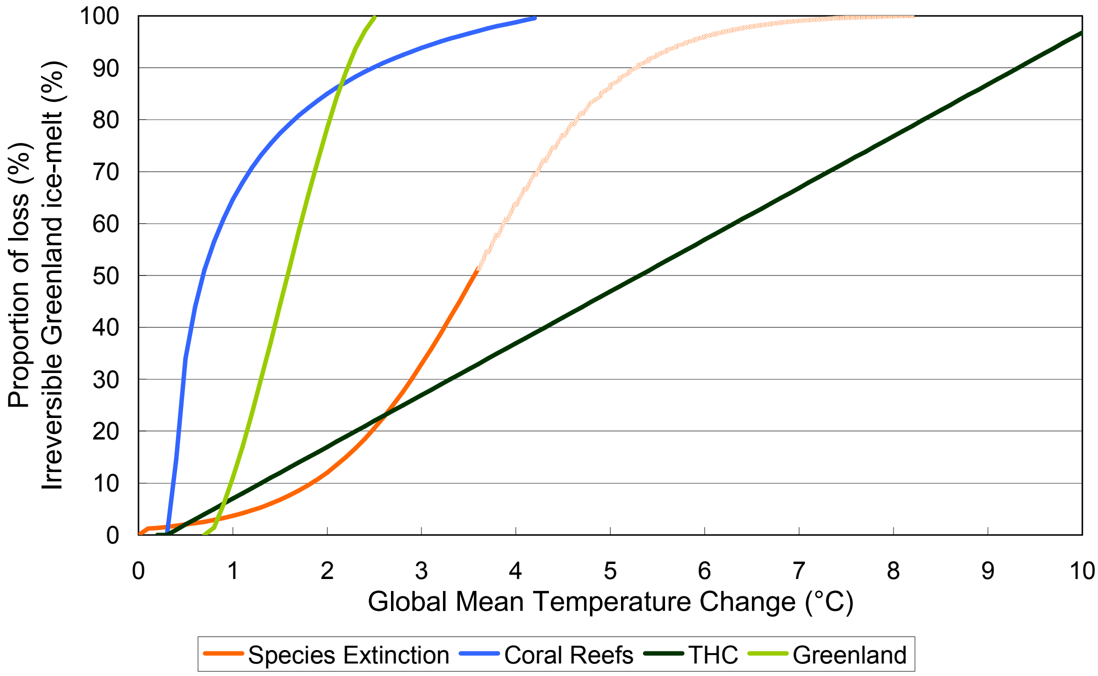

Figure 3.11 Damage curves for four key biophysical vulnerabilities: risk of species extinction, proportion of loss of coral reefs due to thermal bleaching, slowdown in North Atlantic thermohaline circulation and the probability of commencement of irreversible melting of the Greenland ice-sheet (from Sheehan et al., 2006)

Four conceptual damage curves expressed as reductions in percent global Gross Domestic Production (GDP) per degree of global warming were also analysed. Percent damage of GDP has been used as a common metric for first analysing the damage associated with double pre-industrial levels of CO_2 in the atmosphere (Pearce et al., 1996) but is still used, despite the difficulties in assuming different economies, levels of development and adaptive capacity (Tol, 2005; Downing et al., 2005). Estimates from the literature, from economic modelling studies and subjective estimates from expert elicitation are shown in Figure 3.12 and Figure 3.13, respectively. They show a range of economic damages, with those from economists and modelling studies being the lowest and those from natural scientists, the highest.

In this study, four economic damage curves were applied: linear, quadratic, cubic and response to a large-scale singularity. Linear and quadratic economic damage curves were the earliest to be tested, and are still being used in uncertainty analyses (e.g. Page, 2006). In estimates from the literature, losses can be assessed through production changes or can consider changes in equity by allowing for distributional affects. The two most common methods use area-weighting and population-weighting. Here, the quadratic damage curve is similar in shape and magnitude to that developed by Nordhaus and Boyer (2000). The key assumption anchoring all of these curves is that a 3°C increase in global mean average temperature will result in a 3% decrease in GDP. This estimate was obtained by Nordhaus (2006) from his application of a Ricardian approach to a 1° × 1° with a scenario of warming and mid-continental drying[††]. These estimates are obtained by estimating the relationship between climate and output, and estimating the altered output by perturbing climate, the so-called cross-sectional or Ricardian approach (Mendelsohn and Williams, 2004). The result is population rather than output weighted, so has some allowance for equity but

[††] Note that since this analysis was commenced, Nordhaus (New Metrics for Environmental Economics: Gridded Economic Data, Benefits of Climate Policy, OECD, Paris July 2006) published an updated version of this model, which reduces the 3°C impact to a population-weighted change in global GDP from -3.0% to -2.4%.

is restricted to market impacts only. This is an equilibrium method as compared to a dynamic method – the different methods of estimating damages – and some of their assumptions, strengths and weaknesses – are discussed by Tol (2005).

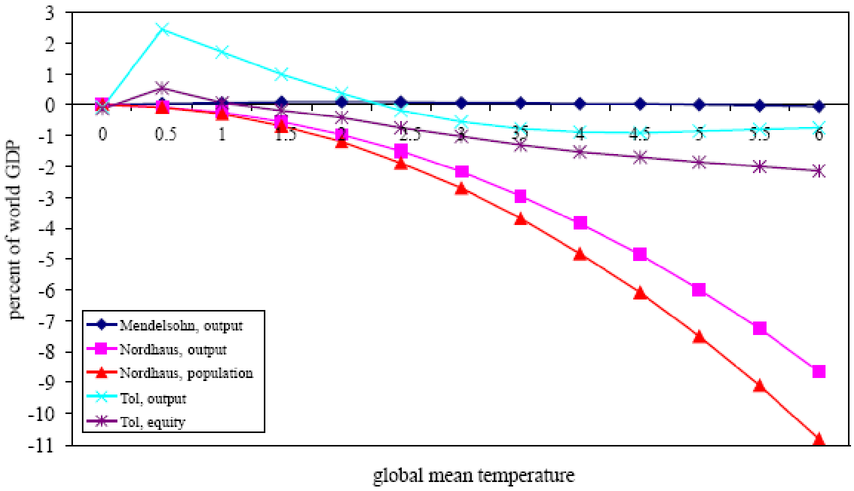

Figure 3.12 Climate change impacts as a function of the global mean temperature change (°C). Estimates according to Mendelsohn et al. (1998), Nordhaus and Boyer (2000), and Tol (2002b). Mendelsohn et al. aggregate impacts across different regions weighted by regional output. Nordhaus and Boyer aggregate either weighted by regional output or weighted by regional population. Tol aggregates either by regional output or by equity, by the ratio of world per capita income to regional per capita income (from Tol et al., 2004). Note that these costs are based on warming from pre-industrial levels.

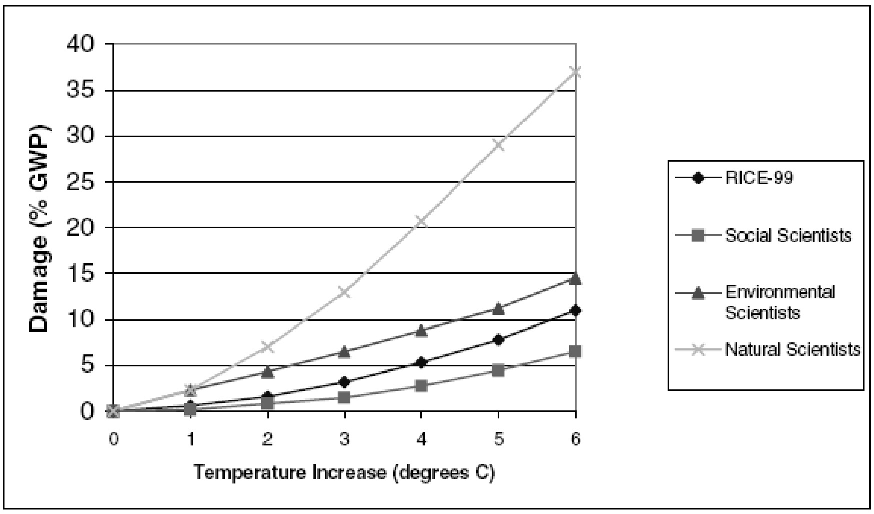

Figure 3.13 Damage functions from a survey conducted by Nordhaus (1994a) and Morgan and Keith (1994), which reflect different subjective views about the extent to which a changing climate would create economic damage (from Yohe, 2003b). Note that these costs are based on warming from pre-industrial levels.

Although the economic impacts analysed here are larger than for most studies (e.g. Tol et al., 2002a; Mendelsohn and Williams, 2004), most of those studies are restricted to market costs and only have a limited allowance for climate variability and extremes so are restricted to the upper left-hand corner of Table 1.1. Nor, or in most cases, are such estimates dynamic, although some do allow for adaptation. The highest warming for which damage functions were estimated was 6°C from pre-industrial temperatures Figure 3.12. Recent economic estimates from the Stern Review (Stern et al., 2006) do allow for market, non-market and the value of ecosystem and social damages in their estimates, and are substantial, ranging up to 20% of the total value of GDP through to 2200, estimated in risk-weighted terms.

It is conceivable that exceeding a 6°C warming could lead to catastrophic impacts, such as the break-up of the West Antarctic Ice Sheet and loss of the Amazon rainforest, and lead to major dislocations in terrestrial and marine ecosystem function. The Mendelsohn et al. (1998) curves are thought not to be plausible, because that analysis only applies to a limited range of sectors and overlooks climate variability and extreme events. It is highly unlikely that a 6°C warming could result in almost no change in net global economic damage (although Mendelsohn et al. (1998) conclude that the regional differences are substantial).

The linear curve mimics some of the earliest damage functions used in integrated assessment. The quadratic and cubic curves produce lesser damages than a line <3°C but greater damages >3°C. The step function combines a sigmoidal curve mimicking a long-term economic response to a single event (e.g. melting of a large ice sheet) that occurs at 3°C superimposed on a quadratic curve, producing an almost straight line. The more non-linear curves are representative of the concerns of natural scientists who factor in the possibility of catastrophic impacts. Although the assumption that ⅓rd of the global economy may be lost seems unlikely (e.g. ⅓rd of global production), the impacts of global warming of 7–10°C remain untested. In terms of our analysis, we wish to account for outcomes with low probability and high consequence along with high probability-low consequence outcomes in a single analysis. Furthermore, if the reference scenario constructed for this study were allowed to proceed unchecked beyond 2100, a 10°C warming reached during the 22nd century is plausible. However, we do not believe that such an outcome would be allowed by the global community.

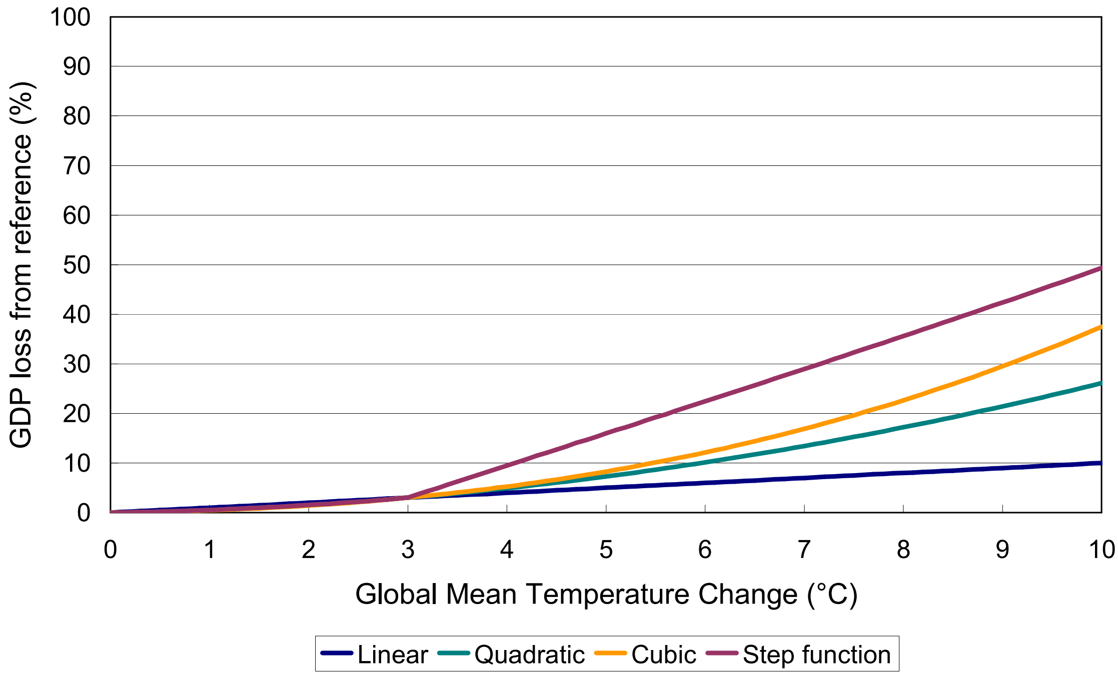

Figure 3.14 Different conceptual damage curves for global impacts expressed as percentage loss in global Gross Domestic Product (GDP) compared to a reference case. Note that economic damage curve is positive, going against economic convention – this is to allow comparisons between the economic and biophysical damage curves.

Although these damage curves are on the high side of published estimates, they are consistent with those estimated in the Stern Review (Stern et al., 2006). However, the likelihood that damages become non-linear at higher temperatures is widely accepted. From Table 1.1, economic damages are expected to be highly non-linear, irrespective of their magnitude. This is because:

- changing climate variability and extremes produce increasingly non-linear responses;
- the larger numbers of activities and locations negatively affected with increasing rate and magnitude of climate change; and
- incorporating non-market, existence and bequest values will also increase damages consistent with the biophysical responses detailed in Chapter 2.

To allow for the possibility that these damages are over-estimated, in Chapter 3.2.5 we estimate the minimum economic damage required in 2100 to balance mitigation costs accrued to 2050.

As outlined in Chapter 1.9, risk-weighted damages are calculated by multiplying the likelihood of attaining a particular level of global warming with the damage estimated to occur at that level. Figure 3.15 shows how a risk-weighted outcome is produced. The example shown here is species at risk. The probability density curve for global mean temperature change in 2100 is multiplied by the curve for species at risk as a function of global warming. The resulting damage functions are then totalled to determine the risk-weighted number of species, in this case 58%. The result is different to that which would be obtained by using the most likely scenario because of the use of right-skewed damage functions. The most likely scenario approach in this case would suggest that 48% of species at risk. Also shown is the precautionary approach where a predetermined minimum damage is used to set a temperature target. For example, if it was decided that species at risk should not exceed 10%, a warming target of 1.8°C would be set.

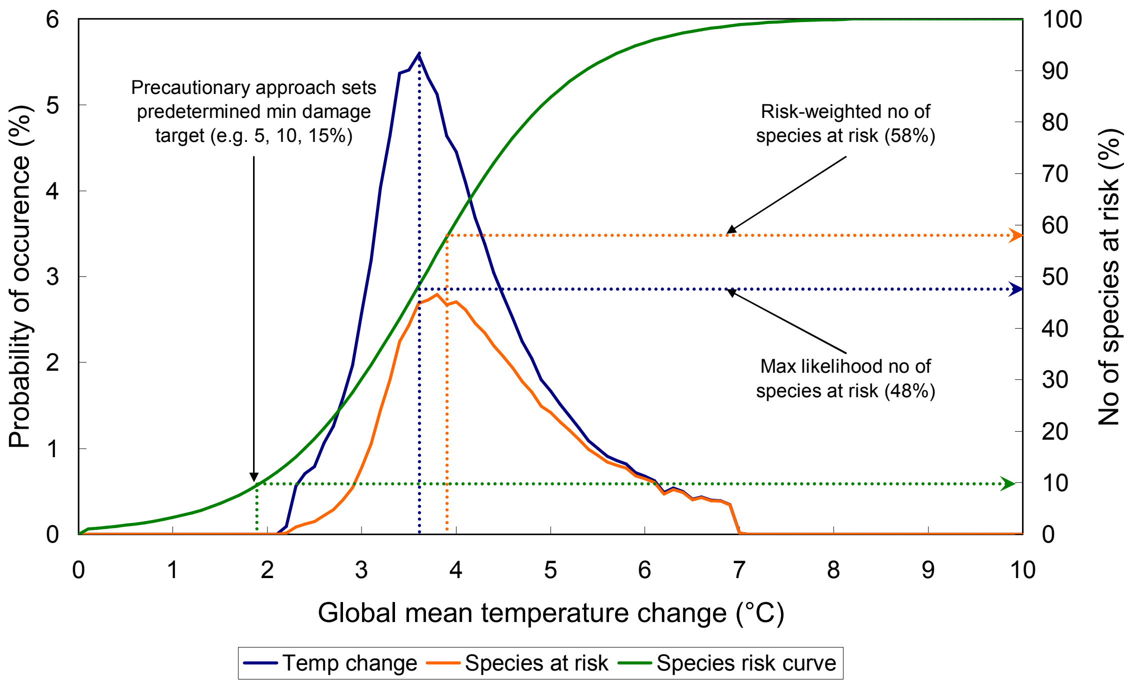

Figure 3.15 Graphic representation of how a risk-weighted impact is calculated. The probability density of global mean temperature change (blue) is multiplied by the damage curve, in this case the species at risk damage curve (green), to produce the number of species at risk (orange). The total number of species at risk in this example is 58%. The blue and green curves are associated with the left vertical axis and the green curve with the right axis. Also shown are the maximum likelihood approach and the precautionary approach.

3.2.3 Risk-weighted damages under the reference case

In this section, we address the question "Can we afford to not act on climate change?" This is carried out by first assessing the risk-weighted damages in 2100 associated with the reference scenario. Table 3.2 shows the risk-weighted damages produced by multiplying the probability density functions of the warming curves in Figure 3.8, factoring in four different distributions for climate sensitivity. In some instances, the results are responsive to the underlying climate sensitivity, in others not. For example, where a critical threshold is likely to be exceeded at comparatively low levels of warming (e.g. coral reefs, Greenland), the damages are uniformly high. Where they are close to linear, the damages are also similar. When impacts are non-linear and affected by the upper tail of one or other distribution, then the outcomes are sensitive to climate sensitivity.

For the reference case, roughly half to three-quarters of endemic species at least, may be at risk. Critical damage is projected for coral reefs. Greenland is likely to have irreversible melting underway and the thermohaline circulation is likely to slow down significantly. In fact, there is a risk of it ceasing altogether if sufficient freshwater from ice melt and river runoff enters the North Atlantic (Rahmstorf, 1996). Economic damages are significant four all four curves.

Table 3.2 Risk-weighted changes multiplying the risk of warming in 2100 from the reference scenario for four different climate sensitivities with four curves measuring damages in biophysical systems and four curves measuring economic loss to global GDP. NPV in $2005 calculated from the GTEM economy using the UK Treasury Greenbook long-term discount curves.

Biophysical				
Sensitivity	Species	Coral Reefs	THC slow-down	Greenland ice sheet
	(% damage)			Chance of loss (%)
Murphy et al.	79.0	99.8	46.6	100.0
Wigley & Raper	58.4	98.2	37.3	99.9
IPCC TAR	60.4	98.5	37.7	100.0
Andronova & Schlesinger	52.9	96.2	40.4	98.4

Economic				
Sensitivity	Linear	Squared	Cubic	Step change
	(% decrease in GDP)			
Murphy et al.	5.0	7.4	8.6	15.8
Wigley & Raper	4.0	5.2	5.7	9.9
IPCC TAR	4.1	5.2	5.7	10.0
Andronova & Schlesinger	4.4	6.9	8.5	12.8
	(NPV $Trillion 2005)			
Murphy et al.	120.5	135.5	144.5	312.6
Wigley & Raper	98.8	96.8	98.4	196.6
IPCC TAR	99.7	97.4	98.9	196.9
Andronova & Schlesinger	105.3	124.5	134.8	292.9

Short-term (over the coming decades) net economic benefits may be positive (Figure 3.12) if the agricultural and forestry benefits of warming in high latitudes outweigh the costs of climate-induced damages from changing variability and extremes such as tropical storms, sea level rise, more intense drought and heat waves. A strict interpretation of the cost-benefit approach may suggest that the short-term benefits of mitigating greenhouse gases may be negative, therefore abatement should not begin until impacts become negative. However, this overlooks the delays between GHG emissions and the climate response, shown quite clearly when Figure 3.2 is contrasted with Figure 3.5 and Figure 3.6. Therefore, a proper effort to assess the benefits of climate policy requires that for any assessment of abatement costs, the resulting impacts damages/benefits be assessed over a period of sufficient length to register the progression of impacts throughout the Earth's systems.

3.2.4 Benefits of mitigation

The benefits of mitigation can be assessed by contrasting the risk-weighted damages of a set of mitigation scenarios with that of a reference scenario. We do this by repeating the analysis carried out in the previous section for the mitigation scenarios described in Chapter 3.1 and comparing these with the risk-weighted damages produced by the reference scenario. The analysis is restricted to two distributions, that of Wigley and Raper (2001) and Murphy et al. (2004), that have median estimates of climate sensitivity of 2.6°C and 3.5°C, respectively.

Risk-weighted damages for the mitigation scenarios are shown in Table 3.3. They show significant reductions for some impacts, species and risk and THC slowdown; but not for others, coral reefs and Greenland, reductions are only small. This is because most of the warming range remains above the critical limits of exceedance for those impacts. Reductions in economic impacts are greater for the more non-linear curves. The differences between risk-weighted damages for the reference and mitigation scenarios are shown in Table 3.4.

Table 3.3 Risk-weighted changes multiplying the risk of warming in 2100 for the 1, 1-575, 2 and 2a-550 mitigation scenarios for four different climate sensitivities with four curves measuring damages in biophysical systems and four curves measuring economic loss to global GDP. NPV in $2005 calculated from the GTEM economy using the UK Treasury Greenbook long-term discount curves.

Biophysical					
Scenario	Sensitivity	Species	Coral Reefs	THC slow-down	Greenland ice sheet
		(% damage)			Chance of loss (%)
1S	Murphy et al.	33.5	94.8	27.8	99.0
	Wigley & Raper	20.5	90.8	21.7	89.1
1-575	Murphy et al.	29.3	93.9	26.1	98.0
	Wigley & Raper	17.8	89.6	20.3	84.9
2S	Murphy et al.	27.5	93.4	25.3	97.4
	Wigley & Raper	16.7	89.2	19.8	83.3
2a-550	Murphy et al.	25.4	92.8	24.3	96.1
	Wigley & Raper	15.2	88.2	18.8	79.5

Economic					
Scenario	Sensitivity	Linear	Squared	Cubic	Step change
		(% decrease in GDP)			
1S	Murphy et al.	3.1	3.2	3.3	4.5
	Wigley & Raper	2.5	2.3	2.2	2.6
1-575	Murphy et al.	2.9	2.9	3.0	3.8
	Wigley & Raper	2.3	2.1	2.0	2.3
2	Murphy et al.	2.8	2.8	2.8	3.5
	Wigley & Raper	2.3	2.0	1.9	2.2
2a-550	Murphy et al.	2.7	2.7	2.7	3.3
	Wigley & Raper	2.2	1.8	1.8	2.0
		(NPV $Trillion 1990)			
1S	Murphy et al.	95.0	84.5	82.6	119.8
	Wigley & Raper	77.8	60.8	57.3	82.4
1-575	Murphy et al.	90.2	77.4	74.9	107.1
	Wigley & Raper	73.7	55.8	52.0	76.4
2	Murphy et al.	86.6	72.6	69.6	97.1
	Wigley & Raper	77.8	60.8	57.3	82.4
2a-550	Murphy et al.	83.9	68.9	65.7	92.6
	Wigley & Raper	68.2	49.4	45.4	69.2

Table 3.4 Benefits of implementing mitigation actions in 2100 measured as the difference between risk-weighted impacts for a reference and four mitigation scenarios (the 1, 1-575, 2 and 2a-550 mitigation scenarios). Measures are four damages in biophysical systems and four measures of economic loss to global GDP. NPV in $2005 calculated from the GTEM economy using the UK Treasury Greenbook long-term discount curves.

Biophysical					
Scenario	Sensitivity	Species	Coral Reefs	THC slow-down	Greenland ice sheet
		(% damage)			Chance of loss (%)
1S	Murphy et al.	45.5	5.0	18.8	1.0
	Wigley & Raper	37.9	7.5	15.6	10.9
1-575	Murphy et al.	49.6	5.9	20.5	2.0
	Wigley & Raper	40.6	8.6	17.0	15.0
2	Murphy et al.	51.5	6.4	21.2	2.6
	Wigley & Raper	41.7	9.1	17.6	16.6
2a-550	Murphy et al.	53.6	7.0	22.2	3.9
	Wigley & Raper	43.2	10.0	18.5	20.4

Economic					
Scenario	Sensitivity	Linear	Squared	Cubic	Step change
		(% decrease in GDP)			
1S	Murphy et al.	1.9	4.2	5.3	11.3
	Wigley & Raper	1.6	2.9	3.5	7.3
1-575	Murphy et al.	2.1	4.5	5.6	12.0
	Wigley & Raper	1.7	3.1	3.7	7.6
2	Murphy et al.	2.1	4.6	5.8	12.2
	Wigley & Raper	1.8	3.2	3.8	7.7
2a-550	Murphy et al.	2.2	4.8	6.0	12.5
	Wigley & Raper	1.8	3.4	3.9	7.9
		(NPV $Trillion 1990)			
1S	Murphy et al.	25.6	51.0	61.9	192.8
	Wigley & Raper	21.0	35.9	41.2	114.2
1-575	Murphy et al.	30.3	58.1	69.6	205.4
	Wigley & Raper	25.1	41.0	46.4	120.2
2	Murphy et al.	34.0	62.9	74.8	215.4
	Wigley & Raper	21.0	35.9	41.2	114.2
2a-550	Murphy et al.	36.6	66.6	78.7	219.9
	Wigley & Raper	30.6	47.4	53.0	127.4

The benefits of implementing mitigation actions in 2100, as described by the EFF reference and mitigation scenarios are summarised as (based on the climate sensitivities in Table 3.3 and Table 3.4 and the two 575 stabilisation scenarios and rounded to the nearest 5%):

- Species at risk of extinction reduce from approximately 60–80% by 35–55% to 15–35%
- Damage to the Great Barrier Reef from heat stress reduces from almost 100% by 5–10% to 90–95%.
- THC slowdown reduces from 35–45% by 15–20% to 20–30%
- The likelihood of irreversible Greenland ice-melt commencing reduces from 100% by 1–20% to 80–99%.

For the economic damages (rounded to nearest whole number):

- The linear damages reduce from 4–5% by about 2% to 2–3%
- The quadratic damages reduce from 5–7% by about 3–5% to 2–3%
- The cubic damages reduce from 6– 9% by about 4–6% to 2–3%
- The step change damages reduce from 10–16% by about 7–13% to 2–5%

The economic benefits are strongly influenced by the hinge point, i.e. the point at which damages become strongly non-linear, and the degree of linearity. For these tests, the hinge point is 3°C. Therefore, when the range of warming in 2100 for the reference scenario, which is largely above 3°C, shifts to largely below 3°C for the reference scenarios, then the damage reductions are most significant for the most non-linear curves, but below 3°C the damages for all curves are similar. Therefore, stabilising greenhouse gases at levels that provide a high likelihood of avoiding a 3°C warming (which is relevant to this example, and is not a hard and fast conclusion) will provide significant benefits.

3.2.5 Contrasting costs and benefits

The final set of analyses compares the economic benefits of mitigating climate change with the costs. This is done through a Bayesian analysis that asks "What is the minimum economic damage in 2100 required to balance the costs of mitigation to 2050?" The results can help shed light on the different strategies outlined in Figure 1.7. Note that this is a partial analysis, because the benefits of mitigation will accrue beyond 2100 for slow-to-respond systems such as sea level, ice-caps and some ecosystems.

If the minimum economic damages prove to be on the high side of those from the published literature, then mitigation costs will look comparatively expensive with regard to the benefits. Therefore, as part of a multi-criteria analysis, added weight would need to be placed with the non-economic damages to balance the costs and benefits of action. However, if the minimum damages are on the low side of those published in the literature, then with added benefits of non-monetary and post-2100 damages avoided, the (total) benefits of mitigating climate change are likely to outweigh the costs. The main conditions where this would not be the case, would be if (both monetary and non-monetary) damages were much lower than projected and/or if climate sensitivity was at the very low end of expectations (~1.5–2°C).

Mitigation costs to 2050 calculated from the GTEM model by ABARE (Ahammad et al., 2006) provide estimates of the costs required to move towards a position in 2050 (Table 3.5), where stabilisation of CO_2 in the range of 550–575 ppm (excluding other greenhouse gases) can be achieved. However, the costs of mitigation are invested some time before the benefits of avoided damaged are realised. The analysis was carried out using a model that optimised the economic damage curve so that Net Present Value damage in 2100 equalled the Net Present Value of costs in 2050. UK Treasury Greenbook discounting was used to calculate damages on an annual basis from 1990 to 2100 in US$(2005) figures and a relationship between warming in 2100 and NPV established. This was achieved with statistical r^2 values exceeding 0.99 in all cases.

Table 3.5 Key projections for the global economy under alternative scenarios, 2050 (Ahammad et al., 2006).

Scenario	1	2a	2b	2c	2d
'Global' carbon tax 2005US$/t CO_2-e	59	75	119	119	74
Abatement of all GHGs relative to the reference case %	34	39	39	39	39
Total global product 2005US$trillion	161.3	160	158.7	158.7	160
Change in total global product relative to the reference case	−1.7	−2.6	−3.4	−3.4	−2.6
NPV of abatement in 2050 2005US$trillion	8.9	24.3	28.4	28.3	24.8
Overall economic costs per unit of abatement 2005US$/t CO_2-e	99	128	167	167	132

By changing the constants in the damage relationship, the relationship between warming in 2100 and NPV was then re-optimised so that NPV of mitigation in 2050 equalled the NPV of monetary damages in 2100. This provided new damage relationships between GDP and global warming. Two solutions were sought: 1) where the decrease in GDP is linear; and 2) where the decrease in GDP is a fully quadratic curve with no linear component.

Scenario 1 requires benefits with an NPV of $8.9 trillion in 2100 to fully account for the costs to 2050. The solution for scenario 1 using the Wigley and Raper (2001) climate sensitivity is shown in Figure 3.16. The linear solution requires slightly higher initial costs and the quadratic solution, slightly lower costs with a cross-over point of 3°C. The linear damage curve shows damages of 0.22% GDP per °C of global warming compared to the 1% used in the previous two analyses. Using the Murphy et al. (2004) sensitivity, the figure is 0.18% per °C of warming. The quadratic figures are losses in GDP of 0.076% and 0.052% per $°C^2$ global warming, respectively. These levels of damage are similar to Tol's (1992a) equity weighted curve (Figure 3.12), except for Tol's initial positive response, and lower than both Nordhaus and Boyer (2000) curves. This shows that damages much lower that those we analysed earlier, are likely to be sufficient on economic benefits alone, to justify the cost of moving from a reference to a Mitigation 1 future, using the GTEM reference economy.

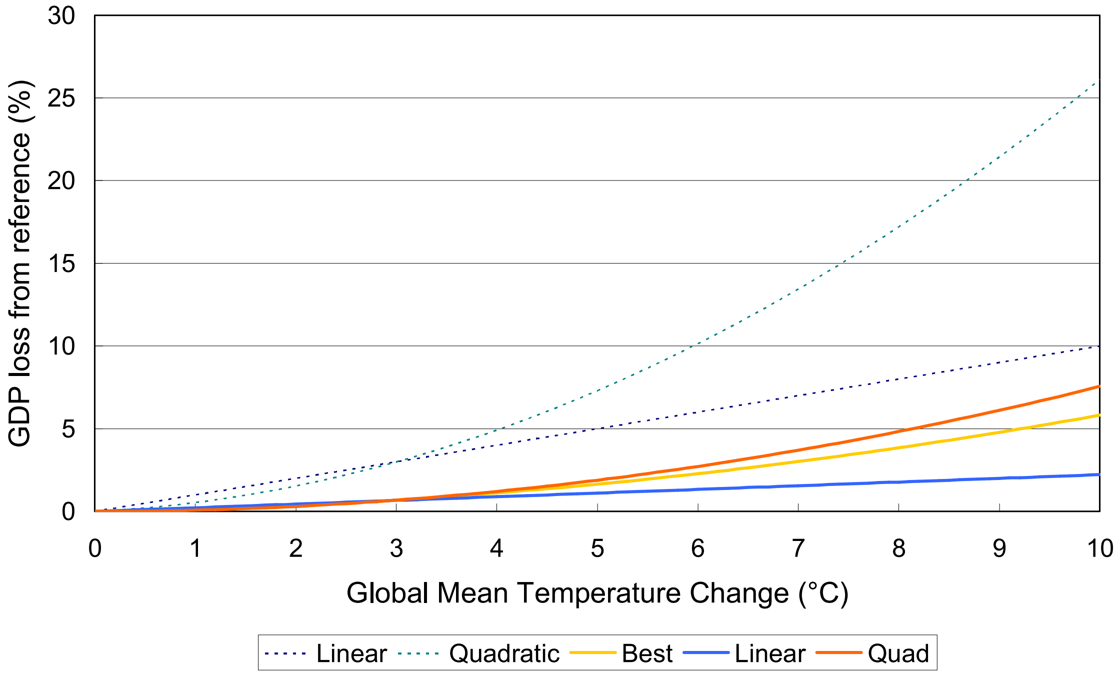

Figure 3.16 Minimum damage curves for the Mitigation 1-575 scenario measured as GDP loss per degree of global warming showing the best fit, linear and quadratic solutions. They are compared with the linear and quadratic damage functions from Figure 3.14. The climate sensitivity used is from Wigley and Raper (2001).

The solution for scenario 2a shows that a higher damage function is required to equalise the higher costs incurred in abatement. The linear damage functions are 0.60% and 0.50% per °C of global warming for the Wigley and Raper (2001) and Murphy et al. (2004) sensitivities, respectively, and the quadratic functions 0.20% and 0.14% per $°C^2$ global warming, respectively (Figure 3.17). These cost curves are significantly lower than the linear and quadratic cost curves used to estimate avoided damages in the previous section and are similar to Nordhaus and Boyer's (2000) output-weighted curve (Figure 3.12). The solution for scenario 2c ranges from 0.57–0.69% per °C of global warming and 0.16–0.24°C per $°C^2$ global warming.

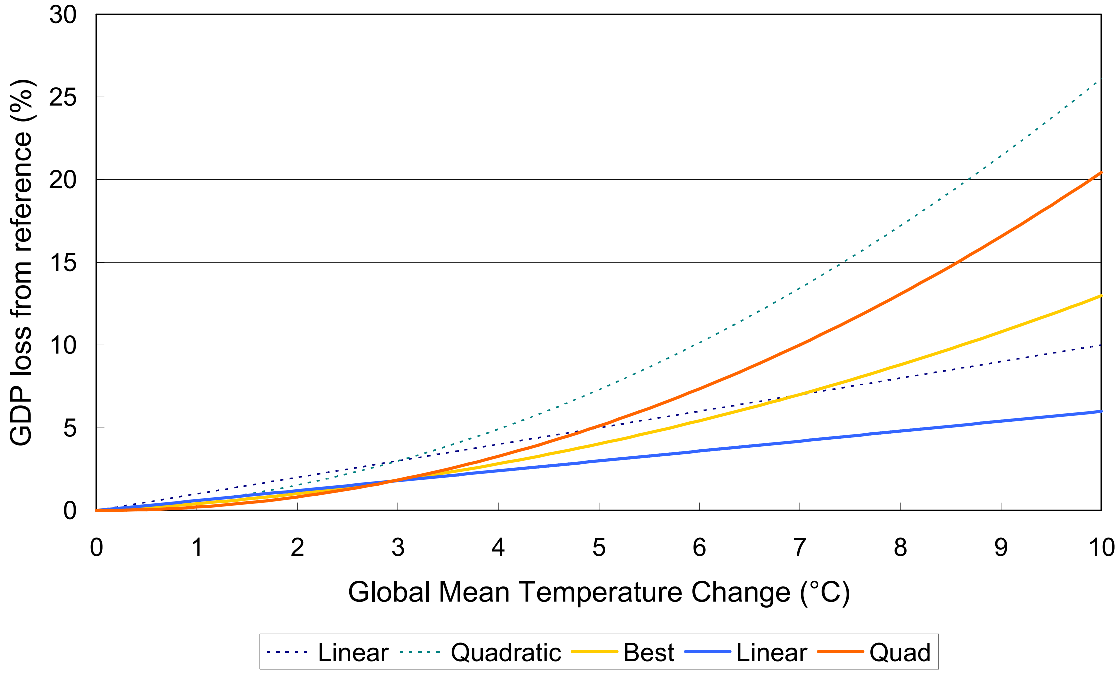

Figure 3.17 Minimum damage curves for the Mitigation 2-550a scenario measured as decrease in GDP per degree of global warming showing the best, linear and quadratic solutions. They are compared with the linear and quadratic damage functions from Figure 3.14. The climate sensitivity used is from Wigley and Raper (2001).

The assumption that the costs incurred to 2050 were relevant to damages avoided by 2100 were tested by creating another two scenarios, the 1W and 2aW or wedge scenarios, where only the amount abated by 2050 (i.e. 35% and 39% in 2050, or 6.2 and 7.2 Gt respectively), was subtracted from the reference scenarios, producing higher temperatures in 2100 than the stabilisation curves. The optimised economic damage curves were the same as those listed above confirming that accrued abatement costs by 2050 can be contrasted with avoided damages in 2100.

The costs of implementing scenario 1 is significantly less than for Scenarios 2a–d, but it yields 5% fewer cuts to emissions by 2050 and results in a slightly higher level of GHG stabilisation. Most of the difference between the 1 and 2a–d mitigation scenarios in terms of damages will only become apparent beyond 2100.

Although the damage estimates in Figure 3.16 and Figure 3.17 are inferred from the costs of abatement, they are consistent with damage estimates from the literature. This suggests that balance between costs and benefits can be achieved without taking the corollary benefits of mitigation and the non-monetized environmental and social benefits of avoided damages into account, i.e. a single bottom line assessment as opposed to a more complete triple-bottom line assessment. This inverse technique cannot be applied to the non-monetary damages because they are incommensurate with mitigation costs (see Jacoby, 2004). However, risk-weighting does allow both monetary and non-monetary damages to be compared and contrasted within a common framework. When the environmental and social benefits not included the monetary analysis are factored into the results, then the benefits of reducing emissions from the mitigation to reference case look increasingly positive.

3.3 Conclusions

In this report we have outlined a framework for comparing the climate and policy-related risks and benefits of climate change (Chapter 1). The psychological framing of risk suggests that the decision space comparing climate with policy risks is asymmetrical. This is because losses are perceived differently to gains. Where there are losses to a particular area that have a high degree of risk averseness or precaution attached to it, then a higher burden of proof is required to engage in risk-taking, or change, behaviour (e.g. Hansson, 1999). Therefore, the questions "*Can we afford to act on climate change?*" and "*Can we afford to not act on climate change?*" are not interchangeable.

For this reason, we have developed risk assessment techniques that allow the comparison of climate and policy risks by comparing risks to both monetary and non-monetary impacts under reference and mitigation greenhouse gas emission scenarios. The monetary analyses take the form of an expected value analysis that takes into account risk-weighted estimates of climate sensitivity and cost curves, expressed as the percentage damage to GDP as a function of global warming. Different estimates of climate sensitivity from the literature are also applied. Non-monetary risk analyses are carried out for damage functions developed to assess extinction risk to species, damage to coral reefs, decline in north Atlantic thermohaline circulation and melting of the Greenland ice sheet.

Chapter 2 describes the major uncertainties contributing to the assessment of climate impacts and demonstrates methods used in climate risk analysis. Risks facing a range of Australian sectors exposed to climate, namely: natural ecosystems, cropping, forestry, and livestock, water resources, public health, settlements and infrastructure and extreme weather events are summarised as are large-scale singularities, which are global in scale. Damage functions for the four key biophysical impacts chosen for further assessment are described. In Chapter 3, we assess the benefits of implementing the mitigation scenarios in terms of reduced biophysical and economic risks.

3.3.1 The costs of not addressing climate change

The reference scenario produced by ABARE projects emissions similar to the IPCC SRES A2 scenario to 2030, and then slightly higher emissions growth to 2050. This scenario was extended to 2100 by projecting a constant rate of emissions growth from 2050. For climate sensitivities of 1.5°C, 2.6°C and 4.5°C, mean global warming in 2100 ranges between 2.6°C and 5.7°C with a mid-range (as measured for climate sensitivity) warming of 4.0°C. These levels of warming are in higher part of the IPCC (2001a) range of 1.5–5.8°C. Higher, but much less likely values of climate sensitivity would push warming beyond 5.7°C.

Chapter 2 assesses impacts for a range of Australian sectors as a function of global warming, suggesting that the risks to some aspects of natural systems and water resources are high, whereas most systems with a strong socio-economic component face more moderate risks due to their adaptive capacity (Table 3.6). However, risks to food and fibre production depend greatly on the direction of rainfall change, so for many regions the risks could range from low to high. Higher atmospheric CO_2 could also lead to net improvements in yield if temperature increases can be constrained. Warming of 4.0°C by 2100 is rated as >40% likely by all four probability distributions of climate sensitivity. Such levels of warming would very likely result in severe impacts for both Australia and the world, the resulting impacts possibly constituting "dangerous anthropogenic interference with the climate system" as defined by the ordinary observer. Such changes would result in loss of most of all of the worlds coral reef systems, the majority of species being at risk, melting of the Greenland ice-sheet and a severe curtailing of the ocean's thermohaline circulation. They would exceed the capacity of many systems to adapt, including some of these rated as having moderate to high capacity in Table 3.6.

Table 3.6 Summary of risks to a range of sectors in Australia, rated low, moderate or high. The risks are judged subjectively based on a broad literature (summarised in the report) associated with the range of mean global warming of 2.6°C and 5.7°C in 2100, projected from the reference scenario. Low risks imply that damages are relatively minor after adaptation, moderate risks imply significant damages after adaptation and high risks imply severe damages after adaptation.

System	Sensitivity	Adaptive Capacity	Risk
Natural Systems			
Coral Reefs	High	Low	High
Alpine Ecosystems	High	Low	High
Endemic Species	Moderate to high	Unknown (limited?)	Moderate to high
Cropping, forestry and livestock			
Cropping	Low to High	High	Moderate
Livestock	Moderate to high	Moderate	Moderate to high
Forestry	Low to moderate	Moderate	Moderate
Water Resources			
Urban Water Supply	High	High	Moderate to high
Irrigated agriculture	High	Moderate	Moderate to high
Industry (inc hydro)	Moderate	High	Moderate
Wetlands	High	Moderate	High
Public Health			
Heat stress	Moderate	High	Low to moderate
Disease vectors	Moderate	High	Low
Indigenous health	High	Low to moderate	High
Settlements and Infrastructure			
Energy	Low to moderate	Moderate to high	Low to moderate
Coastal Settlements	Low to high	Moderate to high	Moderate to high
Extreme weather events			
Floods	Moderate	Moderate to high	Moderate
Fire	High	Moderate	Moderate to high
Tropical cyclones	Moderate	Moderate	Moderate
Extreme hot days	Moderate to high	Moderate	Moderate

3.3.2 The benefits of addressing climate change

Two sets of mitigation scenarios, 1 and 2a–d, projected to 2050 by ABARE, were extended to 2100. Two types of projection are used for these scenarios: (1) constant emissions from 2050 and post-2050 reductions along the lines of the IPCC A1T marker scenario. The latter leads to CO_2 stabilisation in the range 550–575 ppm CO_2.

The mitigation scenarios produce significantly lower ranges of warming by 2100 (Table 3.7). Reductions in warming by 2050 are about 20–35% and by 2100 are 50–65% of the reference scenario. The reductions are proportionally greater for cases with low climate sensitivity. The small differences between the constant rate and stabilisation mitigation scenarios beyond 2050 show that most of the benefits in 2100 can be attributed to mitigation before 2050. This is due to the inertia of the Earth's climate system, where most greenhouse gases remain for many years in the atmosphere and radiative changes take some time to warm the atmosphere and especially, the oceans. Compensating changes in greenhouse gas emissions (positive radiative forcing) and sulphate aerosols (negative radiative forcing) also contribute to similar warming between each set of constant emission and stabilisation scenarios.

The benefits of avoiding climate-related damage by 2100 were estimated by applying risk-weighted damages to both the reference and mitigation scenarios and assessing the resulting reductions in risk. Temperatures for the EFF reference, mitigation 1 stabilising at 575 ppm CO_2 and mitigation 2a–d scenarios stabilising at 550 ppm CO_2 are shown superimposed with biophysical damage curves in Figure 3.18 and with monetary damage curves in Figure 3.19. The bands of temperature exceedance span the uncertainty between probabilistic estimates produced by Wigley and Raper et al. (2001) and Murphy et al. (2004). A benefit of moving from the reference to a mitigation scenario can be read from the graphs by moving left from the reference to a mitigation scenario in a horizontal direction to estimate probability of exceedance, then moving down towards the x-axis. The point where the line crosses a damage function will be the risk of damage at a given temperature.

Table 3.7 Global mean warming in 2050 and 2100 in °C for the EFF reference and mitigation scenarios at three levels of climate sensitivity (1.5, 2.6 and 4.5°C).

Year		**2050**			**2100**	
Sensitivity (°C 2xCO_2)	***1.5***	***2.6***	***4.5***	***1.5***	***2.6***	***4.5***
Reference	1.2	1.8	2.4	2.6	4.0	5.7
1S	1.0	1.5	2.1	1.5	2.4	3.5
1-575				1.5	2.3	3.4
2aS	0.9	1.4	1.9	1.4	2.2	3.2
2a-550				1.3	2.1	3.2

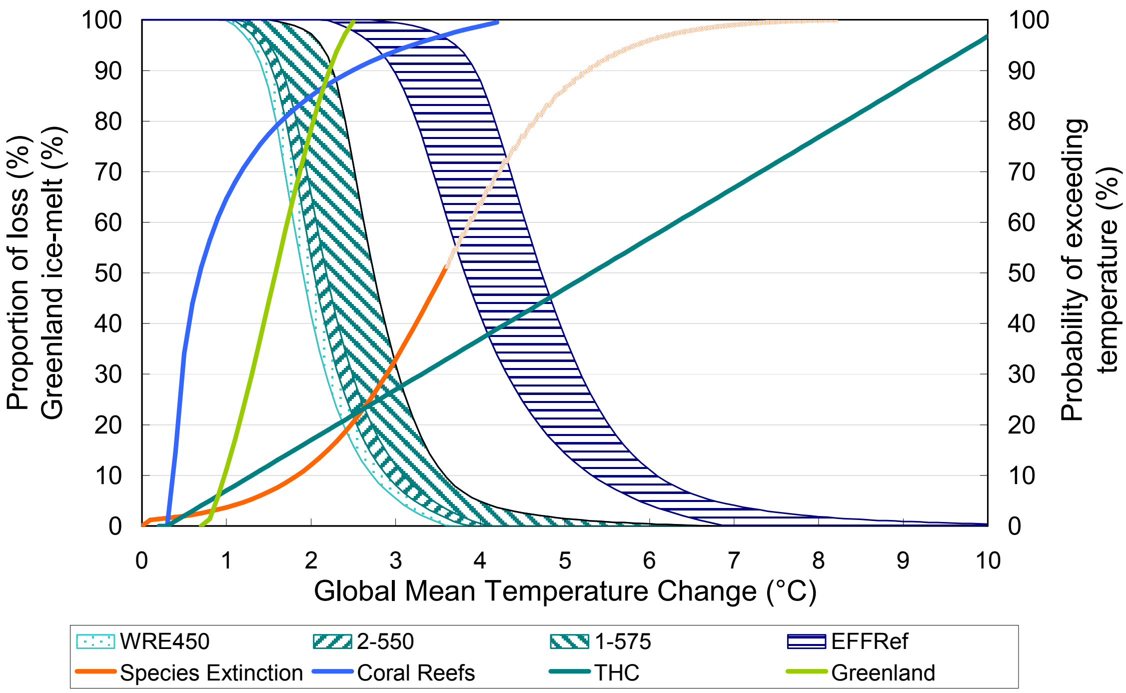

Figure 3.18 Damage curves for four key biophysical vulnerabilities plotted with the probability of exceeding a given level of global mean temperature change. Biophysical vulnerabilities are risk of species extinction, proportion of loss of coral reefs due to thermal bleaching, slowdown in North Atlantic thermohaline circulation and the probability of commencement of irreversible melting of the Greenland ice-sheet. Scenarios are EFF reference, mitigation 1 stabilising at 575 ppm CO_2, mitigation 2a–d scenarios stabilising at 550 ppm CO_2 and the WRE450 scenario stabilising at 450 ppm CO_2. The exceedance warming curves incorporate probability density functions for climate sensitivity from Wigley and Raper (2001) and Murphy et al. (2004). Note that part of the range of exceedance for the mitigation 2-550 and WRE 450 scenarios are obscured.

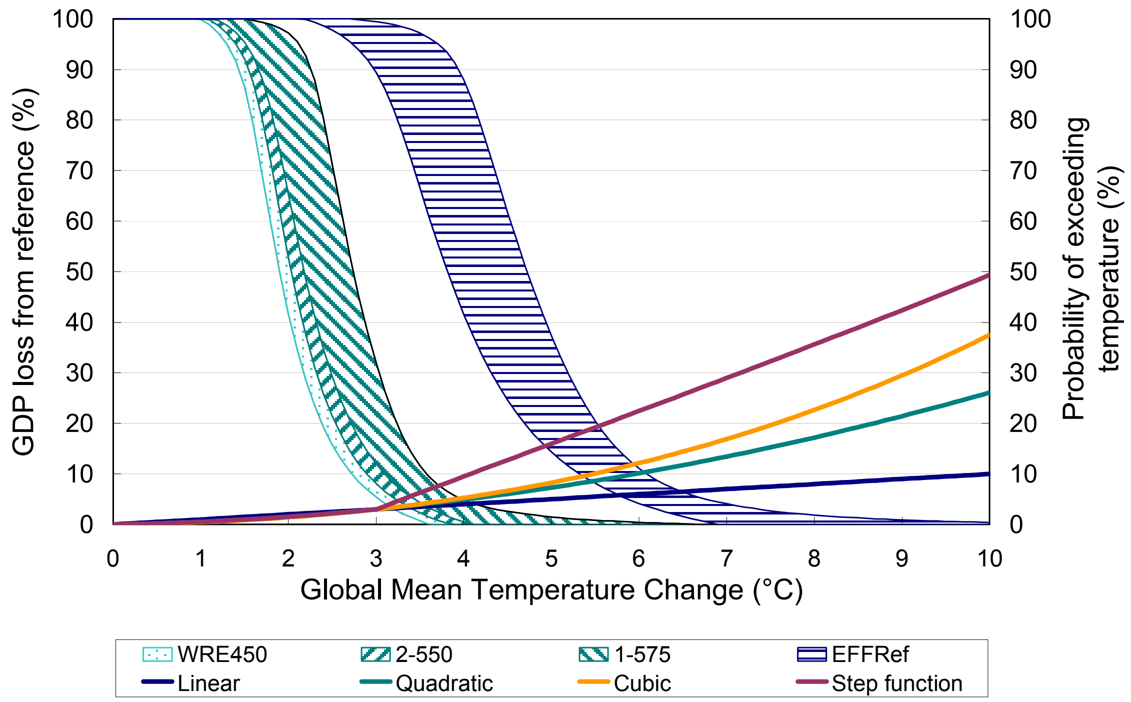

Figure 3.19 Different conceptual damage curves for percentage decrease in global GDP plotted with the probability of exceeding a given level of global mean temperature change. Biophysical vulnerabilities are risk of species extinction, proportion of loss of coral reefs due to thermal bleaching, slowdown in North Atlantic thermohaline circulation and the probability of commencement of irreversible melting of the Greenland ice-sheet. Scenarios are EFF reference, mitigation 1 stabilising at 575 ppm CO_2, mitigation 2a–d scenarios stabilising at 550 ppm CO_2 and the WRE450 scenario stabilising at 450 ppm CO_2. The exceedance warming curves incorporate probability density functions for climate sensitivity from Wigley and Raper (2001) and Murphy et al. (2004). Note that part of the range of exceedance for the mitigation 2-550 and WRE 450 scenarios are obscured.

For example, if we were interested in hedging against outcomes with a 50% likelihood of occurrence, then the likely warming in 2050 is about 3.8–4.8°C with the uncertainty being due to different probability distributions of climate sensitivity. Reading vertically, from these temperatures, this would mean melting of the Greenland ice sheet, >95% of coral reefs critically damaged, 60–85% of species at risk and a slowdown in the thermohaline circulation from about 35–40%. Damages to Australian systems are less quantified but risks to coral reefs and species are as above, snow cover and alpine ecosystems are almost totally removed, damages from extreme events (temperature, rainfall, extreme winds) have increased by about 150% to more than double, globally averaged sea level rise would exceed 40 cm. Impacts to water, agriculture, forestry and fire will largely be dictated by changes in rainfall, but if declines over large regions of Australia occur, then impacts to these sectors will also be substantially negative. According to the economic sensitivity analysis, damages would exceed 5% GDP.

50/50 hedging with mitigation scenarios, would see a decline in projected temperatures to a range extending from <2°C to about 2.7°C, with a range of benefits across most sectors. Substantial risks to Greenland ice sheet melting and coral reefs remain, species risk is still large but is reduced to <25% and THC reduces to a similar amount. Economic damages reduce by more than half.

Most of the analyses in this assessment used risk-weighted damages rather than hedging according to a particular probability of exceedance for temperature or damage. In terms of where they are located on the scale of exceedance, risk-weighted damages are still relatively conservative compared to a precautionary approach, but gives more weight to low probability – high consequence outcomes than does the use of the maximum likelihood approach (Figure 3.15). Most of the impact relationships are right-skewed towards higher temperatures.

The benefits of mitigation actions are expressed in the reduction of risk-weighted damages between the reference and mitigation scenarios. Risk-weighted damages shown in Table 3.8 take into account two expert distributions of climate sensitivity that count as low and high-weighted examples of the plausible range of sensitivity. Biophysical benefits include significant reductions in the risk of species extinction and a reduced rate of THC slowdown. Furthermore, the range of impacts listed in Table 2.2 to Table 2.7 will reduce from >3–4°C by 2100 to ~1.5–3°C. Benefits are greatest where temperatures move down the damage curve substantially. If warming associated with the mitigation scenario is still high on the damage curve, then there will be some benefit. Emissions would have to be reduced even further to produce more substantial benefits. Table 3.8 also shows the avoided economic damages for the four reference scenarios. Benefits are in the range of 2–3% GDP by 2100 for most of the scenarios.

Table 3.8 (Upper) Summary of damages for the EFF reference and mitigation 1-575 and 2-550 scenarios taking into account two expert distributions of climate sensitivity, along with the benefits of avoided damages. (Lower) Summary of costs of mitigation for the four reference scenarios (see Ahammad et al., 2006 for scenario assumptions).

Benefits			
	Reference (%)	**Mitigation (%)**	**Benefit (%)**
Biophysical impact			
Species at risk	60–80	15–35	35–55
Coral reefs	~100	90–95	5–10
THC slowdown	35–45	20–30	15–20
Greenland ice melt	~100	80–99	1–20
Economic impact			
Linear	4–5	2–3	2
Quadratic	5–7	2–3	3–5
Cubic	6– 9	2–3	4–6
Step change	10–16	2–5	7–13
Costs			
Scenario	**Global carbon tax (2005US$/t CO_2-e)**	**Total GDP (2005US$trillion)**	**Change in GDP (%)**
1	59	161.3	−1.7
2a	75	160.0	−2.6
2b	119	158.7	−3.4
2c	119	158.7	−3.4
2d	74	160.0	−2.6

Given that the economic scenarios are on the high side of published estimates, we conducted an inverse analysis to optimise the minimum damage curves required to balance the costs of mitigation in 2050 with the benefits of avoided economic damage in 2100. Both sets of costs were accumulated costs/damages measured in Net Present Value and discounted according to the UK Treasury Greenbook (beginning at 3.5% pa and decreasing to 2.5% over time). Two solutions were sought: a linear solution in percent damage per °C of warming, and a quadratic solution per $°C^2$ of warming (Figure 3.16, Figure 3.17).

For the mitigation 1 scenario, the damage curve required to balance costs with economic benefits was about 20% of that used in the economic sensitivity analysis. The result was slightly higher than 20% for the Wigley and Raper (2001) climate sensitivity and slightly lower for the Murphy et al. (2001) climate sensitivity. Higher climate sensitivity, because of the resulting higher warming will optimise into a lower damage curve required to balance benefits with costs. Figure 3.20 compares damage curves per degree of global warming from Nordhaus and Boyer (2000) and Tol (2002b) with the minimum damages required to optimise the NPV of costs in 2050 with that of benefits in 2100. Both the N&B and Tol equity-weighted damage curves are higher than the optimised damage curves for the mitigation 1 scenario. Although the Tol curve is positive for low increases, these increases are committed to in both the reference and mitigation 1 scenarios. Note that the Nordhaus and Boyer (2000) and Tol (2002b) curves originally shown in Figure 3.12 have been changed by 0.5°C to match the baseline for warming of 1990.

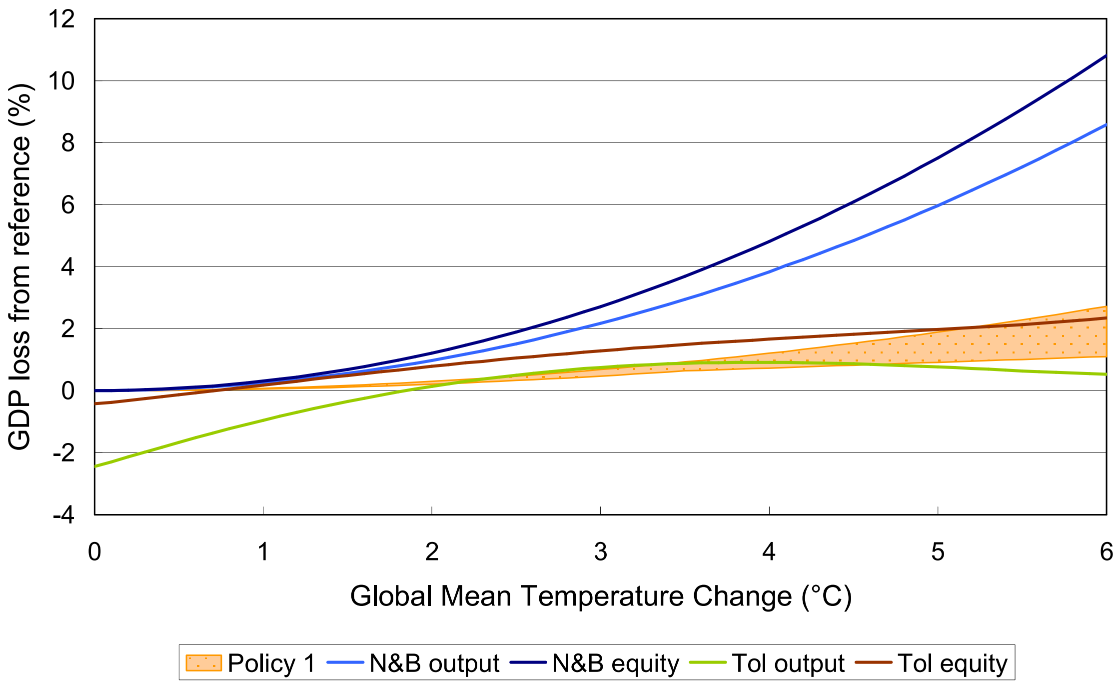

Figure 3.20 Comparison of optimised damage curves required to balance NPV of costs of mitigation in 2050 with the benefits of reduced damages between the reference and mitigation 1 scenarios in 2100. The curve includes results under climate sensitivity from Wigley and Raper (2001) and Murphy et al. (2004). Damage curves from Nordhaus and Boyer (2000) and Tol (2002b) are also shown.

The mitigation 2a scenario (the least cost of the 2a–d scenarios) has optimised damage curves of about 60% of the damages used in the sensitivity analysis. The mitigation 2b and c scenarios, the most expensive in NPV terms to 2050, reach about 70% of the damages used in the sensitivity analysis. Figure 3.21 shows that the optimised minimum damages are higher than both Tol curves but lower then the N&B curves.

The optimised damage curves represent somewhat different damages. The published damage curves are based on a long-run static assessment – e.g. the Tol (2002b) assessment extends to 2200. If NPV estimating the balanced benefit/cost was calculated to 2200, the optimised damage curves would be substantially lower than they are here. Therefore, in one sense the optimise damage curves to 2100 do not represent the total monetary benefits that would be gained beyond 2100, so they are conservative.

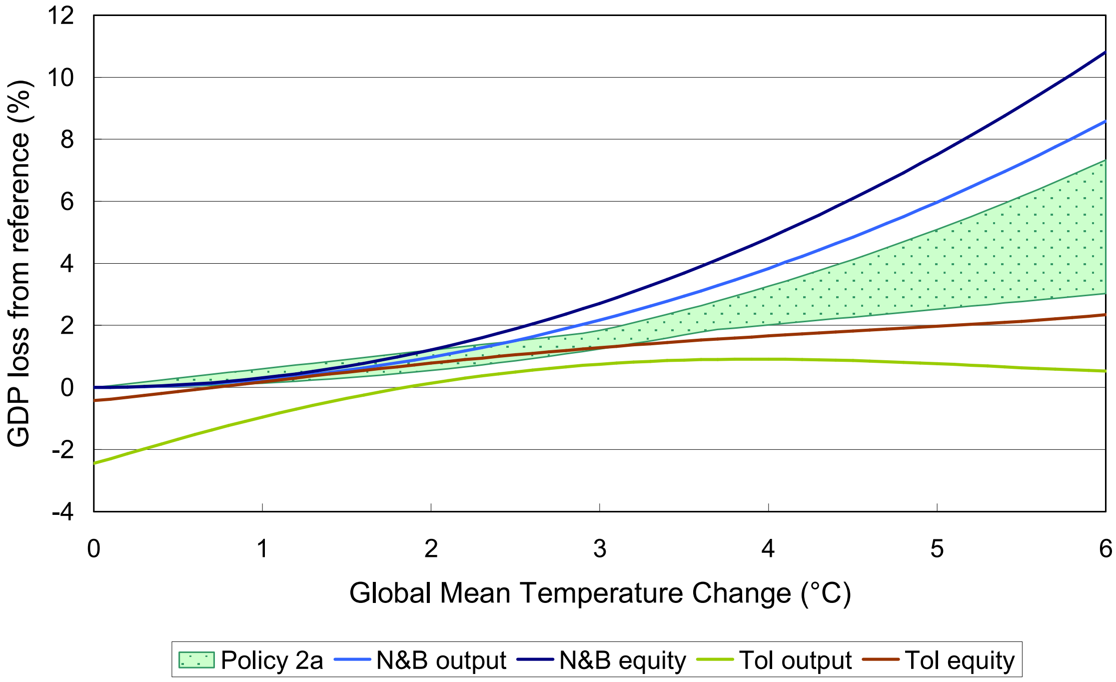

Figure 3.21 Comparison of optimised damage curves required to balance NPV of costs of mitigation in 2050 with the benefits of reduced damages between the reference and mitigation 2a scenarios in 2100. The curve includes results under climate sensitivity from Wigley and Raper (2001) and Murphy et al. (2004). Damage curves from Nordhaus and Boyer (2000) and Tol (2002b) are also shown.

The value of the optimised damage curves is that they show that the benefits of avoided damage on a global basis can be achieved by 2100 with damage costs in the low to mid range of published estimates. The limitations of published estimates is that they fail to accommodate fast rates of warming, climate variability, the adjustment costs of adaptation and damages from large-scale singularities (e.g. Stern et al., 2006). This suggests that costs that may be anticipated under high emissions business-as-usual, or reference scenarios such as the one used in this study, may be significantly under-estimated. When the non-monetary benefits of avoiding damage to ecosystems and to natural, social and cultural environments are added to the monetary benefits of avoided damage, then the costs to 2050 as modelled by ABARE (Table 3.5), are likely to be outweighed by the benefits, unless climate sensitivity is very low (i.e. ~1.5°C). This is thought not to be very likely (Kerr, 2004).

Tol (2005) correctly states that the marginal costs of different strategies in reducing climate change damages over time are more important than calculating the total costs. This is certainly the case in jurisdictions where policies to achieve stabilised greenhouse gas concentrations in the atmosphere are being explored. However, it is still a valuable task to undertake because of the limited consideration of the benefits of mitigation in some areas of the policy community. The methods applied here can also be used to assess marginal benefits, offering a range of new techniques to such analysis (Jones and Yohe, 2006).

3.3.3 Caveats and confidence

In this study, we have endeavoured to use the full range of quantified uncertainty where possible and conservative assumptions where using a range of uncertainty has not been possible. However, our assumptions were not conservative in the use of economic damage curves to estimate benefits of mitigation. The monetary damage curves utilised qualify as sensitivity tests only; the relatively high rates of damage would be disputed by many economic experts, especially for those at higher temperatures. For example, Tol (2005) believes that the social costs of carbon in US$2000 are likely to be less than $50 per tonne. The total costs of mitigating greenhouse gases in 2050 according to ABARE are attached to tonnes CO_2, and when converted into tonnes C range between $27 and $46 US$2005. Because these latter figures are undiscounted and those assessed by Tol are, they are likely to fall into the lower part of Tol's range. Few economic assessments have been carried out for temperatures >5°C, therefore the likely costs for high emission scenarios with climate sensitivities >3°C are unknown.

We still have little idea about how the economy might be affected if large-scale biophysical systems were to substantially alter – it is these uncertainties that lead natural and environmental scientists to attach much higher damages to climate change than economists (Figure 3.13). Therefore, even though economic damages may be relatively low at warmings of <3°C, the shape of an economic damage curve is likely to be highly non-linear, especially at higher levels of warming. However, its magnitude and degree of non-linearity is uncertain. Downing et al. (2005), Tol (2005), Nordhaus (2006) and Stern et al. (2006) nominate a number of ways in which economic damage estimates can be improved.

Uncertainty as to economic damages was the main reason why we used inverse methods to balance the benefits to 2100 against the costs to 2050. This analysis suggests that the benefits could well outweigh the costs, even with conservative assumptions about likely economic damages. Because significant environmental damage is likely under the reference scenario, those with a high willingness to pay to avoid such damage (the environmentally risk-averse), would conclude that the costs are very affordable. As such, best risk management policy from Figure 1.7 may be early intervention, with the chance of committing a false positive, or finding out in hindsight that such actions were not warranted, being very low. Further work would help to illuminate the likely outcomes of a range of strategies, such as those summarised in Figure 1.7.

Uncertainties also surround the key biophysical vulnerabilities detailed in the report. The use of damages curves summarising estimates from the literature is one method of managing such uncertainties but these estimates continue to be plagued by high uncertainties. Setting a safe minimum standard is one method that applies a precautionary approach, but we detail why some decision makers eschew such an approach in Chapter 1 of the report.

Uncertainties also surround the emissions scenarios themselves. The ABARE modelling did not explicitly provide estimates of some important emissions, including non-fossil fuel CO_2, sulphate aerosols, nitrous oxides, carbon monoxide and volatile organic carbons. Emissions from 2050 were not modelled explicitly and were assumed to increase at rates similar those between 2030 and 2050. Nor did our modelling take any account of impacts of climate on emission rates, science which is still in the exploratory phase.

However, there are a range of aspects of this work in which we have a reasonable degree of confidence:

- Due to recent growth in energy use and in projections of energy use high rates of emissions under reference conditions are expected to 2050 (and see Sheehan et al., 2006).
- Such rates of emissions growth combined with estimates of climate sensitivity higher than the previous IPCC consensus estimates suggest that the range of warming in 2100 under the reference scenario is in the upper part of the IPCC (2001a) range.
- Testing of different probability distributions for climate sensitivity also indicate how the results may change if other underlying uncertainties were to vary substantially.
- Dangerous anthropogenic influence to the climate system as defined by the UNFCCC Article 2 is possible under the reference scenario.
- Impacts for Australia under the reference scenario are likely to be overwhelmingly negative, especially if projected rainfall decreases eventuate.
- The mitigation scenarios developed by the EFF produce significant benefits by 2100.

In conclusion, the reference scenario of the EFF encompasses a business-as-usual future with some mitigation efforts which has an emphasis on using the cheapest available energy and technology. Emissions produced by the ABARE model GTEM applied to a simple climate model projects mean global warming by 2100 between 2.6°C and 5.7°C (1.5 and 4.5°C climate sensitivity, respectively) with the prospect of significant further warming beyond 2100. Such a pathway would set the world well on the path to achieving "dangerous anthropogenic interference with the climate system" as outlined in the United Nations Framework Convention on Climate Change. Mitigation scenarios produced by the Energy Futures Forum and modelled by ABARE suggest that significant benefits will be produced by 2100. Inverse modelling of the minimum damage curve required to balance the costs of mitigation to 2050, suggests the following conclusions:

1. The "minimum economic benefit" for Scenario 1 in 2100 is at the low end of estimates from the literature showing that, even after allowing for uncertainty, most outcomes are *very likely* to be positive. In other words, regrets due to over-expenditure on mitigation are *very unlikely*[‡‡] for this scenario. A high value placed on accompanying environmental and social benefits will strengthen this conclusion.

2. The "minimum economic benefit" for Scenarios 2a–d in 2100 is near the middle of the range of estimates from the literature showing that, even after allowing for uncertainty, most outcomes are *likely* to be positive. In other words, regrets due to over-expenditure on mitigation are *unlikely* for this scenario (less than one-third probability). A high value placed on accompanying environmental and social benefits will strengthen this conclusion.

[‡‡] Here, terms used to communicate uncertainty are consistent with those used in the IPCC Third Assessment Report (IPCC, 2001), where *likely* is >66% probability and *very likely* is >90% probability. *Very unlikely* is <10% and *unlikely* is <33%.

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