ECONOMIC MODELLING TECHNICAL PAPER 2

CLIMATE DATA METHODOLOGY AND ASSUMPTIONS

OCTOBER 2008

Garnaut
CLIMATE CHANGE
REVIEW

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This is the second in a series of Technical Papers of the Garnaut Climate Change Review's discussion of the methodology and results of Modelling of the Net Costs of Climate Change Mitigation. Other Papers in the series, available on the Review's website www.garnautreview.org.au are as follows:

Technical Paper Number 1: Overview and approach to the economic modelling

Technical Paper Number 2: Climate data, methodology and assumptions

Technical Paper Number 3: Assumptions and Data Sources

Technical Paper Number 4: Methodology for modelling climate change impacts

Technical Paper Number 5: Modelling the costs of unmitigated climate change

Technical Paper Number 6: Global Climate Change Mitigation: Implications for Australia

Technical Paper Number 7: The net costs of global mitigation for Australia

1 Introduction

Modelling the economic costs of climate change impacts and the extent to which impacts might be avoided through mitigation requires assumptions regarding the extent of climate change under the no-mitigation and policy scenarios.

This Technical Paper outlines the major assumptions, methodology and models used to determine the climate outcomes at the global, regional and local scale. The climate outcomes were used as inputs into the Review’s modelling and discussion of climate change impacts, and the assessment of climate risk in the Final Report.

Section 2 of this paper addresses the treatment of scientific uncertainty in future climate change in the Review’s modelling exercise.

Section 3 of this Technical Paper outlines the choice and development of the climate scenarios used in the modelling of climate change impacts in the Review’s modelling. Section 2.2 describes the methodology and key elements of the climate data used in the Review’s economic modelling of climate change impacts in Australia – also referred to as the SIMCAP/SRES scenarios after the source of the data. These scenarios are also the basis of the qualitative analysis of climate change and impacts in Australia in Chapters 5 and 6 of the final report.

Section 3.3 describes the more complex methodology that utilised the economic, concentration goal and technology assumptions in the joint Garnaut-Treasury modelling exercise (detailed in Technical Papers 3 and 4) to develop internally consistent emissions scenarios and concentration profiles. These concentration profiles were used in two ways. Firstly, they were input into the Global Integrated Assessment Model (GIAM) to develop model inputs relating to changes in Australia’s terms of trade and export demand. Secondly, the concentration profiles were used to inform the broader analysis of global climate change and impacts, and the risk of catastrophic climate outcomes and events undertaken outside of the modelling. These scenarios are referred to as the ‘final Garnaut scenarios’.

Section 3 discusses how the global climate outcomes were used to determine the more varied impacts at the state and local scale within Australia.

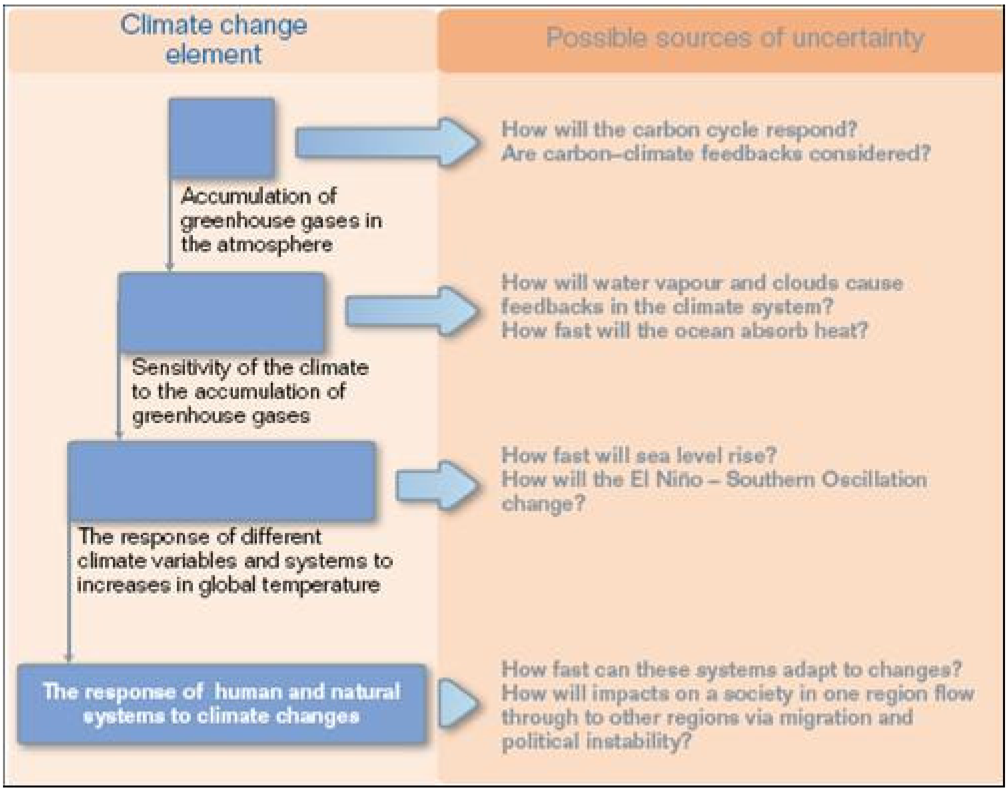
2 Uncertainty in the climate science

As discussed in Chapters 1 and 2 of the Final Report, climate models predict a wide range of outcomes for a given emissions trajectory. The dominant sources of uncertainty in the climate change science relate to:

- the rate of greenhouse gas emissions and how these relate to the concentration of these gases in the atmosphere ;
- the degree of warming that results from that concentration; and
- and the timing and extent of impacts from each degree of warming – these include large scale global impacts such as the melting of the Greenland ice sheet, but also more localised impacts such as variation in rainfall.

The cumulative nature of these uncertainties (see Figure 2) means that the range of outcomes can be considerable.

Figure 2. Cumulative nature of uncertainties in the climate change science for a given pathway of future emissions



Events beyond the control of humans, such as changes to solar radiation or large volcanic eruptions, can also have a considerable impact on the climate. Natural sources of uncertainty, while significant during the 20th century, are expected to diminish in relative importance during the 21st century as emissions continue to grow. However, humans can only directly manage the changes resulting from human activities, and therefore like most assessments of climate change the Review's modelling focuses on the human influence.

In addition to external influences that lead to climate change, the climate system itself is highly complex, so we cannot simply extrapolate past trends to project how the climate might change in the future. Models are therefore an important tool for simulating and understanding the climate, and how it will respond to future changes in greenhouse gas concentration. Atmosphere–ocean general circulation models are representations of the climate system that contain millions of mathematical equations that represent the way the climate system works, based on the scientific theory and tested against observed climate data.

The ability of climate models to accurately simulate responses in the climate system is dependent on the level of understanding of the processes that govern the climate system, the availability of observed data for various scales of climate response, and the computing power of the model – all of which have improved considerably in recent years (CSIRO & BOM 2007). Confidence in models comes from their ability to represent patterns in the current climate and past climates, and is generally higher at global and continental scales. For some elements of the climate system such as surface temperature, there is a high level of agreement on the pattern of future climate changes. Other elements such as rainfall are related to more complex aspects of the climate system such as atmospheric circulation, and are not represented with the same confidence in models.

2.1 Techniques for assessing the range of possible climate outcomes

There are a range of possible techniques for reflecting the range of possible climate outcomes from varying input assumptions and uncertainty in the climate response. The way different types of uncertainty are assessed and communicated depends on the type of uncertainty and the time and resources available to a project.

Emissions scenarios

Greenhouse gas emissions in the future are key to the assessment of future climate change. To estimate the magnitude of climate change in the future it is necessary to make assumptions about aspects of human society in the future including economic growth, political and policy decisions, social response and technology change. An understanding of the level of difficulty in such projections can be gained by considering the changes that occurred in human population and society during the 20th Century – imagine the difficulty of predicting these changes back in 1900.

To deal with this uncertainty, internally consistent and plausible descriptions of possible futures referred to as ‘storylines’ and ‘scenarios’ are often used. Often a number of scenarios are presented that cover a range of possible outcomes, but they are different to predictions or forecasts, which indicate the likelihood of such an outcome. Probabilistic futures are those that have an assigned likelihood, but these are often linked to specific underlying assumptions. The assigned probabilities may also be imprecise or qualitative (CSIRO and BOM, 2007).

To provide a basis for the assessment of future climate change, the IPCC published a Special Report on Emissions Scenarios (SRES) in 2000 that presented series of emissions scenarios based on a variety of assumptions about population and economic growth, and changes in technology and energy use (IPCC 2000).

These scenarios have formed the basis of climate change assessment in both the Third and Fourth Assessments of the IPCC and many other research papers and reports, including the Stern Review on the Economics of Climate Change (2007) and Climate Change in Australia (CSIRO and BoM, 2007).

The SRES scenarios depict a range of different possible futures in a world without climate change mitigation, and are not assigned probabilities of occurrence - there is no single most likely, "central", or "best-guess" scenario. Each scenario group has been considered plausible. However, the latest analysis, presented in Chapter 3 of the Final Report, suggests that the world is growing, and will continue to grow, more rapidly, with higher emissions, than factored into the SRES scenarios. The Garnaut Review develops and utilises new projections based on this analysis..

Multi-model and sensitivity analysis

By using a range of models, it is possible to attach likelihoods to outcomes, with a higher likelihood placed on the most frequent model-derived outcomes. However, the outcomes at the high or low end of a range of model results may also be plausible, and given the lack of confidence and agreement in some model projections it would be misleading to discount them. The choice of method by which likelihoods are calculated is also subjective, with no “best” method currently being recognised, so the management of uncertainty throughout this process is vital. Transparency and robustness (testing how outcomes rely on assumptions) are important. Furthermore, if the scientific understanding underpinning these models is lacking or flawed, the uncertainty range may not be representative of the potential outcomes.

For example, to test the effect a given model assumption may have on a result, a ‘sensitivity analysis’ can be undertaken. These analyses involve varying certain inputs in both plausible and implausible ways in order to explore how they lead to uncertainty in the outputs. If the outputs of interest are found to be insensitive to changing a particular input, uncertainty in that particular input is not material (CSIRO and BOM, 2007).

The uncertainties embodied in different input assumptions and the interactions between them, can be tested through techniques such as 'Monte Carlo' analysis, which involve thousands of simulations being run which draw randomly from a set of input values.

Estimates of likelihood can be established by looking at the range of outcomes from both these techniques. Where computing power is limited, an analysis of the medium, high and low ends of probability of a certain outcome can be used to explore the potential range of impacts.

Assessment of uncertainty in the form of multi-model simulations, Monte Carlo analysis and sensitivity analyses takes additional time and resources, and in some cases extensive cooperation between different parts of the modelling community. In many cases, the rigorous inclusion of all uncertainties will not necessarily change the central outcome, but rather expand or clarify the possible range. The use of resources to establish climate uncertainty more clearly, or establish the outcomes for the full plausible range of climate outcomes, must be weighed up against exploration of other aspects of the modelling exercise, such as the choice of policies and mitigation assumptions.

2.2 The treatment of climate uncertainty in the Review's modelling exercise

The modelling exercise undertaken by the Review was highly complex and involved making assumptions about decisions and actions far into the future. In addition to the large range of 'plausible' climate inputs, other key unknowns on in the modelling of impacts included how sensitive economies, societies and ecosystems would be to those impacts and the level of adaptation.

On the mitigation side of the modelling key uncertainties include the form, timing and strength of international mitigation efforts, the cost and availability of mitigation technologies in the future, the future demand for energy and emissions intensive goods, which policies will be implemented domestically and how successful they will be. The cost of mitigation – and the level of 'avoided climate change'- is also very dependent on the assumptions underpinning the 'no-mitigation' scenario against which policy scenarios are compared, as this influences key cost determinants including the structure of the future economy and the amount of mitigation required.

As mentioned above, understanding how sensitive the outcomes of a model are to given assumptions takes time and resources. The complexity of the Review's modelling task and the limited time available made a comprehensive 'sensitivity analysis' very difficult – particularly given the huge scope of potential climate outcomes and impacts.

This section briefly outlines the approach taken by the Review in dealing with the large plausible range of potential climate outcomes. Sensitivity analysis of mitigation costs are discussed in Technical Papers 3, 4, and 7.

Climate uncertainty at the global scale

The future trajectory of global emissions without mitigation is dependent on many factors. Section 2.2 discusses how the IPCC uses a range of emissions scenarios based on different assumptions that are all considered equally plausible. The Review did not have the capacity to fully consider more than one 'no-mitigation' future, so a single set of assumptions was chosen which represents the Review's best assessment of plausible central estimates within the likely range of possible values. As discussed in Chapter 3 of the Final Report, the Review considers that even the higher SRES scenarios underestimate the rate of emissions growth early in the 21st century, making them an inappropriate basis for climate change and mitigation modelling.

The time and resources of the Review did not allow the use of multiple models to assess the associated global temperature increase. The climate response to these scenarios was assessed using a climate model (MAGICC – see Box 2) and the IPCC's 'best-estimate' climate sensitivity of 3ºC (see box 1).

The temperature outcomes could be considered to estimate the median of the potential range. Sensitivity runs of the final Garnaut scenarios were undertaken to establish the temperature outcomes under climate sensitivities of 1.5ºC and 4.5ºC, but these were not included in the modelling exercise. The possibility, potential impacts and risks of lower or much higher sensitivities that contribute to the 'Type 3' modelling costs are discussed qualitatively in Chapters 1, 4 and 11.

Box 2.1. Climate sensitivity

Climate models generate a wide range of estimates as to how the climate system will respond to increased concentrations of greenhouse gases in the atmosphere. This range occurs as a result of limitations in scientific understanding and in the computing power of the models. Since the IPCC Third Assessment Report (2001), substantial progress has been made in understanding differences in climate response between models. The largest source of uncertainty in the current estimates is in the direction and magnitude of changes in cloud properties in response to other atmospheric changes.

The response of the climate system to greenhouse gas concentrations is referred to as 'climate sensitivity'. The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing, defined as the global average surface warming following a doubling of carbon dioxide concentrations. In the Fourth Assessment Report (2007), the IPCC estimates that it is likely that climate sensitivity is between 2°C and 4.5°C. It is considered very unlikely that climate sensitivity will be less than 1.5°C, but values substantially higher than 4.5°C – including as high as 10ºC - cannot be excluded, but agreement with observations is not as good for those values (see Figure x.x). The best estimate of the IPCC is about 3°C.

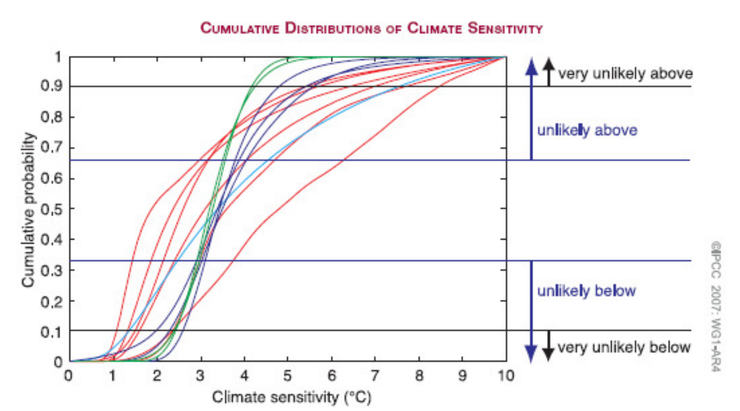


Figure x.x (IPCC, 2007 (WG1 TS), Fig TS25). Cumulative distributions of climate sensitivity derived from observed 20th-century warming (red), model climatology (blue), proxy evidence (cyan) and from climate sensitivities of AOGCMs (green). Horizontal lines and arrows mark the boundaries of the likelihood estimates defined in the IPCC Fourth Assessment Uncertainty Guidance Note.

Climate uncertainty at the local scale

The method used to determine the local response to global temperature rises in terms of a range of climate variables is discussed in further detail in Section 4. This method produces probability density functions that assign a likelihood to a given climate response. The Review was therefore able to consider the median, or 50th percentile outcome, as well as the higher and lower ends of the distribution – the 10th and 90th percentiles – for a given climate sensitivity.

There is a high level of disagreement between models in the projected changes in local rainfall levels and patterns in response to a given temperature increase (Chapter 4). Rainfall and water availability are of key importance to many areas of the economy, and hence the rainfall assumptions in the model could be expected to be a key factor in the assessment of climate change impacts.

To take into account the uncertainty in local rainfall outcomes, two rainfall sensitivities were investigated for the no-mitigation and 550 scenarios. Under the 450 scenario the difference between the two outcomes was small enough not to be relevant. Chapter 4 notes that local temperature and rainfall are linked – higher rainfall outcomes are also likely to be locally cooler. To retain internal consistency, the local temperature outcomes were also adjusted to give the following scenarios, discussed in further detail in Section 3:

- Central case: 50th percentile rainfall and relative humidity surface for Australia (best-estimate), 50th percentile surface temperature.
- Hot/dry case: 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile surface temperature.
- Warm/wet case: 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile surface temperature.

Time limitations meant that only the central case could be fully incorporated into the Review's modelling exercise. The outcomes of the warm/wet and hot/dry scenarios are discussed in Chapter 6.

3 Global climate scenario development

In order to assess the economic impacts of climate change in Australia the Review needed to select a limited set of emissions scenarios reflecting futures with and without climate change mitigation to determine the temperature and concentration profiles for input into the modelling.

The differential impact of climate change and climate change mitigation on the economies of other countries – particularly Australia's key trading partners and competitors – will influence Australia's terms of trade and demand for our exports into the future. To determine the economic impacts of these changes, global economic modelling was required with Australia explicitly recognised as a separate region. As part of this modelling exercise, the recent high levels of economic growth in China and India and the impact on global emissions were incorporated along with up-to-date economic and technology assumptions (see Final Report Chapter 3).

The relevant climate input assumptions for the modelling of Australian climate change impacts, such as the greenhouse gas concentration profile and temperature increase over time, were generated early in the modelling exercise using pre-existing scenarios and models. The methodology for the development of the climate assumptions used in the modelling are described below.

Key global climate assumptions used in the assessment of the economic impacts of climate change were average global temperatures and carbon dioxide concentrations. The methodology for determining localised impacts is discussed in Section 4.3.

As noted in Technical Paper Number 1, due to time constraints it was not possible to base the climate change impacts modelling on the same scenarios and assumptions used in the mitigation modelling. The complexity of the analysis and modelling required that the impacts modelling commence prior to the Review's development of its own no-mitigation and mitigation global scenarios.. Thus the Review used externally available scenarios for the impacts modelling (3.2) chosen to correspond closely to the Review's own scenarios (3.3) The two sets of scenarios are compared in section 3.4 below.

3.1 Choice of concentration goals

To represent mitigated climate change, the Review needed to identify appropriate concentration goals to model. The Terms of Reference for the Review referred to stabilisation at between 450 and 550 ppm Some stakeholders recommended that the Review explore lower targets such as 400 ppm CO2-e.

On 14 November 2007 the Review held a public forum and roundtable discussion aimed at gathering both public and expert opinion on the choice of stabilisation levels to model. Feedback from these discussions indicated that targets of 450ppm and 550ppm CO2-e (hereafter 450 and 550 levels) were the most relevant for investigation as part of the modelling process, including because of the prominent position this range holds in international policy discussions. The Review therefore chose these to underpin the global mitigation futures in the economic modelling.

Given the current atmospheric concentration of greenhouse gases, it is only feasible to model a 450ppm CO2-e stabilisation goal with a concentration overshoot - that is, allowing for a period during which concentrations exceed the target level.

3.2 Scenario development for Australian climate change impacts (SIMCAP/SRES scenarios)

This section describes the methodology and key results of the climate data used in the Review's economic modelling of climate change impacts in Australia. It is also the basis of the qualitative analysis of climate change and impacts in Australia in Chapters 5 and 6 of the final report.

No-mitigation scenario

The climate data assumptions for the assessment of the economic impacts of climate change in Australia in the absence of mitigation were based on an existing high emissions growth scenario from the Special Report on Emissions Scenarios (SRES) published by the IPCC in 2000.

The SRES scenarios are well established in the literature, and are detailed in their assessment of non-carbon dioxide gases and anthropogenic land emissions and sequestration. A considerable amount of data is available from a large number of global climate models in relation to the projected climate change impacts associated with each of the SRES scenarios. The use of an SRES scenario allowed the Review to draw on these existing studies, and also enables comparison with the outcomes of other international impact studies.

As discussed in the 'Garnaut Review Interim Report to the Commonwealth, States and Territory Governments of Australia', early analysis carried out for the Review suggested the likelihood, in a world without mitigation policy, of continued growth of emissions in excess of the highest IPCC scenarios. A1FI – the fossil fuel intensive scenario with the highest cumulative emissions over the 21st century – was considered the most plausible scenario in terms of realistic assessments of future carbon intensity, population growth and technology options. A1FI was used as the basis for determining the Australian impacts of climate change. The climate outcomes for the A1FI scenario were taken from MAGICC 4.1 (Wigley, 2003), using the A1FI-MiniCAM illustrative scenario.

Box 3.1 The MAGICC simple climate model

MAGICC (a Model for the Assessment of Greenhouse gas Induced Climate Change) is a simple climate model consisting of a suite of coupled gas-cycle, climate and ice-melt models. It reproduces changes for major variables such as greenhouse gas concentrations, mean global radiative forcing, warming and sea level rise consistent with more complex climate models.

MAGICC is readily available and is designed to allow users to assess the global-mean temperature and sea level changes that might arise from future emissions of greenhouse gases and other atmospheric components, such as aerosols, which affect the extent of global warming. It also allows users to determine the sensitivity of key climate outcomes for a chosen emissions scenario to changes in and uncertainties in model parameters, such as the climate sensitivity.

The Review's analysis used MAGICC version 4.1, which is calibrated to the climate outcomes to the results of seven global climate models used in the Third Assessment Report (TAR) of the IPCC. The corresponding version for the IPCC Fourth Assessment Report (2007) - version 5.3 - became available only in June 2008, but was too late for use in the Review's modelling exercise. The standard settings for MAGICC were used with the exception of climate sensitivity, where the 'best-estimate' of 3°C was used based on the outcomes of the IPCC Fourth Assessment Report 2007.

The latest version of MAGICC can be download a http://www.cgd.ucar.edu/cas/wigley/magicc/index.html

Policy scenarios - assumptions and development

The temperature and concentration outcomes for the climate change impacts element of the mitigation scenarios were developed using Simple Model for Climate Policy assessment (SIMCAP) developed by Meinshausen et al (2005), available for download at http://www.simcap.org/.

SIMCAP was developed as a tool for analysing emissions mitigation actions. It derives emissions pathways from existing multi-gas IPCC baseline and stabilisation scenarios and for a mitigation target defined by the user. Climate change outcomes are calculated using an in-built simple climate model, MAGICC 4.1, (which is a built-in module of SIMPCAP).

SIMCAP allows the user to enter mitigation targets in various forms and modify various parameters to provide outputs out to 2400 for greenhouse gas emissions and concentrations in the atmosphere, and a range of climate outcomes. SIMCAP does not analyse the economic impact or assess the feasibility or source of emissions reductions. However, restrictions are placed on the range of possible outcomes by assumptions relating to the maximum rate of reductions in emissions, as well as a maximum rate of change in the rate of emissions (i.e. it will not allow a very sharp move from rising emissions to decreasing emissions).

While there are a small number of comprehensive mitigation scenarios in the literature (den Elzen et al, 2007), the flexible, accessible and reproducible nature of the SIMCAP outputs was considered appropriate for this element of the modelling. The resulting pathways were assessed for the feasibility of the maximum rate of emissions reduction and land use assumptions as per the current available literature.

Two global emission pathways from SIMCAP were used in the impacts modelling – a 550 ppm CO2-e scenario in which concentrations approach the stabilisation level without overshoot; and a 450 ppm CO2-e scenario in which concentrations initially overshoot to 500 ppm before returning to a lower level. The overshoot assumption reflects the practical barriers to the extremely rapid short-term emissions reductions that would be needed to achieve 450 ppm without overshoot. The assumptions used to develop the policy scenarios are described in Appendix B.

A limitation of the SIMCAP model is that the emission pathway for the early years of the 21st century are based on emissions scenarios such as SRES and WRE stabilisation scenarios, which have not been updated to reflect the recent high growth in global emissions or reductions in aerosol emissions as a result of recent aggressive cuts in sulphate emissions in OECD countries and future aggressive cuts assumed for regions such as India and China (Sheehan et al, 2008). Higher levels of emissions will affect the rate of increase in atmospheric concentrations, and the reduction in aerosols will affect the temperature outcome.

3.3 The Garnaut Review global scenarios

The Review also developed its own no-mitigation and mitigation global scenarios.

No-mitigation scenario

The population, energy and economic assumptions relevant to the global emissions outcomes of a world with no mitigation policy were developed as part of the joint modelling between the Review and the Australian Treasury, and underpinned by the analysis in Chapter 3 of the final report. The reference case technology and economic assumptions are described in further detail in Technical Paper no. 3.

The trade impacts of climate change and its mitigation were determined using the Global Integrated Assessment Model (GIAM) (see Box 3.2).

Box 3.2 The Global Integrated Assessment Model

The impact of unmitigated climate change on regional and global economic growth was determined using the Global Integrated Assessment Model (GIAM) (Gunasekera et al. 2008), developed collaboratively by the CSIRO and the ABARE. The principal reason for using GIAM was to capture the trade effects of the different levels of climate change associated with mitigation. However, GIAM also allowed global estimates of climate change damages to be modelled. GIAM is structured through a five step process:

1. Develop a scenario of the world's economy without climate impacts using GTEM (the Garnaut-Treasury reference case). GTEM is a long-run version of ABARE's global; trade and environment model resolved in 13 geographic regions and 19 economic sectors. It is designed to capture the impact of policy changes on a large number of economic variables across all sectors of the economy, and it includes comprehensive treatment of greenhouse gas emissions and different global energy sources.
2. Use the emissions outputs from GTEM to determine the change in greenhouse gas concentrations over the modelling period using the climate and atmospheric component of the simple climate model MAGICC version 4.1 (Wigley 2003).
3. Using the concentration profile, determine the associated changes in regional temperature using the low-resolution general circulation model, CSIRO MK3L (Phipps 2006).
4. Use the damage function in GIAM, adapted from the integrated assessment model MERGE (Manne and Richels 2004) to determine the regional loss in factor productivity as a result of projected changes in regional temperature and the ratio of GNP per person relative to that of a benchmark economy (United States).
5. Re-run the economic module of GIAM after incorporating climate change damages as a reduction in regional total factor productivity.
6. Repeat steps 2-5 until successive trajectories of climate and economic output differ less than some small predetermined criteria.

As GIAM is iterated to convergence, the economic damage from climate change leads to a small reduction in emissions and hence smaller temperature increases and lower climate change impacts. For the mitigation scenarios the emissions limit is externally imposed. Therefore changes to the economy as a result of climate change impacts do not reduce emissions further, but changes to economic variables are taken into account.

Mitigation scenarios - assumptions and development

This section outlines the approach taken to develop emissions scenarios to meet a given concentration target. Defining the global target in terms of a concentration target rather than an emissions limit means that the complexities of carbon cycle modelling must be considered in the development of the emissions pathway, as the time and type of emissions changes the concentration outcome (see Chapter 2 of the Final report).

The global emissions pathways used in the mitigation modelling were constructed within the global model GTEM. While GTEM has a sophisticated economic component and greenhouse gas emissions database, it does not have an internal carbon cycle model. As a result, simultaneous analysis of the atmospheric concentrations and emissions pathway was not possible. Instead, an iterative approach was used where the GTEM outputs were run through the carbon cycle component of MAGICC, and the initial carbon price assumptions adjusted until the atmospheric concentrations broadly matched the desired target levels.

GTEM includes sectoral emissions of combustion and non-combustion carbon dioxide, methane, and nitrous oxide. All outputs are provided in carbon dioxide equivalent emissions using the Kyoto global warming potential conversion factors.

As noted in Chapter 9 of the Final Report, and discussed further in Technical Paper 7, the global emission pathways were developed in a way that imitates an efficient allocation of global mitigation effort over time.

GTEM generates estimates of global emissions of the gases covered by the Kyoto Protocol (the Kyoto gases). Emission estimates are converted within GTEM to the common metric of CO2-equivalent using the 100-year global warming potentials specified in the Kyoto Protocol. While this is a convenient metric for communicating aggregate emission levels, it is less appropriate for calculating climate effects such as radiative forcing and temperature change. The GTEM outputs were therefore converted back to estimates for each individual gas before being input into MAGICC. Emission estimates for methane and nitrous oxide were adjusted upwards to account for emission sources not fully represented in GTEM.

In determining aggregate concentration and temperature outcomes used in the Review's analysis of climate outcomes and risks for the final report, the following assumptions were made about the non-Kyoto greenhouse gases:

- Sulphate aerosols (and other aerosols) and tropospheric ozone were not included in the consideration of the long-term target. As discussed in Chapter 2 of the final report, emissions of aerosols and ozone pre-cursors are closely associated with fossil fuel combustion, which is expected to be close to zero under mitigation scenarios. These gases are also short-lived in the atmosphere, so they will not persist for long after emissions have ceased – hence, they are less relevant in the context of long-term target setting.
- The assumptions for the Montreal Gases were based on the SRES scenarios. While the SRES scenarios do not accurately represent recent trends in fossil fuel emissions, they provide robust estimates of Montreal gases due to the effectiveness of the Montreal Protocol.
- Other greenhouse gases such as tropospheric ozone, nitrogen oxides other than N2O, the fluorinated gases were scaled from the updated WRE550 and WRE450 scenarios (Wigley et al., 1996), according to updated CO2 in the 550 and 450 scenarios, respectively.

The reduction of aerosol emissions from fossil fuel combustion is now considered to be likely to happen much faster and to be deeper than in the SRES emission scenarios. Sulphate aerosols were therefore scaled from figures derived as part of the work done in the exploration of future emissions in Garnaut et al 2008, representing recent aggressive cuts in OECD countries (van Vuuren and O'Neill, 2006) and future cuts assumed for current high aerosol emitting regions such as India and China. Aerosol emissions were scaled down to minimal levels by 2100 in line with the significant cuts in CO2 emissions. All parameters used in MAGICC were set at the default settings with the exception of climate sensitivity, which was set at 3ºC in line with the Fourth Assessment Report 'best-estimate' (see Box 2.1).

Regional temperature outcomes for the final Garnaut scenarios

The regional temperature outcomes for the final Garnaut scenarios - needed to estimate climate change trade impacts - were determined using the climate component of GIAM, a low-resolution general circulation model known as CSIRO Mk3L (see Box 4).

Box 3.3 The CSIRO MK3L Model

The CSIRO Mk3L climate system model (Phipps 2006b) is a low-resolution, computationally efficient climate model. It includes three-dimensional representations of the motions of the atmosphere and ocean, and therefore is classified as a general circulation model. The atmospheric component contains descriptions of atmospheric transport, radiative exchange, convection and clouds. The radiation calculations treat longwave and shortwave radiation separately, and include the effects of carbon dioxide, ozone, water vapour and clouds. The quantities that are predicted include temperature, humidity, precipitation, evaporation, wind speed, cloud cover and the radiative fluxes.

It also contains a land surface model, an oceanic component and a sea ice model is included. Mk3L divides the Earth's surface into 64 by 56 horizontal grids This comparatively low resolution enables the components to be integrated relatively quickly, so that a 100- year simulation can be completed in around 5 days on a typical high-performance computing facility.

MAGICC v4.1 was used to determine the change in atmospheric concentration over time for carbon dioxide, methane and nitrous oxide. The concentration time series for the three gases were then converted into carbon dioxide equivalent concentrations, and input into the MK3L model. Regional temperature outputs were obtained for input into the climate change damage function.

3.4 Scenario outcomes

SRES/SIMCAP scenarios

The A1FI scenario demonstrates consistently high global emissions growth throughout the 21st century. In 2100, the projected global average temperature is 4.5ºC above 1990 levels (using a climate sensitivity of 3ºC), carbon dioxide concentrations are 976 ppm CO2, and the concentration of long-lived greenhouses is 1434 ppm CO2-e. A summary of the policy scenarios is included in Table 1.

Table 3.1 Summary of the SIMCAP mitigation and SRES no-mitigation scenarios (used for Australian impact analysis)

Scenario	550 ppm CO2-e	450 ppm CO2-e	A1FI (no-mitigation)
Global carbon dioxide emissions	Emissions peak in 2025 at 10 Gt C	Emissions peak in 2015 at 8.5 Gt C	Emissions increase throughout century to over 30 Gt C in 2100
Long-lived greenhouse gas concentrations	Peaks at 560 ppm CO2-e around 2080	Peaks at 500 ppm CO2-e around 2050	Reach 1240 in 2100
Timing of stabilisation	After 2120	After 2140	N/A
Carbon dioxide concentrations	Reaches 470 ppm CO2 in 2100	Peaks at 420 ppm CO2 around mid-century, less than 410 ppm CO2 by 2100	Reach 976 ppm CO2 in 2100
Global temperature in 2100 (above 1990 levels)	2ºC	1.5ºC	4.5ºC
Global temperature in 2400 (above 1990 levels)	2.3ºC (still increasing)	1.6ºC	N/A – scenario does not go beyond 2100.

Garnaut Review scenarios

Under the no-mitigation scenario, emissions continue to increase throughout the 21st century, with carbon dioxide emissions from fossil fuels and industrial activities reaching over 35 Gt C by the end of the century, almost 5 times current levels and 6 Gt C higher than the A1FI scenario in 2100. This leads to an accelerating rate of increase in atmospheric concentrations. By the end of the century, the concentration of long-lived greenhouse gases is 1565 ppm CO2-e, and carbon dioxide concentrations are over 1000 ppm—more than 3.5 times higher than pre-industrial concentrations. A summary of outcomes from the Garnaut scenarios is shown in Table 2, and the emissions of carbon dioxide, methane, nitrous oxide and sulphur aerosols for the final Garnaut scenarios are shown in Appendix C.

Table 3.2 Summary of Garnaut Review scenarios

Scenario	550 ppm CO2-e	450 ppm CO2-e	Reference case
Global carbon dioxide emissions	Emissions peak in 2030 at 10 Gt C	Emissions peak in 2030 at 9.5 Gt C	Emissions increase throughout century to over 36 Gt C in 2100
Long-lived greenhouse gas concentrations	Peaks at 575 ppm CO2-e around 2065	Peaks at 520 ppm CO2-e around 2050	Reach 1565 ppm CO2-e in 2100
Timing of stabilisation	After 2080	After 2100	N/A
Carbon dioxide concentrations	Peak at 476 ppm CO2 in 2065, reduce to 450 ppm CO2 by 2100	Peak at 440 ppm CO2 in 2050, reduce to 404 ppm CO2 in 2100	Reach 1030 ppm CO2 in 2100
Global temperature in 2100 (above 1990 levels)	2ºC	1.5ºC	5.1ºC
Global temperature in 2200 [1](above 1990 levels)	2.2ºC	1.1ºC	8.3ºC

Comparison of scenarios

The concentration pathways for the SRES/SIMCAP and Garnaut Review scenarios are compared in Figure 1. The Kyoto-gas concentration pathways for the Garnaut Review scenarios show a higher and later peak in concentrations. The slower approach to the peak reflects differences in the time profile of the SIMCAP and GTEM global emission pathways.

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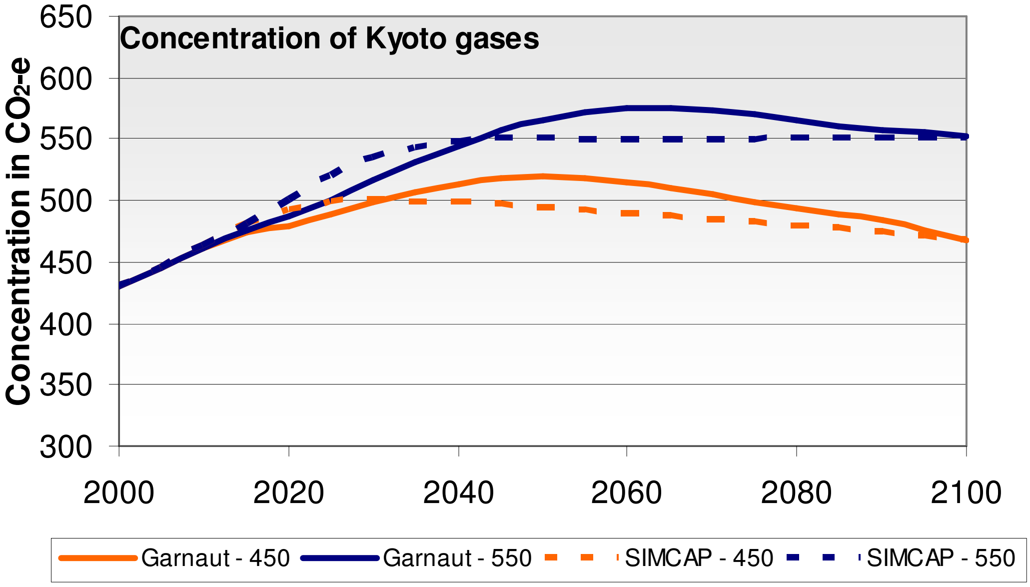
[1] Temperature outcomes beyond 2100 are calculated under the simplifying assumption that emissions levels reached in each scenario in the year 2100 continue unchanged. They do not reflect an extension of the economic analysis underlying these scenarios out to 2100, and are illustrative only. It is unlikely that emissions in the reference case will stabilise abruptly in 2101 with no policies in place, and hence the temperatures shown underestimate the likely warming outcomes if continued growth in emissions was assumed.

Figure 1. Comparison of concentration pathways for the 450 and 550 ppm CO2-e cases under the Review's mitigation scenarios (GTEM) and under the SIMCAP scenarios[2]



The global average temperature outcomes for the no-mitigation, 450 and 550 scenarios used in the Australian impacts assessment (SIMCAP) and the Garnaut Review scenarios are shown in Figure 2. The temperature outcomes under no-mitigation for the Garnaut Review scenarios are considerably higher than A1FI, largely due to the higher levels of emissions throughout the century (see Tables 3.1 and 3.2).

As discussed above, the sulphur dioxide emissions in the Garnaut Review scenarios reflect the aggressive cuts in these emissions that have been demonstrated recently in OECD countries and expected to continue. A1FI and the SIMCAP 450 and 550 scenarios are based on the higher aerosol emission assumptions from the older SRES (IPCC 2000) and WRE (Wigley et al. 1996) scenarios, leading to a much higher cooling influence in the early half of the century, shown by lower temperature outcomes for the SRES/SIMCAP scenarios in the short term (Figure 2).

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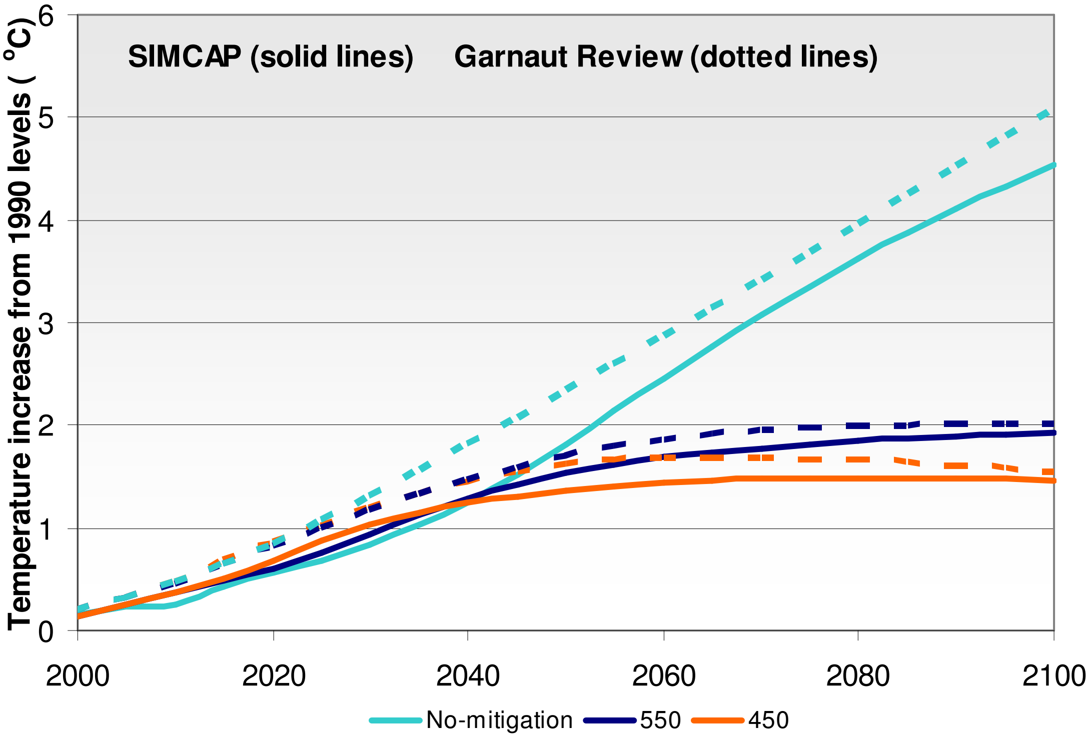
[2] The 450 scenario presented here is very marginal different to that presented in the Final Report. It is based on the same GTEM outputs but treat the non-CO2 gases slightly differently.

Figure 2. Global average temperature outcomes for the no-mitigation, 450 and 550 scenarios for the Garnaut Review and the SRES/SIMCAP scenarios[3]



The temperature profiles also demonstrate the extent to which the aerosol assumptions influence the temperature outcomes, as shown in Figure 3. In the 450 and 550 scenarios, the reduction in fossil fuel combustion as the carbon price is introduced leads to a reduction in sulphur dioxide aerosols which are associated with the combustion of fossil fuels. Figure 3 shows that this actually leads to an immediate increase in temperatures in the policy scenarios as the cooling influence of aerosols is very quickly reduced due to their short lifetime in the atmosphere. This is more pronounced in the SIMCAP/SRES scenarios due to assumptions of higher aerosol emissions in the no-mitigation scenario. In the modelling of economic impacts, this short term increase in temperatures under the policy scenarios actually leads to higher initial economic impacts from climate change (see Technical Paper 5).

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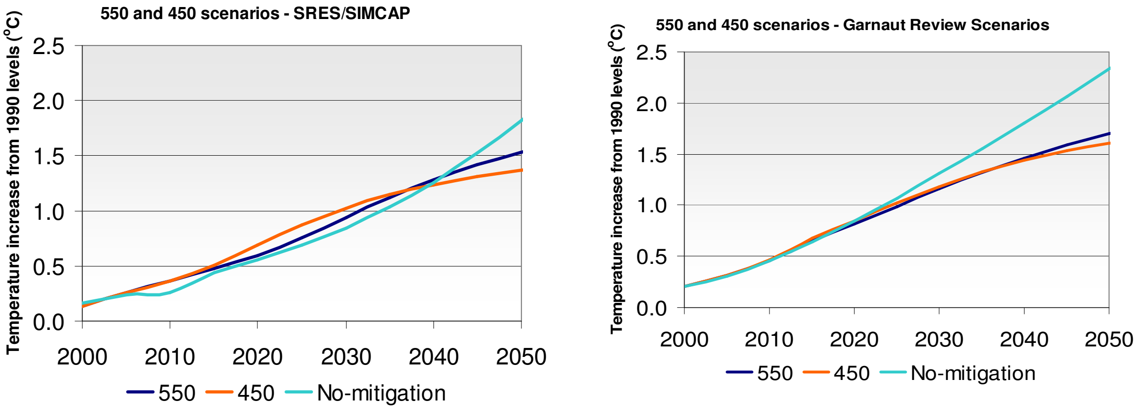
[3] The 450 scenario presented here is very marginal different to that presented in the Final Report. It is based on the same GTEM outputs but treat the non-CO2 gases slightly differently.

Figure 3. Global average temperature outcomes for the 450 and 550 scenarios for the Garnaut Review and the SIMCAP/SRES scenarios



As discussed above, regional temperature outcomes were determined using CSIRO MK3L general circulation model. Unlike MAGICC, which allows the user to impose a climate , the more complex nature of the Mk3L model that allows for regional temperature analysis means that the sensitivity of its climate response is endogenous to the model and cannot be externally imposed. However, equilibrium climate sensitivity is a measure of the amount of temperature change occurring from a doubling of carbon dioxide concentrations when the system reaches equilibrium, which can take thousands of years (see Chapter 2 of the Final Report). The rate at which the climate system changes is known as the 'transient climate response', and is more relevant to near-term climate outcomes.

To understand how the temperature outcomes of the MK3L model relate to other models, the temperature response was compared to other model outcomes for a selection of the SRES scenarios. The global average warming was found to lie within the given IPCC range for all the respective scenarios. However, Mk3L consistently lies within the lower half of the IPCC ranges for the 21st century. The temperature outcomes for the Garnaut Review scenarios were also found to be lower than the MAGICC outcomes in the period out to 2100 for the same set of assumptions (see Appendix D). Reasons for this may include the exclusion of long-lived halo-carbons from the forcing assumptions, which have a warming influence. Aerosols are also excluded from the climate forcing in Mk3L - in both the SRES scenarios and the Garnaut scenarios, aerosols are assumed to decrease over the 21st century, which would also have a positive warming effect. The CSIRO MK3L model also demonstrates a lower transient climate sensitivity than MAGICC, so that temperature increases are lower in the shorter term, which is the focus of the Review's modelling exercise.

The lower temperature outcomes in the period out to 2100 from the Mk3L model compared to MAGICC mean there could be a tendency to underestimate the international impacts of climate change in the 21st century.

4 Determination of local climate change

Global-scale assessments of climate variables simulated by general circulation models as described in Section 2 and Chapter 4 are generally not appropriate for assessing the impact of climate change at the local and state level. The climate interacts with local topographic features, such as coastlines and mountains, and local land uses to create significant variation in the local climate change response.

Due to the thermal inertia of the oceans, all land areas are expected to warm significantly faster than the global average temperature (see Chapter 4 of the Final Report). Most of coastal Australia will warm by roughly the same as the global average, but inland areas may warm up to 50 per cent more (Pittock 2007). There will also be different rainfall patterns, with much of southern Australia experiencing considerable decreases in annual mean rainfall and changes in the seasonality of that rain.

To assess the impact of climate change on different sectors and regions within Australia, it is necessary to have an understanding of the more localised changes in climate under the no-mitigation and policy scenarios.

The section discusses the methodology and briefly outlines the results of the assessment for the SIMCAP/SRES scenarios which were used to determine the economic impacts of climate change in Australia. These local climate sensitivities were also the basis of the discussion in Chapters 5 and 6 of the final report.

4.1 Methodology

The regional climate variables, including temperature, rainfall and relative humidity were calculated by the CSIRO from a range of climate models that have been tested and screened for their ability to simulate climate in the Australian region. Details can be found in the CSIRO and BoM 2007 climate projections for Australia (http://www.climatechangeinaustralia.gov.au/). A brief summary of the methodology is provided below.

CSIRO and BoM (2007) derived probabilistic changes in annual and seasonal averages for a range of climate variables in response to global average temperature rise. The probability distributions represent the outputs of a range of models available from the Coupled Model Inter-comparison Project (CMIP3). CMIP3 is a collection of outputs from 23 global coupled ocean-atmosphere general circulation models run largely between 2002-2006 to inform the IPCC's Fourth Assessment Report (2007) .

Each of the 23 models was assessed for their performance in simulating key aspects of the Australian climate under present-day conditions. The models were then given a weighting based on a score that reflected the current climate performance for three variables (see CSIRO and BoM 2007, Table 4.1). Models that performed poorly were given a lower weighting rather than being omitted from the assessment. CSIRO and BoM 2007 recognise that a different approach to the weighting of the models would lead to somewhat different projected changes from the outcomes presented.

The CSIRO and BoM 2007 technique assumes that local climate response is proportional to the global warming, based on an analysis of the model results for local climate changes against the average global temperature increase for a given scenario. Determining this relationship allows the local change to be de-coupled from the scenario, so that local response can be easily scaled to a range of global warming values (CSIRO and BoM, 2007).

The likelihood of a given local outcome occurring in response to a given global warming was determined by developing a smoothed probability density function based on the error in the determination of the relationship between the two variables. The net changes for a given degree of global warming are then determined by multiplying the local factor by the global average temperature. Using the end-points of the probability density function gives an indication of the range of possible change. CSIRO and BoM 2007 presented the climate projections in terms of the 50th percentile (or 'best-estimate'), and used the

10th and 90th percentiles as a guide to the uncertainty range.

This probabilistic relationship was very suitable to the needs to the Review, as it was very easily applied to the new scenarios being investigated by the Review, without the need for running computationally intensive general circulation models. It also has the advantage of representing the outcomes of a range of global climate models, which allows the 'sensitivity analysis' approach to be taken to recognising uncertainty within the Review's modelling. The probabilistic approach facilitated the communication and analysis of the potential range of outcomes, and the Review used the 50th, 10th and 90th probabilities as the basis for the sensitivity analysis of local rainfall as described in Section 1.

4.2 Local climate outcomes

A summary of the climate variable assumptions for the local climate scenarios being investigated by the Review is shown in Table 4.1.

Table 4.1 Summary of local climate sensitivities showing percentile outcomes for key climate variables

Global scenario (SIMCAP/SRES)	Local sensitivity	Percentile for rainfall and relative humidity	Percentile for temperature and evaporation
No-mitigation	**Hot/dry**	10th percentile	90th percentile
	Median	50th percentile	50th percentile
	Warm/wet	90th percentile	
550 policy	**Hot/dry**	10th percentile	90th percentile
	Median	50th percentile	50th percentile
	Warm/wet	90th percentile	
450 policy	**Median**	50th percentile	

Note: Percentiles for rainfall are 0% at the wet limit and 100% at the dry limit of the range of uncertainty, and for temperature and evaporation are 0% at the coolest limit and 100% at the warmest limit.

The annual mean changes for the Australian States and Territories for the four main climate variables per degree Celsius of global warming are shown in Table 4.2. These factors were applied to the temperature timepaths from the MAGICC analysis of the no-mitigation and 450 and 550 scenarios discussed in Section 2.2.

Maps of the outcomes for rainfall and temperature for the three scenarios are shown in Appendix A.

Due to the relatively small increases in global average temperature in the policy scenarios, the changes to local climate as a function of global warming are minimal. For rainfall especially, natural climate variability could cause much larger swings in rainfall lasting for periods of several decades or longer.

Table 4.2 Summary of State and Territory average changes in climate variable per degree of global warming for different percentiles

Climate variable	Percentile	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
Rainfall (percentage change)	10th	-12.0	-9.9	-13.6	-15.6	-15.1	-6.3	-13.6	-9.8
	50th	-3.0	-4.2	-2.8	-5.0	-4.8	-1.7	-2.9	-3.4
	90th	5.0	1.1	7.2	4.8	5.0	3.1	7.1	2.4
Temperature (change in ºC)	10th	Not considered in the Garnaut sensitivities							
	50th	1.1	0.9	1.2	1.1	1.2	0.7	1.2	1.0
	90th	1.4	1.2	1.4	1.4	1.5	0.9	1.5	1.2
Relative humidity (percentage change)	10th	-1.6	-1.4	-1.4	-1.6	-1.7	-0.5	-1.5	-1.2
	50th	-0.6	-0.7	-0.4	-0.7	-0.9	-0.2	-0.6	-0.3
	90th	0.4	-0.1	0.6	0.2	-0.1	0.1	0.4	0.5
Evaporation (percentage change)	10th	Not considered in the Garnaut sensitivities							
	50th	3.0	3.0	3.3	2.4	2.7	3.4	3.1	3.2
	90th	4.7	5.1	4.6	4.4	4.6	5.5	4.8	4.7

Precipitation outcomes

As discussed in Chapters 4 and 5 of the Final Report, changes in precipitation are not directly influenced by rising greenhouse gases, but respond to changes in atmospheric temperature and wind patterns. Regional precipitation changes can be very sensitive to small changes in circulation patterns, as demonstrated by the considerable natural variability in Australian precipitation (CSIRO and BoM 2007). Small differences in model assumptions can lead to considerably different rainfall projections.

Unlike temperature, for which all Australian localities experience a positive increase in line with global increases in temperature, best-estimate precipitation varies between locations in the sign of the change as well as the magnitude. Changes in local precipitation are discussed in terms of the percentage change from current levels (to a maximum of 100%). The weighting methodology used gives a best-estimate multi-model mean that shows a decrease in rainfall across the majority of Australia, with the exception of small areas in the north and south. Some models demonstrate the possibility of an increase in rainfall for most parts of Australia which is reflected in probability density functions which show the potential for increased rainfall in most areas of Australia, typically at lower likelihoods. The methodology used means that for high levels of global warming the difference in rainfall outcomes for a given area is quite extreme when the 90th and 10th percentile rainfall outcomes are considered. This has a large bearing on the assessment of economic impacts of climate change which are dependent on rain fall outcomes.

4.3 Limitations in the Review's approach

The Review's approach to the modelling of local climate changes focuses on the median annual outcomes. An understanding of how climate variation will change, as well as the average climate is vital in understanding the potential impacts. Observed changes in precipitation suggest that more frequent heavy rainfall events are occurring even in areas where overall rainfall is decreasing. The extent of changes in rainfall may also vary between seasons. In this context, to assess the climate changes in the context of annual medians alone would limit the understanding of the potential impacts. However, climate models generally find variation harder to represent than median climate outcomes.

For its modelling inputs, the Review utilised published information that was readily available and flexible to the needs of the modelling exercise. A different approach to the treatment and assessment of local climate response, as undertaken by Pitman and Perkins (2008) (see box 4.1), and consideration of daily, seasonal and annual variation would give different climate outcomes that would effect the economic modelling of climate impacts. Further research is urgently needed on weighting schemes that take into account different assumptions about climate model skill.

The Review has incorporated a qualitative assessment of potential for climate change at the extremes of variation as they relate to a given mean, including severe weather events such as heat waves, floods and droughts.

Chapter 4 of the Final Report discusses the level of confidence in the modelling of change to different climate variables and large patterns of climate variability such as the El Nino-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). ENSO and have a considerable influence on Australia's climate, but the understanding of how these may change as a result in increased concentration of greenhouse gases is limited - model outcomes suggest that such events will continue, but some simulations have shown an increase in its variability, while others exhibit no change or even a decrease (Chapter 4). Due to the huge uncertainty in the direction or magnitude of the changes to ENSO out to 2100, the impacts of changes on the Australian climate could not be incorporated into the Review's modelling exercise.

Box 4.1 Different approaches to the assessment of local climate response

Pitman and Perkins (2008) in their paper 'Regional projections of future seasonal and annual changes in rainfall and temperature over Australia based on skill-selected AR4 Models' applied a related but different methodology to the assessment of more localised climate changes in Australia.

To take into account intra-annual variation, the assessment of model 'skill', the whole probability density function of daily temperatures was used rather than the annual mean as in CSIRO's methodology, so that the skill factor reflects the ability of the model to reflect temperature variation as well. The results look at daily maximum and daily minimum temperatures at given percentiles, rather than the average annual mean.

Models that did not achieve a 'skill factor' of greater than 0.8 (when model results were compared to observations) were rejected - this was done on a region by region basis. In the CSIRO study, models with a lower skill factor (calculated using a different method) were still included but giving a lower weighting. Removing the models with lower 'skill' from the assessments reduces bias that may result from a model that poorly reflects the climate in the region. The analysis undertaken by Pitman and Perkins showed that generally the excluded models showed greater drying, suggesting that analyses that considered them would show a bias towards drying.

In terms of rainfall, the results generally agree with the IPCC statement of decreases in southern Australia (IPCC, 2007). However, the amount of the reduction will be relatively small, showing an increase in rainfall intensity rather than in total rainfall. South-west Western Australia demonstrates the most intense drying of any region, which is in line with the CSIRO results. The annual extreme for rainfall increases across almost the entire continent - the largest is in the tropics, the least in south-west western Australia. Along the south coast there is an increase in no-rain days - this is the main mechanism that explains the rainfall reduction, rather than a reduction in extremes.

APPENDIX A: Rainfall and Temperature Graphs

Figure 4.1 Projected mean annual temperature outcomes for Australia under the SRES/SIMCAP scenarios

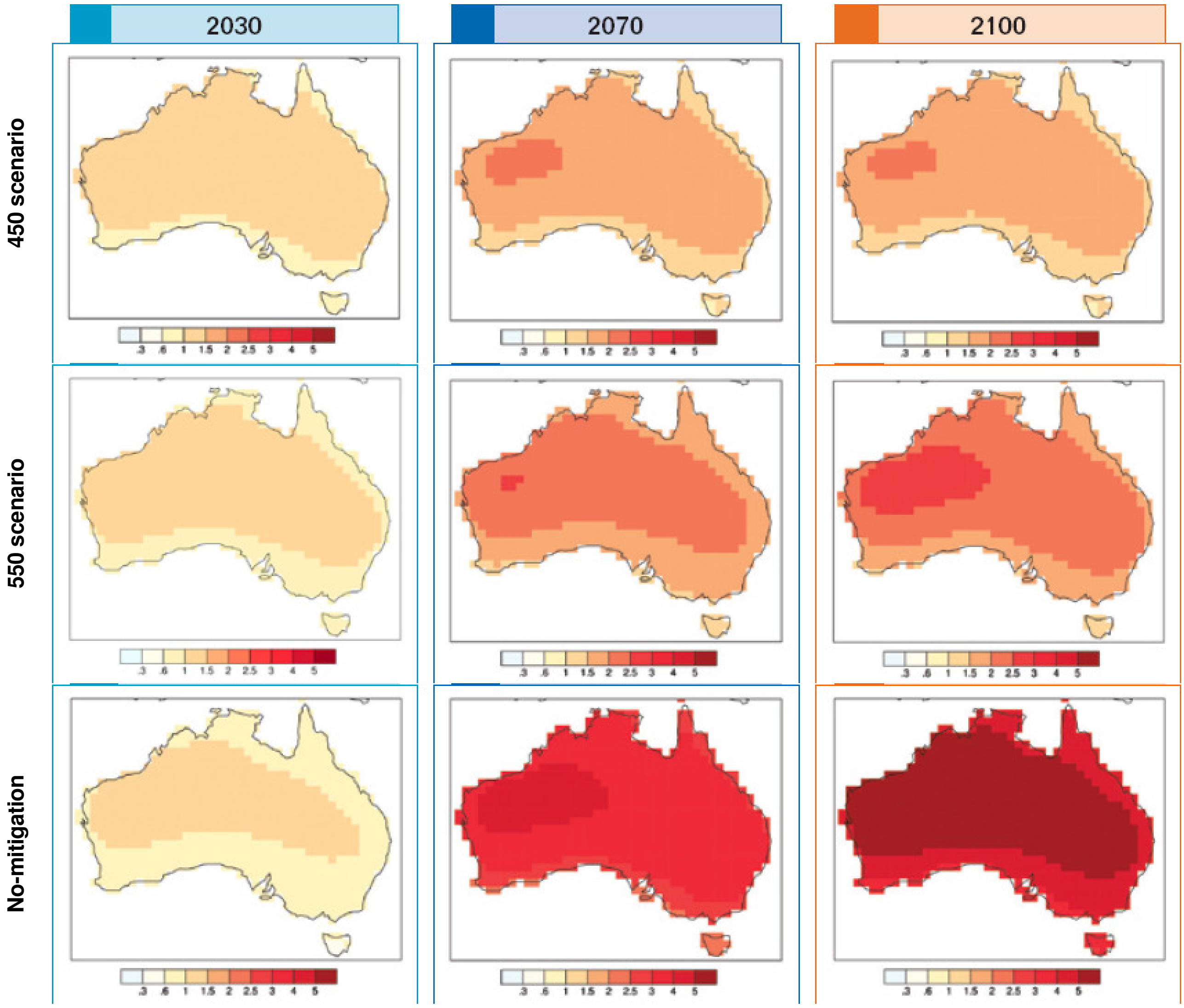
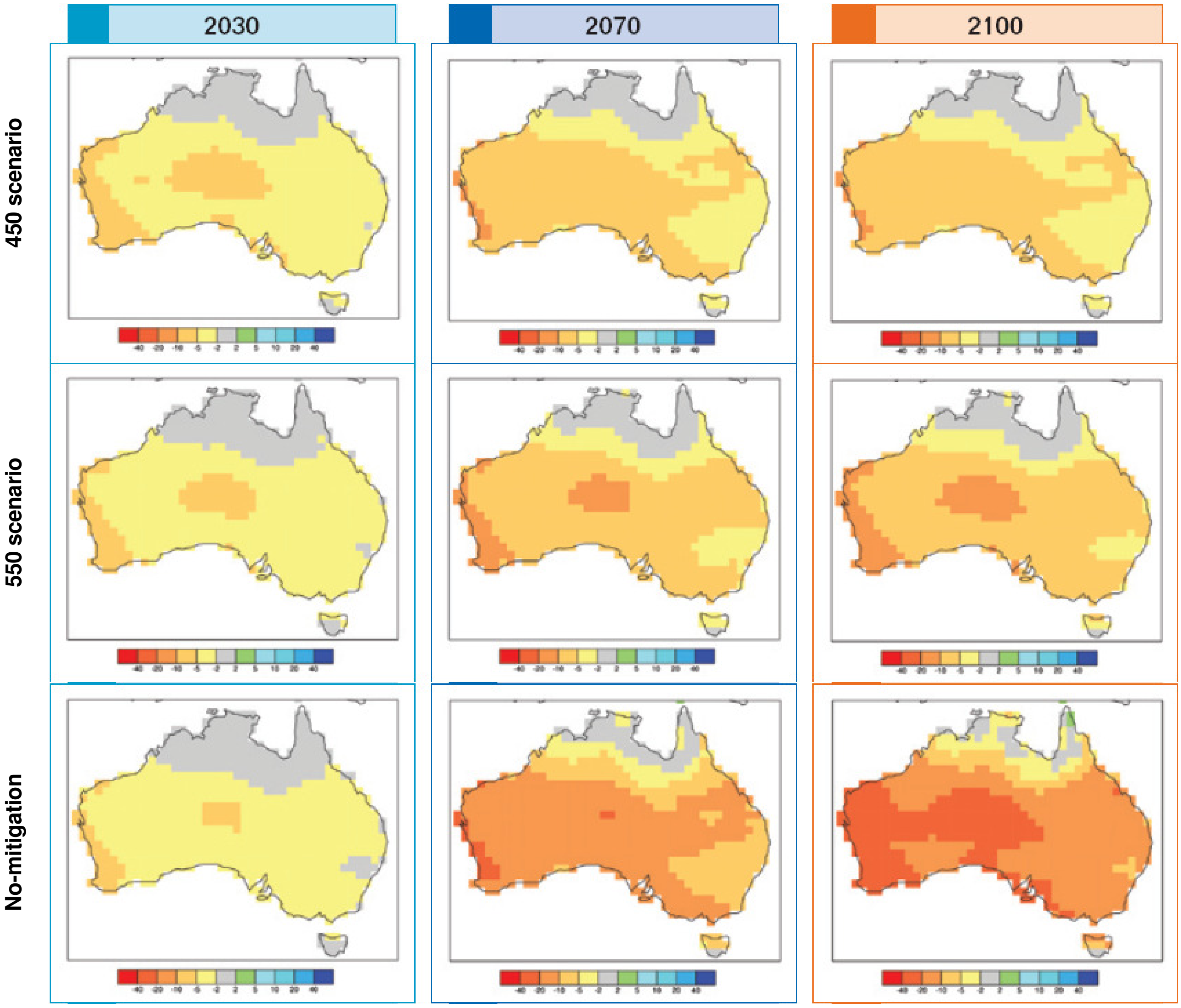


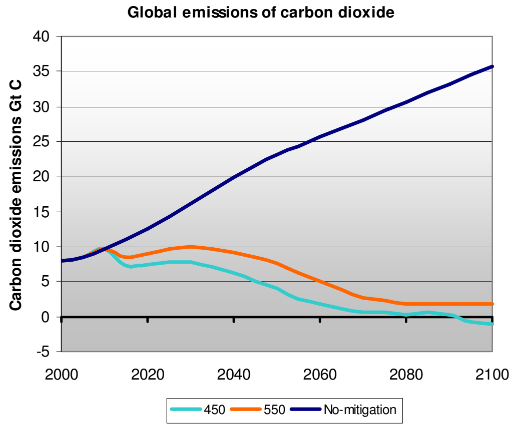
Figure 4.2 Projected percentage change from 1990 levels in mean annual rainfall for Australia under the SRES/SIMCAP scenarios

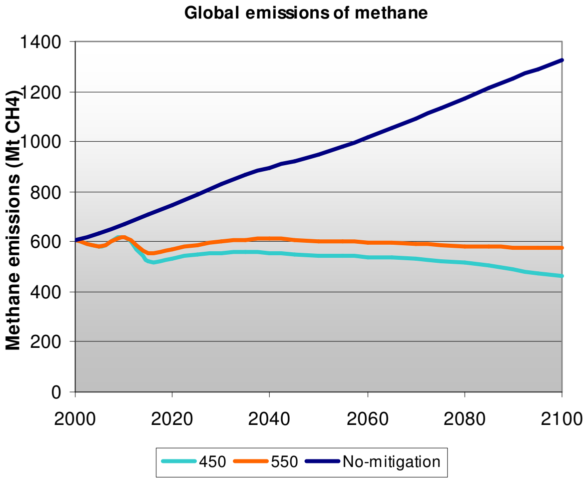


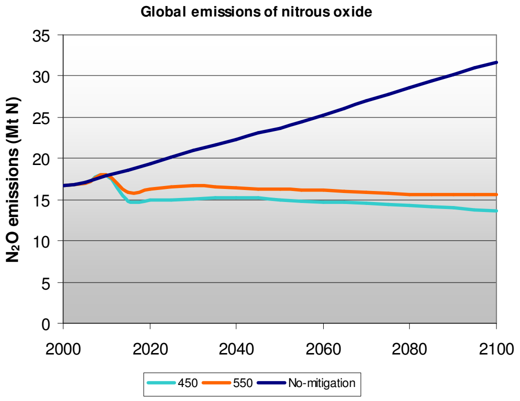
Appendix B. SIMCAP assumptions for 450 and 550 cases for impacts work

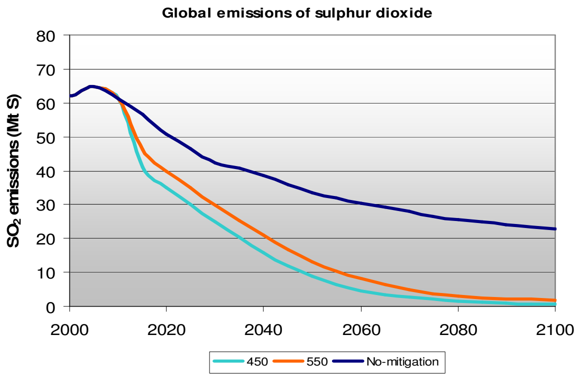
Target	550 ppm CO2-e	450 ppm CO2-e
Method	A ‘peaking’ profile was initially developed, with the stabilisation profile using the rate of emissions reduction from the peaking profile, as described in the technical manual.	
Climate sensitivity	3ºC	
Peaking concentration	550	500
Target concentration at stabilisation	550	450
Input year of stabilisation	2100	2100
Reduction rate I (Maximum and minimum fixed)	-4.06 (from peaking profile)	-3.843 (from peaking profile)
Start Rate and Reduction Rate II	‘Free’ (SIMCAP to optimise)	
Year of emissions departure from business-as-usual, all regions consistent	2025	2015

Appendix C. Global emissions of carbon dioxide (including forestry), methane, nitrous oxide and sulphur dioxide

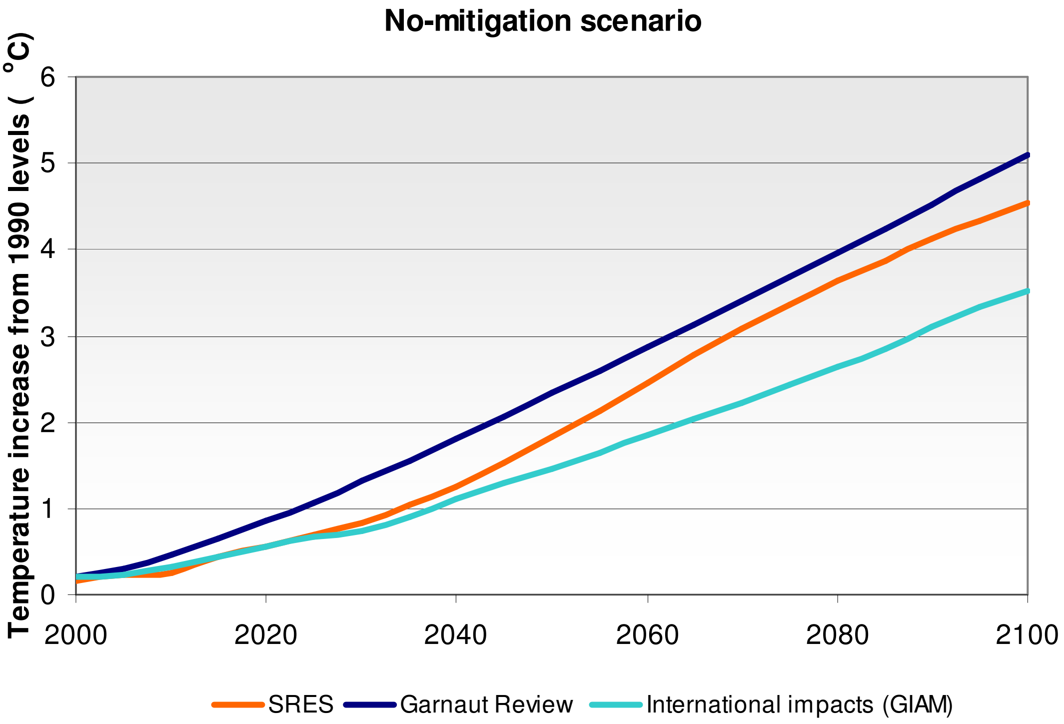


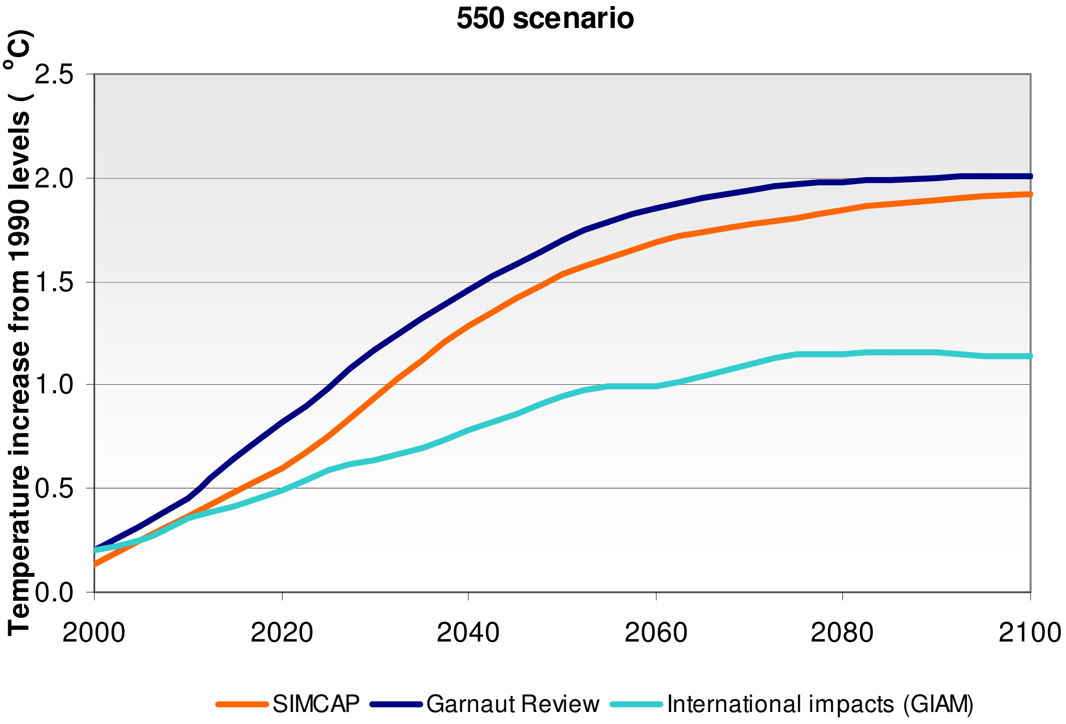


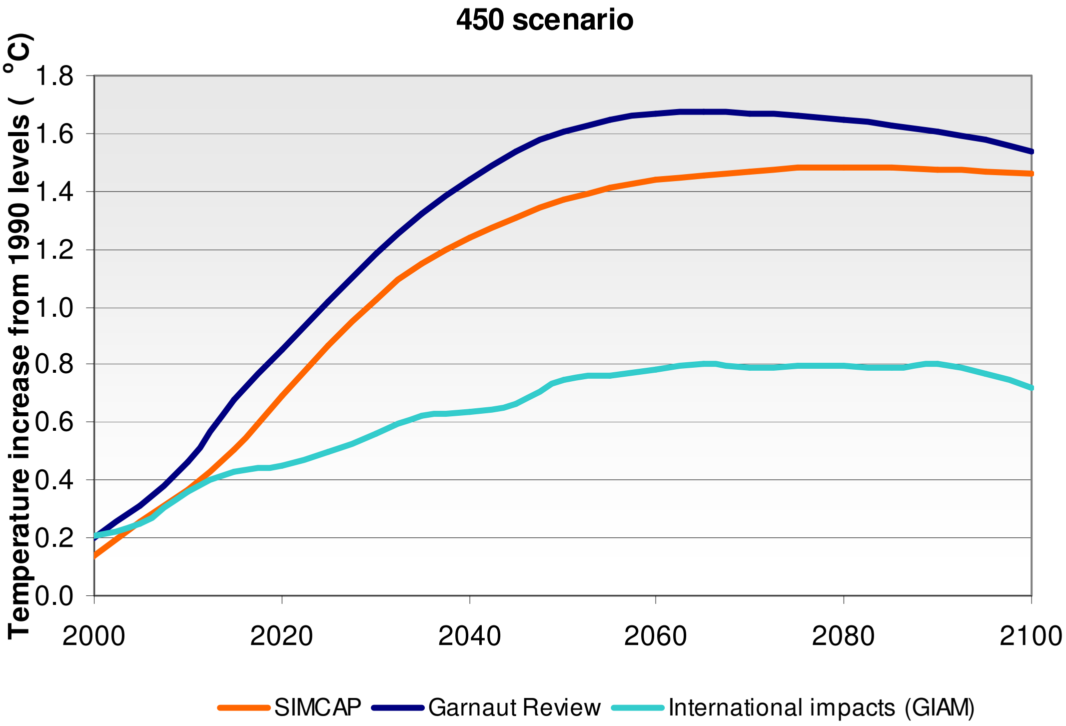




Appendix D. Temperature increase from 1990 levels in inputs for the SRES/SIMCAP (MAGICC), inputs for global impacts work (CSIRO MK3L) and those generated from the Garnaut Review economic modelling (MAGICC)






450 scenario
Temperature increase from 1990 levels (°C)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2000
2020
2040
2060
2080
2100
SIMCAP
Garnaut Review
International impacts (GIAM)

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