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Executive summary

We report on an analysis of the global scenarios considered by the Garnaut Climate Change Review using GIAM – the global integrated assessment model developed by ABARE and CSIRO. Integrated assessment models (IAMs) attempt to integrate the social, economic and biophysical systems that together constitute the world system in order to improve understanding of the relevant feedbacks and interactions within and between these systems. In practice, most IAMs have a better representation of some of these systems than others. GIAM in its current form belongs to the climate-economic class of IAM. GIAM is well suited to analysing the economic costs and benefits of climate change and climate change response policies as it incorporates the economic impacts of climate change. Two mitigation scenarios are assessed, taking into account the projected economic impact from climate change, and the economic costs of mitigation. Both mitigation scenarios result in lower global real gross domestic product (GDP) at 2050 and higher GDP at 2100, relative to a "business as usual" (reference) scenario.

1. GIAM

GIAM is a coupled climate-economic model that allows us to assess the impact of climate change and climate change response policies on the economic system. It is the first model of this type to be developed in Australia and has the following features:

- Climate projections are computed using the CSIRO Mk3L climate system model, a low resolution ocean-atmosphere general circulation model (OAGCM) with a spatial resolution of roughly 380km.
- Economic outcomes are computed using GTEM, a long-run version of ABARE's Global Trade and Environment Model, which is a general equilibrium model of the global economy incorporating 13 economic regions and 19 production sectors.
- These two modules are linked by a climate change damage function implemented in GTEM which quantifies the *economic impacts* of climate change. Climate impacts depend on the temperature change in each region and on the region's economic position relative to a reference economy, the USA – this allows a measure of the region's ability to adapt or respond to climate change.

GIAM is solved iteratively. With chosen initial settings, we run GTEM to 2100 and calculate the emissions of greenhouse gases (GHGs) generated by the world's economic activities. These emissions are converted into GHG concentration trajectories which are input into Mk3L, which is also run to 2100. Using Mk3L output, time series of surface temperature change are calculated for each of GTEM's economic regions. GTEM is then re-run with the damage function turned on so that the economic development path reflects the associated climate change impacts. As a result, a new set of economic outcomes and emission trajectories are simulated. The process is repeated until the pathways of climate and economic outcomes remain unchanged between two successive iterations. At this point of convergence we obtain economic and climate trajectories that are compatible. At convergence we find that economic output measured as gross domestic product (GDP), GHG emissions and the temperature increases are all smaller than in the initial run of GTEM. This is because the inclusion of climate change impacts leads to a contraction in global economic activity resulting in reduced anthropogenic GHG emissions.

2. Garnaut Review scenarios

The Garnaut Climate Change Review commissioned ABARE and CSIRO to assess three core economic scenarios: a reference scenario and two global mitigation scenarios in which the anthropogenic emissions of GHGs are limited in order to constrain their atmospheric concentrations along preset trajectories. For each scenario we have used GIAM to model the projected climate and economic systems with climate impacts. The three scenarios which incorporate climate impacts were based on associated scenarios that do not incorporate climate change that were developed by the Australian Treasury in collaboration with the Garnaut Review and other experts including those from ABARE. The three scenarios are:

- ***'Business as usual' or reference scenario*** with climate impacts

  This is a scenario in which global economic output per person averages close to 2.1% per annum over the century. It results in GHG emissions that are slightly higher than the Special Report on Emissions Scenarios A1FI marker scenario (IPCC 2000).

- ***550 Mitigation scenario*** with climate impacts

  This scenario assumes that the global economy adjusts to constrain GHG emissions from 2013 onwards to achieve atmospheric concentrations of 550 parts per million (ppm) carbon dioxide equivalent (CO_2-e) in the long term.

- ***450 Mitigation scenario*** with climate impacts

  This scenario assumes that the global economy adjusts to constrain GHG emissions from 2013 onwards to achieve atmospheric concentrations of 450ppm CO_2-e in the long term.

2.1 Reference scenario

In the reference scenario, where no mitigation attempts are made to constrain GHG emissions, the global and Australian real gross domestic product (GDP) per person is projected to increase by approximately 2.1% and 1.4% respectively over the period 2005-2100. These growth rates imply that the global real GDP per person in 2100 is 7.2 times greater than that in 2005 and the Australian real GDP per person in 2100 is 3.6 times greater than that in 2005. Growth in real GDP per person is expected to differ significantly between regions.

Global GHG emissions, including those from land use change and forestry (LUCF), are projected to increase by approximately 285% from ~39Gt (gigatonnes) CO_2-e in 2005 to ~150Gt CO_2-e in 2100. Growth in Australia's GHG emissions is projected to be slower. However, Australia's emissions are still expected to increase by approximately 170% from ~588 Mt CO_2-e in 2005 to ~1569 Mt CO_2-e in 2100. These emissions cause the atmospheric GHG concentrations[*] in CO_2-e to rise from 430ppm in 2005, to 710ppm CO_2-e in 2050 and more than 1400ppm CO_2-e in 2100.

[*] Only three GHGs (carbon dioxide, methane and nitrous oxide) are used to force the climate in GIAM. Because of the neglect of other GHGs, the atmospheric concentration of carbon dioxide equivalent in GIAM is therefore different to those presented in other modeling components of the Garnaut Review.

The corresponding change in the global (land and ocean) mean surface temperature is projected to be (approximately) 1.3ºC (degrees Celsius) in 2050 and 3.3ºC in 2100 above the year 2000 values[†]. The change in mean surface temperature for the Australian region is (approximately) 1.5ºC in 2050 and 4.2ºC in 2100 above the year 2000 values. Projected changes in the surface temperature are expected to differ significantly between regions.

A detailed analysis of the economic impacts of climate change shows that they are projected to differ significantly between regions, reflecting regional variations in the change in average temperature, differences in income, which affect the ability to adapt to or respond effectively to changes in climate, and changes in global trade. The growth in Australia's economy is projected to be significantly affected by the changes in trade – more so than any other regional economy considered in GIAM. Developing economies are generally projected to suffer greater economic impacts from climate change than their developed country counterparts.

Global mitigation scenarios

The aim of the mitigation scenarios is to reduce the anthropogenic influence on the Earth's climate by reducing the emissions of greenhouse gases and avoiding significant changes to the climate over the course of the current century. The emissions paths under the 550 and 450 mitigation scenarios are assumed to be those resulting from a globally negotiated emissions target, consistent with a global emissions trading scheme covering all sources of greenhouse gas emissions. The emission permits in each year are allocated across regions using the 'contract and converge' rules supplied by the Garnaut Review (Garnaut 2008c). The global emission paths were chosen such that the emission permit price rises smoothly at approximately 4% a year in real terms, thereby satisfying the inter-temporal arbitrage condition. Since the emission paths are predetermined, so are the corresponding climate projections from Mk3L.

2.2 550 scenario

The aim of mitigation, as simulated by GIAM, is to reduce the emissions of GHG from the 'reference scenario' thereby reducing the anthropogenically induced climate change over the 21st century and beyond. The 550 scenario requires that global emissions of GHG are reduced to less than 17Gt CO_2-e in 2100. Australia's share of these emissions is projected to be 228Mt CO_2-e in 2100. The reduction in emissions under this scenario is projected to considerably reduce the changes in global and regional temperature compared to the reference scenario. Under the 550 scenario the projected global mean surface temperature is (approximately) 0.9ºC in 2050 and 1.2ºC in 2100 above 2000 values, with a peak warming of just over 1.2ºC occurring in 2078. In Australia, the projected increase in temperature is approximately 0.9ºC in 2100.

Associated with these changes in emissions and climate are changes to global economic development. In 2050, the global real GDP per person is projected to be 1.6% lower than that of the reference scenario. However by 2100 the global real GDP per person is projected to be 4.3% *higher* than the reference scenario. This corresponds to the global real GDP per person in 2100 being 7.5 times that in 2005. For the Australian region, the real GDP per person is projected to be 2.9% lower in 2050 and 0.2% lower in 2100 than in the reference scenario.

[†] The Garnaut Review uses 1990 as the baseline year for changes in climate change.

Table ES1. Key results from the 3 Garnaut Review scenarios[‡].

	Reference scenario	**550 scenario**	**450 scenario**
Global mean temperature change at 2100 [a]	3.3ºC	0.9ºC	0.5ºC
Temperature change for Australia at 2100	4.2ºC	0.9ºC	0.6ºC
Global real GDP/person growth 2005 to 2050	×2.7	×2.6	×2.6
Global real GDP/person growth 2005 to 2100	×7.2	×7.5	×7.4
Global real GDP/person relative to reference scenario in 2050	—	-1.6%	-2.9%
Global real GDP/person relative to reference scenario in 2100	—	4.3%	3.4%
Australian real GDP/person relative to reference scenario in 2050[‡]	—	-2.9%	-4.3%
Australian real GDP/person relative to reference scenario in 2100[‡]	—	-0.2%	-1.4%
Global emissions in 2100 (Gt CO_2-e)	150	16.4	6.8
Australian emissions in 2100 (Mt CO_2-e)	1569	228	139

[a] Quoted temperature changes are for the near-surface air temperature, as derived from Mk3L simulations, using 2000 as the base year – see main text for details.

2.3 450 scenario

The 450 scenario represents a stronger mitigation effort than the 550 scenario. The 450 scenario requires that global GHG emissions are reduced to less than 7Gt CO_2-e in 2100. Australia's share of these emissions is projected to be 139Mt CO_2-e in 2100. The reduction in emissions under this scenario is projected to reduce the change in global and regional temperature compared to the reference scenario. Under the 450 scenario the projected change in the global mean temperature is (approximately) only 0.5ºC in 2050 and 0.6ºC in 2100 above year 2000 values. In Australia, the projected increase in temperature is (approximately) 0.6ºC in 2100.

The increased costs associated with the stronger mitigation effort imply slower growth rates in the global and regional economies than under the 550 scenario. In 2050, the global real GDP per person is projected to be 2.9% lower than in the reference scenario. By 2100 the global real GDP per person is projected to be 3.4% higher. This corresponds to the real global GDP in 2100 being 7.4 times that in 2005.For the Australian region, the real GDP per person is projected to be 4.3% lower in 2050 and 1.4% lower in 2100 than the reference scenario.

[‡] The results reported in this paper informed the analysis discussed in the Garnaut Climate Change Review (Garnaut 2008a, b, c). The results reported in this paper have been updated since Garnaut (2008a - the draft report) and as a result may differ to those reported previously. It is also important to understand that the economic impacts of climate change for Australia reported here are different to those reported in Garnaut Climate Change Review as a result of different modelling frameworks.

Hence, under both of the mitigation scenarios the immediate costs of mitigation reduce the growth in the global economy over the early part of the century. However, this is more than compensated for in the latter half of the century as the increasing impacts of climate change are felt under the reference scenario. This means that in 2100, the global economy is larger under the both of the mitigation scenarios than in the reference scenario. For Australia, and indeed some other regions, the comparison is not as clear cut. However it is important to note that other important aspects of global development, for instance non-market impacts, are not included in the GIAM analyses, nor are the continued benefits of reduced climate change post-2100 included.

3. Uncertainty Analysis

It is important to recognise that the output from GIAM is particularly sensitive to the form and parameter choices in the damage function. Although the current specification of the damage function was made using current understanding of how climate change is likely to impact on the development of the global economy it remains an area of empirical and theoretical uncertainty. To complement the reference scenario we consider two further scenarios based around the Garnaut Review reference scenario. First, a scenario where there are no climate impacts on the economy – the no impacts scenario - and second, a scenario where the economy is much more sensitive to climate change – the higher impacts scenario. Under the 'higher impacts scenario' the damage function specifications are altered so that the impact on the economy is approximately 4 times greater for a given temperature change than in the reference scenario.

The degree to which the economy is sensitive to climate change has a marked impact on the projections of the global economy and the global and regional climate. At 2050, the projection for the global real GDP per person is 0.9% higher under the 'no impacts' scenario and 4% lower under the 'higher impacts' scenario than under the reference scenario. At 2100, the projection for the global real GDP per person is 8.7% higher under the 'no impacts' scenario and 19.1% lower under the 'higher impacts' scenario than under the reference scenario. Global real GDP per person in 2100 is then projected to be 7.8 times that in 2005 under the 'no impacts' scenario but only 5.8 times that in 2005 under the 'higher impacts' scenario. An alternative view on these figures is that the GIAM estimate of the impacts of climate change on the global economy is a global real GDP per person at 2100 which is 8% lower than in the, highly unlikely, scenario where there are no climate impacts on the economy.

Global GHG emissions are also dependent on how sensitive the economy is to the climate. In 2100 the reference scenario projects that global GHG emissions will be 150Gt CO_2-e. With 'no impacts' this is increased to 161Gt CO_2-e, whereas with 'higher impacts' the projected emissions are less, at 126Gt CO_2-e. Note that this still implies an increase in global GHG emissions of approximately 220% on 2005 values. As this still represents a large increase in global GHG emissions on current values there are only modest changes to the projections of atmospheric concentration of CO_2-e and the change in climate between these three *no-mitigation* scenarios. Under the 'no impacts' scenario the projected atmospheric concentration of CO_2-e reaches over 1450ppm at 2100 and the projected change in the global mean temperature is approximately 3.4ºC. Under the 'higher impacts' scenario, the projected atmospheric concentration of CO_2-e is lower, at around 1300ppm, and the projected change in global temperature is 3.1ºC.

Table ES2. Key results from the comparisons of the reference scenario with alternate damage functions.

	with no impacts	Reference scenario	with higher impacts
Global mean temperature change to 2100 [a]	3.4ºC	3.3ºC	3.1ºC
Global real GDP/person growth 2005 to 2050c	×2.7	×2.7	×2.5
Global real GDP/person growth 2005 to 2100	×7.8	×7.2	×5.8
Global real GDP/person relative to reference scenario in 2050	0.9%	—	-4.0%
Global real GDP/person relative to reference scenario in 2100	8.7%	—	-19.1%
Global emissions in 2100 (Gt CO_2-e)	161	150	126

[a] Quoted temperature changes are for the near-surface air temperature derived from Mk3L simulations using 2000 as the base year – see main text for details.

Therefore, even the highly contractionary nature of the reference scenario with higher impacts results in large changes in climate by the end of the 21st century. This illustrates the accumulative nature of the anthropogenic influence on the climate system – the impact on the global and regional economies occurring at the end of the 21st century is dependent on the emissions prior to that time. This includes the emissions in the first half the century when the climate related economic impacts are small and, hence, the differences in emissions resulting from the use of different parameter values in the damage function are small.

The uncertainty in the GIAM simulations stems from uncertainty associated with the parameter choices in the damage function but also from uncertainties in the climate and economic models themselves. A more detailed, but preliminary, analysis of the sensitivity of GIAM output and our current understanding and confidence in each of the components of GIAM leads to the conclusion that one of the key aspects of GIAM which requires further work is the quantification of the damage function. Enhancements to the damage function are an ongoing research priority and it will be updated to reflect ongoing improvements in our understanding of how different sectors and regional economies will adjust to climate change.

Foreword

This report covers two substantial areas of research which fall under the broad heading of 'developing the interface between science and socio-economic aspects of climate change modelling.' The Australian Bureau of Agricultural and Resource Economics (ABARE) and CSIRO Marine and Atmospheric Research (CSIRO-CMAR) have jointly developed a new modelling tool – the Global Integrated Assessment Model (GIAM) – to assess the joint evolution of the regional and global economy and climate system under alternative scenarios. The first area covered by the report is a detailed description of GIAM including the scope, methodology, assumptions and caveats involved.

The second part of the report covers analysis completed on behalf of the Garnaut Review of Climate Change. The Garnaut Climate Change Review was commissioned by the State and Territory Governments of Australia to assess the potential impacts of human induced climate change on the Australian economy, the possible ameliorating effects of international policy reform and the role that Australia can play in the development of international policies addressing climate change. Within this remit, the Garnaut Climate Change Review commissioned a number of studies including the one presented in this paper. GIAM is used within these studies to simulate the potential impacts of climate change on the Australian economy including those which arise through impacts on the wider global economy and international trade. Analyses of the economic and climate development associated with three core scenarios which incorporate climate change impacts are presented in this paper.

In this report we raise issues of methodology, completeness and uncertainty associated with Integrated Assessment studies. These are important in the wider debate concerning climate change, mitigation, adaptation and policy development and implementation. This report does not, however, provide any policy recommendations.

Contents

1. Introduction

To develop an appropriate response to the economic and environmental challenges posed by climate change, we need an understanding of the potential costs and benefits of alternative response policies. In Australia, the analysis of climate change has tended to focus on the costs of mitigation without considering the benefits of reduced climate change impacts. This is primarily because the analytical tools to perform this integrated form of economic analysis were underdeveloped. This is particularly the case with respect to the representation of Australia in currently available analytical frameworks.

To overcome these limitations ABARE and CSIRO are developing Australia's first global scale Integrated Assessment Model – the Global Integrated Assessment Model (GIAM) – which will allow the economic costs and benefits of climate change policy to be assessed. GIAM extends prior studies within ABARE (see Hinchy et al. 1998; ABARE 2006; Pant and Cao 2005a, b; 2006; Pant et al. 2005) by enhancing the climate component of the analytic framework and the interactions between the global economy and climate.

The development of an Australian focussed IAM is now particularly relevant as Australia and several other countries are planning significant policy measures to deal with the impacts of climate change. These measures include emissions trading schemes, carbon taxes, research and development schemes to encourage energy efficient technologies, sectoral technology standards and adaptation.

Here we describe how GIAM is used to assess three illustrative scenarios that incorporate climate impacts: a long-term "business-as-usual" or "reference" scenario, and two mitigation scenarios. The economic settings of these three scenarios are based on scenarios that do not consider climate impacts developed jointly by the Australian Government (Treasury) and the Garnaut Review in consultation with a range of experts, including those from ABARE. GIAM determines how these scenarios are modified when climate impacts are incorporated. The development of a reference scenario that includes the impacts of climate change is fundamental as it provides a standard against which the costs and benefits of alternative policy options can be compared.

What are Integrated Assessment Models?

Integrated Assessment Models (IAMs) used in climate change policy analysis are multiple-equation computer-simulated models that capture the feedbacks between dynamic economic and scientific systems (Weitzman 2007). A comprehensive IAM would incorporate the full climate change cause and effect chain including the socio-economic drivers of greenhouse gas emissions, climate forcing, atmospheric greenhouse gas concentrations, climate change and the impacts of these changes on economic activity, ecosystems, food production, water supply, the environment and other aspects of socio-economic systems (van der Sluijs 1996). At present there are a number of IAMs being used by analysts around the world. These include DICE/RICE, MERGE, PAGE, FUND, WIAGEM and Minicam (van der Sluijs 1996). None of these IAMs adequately represent Australia.

IAMs provide insights into the potential economic and environmental impacts of climate change as well as responses to adaptation and mitigation. Information generated by IAMs can be used by policy makers to evaluate certain policy options more effectively (policy evaluation IAMs) or to identify optimal policy approaches (policy optimisation IAMs) within the current understanding of the uncertainties surrounding the underlying drivers of greenhouse gas emissions and likely impacts of climate change and adaptation and mitigation responses.

Some of the key policy questions that can be analysed using IAMs include:

- What are the potential impacts and economic costs and benefits of:
  - Climate change?
  - Mitigation responses?
  - Adaptation responses?
- What is the optimal level of mitigation and adaptation?
- What is the least-cost way to satisfy a given emission limit?
- What is the optimal timing of mitigation and adaptation action? How much does society stand to lose or gain by delaying action on climate change?
- Does a certain policy response conflict with other policies or with other societal functions and needs? For example, how much pressure will an increase in biomass energy cropping place on food production?

Challenges in developing and using Integrated Assessment Models

IAMs represent very complex socio-economic and geophysical systems and their interactions. Considerable uncertainty remains about virtually every relationship in these systems (Weyant 1996; 2003). However, a range of insights into the potential net impacts of alternative climate change response policies can still be gathered using IAMs, based on plausible assumptions and on the best information that is currently available.

A key challenge in the development and use of IAMs is that many of the assumptions underlying the components of a model are not explicit. This can lead to the inappropriate use of IAMs (e.g. the study objectives are incompatible with assumptions in the model) and the incorrect interpretation of results (e.g. conclusions may be the direct result of the assumptions or parameter choices). When using IAMS it is recommended that the assumptions within the model and its components are transparently documented and are properly tested (Schneider 1997).

A range of options, including sensitivity testing and statistical methods, are available which either allow the importance of different assumptions in IAMs to be tested or which account probabilistically for uncertainties (Kann and Weyant 2000; Kelly and Kolstad 1998; van der Sluijs 1996) – see Section 7. In GIAM, the underlying model assumptions, and parameter values are based on the best available understanding of the drivers of various economic and scientific relationships. Further, in Section 7 we present a formal analysis of the sensitivity of GIAM to uncertainties in both the climate model output and the parameter settings in the economic model GTEM including the damage function.

Many aspects of 'global development' and climate change policy cannot be assessed using current IAMs. Important dimensions of the problem cannot yet be incorporated into available analytic frameworks, including inter-alia, non-market impacts, impacts on the structure of human society, and impacts on the world's ecology. Consequently, economic-climate IAMs, such as GIAM, should only be viewed as one component in the climate change and policy development debate.

Relationship to the IPCC process

The Intergovernmental Panel on Climate Change (IPCC) was established to 'provide an authorative international statement of scientific understanding of climate change' and, specifically, to provide 'periodic assessments of the causes, impacts and possible response strategies to climate change' (IPCC 2007a). The role of the IPCC is therefore, largely one of review. However, the underlying process has been instrumental in guiding much of the research into climate change and associated policy questions over the past twenty five years.

At the outset the IPCC partitioned research into four main areas. The three main science areas are the 'Physical Science' (Working Group I), 'Impacts, Adaptation and Vulnerability' (Working Group II) and 'Mitigation' (Working Group III) areas. The fourth area concerns 'Emissions Scenarios' and the underlying economic, demographic, technology and social studies that are required to produce projections of anthropogenic greenhouse gas emissions (GHGs) in the future (e.g. Special Report: Emissions Scenarios or SRES - IPCC 2000). Each of the research areas is largely self-contained. Results or substantially simplified frameworks are taken as needed from the other areas with little study of how the areas could (and will) interact with each other. One important example of 'missing' interactions is the role of changes in the global economy induced by climate change in determining global GHG emissions.

The most important feature of GIAM is the attempt to 'complete the circle' – at least partially. An economic model (GTEM) with underlying assumptions and projections concerning demography, technology, social structure and, critically, how climate change impacts on the economy, is used to determine the regional and global emissions of GHGs. The emissions then determine the future projection of global and regional climate as given by a general circulation model (CSIRO Mk3L). Information from the climate projection is then fed back to the economic model. This complex structure removes some of the potential inconsistencies that arise when the economic and climate projections are separate, and in doing so allows for a more complete assessment of the costs and benefits of climate change and policy responses. However, because linking the models adds complexity, some aspects of the individual components are simpler than the current state of the art. Furthermore, this linkage does not remove all internal inconsistencies.

Several other IAMs now also attempt to include interactions between climate and global development – including those used within the SRES (IPCC 2000). However each of these models exhibits different choices of regional disaggregation and component complexity, particularly of the climate components. This has meant that none of them could be used for the purposes of the current study associated with the Garnaut Review of Climate Change.

2. *The Global Integrated Assessment Model (GIAM) framework*

ABARE has been developing its Australian focussed integrated assessment modelling capacity over the past several years. Since 2007 ABARE has been working collaboratively with the CSIRO to develop a preliminary "proof-of-concept" IAM. ABARE and the CSIRO have developed a preliminary version of GIAM that incorporates economic and climate modules which allow for the determination of long run economic activity and greenhouse gas emissions and the resulting regional temperature increases and climate change impacts. The modules are solved iteratively to determine the resulting impacts of climate change on economic activity and greenhouse gas emissions.

GIAM overview

GIAM is structured through a five step process as shown schematically in Figure 2.1. They are

1. Develop a reference scenario of the world economy (to 2100) without climate change impacts using the economic module of GIAM (GTEM).
2. Using the emissions pathway resulting from the reference scenario, determine the time series of the atmospheric concentration of carbon dioxide equivalent[§] using the MAGICC v4.1 climate and atmospheric chemistry model.
3. Determine the associated changes in regional temperature using the CSIRO Mk3L climate model.
4. Use the damage function in GTEM to determine the regional loss in factor productivity as a result of the projected changes in regional temperature.
5. Rerun the economic module of GIAM after incorporating climate change impacts as a change in regional total factor productivity. Steps 4 and 5 occur simultaneously.

Steps 2 to 5 are repeated to account for the feedbacks in the economic and climate systems until an appropriate level of convergence in changes in global mean temperature and changes in gross domestic product (GDP) is reached. The resulting economic pathway is the "reference scenario with climate impacts." Each of the four components of GIAM is discussed in further detail below.

Economic module

The economic module of GIAM is a long-run version of ABARE's Global Trade and Environment Model (GTEM), which is a multi-regional and multi-sectoral computable general equilibrium (CGE) model of the global economy (Pant 2007). The economic module provides projections of the major human induced greenhouse gas emissions associated with regional and global economic production and consumption decisions and international trade flows.

CGE models are widely used as the economic components of IAMs. For an accessible introduction see Nordhaus (2008). At the same time, a range of caveats are associated with their use (Pant 2007). A full discussion of these questions can be found in DeCanio (2003) and they will not be canvassed further in this paper.

[§] Only three GHGs (carbon dioxide, methane and nitrous oxide) are used to force the climate in GIAM.

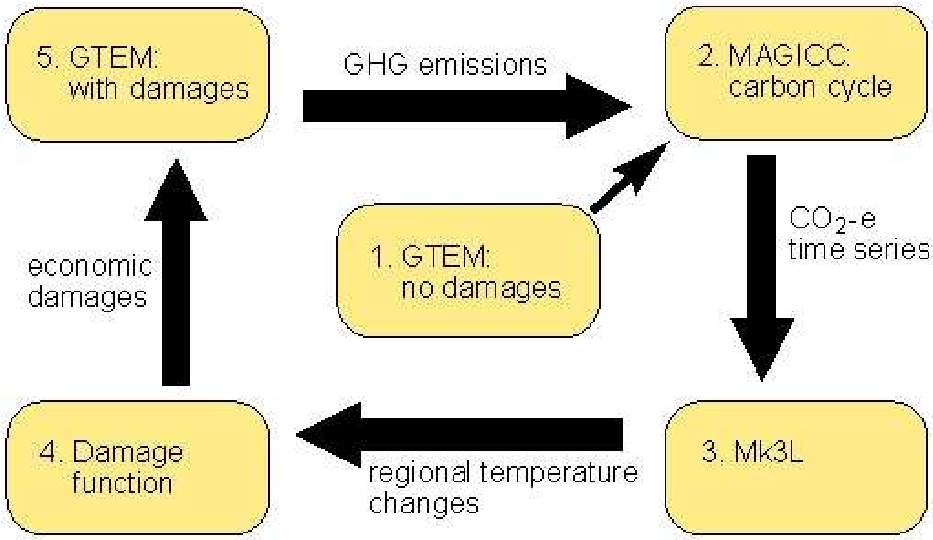

Figure 2.1. Schematic representation of GIAM.

In essence, the economic module of GIAM represents the interactions between economic agents in a multi-region, multi-sector world economy in which economic agents in each regional economy produce, trade and consume goods and services across the global economies (Pant 2007). The 'agents' of the model are assumed to be economic optimisers. The agents consume and produce goods and services, innovate, invest, change technologies and use natural resources, labour and other human-produced tools (capital), subject to national and international policy constraints and the natural environments in which they operate. These human activities produce GHG emissions subject to the technologies in use at the time. These emissions may cause climatic changes capable of altering the environment, ecosystems, economic activities and human welfare (Pant 2007).

The economic module of GIAM used in this paper currently aggregates the global economy into 13 regions, 19 commodities or sectors, four primary factors and ten categories of greenhouse gas emissions and precursors (Appendix A, Table A1).

Representation of energy technologies

The development and deployment of low emission energy technologies is critical to the successful mitigation of greenhouse gas emissions and the maintenance of regional and global economic growth over time.

Given that electricity currently accounts for just less than 30% of global anthropogenic greenhouse gas emissions, low-emission technologies in this sector will be particularly important. The economic module of GIAM incorporates cost and emissions characteristics of twelve electricity generation technologies, which include six conventional technologies (coal, oil, gas, nuclear and hydroelectricity), five embryonic renewable energy sources (waste, biomass, solar, wind and other renewables) and carbon capture and storage technologies applied to coal and gas fired power generation. The economic module of GIAM also accounts for potential cost declines through *learning by doing* for specified emerging technologies and regional capacity constraints for other technologies, such as hydroelectricity, biomass and waste (Pant 2007).

Climate modules

The climate module of GIAM provides the link between human induced greenhouse gas emissions and changes in regional climate, such as temperature.

Calculation of atmospheric greenhouse gas concentrations

MAGICC v4.1 (Wigley et al. 2002) is used to determine the atmospheric concentration of greenhouse gases over time. This module uses the projected emissions from the economic module of GIAM to update atmospheric stocks of these greenhouse gases each year and then to calculate their atmospheric concentrations. MAGICC contains assumptions about the continued efficiency of the terrestrial and oceanic sinks of carbon dioxide. There remains continued uncertainty in this area of Earth System science and the topic remains an active area of scientific research (e.g. Friedlingstein et al. 2006; IPCC 2007a).

The only anthropogenic greenhouse gas explicitly treated by Mk3L is carbon dioxide. The greenhouse gas concentrations calculated by MAGICC therefore need to be converted into equivalent concentrations of carbon dioxide (CO_2-e). A simple approach (as used by IPCC 2001) is used to derive the CO_2-e values, based on the respective impacts of each greenhouse gas on the global radiation balance.

Calculation of regional changes in temperature – the CSIRO Mk3L climate system model

In order to calculate regional changes in long term temperatures, the CSIRO Mk3L climate system model (Phipps 2006a, b) is used. This is a low-resolution, computationally-efficient climate model. It includes three-dimensional representations of the motions of the atmosphere and ocean and, therefore, falls into the category of models known as general circulation models (McGuffie and Henderson-Sellers 1997).

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.

A land surface model is also included. This allows for thirteen different surface and vegetation types, and nine different soil types; however, these properties are predetermined, and are therefore static. The model predicts the temperature and liquid water and ice contents of each of six soil layers, and also the temperature and thickness of each of three snow layers. The rate of surface runoff is calculated, with the runoff assumed to travel instantaneously to the ocean via the path of steepest descent. The oceanic component predicts quantities that include temperature, salinity and oceanic currents. A sea ice model is included, which contains descriptions of ice dynamics and thermodynamics.

Mk3L divides the Earth's surface into a 64 x 56 horizontal grid, with the average dimension of each grid box being approximately 380 kilometres. There are eighteen vertical levels in the atmosphere, and twenty-one in the ocean. This comparatively low resolution enables the components to be integrated using time steps of 20 minutes for the atmosphere, and 60 minutes for the ocean. A 100-year simulation can be completed in around five days on a typical high-performance computing facility.

For the simulations presented here, Mk3L is run as an ensemble consisting of three independent realisations. While the physics is identical for each member of this ensemble, slightly differing initial conditions are used. The 'climate' of the ensemble is derived by calculating the mean state across each member. Further discussion of Mk3L and its performance is given in Appendix C.

Economic impacts

Climate change is expected to cause a wide range of impacts on economic and environmental systems. For example, it is expected to have an impact on human health, labour productivity, and demand for and production of a range of goods and services, including agricultural, ecosystem and environmental services. In GIAM, to estimate the potential economic impacts associated with climate changes, a stylised damage function is implemented in the economic module, GTEM. The damage function estimates and translates regional changes in temperature through time to changes in factor productivity at the economy wide level in each country or regional economy represented in GIAM.

Regional climate change impacts are assumed to be a function of regional changes in average temperature (relative to 2000), and the vulnerability of a region to potential climate change. Vulnerability of a regional economy is expressed in relative terms by a proxy, which is the ratio of gross national product (GNP) per person of the economy relative to that of a benchmark economy (the United States). This aims to capture the notion that the relative economic impacts of climate change for a given change in temperature will be higher in developing economies than in more developed economies (e.g. Pearce et al. 1996; IPCC 2007b).

The damage function used in GIAM allows economic impacts to increase gradually for small changes in temperature before increasing more rapidly until the catastrophic temperature is reached (for details, see Box 1). The damage function also allows for a catastrophic reduction in all economic activity beyond a specified temperature. One key change has been made to the GIAM damage function since Gunasekera et al. (2008). The parameters have been modified such that the global loss in real GDP with a 4°C increase in global average temperature relative to 1990 is approximately 5%. This is in line with the likely upper bound currently anticipated in the IPCC Fourth Assessment Report (IPCC 2007b; Nordhaus 2008).

Box 1: A stylised climate change damage assessment function in GIAM

The damage function used in GIAM is derived from the willingness to pay for the avoidance of non market damages function used in the integrated assessment model MERGE (Manne and Richels 2004). In this report, only market impacts are considered explicitly. The damage function used in GIAM is specified as:

$$\Lambda_r(t) = \begin{cases} \left[1-\left(\Delta T_r(t)/\Omega\right)^{\delta}\right]^{\mu_r(t)} & \text{if } 0<\Delta T<\Omega \\ 1 & \text{if } \Delta T \leq 0 \\ 0 & \text{else} \end{cases} \tag{1}$$

where:

– $\Lambda_r(t)$ is the region-specific climate change-induced net economic loss factor (ELF) – reflecting the change in total factor productivity as a result of climate change – in year *t*. ELF = 1 means that total factor productivity is unchanged, while ELF = 0 means that there has been a 100% loss in total factor productivity;

- $\Delta T_r(t)$ is the increase in average surface temperature from the reference year (2000) for region *r* in year *t*;
- Ω is the catastrophic change in average surface temperature, relative to the reference year (2000), at which economic activity is reduced to zero; and
- δ and $\mu_r(t)$ are parameters affecting the severity of damage for a given temperature change.

The region specific ELF, $\Lambda_r(t)$, in GIAM is currently linked to an index of total factor productivity in the economic module. The difference between unity and the value of $\Lambda_r(t)$ at time *t* indicates the loss in productive capacity of the region by a factor of $(1-\Lambda_r)$. This can also be viewed as losses in factor supplies or a combination of both. In the current implementation of GIAM, a rise in global average temperature means a loss in economic well–being through a decline in factor productivities across all sectors in a region. Equation (1) governs the level of economic loss attributable to a given change in average temperature. Larger values of $\mu_r(t)$ and smaller values of δ imply higher damages from a given temperature change. Conversely, larger values of δ and smaller values of $\mu_r(t)$ imply smaller or no damages from temperature changes that are less than Ω. For all temperature increases below Ω, the loss in economic activity as a result of climate change depends on the value of δ. A larger value of δ implies higher resilience and that economic activity will drop only near the catastrophic value of the temperature change. The time-variant parameter $\mu_r(t)$ is set equal to 1 throughout the projection period for the reference region, namely the United States. For other regions, $\mu_r(t)$ is further defined as below, in order to capture the vulnerability of a given country/region to climate change by linking the region's real per person income to that of the reference region as:

$$\mu_r(t) = \sigma_1 + \sigma_2 \ln\left[I_{ref}(t)/I_r(t)\right] \tag{2}$$

where

- I_{ref} is the reference region's per person real income;
- I_r is the per person real income of the country/region *r* and
- σ_1 and σ_2 are adjustable parameters that specify how differences in real income affect a region's vulnerability to temperature changes.

For the results shown in Sections 4 and 5, $\Omega = 17$, $\delta = 2.35$ $\sigma_1 = 1$ and $\sigma_2 = 0.5$. The specification of Ω is based on the parameterisation in MERGE. A positive value of σ_2 in Equation (2) means the losses are higher for poorer regions compared to richer regions. The sensitivity around the choice of parameter values is considered in more detail in Section 7. The variation of $\Lambda_r(t)$ for a range of $\Delta T_r(t)$ and I_{ref}/I_r is shown in Figure 2.2.

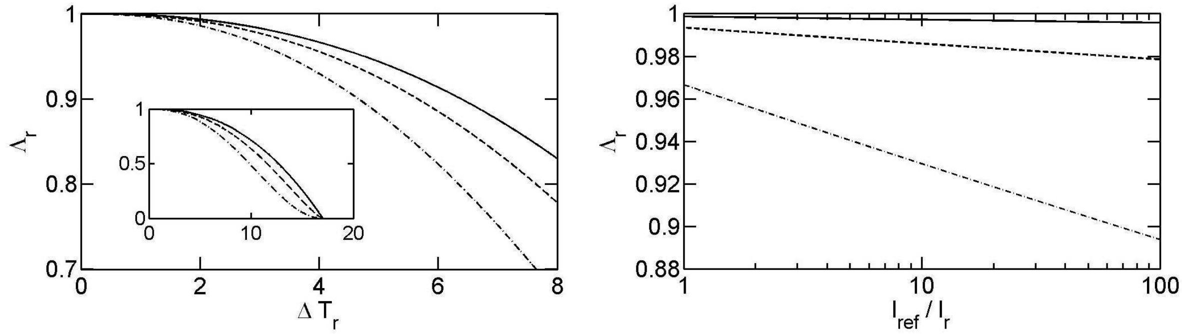

Figure 2.2. Example of the variation of the default Economic Loss Factor with temperature change and relative income. Left panel: solid line, ELF for the reference region (USA) where $\mu = 1$; dashed line, ELF for a region where $I_{ref} / I_r = 2$; dash-dotted line, ELF for a region with $I_{ref} / I_r = 10$. Right panel: solid line, ELF for different regions when $\Delta T = 1°\mathrm{C}$; dashed line, ELF for different regions when $\Delta T = 2°\mathrm{C}$; dash-dotted line, ELF for different regions when $\Delta T = 4°\mathrm{C}$.

Choice of parameterisation and functional form of the damage function

The "hockey-stick" shape of the damage function aims to represent the idea that relative economic impacts from climate change are expected to increase at a greater rate as temperature increases. This functional form is consistent with much of the literature on damage functions, and with the functions which are currently employed in IAMs (e.g. Manne and Richels 2004; Nordhaus and Boyer 2000). The parameterisation of the damage function aims to represent our current understanding of how climate change could affect the market economy, the vulnerability of different economies and the degree of temperature change that would be sufficient to halt all economic activity (the threshold or catastrophic temperature change).

The damage function used in GIAM has a number of uncertainties regarding the choice of parameters. There are numerous studies of the impacts of the climate and weather on certain aspects of individual sectors of the economy in individual countries or regions, but little information on how these results should scale to the entire sector, regional or global economy. Other key uncertainties concerning economic impact due to climate change include:

- How does climate change impact on different sectors of an economy?
- Should climate change always involve an economic loss, as currently parameterised?
- How do we correctly aggregate impacts over regions exposed to differing levels of climate change?
- Are there additional climate metrics which should be included? (Water availability is one obvious variable on which the economy is dependent.)
- How should the costs and benefits associated with adaptation (planned or otherwise) be incorporated?

As more information becomes available about how different economic systems adjust to climate impacts, the damage function can be updated. Given the current uncertainties surrounding the damage function, GIAM results should be considered as indicative and illustrative only.

Convergence of GIAM

The structure of GIAM requires that each component of the model is run in turn until successive runs of each component are statistically equivalent. In practice this requires that a number of convergence criteria must be satisfied for the run to be complete. Complex statistical measures can be defined, however, for simplicity three metrics on the principal outputs of GIAM are used, namely

1. the global real GDP agrees to within 1% throughout the period of interest.
2. the global atmospheric CO_2-e concentrations agree to within 2% throughout the period of interest.
3. the global mean surface air temperature agrees to within 0.1ºC throughout the period of interest.

For the scenarios considered in this report, the final criterion controls the number of iterations of GIAM needed for convergence. For the majority of simulations, with the current damage function, convergence is achieved in two iterations of GIAM.

3. Garnaut Review scenarios

The Garnaut Review commissioned ABARE and the CSIRO to assess the potential domestic and international economic impacts of climate change. The potential economic impacts of climate change were identified with reference to three scenarios (without climate impacts) developed by the Review in consultation with the Australian Treasury and a range of experts including those from ABARE. Using GIAM, these three scenarios are assessed with climate impacts in this paper. The three scenarios are: a reference scenario and two global mitigation scenarios in which the anthropogenic emissions of greenhouse gases (GHGs) are limited in order to constrain the atmospheric concentration of the greenhouse gases along preset trajectories. The scenarios are further described below.

As described earlier, the forcing of the climate system is the result of changes in the concentrations of multiple gases, predominantly carbon dioxide, methane, and nitrous oxide. When analysing climate change and mitigation it is convenient for the GHGs to be combined into a single measure termed 'carbon dioxide equivalent' (CO_2-e). In this report, when we discuss emissions of individual greenhouse gases, these gases will be combined according to their 100 year Global Warming Potentials (GWPs) as set out in the Kyoto Protocol conventions (e.g. UNFCC 2007; 2008). Unless stated otherwise, the given values of emissions are the emissions per calendar year. However, when we discuss climate forcing or the atmospheric concentrations of GHGs, a more appropriate method to combine the gases is via the associated radiative forcing for each of the gases so as to obtain a single measure of the concentration of carbon dioxide-equivalent at that time.

Scenarios

Reference scenario

The reference scenario illustrates the economic development and climate pathway that could occur if there were climate change impacts and no domestic or global policies to mitigate GHG emissions. The reference scenario provides an indicative illustration of the potential changes in economic growth, population, industry growth, productivity improvements, energy consumption, greenhouse gas emissions and regional and global temperatures to 2100.

550 mitigation scenario

In this scenario the potential economic impacts of achieving an atmospheric concentration of greenhouse gases of 550ppm CO_2-e to 2100 are assessed. Under the 550 mitigation path, global GHG emissions are constrained from 2013 onwards such that atmospheric concentrations of GHGs are approximately at[**] or below 550ppm of carbon dioxide equivalent over the period to 2100. The mitigation paths are achieved by implementing a global emissions trading scheme covering all sources of GHG emissions. The emission permits in each year are allocated across regions using the 'contract and converge' rules supplied to ABARE by the Garnaut Review (Garnaut 2008c).

[**] Under the strong mitigation scenario provided by the Garnaut Review and Australian Treasury the atmospheric concentration of CO_2-e in GIAM does exceed 550ppm by at most 5ppm between the years of 2055 and 2075. This is deemed to be of no serious consequence given the other uncertainties in the climate and economic systems.

450 mitigation scenario

In this scenario the potential economic impacts of achieving an atmospheric concentration of greenhouse gases at around 450ppm CO_2-e by 2100 are assessed. Under the 450 mitigation path, global GHGs are constrained from 2013 onwards such that atmospheric concentrations of GHGs reach 450ppm of carbon dioxide equivalent in 2100. Due to the near-term inertia in the world economy, atmospheric concentrations of GHGs are allowed to rise above 450ppm of carbon dioxide equivalent, peak at 500ppm around mid-century and then fall toward 450ppm of carbon dioxide equivalent by 2100. The mitigation paths are achieved by implementing a global emissions trading scheme covering all sources of greenhouse gas emissions. The emission permits in each year are allocated across regions using the 'contract and convergence' rules supplied to ABARE by the Garnaut Review (Garnaut 2008c).

A more detailed description of the background to these scenarios and the economic assumptions involved is given in Garnaut (2008a, b, c) and Treasury (2008).

Incorporating climate change impacts

As discussed above, the three scenarios are assessed 'with climate impacts' in this paper, where the climate impacts are determined within GIAM using a damage function. The regional and world economies adjust based on the regional temperature induced changes in average factor productivity. No additional mitigation or planned adaptation measures are assumed to take place compared with the Garnaut 'without impacts' scenarios.

Under the reference scenario the climate impacts result in changes in the demand and supply of all commodities and hence, alter the global emissions path relative to the reference scenario without impacts. However, the emissions paths under the 550 and 450 mitigation scenarios are assumed to be a globally negotiated emissions target and hence the pathways are not altered by climate impacts. Consequently, the impacts of climate change under the two mitigation scenarios were limited to changes in the economic variables and did not affect the temperature projections from Mk3L.

Population projections

One of the key drivers of economic development is population growth. In the version of GTEM used within GIAM, climate change is not assumed to impact on regional or global population. However, labour productivity is assumed to decline in response to climate change impacts. The demographic projections used within the GIAM simulations are those used in the Garnaut Climate Change Review (2008a, b, c) and generally consistent with Treasury (2008).

4. Reference scenario

Climate forcing and climate change

The atmospheric concentration of greenhouse gases is the result of the long term pathway of emissions of greenhouse gases and the natural sinks of these gases. In the GIAM reference scenario with climate impacts, the atmospheric concentration of greenhouse gases is projected to increase from a CO_2-e concentration of about 430ppm (parts per million) in 2005 to above 1400ppm in 2100[††]. The increase in the atmospheric concentration of greenhouse gases is expected to drive changes in regional surface temperature such that by 2100 the average surface temperature in Australia will have increased by approximately 4.2ºC relative to 2000 levels. Relative to 2000 levels, the increase in the global mean surface temperature (including both the oceans and land) temperature is expected to be approximately 3.3ºC while that for the global land surface only is expected to be approximately 4.4ºC at 2100 (Figure 4.1).

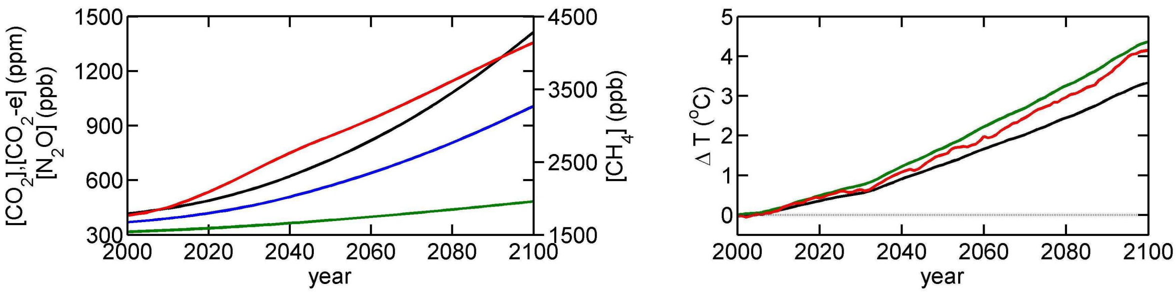

Figure 4.1. Left: Projected evolution of the atmospheric concentration of the three principal anthropogenic greenhouse gases under the reference scenario with climate impacts. Concentration of atmospheric CH_4 (in ppb – parts per billion) given in red on the right hand scale. Concentration of atmospheric N_2O (in ppb) in green on the left hand scale. Concentrations of atmospheric CO_2 (blue) and atmospheric CO_2-e (in black) in ppm given on the left hand scale. Right: the associated change in surface air temperature for the globe (black), global land surface (green) and Australian region (red).

There are noticeable differences between the projected changes in surface temperature for the different geographic regions in GIAM. These projected increases in surface temperature for the reference scenario with climate impacts are presented in Table 4.2. A detailed discussion of the physical mechanisms which account for these differences is given in Appendices C and D. It is important to recognise that climate is intrinsically variable so that quasi-random variations about the underlying warming trend occur.

[††] The GIAM CO_2-e concentration values quoted here, and elsewhere, only consider the contribution due to carbon dioxide, methane and nitrous oxide. These values will, therefore, be less than those presented in the Garnaut Review.

Table 4.2. Projected change in temperature relative to 2000 by region for the reference scenario with climate change impacts.

	2025	2050	2075	2100
	ºC	ºC	ºC	ºC
United States	0.7	2.0	3.3	4.6
EU25	0.9	1.6	2.8	4.0
China	0.6	1.8	3.0	4.3
Former Soviet Union	0.8	1.8	3.3	4.8
Japan	0.4	1.4	2.3	3.5
India	0.7	1.7	3.0	4.6
Canada	0.7	2.0	4.0	5.6
Australia	**0.6**	**1.5**	**2.7**	**4.2**
Indonesia	0.7	1.7	2.9	4.6
South Africa	0.6	1.6	2.5	4.2
Other Asia	0.5	1.5	2.3	3.8
OPEC	0.6	1.7	2.8	4.2
Rest of World	0.6	1.6	2.6	4.0
World	**0.5**	**1.3**	**2.2**	**3.3**
World (land only)	**0.6**	**1.7**	**3.0**	**4.4**

Notes: Mk3L projections using annually averaged ensemble with a 9 year running mean applied to the time series.

Climate change and economic impacts

Through the damage function, climate change impacts act to reduce the productivity of all primary factors (land, labour, capital and natural resources). As a result, growth in labour productivity and thus GDP per person is lower in these 'with climate impacts' scenarios than in the corresponding Garnaut 'without climate impacts' scenarios. As temperatures increase over time the non linear form of the economic loss factor (ELF) ensures the economic impacts of climate increase at a faster rate. The estimated indices of real GDP per person for the world and Australia are shown in Figure 4.3 for the reference scenario with and without climate impacts. It is important to recognise the tentative and preliminary nature of these estimates. Hence, caution needs to be exercised in interpreting them.

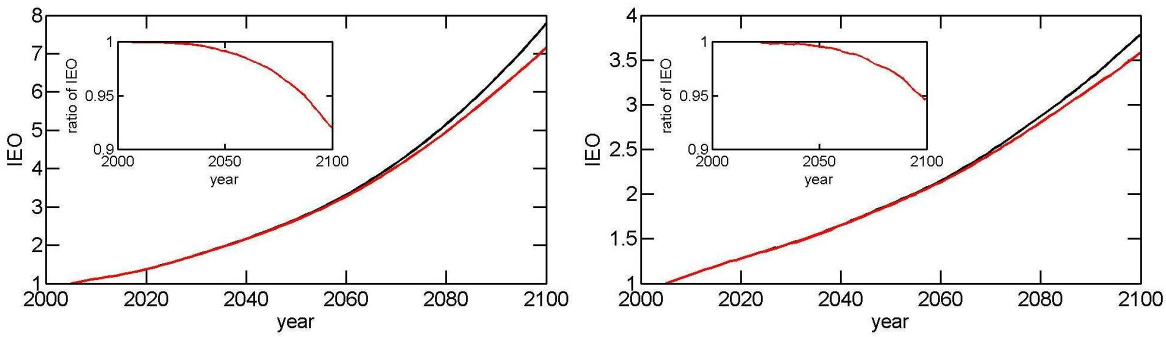

Figure 4.3. Index of economic output (IEO) for the globe (left) and Australia (right) for the reference scenario with (red) and without (black) climate impacts. The IEO is given by the ratio of the real GDP per person in any year to that in the year 2005. Inserted in each panel is the ratio of the IEO for the reference scenario with climate impacts to that for the reference scenario without impacts.

To understand how climate change is projected to impact on the development of the global and regional economies we compare the reference scenario with climate impacts to the reference scenario without impacts (as determined by Step 1 in the GIAM cycle – see Figure 2.1). A clear divergence in economic potential is projected to occur from about 2050 as climate change impacts begin to have a larger effect on the regional economies. Globally, climate change impacts are projected to reduce real GDP per person by about 0.9% in 2050 and 8.0% in 2100, relative to the reference scenario without climate impacts. As a result, global real GDP per person in the reference scenario is estimated to grow by about 7.2 times over the period 2005–2100 as compared with 7.8 times for the reference scenario without climate impacts.

The economic impacts of climate change are projected to differ significantly between regions, reflecting regional variations in the change in average temperature, differences in income which affect the ability to adapt to or respond effectively to changes in climate, and the changes in global trade. As a result developing countries are projected to suffer greater economic impact from climate change. A detailed regional breakdown of the economic development under the reference scenario with climate impacts is given in Table E1 in the appendices.

At 2050, Australia's real GDP per person is estimated to be reduced by about 0.4%, relative to the reference scenario without climate impacts. By 2100 the relative reduction in Australia's real GDP per person as a result of climate change impacts is estimated to increase to about 5.4%. Real GDP per person in 2100 is estimated to be 3.6 times higher in 2100 than in 2005.

Climate change and the emissions pathway

Within the reference scenario, increases in GDP per person are associated with increases in the absolute level of emissions of greenhouse gases. The economic losses associated with climate change impacts are expected to dampen economy wide demand for goods and services. As a result, greenhouse gas emissions (which are associated with the production, consumption and trade of goods and services throughout the economy) are projected to be lower when climate change impacts are accounted for than when they are not.

Globally, human induced greenhouse gas emissions are projected to be approximately 7% less in 2100 as a result of climate change impacts, falling from 161 Gt CO_2–e in the reference scenario without impacts to about 150 Gt CO_2–e in the reference scenario with impacts at 2100. These estimates include emissions from land use change and forestry. In the reference scenario without impacts, Australia's GHG emissions (including those from land use change and forestry) are projected to increase from about 588 Mt CO_2–e in 2005 to about 1624 Mt CO_2–e in 2100. However, after accounting for climate change impacts and the associated decline in economic activity, the growth in Australian GHG emissions is projected to be smaller such that by 2100 they are 1569 Mt CO_2–e. Table E2, in the appendices, gives a detailed regional breakdown of the GHG emissions for the reference scenario with climate impacts.

Climate change and Australia's terms of trade

The inclusion of climate change impacts globally affects the supply and demand for Australia's exports and imports and consequently affects Australia's terms of trade (the ratio of Australian export and import prices). Australia is projected to be the worst affected regional economy in relation to changes in terms of trade (Table 4.4). In particular, Australia's terms of trade are projected to deteriorate due to climate change impacts by about 2.95% at 2100, relative to the reference scenario without climate impacts.

Table 4.4. Change in terms of trade relative to the reference scenario without climate impacts.

	2050	2100
United States	-0.01	-0.73
European Union 25	-0.01	-0.72
China	0.03	1.13
Former Soviet Union	-0.07	0.54
Japan	-0.01	-1.21
India	0.10	0.83
Canada	-0.10	0.48
Australia	**-0.23**	**-2.95**
Indonesia	0.12	1.43
South Africa	-0.10	-1.75
Other Asia	-0.01	0.09
Rest of OPEC	-0.16	-0.53
Rest of World	0.01	0.12

The projected decline in Australia's terms of trade is dominated by declines in Australia's average export prices rather than changes in average import prices. In particular, as a result of climate change impacts and the associated changes in global production and demand for goods, Australia's average export price is projected to decline by about 3.54%, relative to the reference scenario without impacts at 2100. In contrast, Australia's average import price is projected to decline by only 0.60%, relative to the reference scenario without impacts at 2100.

The decline in Australia's overall terms of trade as a result of climate change impacts is driven primarily by declines in the prices received for key commodities; namely, coal, other mining and agriculture (see Table E3 in the appendices). These commodities are projected to account for over 60% of the value of Australia's exports at 2100. The decline in the export price of these commodities is largely driven by two factors. First, by 2100 all of these commodities are projected to be highly trade exposed, with over half of total Australian production exported. Second, Australia's key export markets for these commodities are projected to include India, Indonesia, China and other Asia, all of whom are projected to have significantly lower economic activity as a result of climate change impacts, relative to the reference scenario without impacts (see also Table 6.1).

5. Mitigation scenarios

Modelling the mitigation scenarios

The mitigation paths (Figure 5.1) were chosen by the Garnaut Review and the Australian Treasury such that the permit price for emissions rises smoothly at approximately 4% a year in real terms (Figure 5.2). This satisfies the intertemporal arbitrage condition derived by Hotelling (1931).

The emissions paths chosen by the Garnaut Review and the Australian Treasury are described below.

- Under the 550 mitigation path, global greenhouse gas emissions are constrained from 2013 onwards such that atmospheric concentrations of greenhouse gases are approximately at[‡‡] or below 550 ppm of carbon dioxide equivalent over the period to 2100. Under the 550 mitigation path, the emissions permit price rises naturally at 4% a year until 2080, at which point the growth in the real permit price slows to around 2.2% a year. The reduction in the growth rate of the emissions permit price after 2080 is due to the global emissions allocation flattening (Figure 6.1) in order to maintain atmospheric concentrations at approximately 550 ppm (Figure 6.3). With respect to intertemporal arbitrage possibilities, the flattening of the permit price implies that the incentive for borrowing permits is increased, and the incentive for banking permits is reduced.

- Under the 450 mitigation path, global greenhouse gas emissions are constrained from 2013 onwards such that atmospheric concentrations of greenhouse gases reach 450 ppm of carbon dioxide equivalent in 2100. Due to the near-term inertia in the world economy, atmospheric concentrations of greenhouse gases are allowed to rise above 450 ppm of carbon dioxide equivalent, peak at 500 ppm around mid-century and then fall toward 450 ppm of carbon dioxide equivalent by 2100.

[‡‡] See the footnote in Section 3 concerning the precise details of the atmospheric concentration of CO_2-e under the 550 scenario.

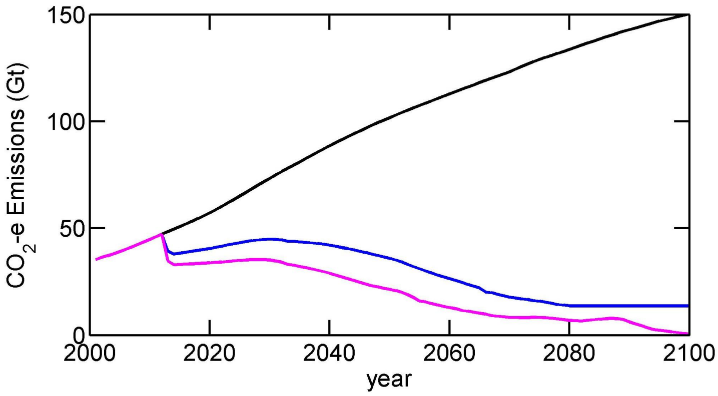

Figure 5.1. Projected net global greenhouse gas emissions (including the emissions from land use change and forestry) under different emissions scenarios. Blue line gives the 550 scenario; magenta line the 450 scenario; and black lines the reference scenario with climate impacts. Emissions of different gases are combined according to the Kyoto Protocol conventions (UNFCC 2007; 2008).

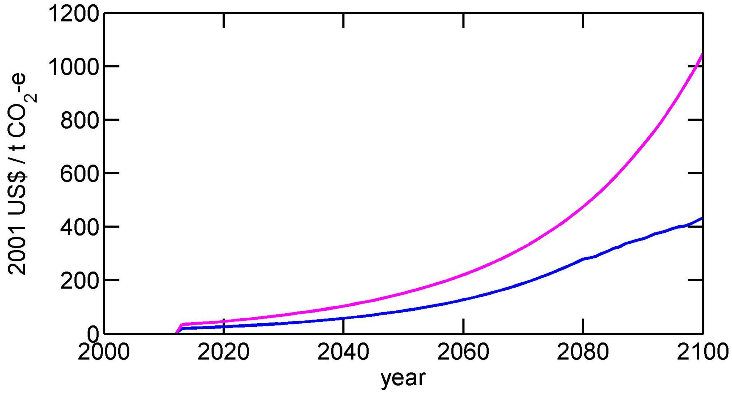

Figure 5.2. Projected global emissions permit price under the mitigation scenarios. Blue line gives the permit price under the 550 scenario, and the magenta line the permit price under the 450 scenario.

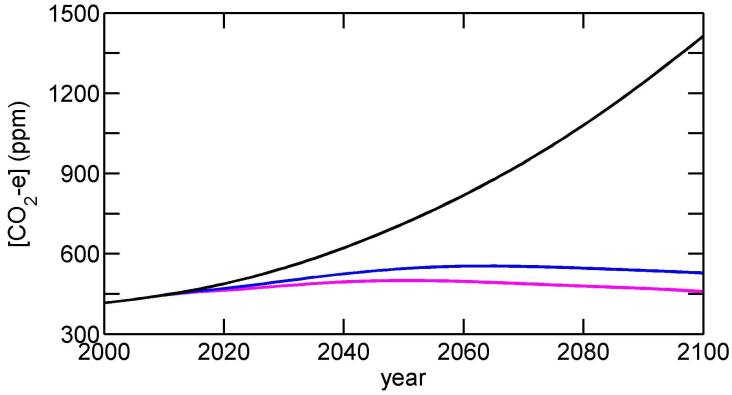

Figure 5.3. Projected atmospheric concentration of carbon dioxide equivalent under the different scenarios as used in Mk3L[§§]. Blue line gives the 550 scenario; magenta line the 450 scenario; and black lines the reference scenario with climate impacts. Concentrations of different chemical species are combined according to their radiative forcing.

[§§] GIAM only considers three GHGs – CO_2, CH_4 and N_2O – differences between the CO_2-e concentrations shown here and those in the Garnaut Climate Change Review are the result of the other GHG not considered here.

The mitigation paths were achieved by implementing a global emissions trading scheme covering all sources of greenhouse gas emissions. The emission permits in each year are allocated across regions using the 'contract and converge' rules supplied to ABARE by the Garnaut Review and Australian Treasury (Garnaut 2008c). Under the contract and converge rules, emissions permits are initially allocated to regions on the basis of current net greenhouse gas emissions per person, with the disparity between allocations gradually falling such that, by 2050, allocations of emission permits are equalised across all regions on a per person basis. Under the rules, currently developing economies are allowed to increase emissions per person for a period of time (with the length of time dependent on their current emissions per person) while most currently developed economies are required to reduce emissions per person from the first year of the mitigation policy.

Under the global emissions trading scheme the price of permits across all regions are equalised. If a region's abatement is greater than their allocation it sells excess permits onto the world market, while if a region's abatement is less than its allocation it buys enough permits to meet its obligations. In the mitigation scenarios modelled in this report, banking and borrowing of permits between years is not allowed. However, the mitigation paths were chosen by the Garnaut Review and the Australian Treasury such that the permit price rises smoothly at approximately 4% a year in real terms due to the assumed intertemporal arbitrage conditions (Figure 5.2).

Temperature projections under the mitigation paths

The aim of mitigation is to reduce the anthropogenic influence on the Earth's climate by reducing the emissions of greenhouse gases. By significantly reducing the emissions of GHGs it is hoped that significant changes to the climate and significant warming over the course of the current century, can be avoided. Under the 550 mitigation path, the projected global (land only) average warming at 2100, as simulated by Mk3L, is 1.2ºC relative to 2000, with a peak warming of just over 1.2ºC at 2078. The projected global (land only) average warming at 2100 under the 450 mitigation scenario is 0.6ºC, relative to 2000, with a peak warming of 0.8ºC in 2063. In contrast, the projected global (land only) warming under the reference scenario with climate impacts at 2100 is 4.4ºC, relative to 2000, with no sign that the warming has approached a peak. Further detail of the projected changes in regional temperatures under the two mitigation paths are presented in Table E4 in the appendices.

Economic impacts under the mitigation paths

As can be seen from Figure 5.1, the mitigation paths require almost complete decarbonisation of the world economy by 2100. A direct consequence of the decarbonisation is the almost complete removal of fossil fuels (for energy purposes) from the world economy with energy systems switching toward electricity generated from nuclear and renewable-based technologies, or, under the 550 mitigation scenarios, from fossil fuels with carbon capture and storage. Therefore, regions whose economic growth over the reference scenario is largely reliant on the production and export of fossil fuels — notably, OPEC and, to a lesser extent, the Former Soviet Union — experience large falls in real GDP under the mitigation scenarios, relative to the reference scenario. Indonesia, China and South Africa are also projected to experience significant declines in real GDP under the mitigation scenarios, relative to the reference scenario, driven by the need to substantially change the reliance of their energy systems from their large low cost coal reserves toward more expensive energy forms. The smallest relative declines in real GDP are projected in regions whose economies in the reference scenario do not rely as extensively on fossil fuels.

Table 5.7. Change in real GDP per person under the mitigation scenarios relative to the reference scenario (with climate impacts) at 2050 and 2100.

	550 scenario at 2050 (%)	**550 scenario at 2100 (%)**	**450 scenario at 2050 (%)**	**450 scenario at 2100 (%)**
USA	–0.1	5.2	–0.1	5.2
European Union 25	–0.2	3.2	–0.5	2.8
China	–2.3	0.6	–4.6	–2.0
Former Soviet Union	–9.1	–2.4	–15.0	–4.2
Japan	0.4	0.4	0.2	–0.2
India	–3.2	12.5	–4.7	11.0
Canada	–2.2	5.9	–3.7	4.8
Australia	**–2.9**	**–0.2**	**–4.3**	**–1.4**
Indonesia	–1.5	2.6	–3.7	–4.7
South Africa	–5.1	–0.8	–7.4	0.6
Other Asia	–1.1	4.2	–2.0	4.8
OPEC	–7.9	–9.5	–13.8	–11.1
Rest of world	–1.2	5.9	–2.5	5.1
World	**–1.6**	**4.3**	**–2.9**	**3.4**

Note**:** Global real GDP per person changes are estimated using 2001 market exchange rates.

Globally, the 550 mitigation scenario is projected to result in an increase in real GDP per person of 4.3% at 2100, relative to the reference scenario (Table 5.7). Hence the reduction in climate change damages outweighs the cost of mitigation in the 550 scenario at 2100. At 2050 however, real GDP per person is 1.6% lower in the 550 scenario compared to the reference scenario. Similarly, the 450 scenario is projected to result in a lower GDP at 2050 and a higher GDP at 2100 compared to the reference scenario. Comparing the two mitigation scenarios, the 550 is projected to have higher GDP at both 2050 and 2100.

6. Reference scenario with higher climate impacts

Within GIAM, the impacts of climate on the global economy are quantified through the damage function (see Box 1). For the results shown in Sections 5 and 6 the damage function has been established according to the current understanding of how climate change is likely to impact on the development of the global economy. However, as will be shown in more detail in Section 7, there is some uncertainty surrounding the choice of parameter values in the damage function and, hence, the corresponding impacts on the economy. In the context of scenario analysis it is also useful to explore the extremes of possibility – the worst and best case scenarios. Such information is critical in the debate concerning the merits, or otherwise, of taking mitigation actions on the basis of an insurance against climate change (Garnaut 2008a, b, c).

Currently GIAM only uses the mean change in surface air temperature for each region to calculate the economic impacts associated with climate change. The mean surface air temperature is, however, only used as a proxy for a range of climate variables, including the minimum and maximum temperature, wind and rainfall (and the consequent effects on water availability). Hence, although the functional form and parameterisation of the damage function is intended to incorporate the impacts of changes in a range of climatic variables, it is possible that the economic impacts for a given temperature change could be different to those projected under the current parameterisation.

Consequently, given such uncertainty, it is prudent to investigate the consequences of the economy being more sensitive to mean temperature changes than in the default (current understanding) case. The converse, an economy which is less responsive to climate change, is essentially covered by the Garnaut reference scenario without climate impacts. Results are presented here for the reference scenario only; changes to the damage function would also affect the mitigation scenarios but these have not been assessed. We expect those relative changes to be significantly smaller than those highlighted here.

The damage function for the higher climate impacts scenario was re-calibrated so the loss in total factor productivity is approximately four-fold higher for a temperature change of 4ºC. Based on current expectations across the literature, the resulting losses in total factor productivity were deemed to be still feasible, particularly if extreme climatic events result in periods of social and political unrest. The revised parameter values in the damage function are $\Omega = 11$ and $\delta = 2$.

The CSIRO Mk3L climate system model has been demonstrated to exhibit a low transient climate response when compared to the ensemble of general circulation models (GCMs) used in the IPCC assessments (see Appendix C). One possible view is that increasing the economic loss factor for a given temperature change could proxy the use of an alternative GCM which exhibits a higher transient climate response. There are a number of reasons why this view is incorrect, but most important is that there is no general relationship between the climate sensitivity or transient climate response of a GCM and the projected changes in global or regional temperature over time which applies under all scenarios (e.g. IPCC 2007a). Hence, the parameters in the damage function cannot be altered to 'correct' for a perceived weakness in the climate model (namely the 'low' projected temperature change for a given forcing over the current century) and by doing so is likely to imply physically unrealistic climate states, with consequent errors on the economic impacts.

Climate and economic impacts under higher climate impacts

Global real GDP per person under the higher impacts scenario is projected to be 19.1% lower at 2100 than in the reference scenario. This compares with the 'no impacts' scenario where global real GDP is projected to be 8.7% higher than in the reference scenario (Table 6.2). Therefore, while the impact on total factor productivity is approximately 4 times greater under the 'higher impacts' scenario than in the reference scenario (for the same change in temperature), GIAM projects impacts on GDP which are approximately only 3 times greater at 2100, due to the associated reduction in emissions and temperature change. As a result of the economic impacts global real GDP per person in the higher impacts scenario is projected to grow by 5.8 times over the period 2005-2100. For comparison global real GDP per person grows by 7.2 times in the reference scenario and 7.8 times in the reference scenario with no impacts.

As in the reference scenario, the economic impacts vary considerably between the regions. At 2050, Australia's real GDP per person under the higher impacts scenario is projected to be 2.2% less than in the reference scenario. By 2100 the economic impact increases substantially with Australia's real GDP per person projected to be 13% lower than in the reference scenario. Under the reference scenario with no impacts Australia's real GDP per person in 2050 is projected to be 0.4% higher than the reference scenario and at 2100 5.7% higher than the reference scenario. Australia's real GDP per person in 2100 is then 3.1 times that in 2005 under the with higher impacts scenario, 3.5 times that in 2005 under the reference scenario and 3.6 times that in 2005 under the reference scenario with no impacts.

Table 6.1. Change in real GDP per person due to climate impacts, relative to the reference scenario with impacts.

	Garnaut reference scenario with no climate impacts		**Reference scenario with higher climate impacts**	
	2050	**2100**	**2050**	**2100**
	%	**%**	**%**	**%**
USA	0.7	6.1	–3.7	–12.6
EU25	0.6	5.5	–3.9	–12.6
China	1.0	8.8	–4.3	–18.8
Former Soviet Union	1.1	11.5	–5.7	–24.7
Japan	0.2	2.3	–1.3	–5.5
India	1.4	15.5	–6.6	–30.0
Canada	1.0	12.0	–5.7	–24.9
Australia	**0.4**	**5.7**	**–2.2**	**–13.0**
Indonesia	1.5	13.9	–7.2	–28.3
South Africa	0.8	8.0	–3.8	–19.6
Other Asia	0.7	6.5	–3.0	–16.7
OPEC	1.0	10.0	–3.8	–23.4
Rest of World	0.9	9.2	–3.9	–21.3
World	**0.9**	**8.7**	**–4.0**	**–19.1**

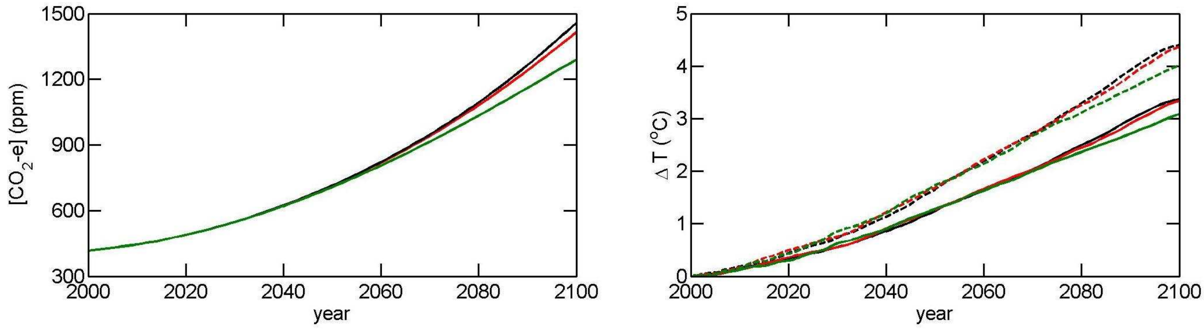

Figure 6.2. Left: Projected atmospheric concentration of CO_2-e under the reference scenario without impacts (black), with impacts (red) and with higher impacts (green) scenarios as used in Mk3L. Right: Associated projections for the change in surface air temperature for the global mean (solid) and mean for the land surface only (dashed), as simulated by Mk3L.

Associated with the impacts to the global and regional economies are impacts on the emissions of GHGs. Global GHG emissions under the reference scenario with higher impacts are projected to be 1.7% lower in 2050 than in the reference scenario and 16% lower in 2100. In comparison, global GHG emissions under the reference scenario with no impacts are projected to be 2.6% higher than the reference scenario in 2050 and 7.1% higher in 2100. The lower emissions path is reflected in lower projections of the atmospheric concentration of GHGs (Figure 6.2). Under the reference scenario with higher impacts the atmospheric CO_2-e concentration is projected to be less than 1300ppm in 2100 as compared to greater than 1400ppm in the reference scenario[***].

The differences in the economic and emissions projections between the reference scenario and the reference scenario with higher impacts would appear to be substantial. The increase in emissions still represents a 280% increase in the emissions of GHGs over 2005 levels. Consequently, while there are differences in the projected changes in regional and global temperature, these changes are more modest in comparison (see Figure 6.2). By 2100 the mean surface temperature for Australia is projected to increase by 3.8ºC over 2000 levels. The global mean temperature and mean temperature over the land surface are projected to increase by 3.1ºC and 4.0ºC, respectively, at 2100, over 2000 levels. The temperature changes for the different regions under all scenarios are given in Table E4 in the appendices.

Even the highly contractionary nature of the reference scenario with higher impacts results in large changes in the climate system by the end of the century. This illustrates the accumulative nature of the anthropogenic influence on the climate system. The changes in the climate occurring at the end of the 21st century are dependent on the total emissions prior to that time. This includes those emissions in the first half the 21st century when the global economy and, therefore, GHG emissions are projected to be relatively unaffected by climate change, even under the reference scenario 'with higher impacts'.

[***] These values for the atmospheric concentration of CO_2-e include only the contribution due to carbon dioxide, methane and nitrous oxide. The CO_2-e concentration due to all GHGs will be somewhat higher.

7. Uncertainty analysis

This section of the report addresses the important question of uncertainty: both relative and compounding uncertainty. Each component of GIAM is, to a greater or lesser degree, uncertain in its projections. Which component is the most uncertain and how do the uncertainties combine?

There are two broad areas of uncertainty within GIAM. First, although the climate system is deterministic, it is also chaotic. Two instances of a GCM, which are identical except for a small difference in the initial conditions, will therefore have the same *climate* (i.e. the mean state of the model over time), but different *weather* (i.e. the day-to-day, month-to-month and year-to-year variations about the mean state). Within GIAM, the climate component consists of three independent instances of the CSIRO Mk3L climate system model; each member of this ensemble differs only in the initial conditions. The mean state of the ensemble provides a best estimate of the mean state of the climate system, and is therefore used as the 'climate'. The differences between the ensemble members allow the uncertainties arising from internal variability to be quantified. Note that this type of uncertainty, which is a physical feature of the climate system, is distinct from uncertainties inherent in the physical formulation of individual climate models.

Second, Mk3L, GTEM and the damage function used in GIAM contain a number of parameters whose values, while chosen according to our current understanding, are not fixed by theory or observational constraints. (IAMs do not currently agree on the functional form of the damage function or the method of application (e.g. Warren et al. 2006).) The associated uncertainty in these parameter values then imposes an uncertainty on the projected economic impacts due to climate change. The computational expense of GIAM prevented a full assessment of the uncertainty associated with the choice of parameter values in this paper. Instead we present here a preliminary analysis which compares the uncertainty due to the damage function parameters with that due to climate variability and parameter choices in GTEM.

We focus on the uncertainties over part of the GIAM cycle, namely steps 4 and 5 of the first iteration of the reference scenario (see Figure 2.1). In effect, the second iteration of GTEM is rerun for a number of cases where either the regional temperature changes or parameter values have been altered. For ease of comparison between the different forms of uncertainty the results are compared to the reference scenario without climate impacts. The changes in GDP and anthropogenic emissions are used as proxies for the economic impacts of climate change; changes in the structure of the underlying economy also occur.

Uncertainty due to climate variability

Using alternate, but physically consistent, values for the regional temperature changes in GIAM allows two questions to be addressed in addition to that of the uncertainty due to climate variability. First, how comprehensive does the climate component of GIAM (and other IAMs) need to be? Could a simpler (quicker) climate model be used instead of Mk3L? Second, how different would the results from GIAM be if a climate model with a different overall climate sensitivity were used?

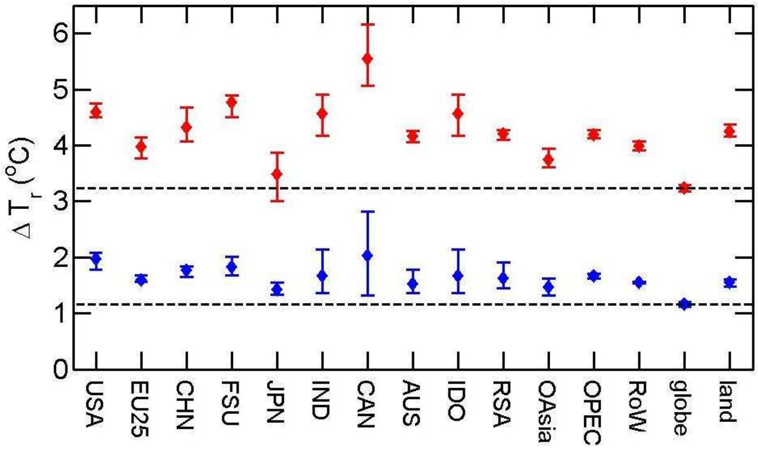

Figure 7.1. Regional temperature changes at 2050 (blue) and 2100 (red) as simulated by Mk3L under the reference scenario with climate impacts. The error bars show the range of temperature changes simulated by individual ensemble members. The region labels are (where not self-explanatory): CHN, China; FSU, Former Soviet Union; JPN, Japan; IND, India; CAN, Canada; AUS, Australia; IDO, Indonesia; RSA, South Africa; OAsia, other Asia region; RoW, Rest of World; land, average over the land surfaces on the globe.

To address these questions, three sets of analysis are shown:

1. Where the global-mean temperature change, both from the ensemble average and from the individual ensemble members, is used in place of the temperature change for each region.
2. Where the mean temperature change over the global land surface, both from the ensemble average and from the individual ensemble members, is used in place of the temperature change for each region.
3. Where the temperature changes from each individual ensemble member are used in place of the ensemble mean temperature change for each region.

The use of temperature changes from both the ensemble mean and the individual ensemble members allows the uncertainty due to climate variability to be quantified. It also indicates whether or not the temperature changes are statistically significant.

Figure 7.1 illustrates the range of temperature changes simulated by the Mk3L ensemble for each of the regions at 2050 and 2100. The uncertainty in the change in global temperature is generally small. There are however some regions where the uncertainty is much larger. This uncertainty is a consequence of the large magnitude of the simulated climate variability in some regions, particularly those that are geographically small.

Figures 7.2-7.5 illustrate the subsequent variation in real GDP per person and emissions at the global and regional level upon using the three sets of temperature changes within the damage function in GIAM. As with the reference scenario with climate impacts the impacts associated with climate change are projected to increase over time and are highly non-uniform across the regional economies. The range of impact on the global economy due to climate variability is reasonably small, around 0.5% difference on an 8% overall change at 2100. The impacts on the regions' economies are, however, much more influenced by climate variability.

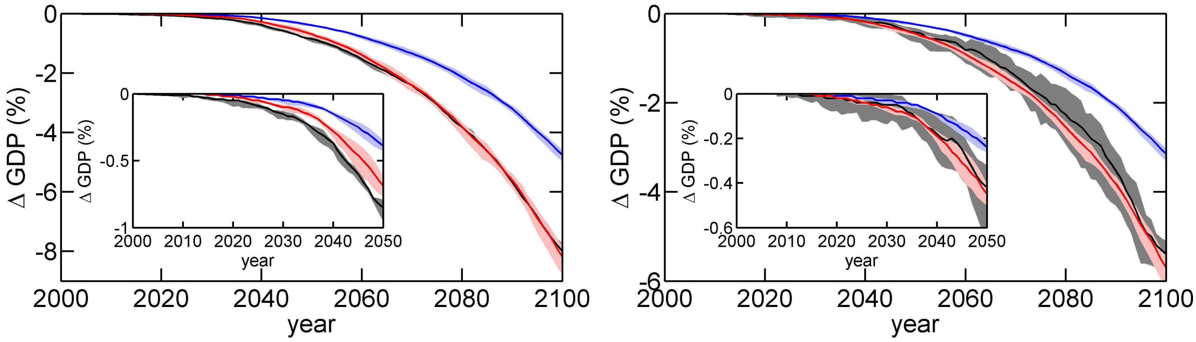

Figure 7.2. Change in global (left) and Australian (right) real GDP per person, relative to the reference scenario without climate impacts, when different forms for the regional temperature change are used within the standard damage function. Black line: using Mk3L regionally resolved temperature changes; red line: using Mk3L temperature change for the global land surface for all regions; blue line: using the globally averaged temperature change for all regions. Shaded areas represent the range over the individual ensemble members.

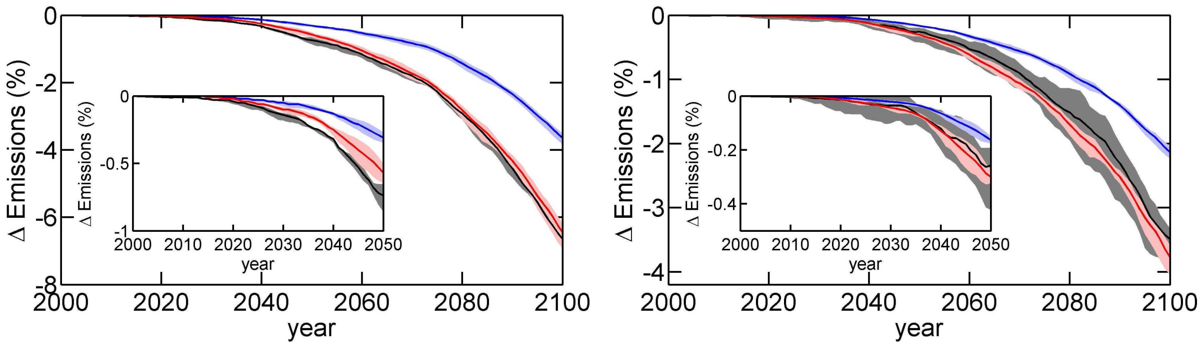

Figure 7.3. Change in global (left) and Australian (right) GHG emissions[†], relative to the reference scenario without climate impacts, when different forms for the regional temperature change are used within the standard damage function. Lines and shading as in Fig. 7.2.

Comparing the three sets of results provides a number of key insights. First, there is a significant difference, at the level of the global economy, between using a climate model that simulates the land and ocean surface separately and one that does not. Second, there are significant differences, at the level of the regions' economies, between using a climate model which resolves at the regional scale and one that does not. Together these results imply that IAMs need to ensure that the complexity of their climate components, damage functions and economic regionalisation is understood and taken into account in interpreting the results. The analysis here also suggests the need for regionally averaged climate variables to be used in regionally resolved IAMs. Third, the use of global average temperature changes may act to artificially suppress the influence of climate variability on the economy, especially at the regional scale.

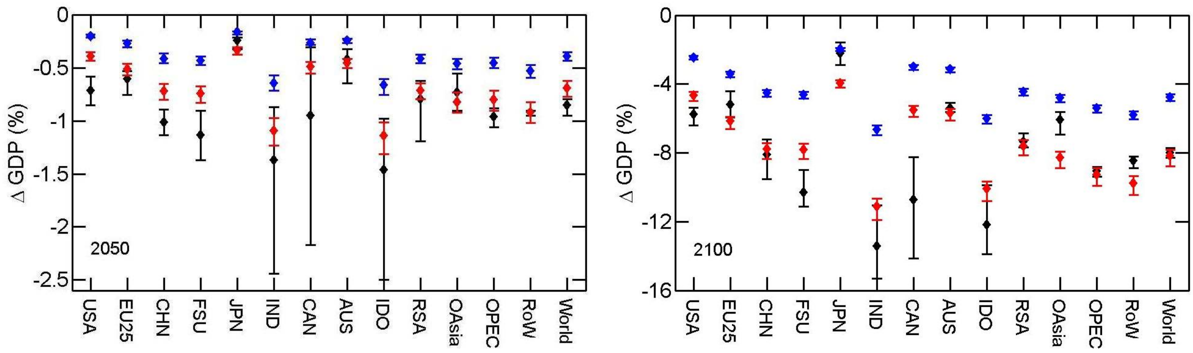

Figure 7.4. Regional breakdown of the impacts on real GDP per person, relative to the reference scenario without climate impacts at 2050 (left) and 2100 (right) when different forms for the regional temperature change are used within the standard damage function. Black: using Mk3L regionally resolved temperature changes; red: using Mk3L temperature change for the global land surface for all regions; blue: using the globally averaged temperature change for all regions. The symbols show the result when the ensemble average is used, the error bars show the range of responses over the individual ensemble members.

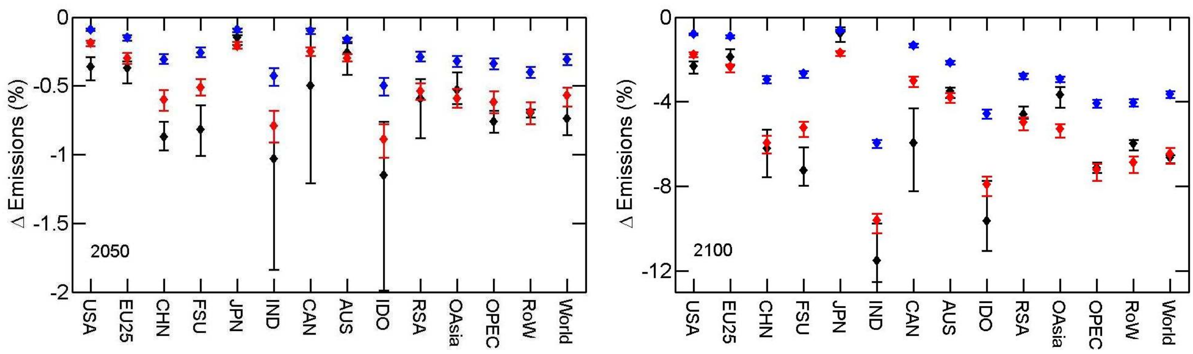

Figure 7.5. Regional breakdown of the impacts on emissions[†††], relative to the reference scenario without climate impacts at 2050 (left) and 2100 (right) when different forms for the regional temperature change are used within the standard damage function. Symbols and lines as in Fig. 8.4.

Finally, the difference in the projections of temperature change for the globe and global land surface is of the same order as differences in the projections of global temperature change from different climate models. This suggests that the choice of climate model, and particularly the choice of climate model in conjunction with the damage function, will play an important role in determining the overall magnitude of, and details within, projections of the impacts of climate change on the global economy.

Sensitivity analysis of economic parameters in GTEM

The second component of this section considers the uncertainty due to parameters within the economic model GTEM. Parameters within GTEM are drawn from the Global Trade Analysis Project (GTAP) database complemented by empirical estimation and calibration drawn from the literature and expert research. However these parameter values are still uncertain. Here we consider how the prescribed values of the energy efficiency parameters within GTEM affect the projections of future emissions within the reference scenario without climate impacts.

[†††] Anthropogenic emissions of CO_2, CH_4 and N_2O combined according to the Kyoto Protocol conventions (UNFCC 2007; 2008). The Land Use Change and Forestry emissions are not included.

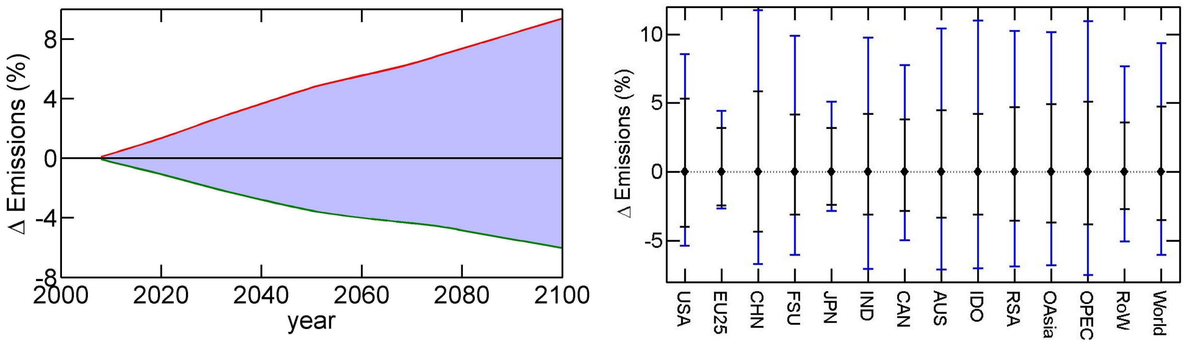

Figure 7.6. Left: Sensitivity of the global emissions to the energy efficiency parameter in GTEM. Green line shows the impact on the reference scenario without climate impacts of an increase in efficiency of 20%, red line gives the impact with a decrease in efficiency of 20%. Right: regional breakdown of GHG emissions at 2050 (black) and 2100 (blue) when the energy efficiency parameter is varied by ±20%. A decrease in efficiency leads to increased emissions in all regions at all times. The differences are referenced to the reference scenario without climate impacts.

The energy efficiency parameter affects the emissions per unit of energy with a higher efficiency implying fewer emissions are produced. Figure 7.6 shows the evolution of the global emissions over the 21st century and the regional breakdown of emissions at 2050 and 2100 when the energy efficiency parameter is changed by ±20%. As expected the impact on emissions is monotonic and increasing over time with a decrease in efficiency leading to an increase in emissions and vice-versa.

Choice of damage function parameters

The third, and final, component of this section considers the uncertainty in the parameter choices within the damage function and how this uncertainty is reflected in the economic projections. The damage function and its parameters are defined in Box 1 (Section 2). Individual parameters in the damage function are incremented separately by ±10% and ±25%. The accompanying changes in the economic outcomes then indicate the sensitivity to the parameter choice. The associated uncertainty due to the damage function is less well defined as this requires reasonable bounds to be placed on each parameter value.

Figures 7.7-7.9 show how the choice of parameter values influences the global real GDP per person over time and the regional real GDP per person at 2100. Similar, but slightly smaller, variation is shown in the emissions data. There are a number of important implications from these results. First, regional and global GDP and emissions are more sensitive to the value of Ω and δ than to that of σ_2 – we return to the implication of this below. Second, GDP and emissions are proportionally more sensitive to the parameter values than the damage function itself. For example, changing the value of Ω by ±10% leads to a change in the economic loss factor of approximately ±30% but a change in the magnitude of the reduction in global real GDP per person of around ±50%. This illustrates the compounding nature of the evolution of the economy and damages and the non-linearity in the system.

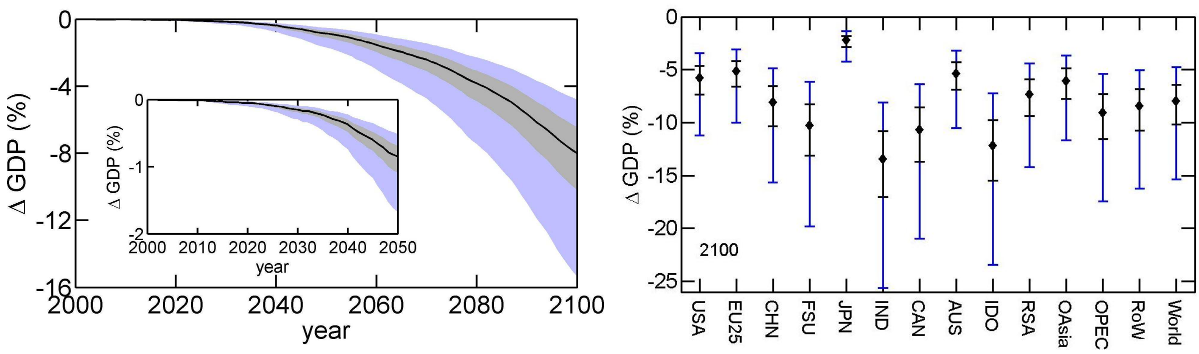

Figure 7.7. Sensitivity of the regional and global GDP to the parameter Ω in the damage function. Left panel: line gives value with the default parameter values; the grey region represents the range when Ω is varied by ±10%, blue area the range when Ω is varied by ±25%. Right panel: Symbols give the values with the default parameter value, the black errors bars give the range when Ω is varied by ±10%, the blue lines when Ω is varied by ±25%. Smaller magnitudes of impacts are associated with larger values of Ω. Differences are referenced to the reference scenario without climate impacts.

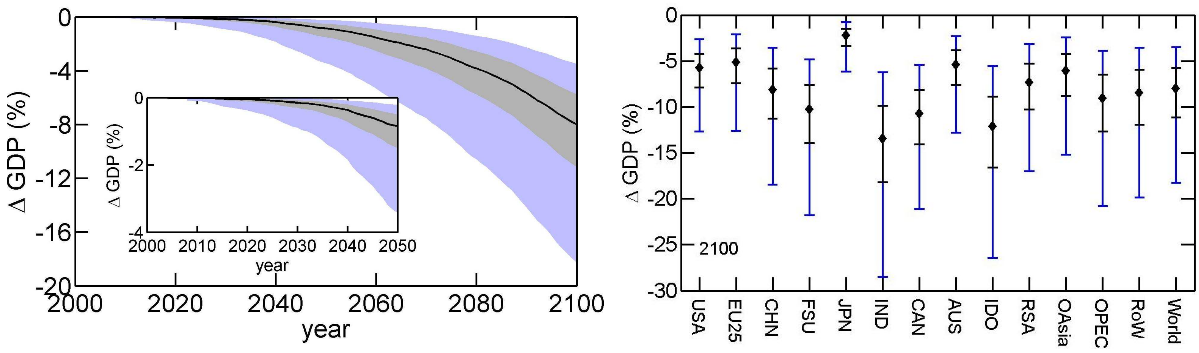

Figure 7.8. Sensitivity of the regional and global GDP to the parameter δ in the damage function. Lines and symbols as Fig. 8.8 but with δ varied in place of Ω. Smaller magnitudes of impacts are associated with larger values of δ. Differences are referenced to the reference scenario without climate impacts.

Third, the non-zero value of σ_2 was an attempt to quantify the belief that poorer countries would be more susceptible to climate related economic impacts than richer countries (e.g. Pearce et al. 1996). The relative lack of sensitivity to the parameter σ_2 would appear to indicate that inequality in per person income will not play as important a role as believed. However, this result is driven by an assumption within the reference scenario that rapid convergence in per person income occurs early in the 21st century. This assumption reduces the impact of σ_2 later in the simulations when the economic impacts are greater, thereby potentially reducing the possible sensitivity to this parameter. This issue demonstrates that the sensitivity of the system to any one parameter is also dependent on the overarching assumptions and upon the values of other parameter values.

Fourth, the large sensitivity of the projected economic evolution to the parameter values within the damage function would often lead to additional iterations between the economic and climate modules in GIAM being required for convergence. We suspect that the sensitivity of the full GIAM model is slightly less than shown in these results.

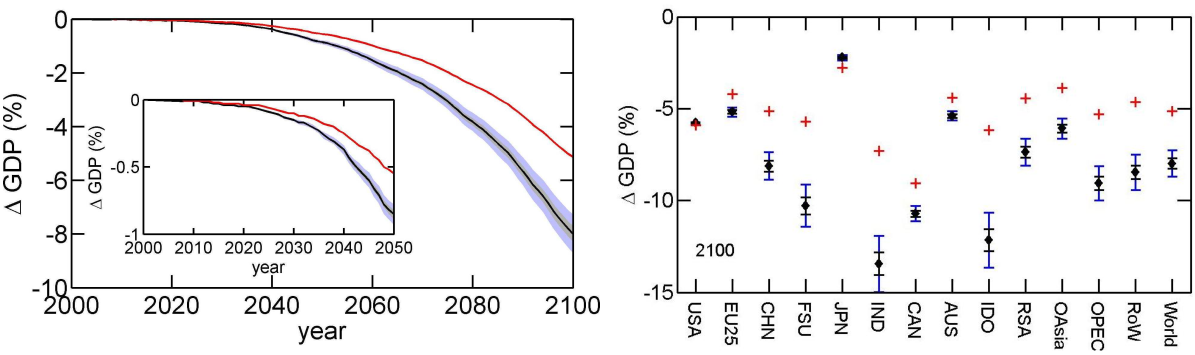

Figure 7.9. Sensitivity of the regional and global GDP to the parameter σ_2 in the damage function. Lines and symbols as Fig. 8.8 but with σ_2 varied in place of Ω. Red line/crosses give the value when σ_2=0. With the exception of the USA and Japan regions, smaller magnitudes of impacts are associated with smaller values of σ_2. Differences are referenced to the reference scenario without climate impacts.

Finally, while it is difficult to compare the sensitivity of the overall system using these discrete studies we can make a preliminary assessment concerning the relative uncertainties by comparing the changes to the model parameters needed in each model component in order to achieve an equivalent change in the global real GDP or emissions. The results show that a 4% change in global real GDP per person or emissions at 2100, relative to the reference scenario without climate impacts, cannot be obtained as a result of climate variability but, by comparing temperature changes and impacts, could be obtained with a change in climate sensitivity of around 30%. Similarly a 4% change in global emissions can be obtained by changing the energy efficiency by around 15%. However, a 4% change in global real GDP per person or emissions is easily obtained by relatively smaller changes (10%) in the parameters of the damage function. Overall, these results illustrate that much of the understanding concerning the possible economic impacts due to climate change is highly dependent on how those impacts are quantified. The associated uncertainty must then be a critical component of any climate change cost-benefit analysis and/or policy development.

8. Discussions and conclusions

The principal aims of this report are to document GIAM and to report on the analysis of the global scenarios undertaken using GIAM for the Garnaut Climate Change Review – these aims are covered in Sections 1-7. In this final section we briefly highlight some key results from this work and place them in a broader context.

GIAM analyses the co-evolution of the global market economy and climate system. By jointly considering these two, traditionally separate, areas the many inconsistencies which have been encountered in both areas can be reduced. The two principal components of GIAM - ABARE's GTEM and the CSIRO Mk3L climate system model - are coupled together using a damage function which encapsulates the current understanding of how the economic system will be impacted by changes in climate. However, all components of GIAM have associated qualifications, as introduced throughout the report. The main strength of GIAM is that it allows the comparison of different scenarios and/or policies in the context of these qualifications and associated uncertainties.

A fundamental aspect of the results shown is the illustration of the connectivity of the global market economy and climate system. From a climate perspective, there are regions which play little role in producing emissions; but which are projected to experience significant changes in climate; the converse is also true. In addition, the projected impacts of climate change on the economy cannot be explained solely through changes to the local climate. Changes in the terms of trade are a critical component to the projections.

The analysis of the three Garnaut Review scenarios covered in this report indicate that, globally, some mitigation effort is warranted in order to minimise the combined economic impacts of climate change at 2100. The analysis also indicates that the degree of mitigation warranted, as indicated by the economics, is likely to be different between regions. It should be noted that only market impacts of climate change were considered in this analysis.

Next we highlight two features of the results which are direct consequences of assumptions we have made. The first is that climate change necessarily damages the global economy. The second is that the economy and climate systems are linked through a negative feedback process (economic activity produces emissions which leads to climate change which damages the economy thereby resulting in less emissions and smaller climate change). While these results are consistent with our broad understanding of the market economy and climate change, in this study these results are the direct consequence of requiring the damage function to (monotonically) take a value between 0 and 1, i.e. climate change can only reduce regional productivity not increase it.

A key result from this work, which has been highlighted many times before but is worth restating, concerns the different time scales acting in different parts of the system. The climate system acts as an integrator of emissions over time. A change in the mean climate state at a particular time is the net effect of the accumulated emissions over a long period in the past in combination with other, natural, sources of variability. A direct consequence of this integrating effect is that the impacts of present day emissions will not be noticeable climatologically for some time; for the scenarios analysed here the simulations do not diverge until 2020-2030. Our current understanding of how the climate impacts on the market economy then suggests that the differential economic impacts of climate change will not be appreciable economically until around 2050. This issue of time scales presents a fundamental problem in the mitigation and adaptation debate as any benefits (climatological or economical) of policy actions will not be felt for many years yet there may be an immediate economic cost. For a fuller discussion of this issue see Jones and Preston (2006).

As noted by Weyant (1996), and reinforced here, uncertainties remain in just about every aspect of the socio-economic and climate systems. It is therefore important that the debate surrounding climate change, the pros and cons of mitigation and adaptation and/or policy development recognises this uncertainty. It is also important that all sources of uncertainty be recognised – not simply those sources upon which it is advantageous to concentrate (depending on the point being debated). The uncertainty involved should not be used to dismiss the need for debate or, if warranted, action. Rather, the debate should be phrased in such a manner as to recognise uncertainty and actions developed in a framework of risk-analysis (e.g. Jones and Preston 2006). The uncertainty also demonstrates the continued need for further research aimed at producing quantitatively more robust analyses. One specific area where research is needed is in quantifying better the link between climate, climate change and the market and non-market economy.

Finally, while GIAM is complex in many aspects, it is important to recognise that, like all IAMs, it addresses only part of a much larger issue. For instance, there are examples of market effects not included, or only included indirectly through proxies, in GIAM. There are aspects of politics, economics, climate science and, more generally, environmental change (e.g. poor governance, regulatory tariffs, abrupt climate change, ocean anoxia) which may be critical for global development, but which may defy inclusion in the underpinning economic or climate models and for which we currently have little or no capacity to quantify. There is also a huge range of non-market aspects to global development which cannot easily be incorporated into GIAM, or indeed any quantitative model, at this point in time. Hence while GIAM, and the results shown, are useful in addressing questions concerning global development, they must be viewed as only part of a much wider debate. It is this debate, covering not only climate change science and economics, but also the social sciences, ecology and politics (among others), which forms the true ‘diabolical challenge of our times’ (Garnaut 2008b).

Appendices

A: GIAM regional economies, sectors, primary factors and greenhouse gases

Table A1. Regional economies, commodities/sectors, primary factors and greenhouse gas emissions in GIAM.

Regions [a]	Commodities/sectors	Primary factors	Greenhouse gases and precursors
United States of America	Coal	Capital	Carbon dioxide
European Union 25 [b]	Oil	Land	Methane
China [c]	Gas	Labour	Nitrous oxide
Former Soviet Union [d]	Petroleum and coal products	Natural resources	Hydrofluorocarbons
Japan	Electricity		Perfluorocarbons
India	Iron and steel		Sulphur hexafluoride
Canada	Nonferrous metals		Chlorofluorocarbons
Australia	Chemicals, rubber and plastics		Volatile organic compounds (VOCs)
Indonesia	Other mining		Carbon monoxide
South Africa	Non-metallic minerals		Sulphur dioxide
Other Asia	Manufacturing		
OPEC	Other transport		
Rest of world [a]	Water transport		
	Air transport		
	Livestock		
	Crops		
	Forestry and fishing		
	Food		
	Services		

[a] Key climate variables for all regional economies are derived from the output of the CSIRO Mk3L climate system model. The 'Rest of world' region excludes Antarctica and Greenland.
[b] European Union 25 comprises Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Hungary, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden and United Kingdom.
[c] Including Hong Kong
[d] Comprises Azerbaijan, Armenia, Belarus, Georgia, Kazakhstan, Kyrgyz, Moldova, Russian Federation, Tajikistan, Turkmenistan, Uzbekistan and the Ukraine.

B: GIAM regions within the CSIRO Mk3L climate system model

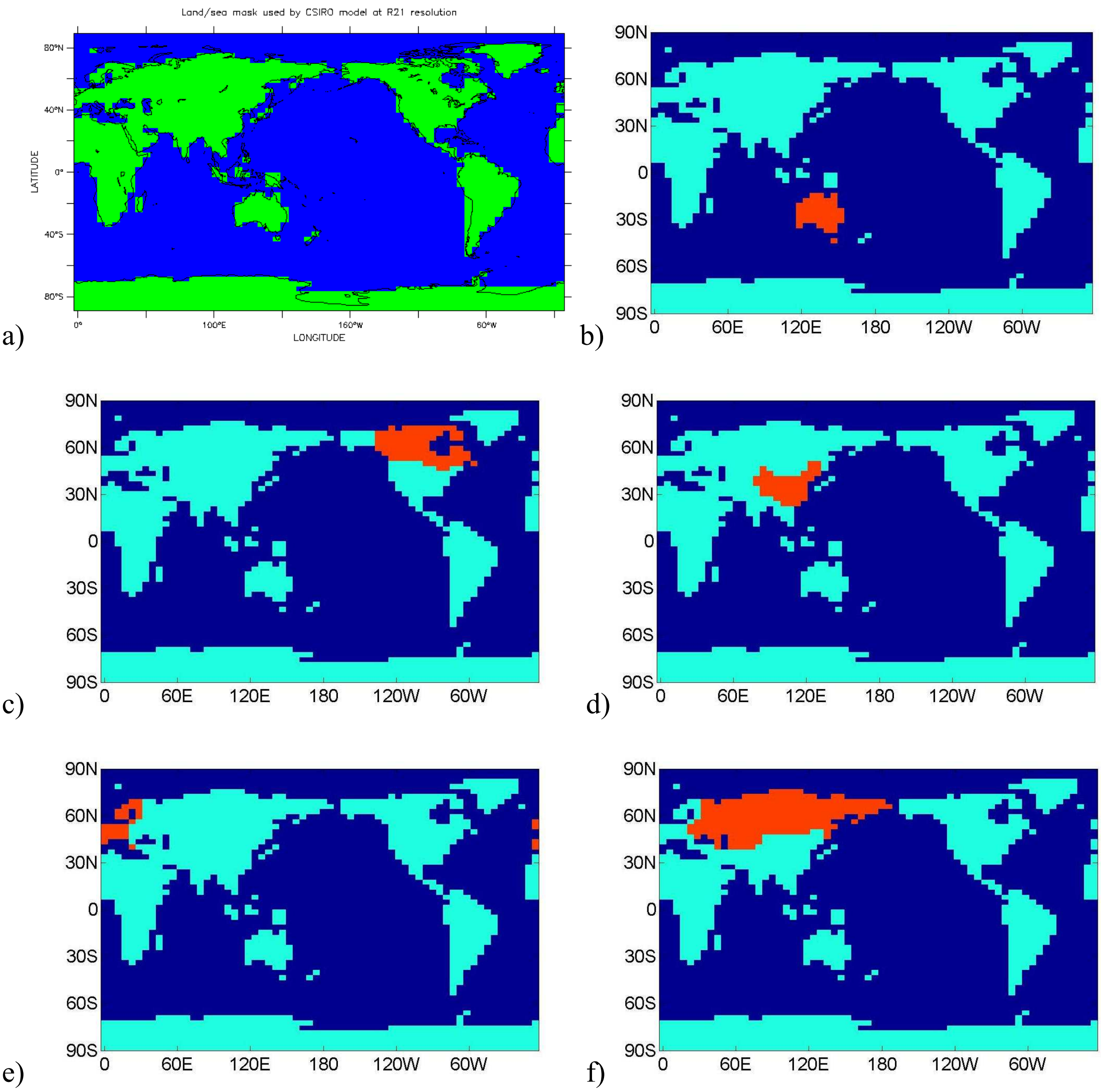

Figure B1. a) Land-sea demarcation within Mk3L overlain by the global coastline.
b)-n) Geographical location of the 13 GIAM economic regions in Mk3L. Climate variables for each region are averaged over the areas shown in red. b) Australia, c) Canada, d) China, e) European Union 25, and f) Former Soviet Union.

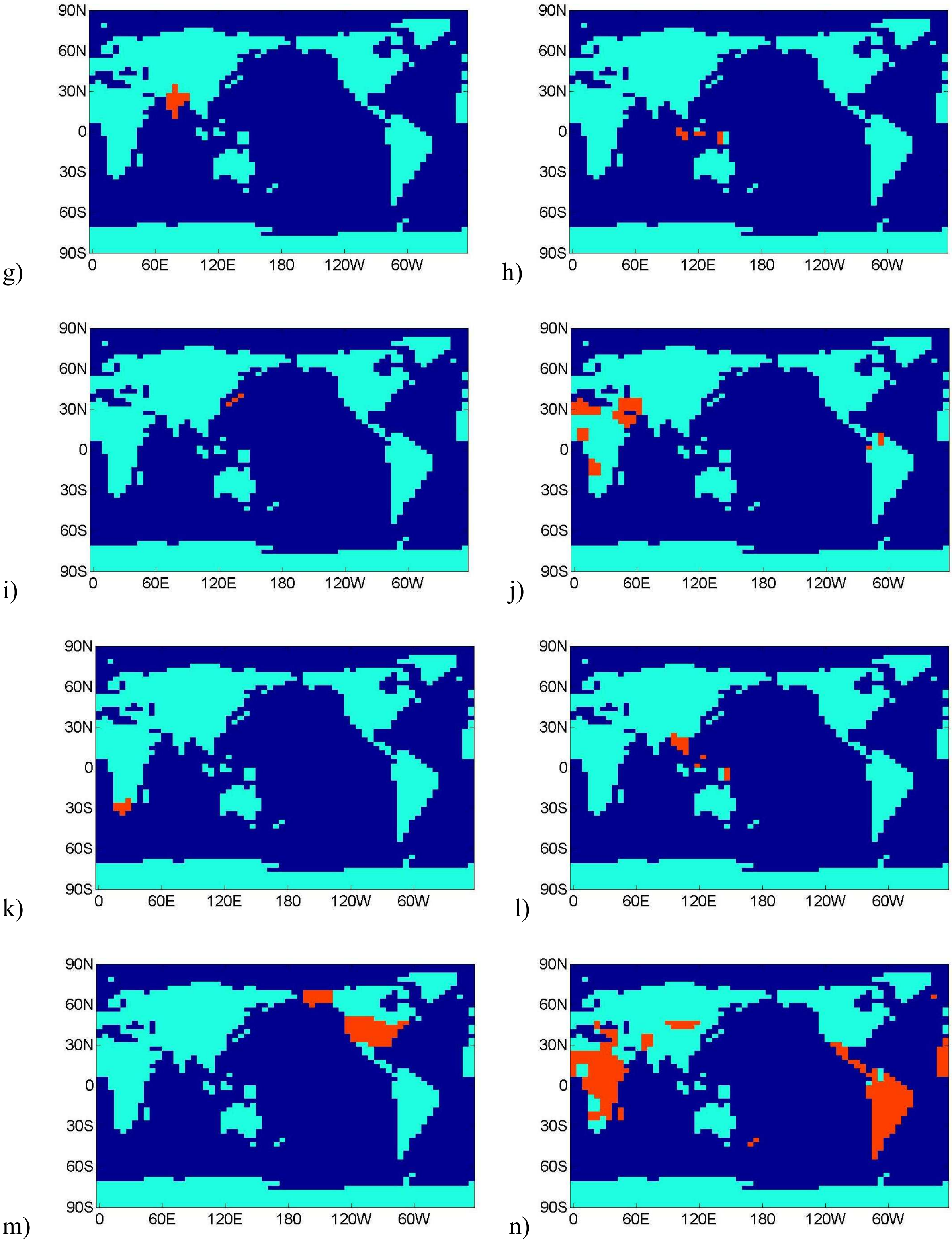

Figure B1 cont. g) India, h) Indonesia, i) Japan, j) OPEC, k) Republic of South Africa, l) Other Asia, m) United States of America and n) Rest of World. Antarctica and Greenland are not included in any of the economic regions.

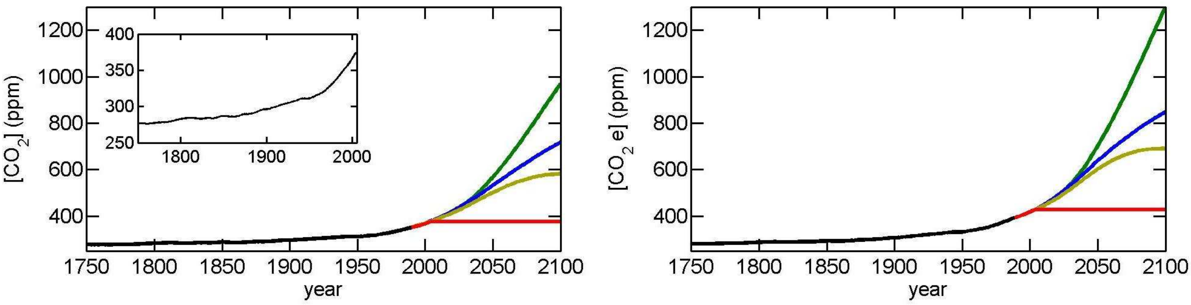

Figure C1. Time series of the atmospheric CO_2 concentration (left) and equivalent CO_2 concentration (right) used to force Mk3L. The equivalent concentration is determined from the concentrations of CO_2, CH_4 and N_2O only. Observed concentrations are given in black; SRES marker scenarios for A1FI are given in green, for A1B in blue, for A1T in orange and for the S2004 stabilisation scenario in red.

C: The response of Mk3L under the SRES scenarios

Before analysing the output of a climate model, its ability to simulate observed features of the climate system must first be evaluated. It can also be useful to compare the response of different climate models to the same external forcing (e.g. IPCC 2007a). Mk3L was therefore used to simulate the period from the pre-industrial era (1750) through to the present day. These simulations were extended to 2100 for a number of the scenarios introduced in the SRES (IPCC 2000). Simulations of the historical period allow us to validate the model's performance against observed changes, whilst also establishing the present day tendencies in the climate. These are important when simulating the evolution of the climate system during the 21st century.

For the simulations presented in this appendix, only three forcing agents are considered – global atmospheric carbon dioxide, methane and nitrous oxide. A number of other significant forcing agents are omitted. These include atmospheric halocarbons, ozone and the direct and indirect affects of aerosols (IPCC 2007a, Figure TS.5). These are excluded here because of the associated low level of scientific understanding, the lack of reliable historical records or future projections, or the inability of Mk3L to explicitly consider these forcing agents. When comparing the output of Mk3L to that of other models, these differences in the configuration of the model should be remembered.

For the historical period, which we take here as being the period to 1990, observed GHG concentrations are used to drive the model. These concentrations are derived from ice core records, and from observations made at the Cape Grim measurement site in Tasmania. Further details of these time series of the composition of the atmosphere are given by Etheridge et al. (1996; 1998) and Trudinger et al. (2002).

Four projections of the 21st century are considered: a stabilisation scenario, and three of the marker scenarios from the SRES (IPCC 2000). The stabilisation scenario (S2004) uses observed concentrations from 1991 to 2004, and then assumes that these concentrations remain constant out to 2100. Note this is *not* equivalent to reducing emissions of GHGs to zero. The three SRES scenarios considered are the A1FI, A1B and A1T marker scenarios. The SRES gives projections of *emissions* of the various forcing agents into the future. Here we use the ISAM carbon cycle model (with a mid-range carbon fertilization effect, Jain et al. 1994) to convert these emissions into GHG concentrations – these time series are given by IPCC (2001). Together these four simulations span the majority of future projections of

GHG concentrations (IPCC 2000; 2001; 2007a). The time series of the atmospheric concentration of carbon dioxide and carbon dioxide equivalent are shown in Figure C1.

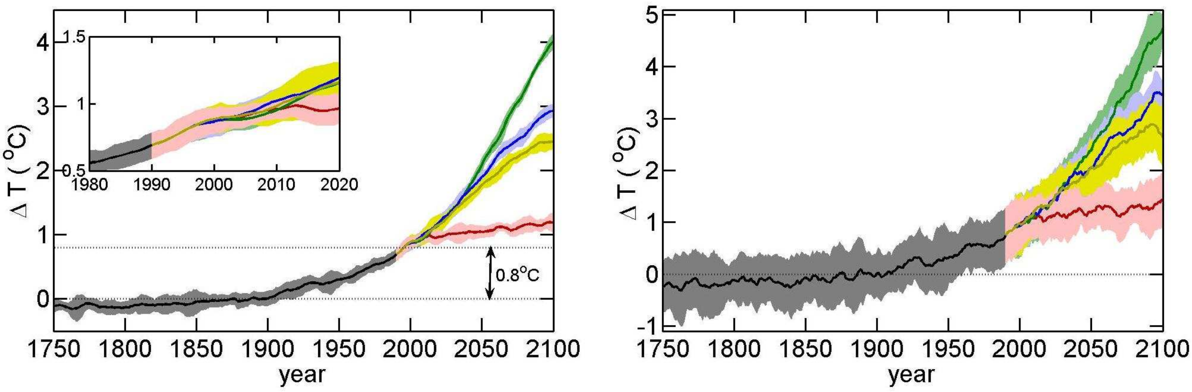

Figure C2. Projected evolution of the surface air temperature for the globe (left) and Australian region (right) as simulated by Mk3L. Lines give the 9-year running mean of the ensemble average, with the shaded area giving the 95% confidence interval around the mean. Simulated historical warmings given in black; SRES marker scenarios for A1FI are given in green, for A1B in blue, for A1T in orange and for the S2004 stabilisation scenario in red.

Global-mean surface warming

The global-mean surface temperature is, perhaps, the key metric within the climate system which describes the overall response of the model. Figure C2 (left) shows the change in global mean surface air temperature, as simulated by Mk3L, from 1751 to 2100 for the four scenarios considered. The shaded area gives the 95% confidence interval around the ensemble mean of the climate; a nine-year running mean has been applied.

The change in global-mean surface air temperature over the 20th century is within the range of the observed temperature change given in the most recent IPCC assessment. Specifically, the simulated temperature change from 1850-1899 to 2001-2005 is 0.92°C, while the observed value is 0.76±0.19°C (IPCC 2007a). Mk3L therefore lies within the range of uncertainty, albeit towards the upper end. Any overestimation of the observed warming is most likely due to the neglect of the impacts of aerosols within Mk3L; these are believed to have had a net cooling effect on the climate over the 20th century (IPCC 2007a, Figure TS.5).

The Mk3L projections for the future show increasing differences in global surface warming over time, as expected given the differences in forcing applied. However, for each of the four scenarios, there are no statistically-significant differences in the mean warming for the period to 2020. Internal climate variability dominates over the impact upon the mean climate state from the differences in the radiative forcing between the scenarios.

The projected global warming from 2020 to 2100 does, however, vary significantly with the scenario considered. The simulated temperature change from 1850-1899 to 1990-1999 is 0.8°C. The A1FI scenario warms an additional 3.1°C, the A1B scenario an additional 2.1°C, and the A1T scenario an additional 1.6°C over the 21st century (1990-1999 to 2090-2099). These numbers compare with the IPCC estimates of 4.0 (2.4-6.4) °C, 2.8 (1.7-4.4) °C and 2.4 (1.4-3.8) °C respectively (IPCC 2007a, Table TS.6). Furthermore the S2004 stabilisation scenario has an additional warming over the 21st century of 0.4°C, which compares with a warming of 0.6 (0.3-0.9) °C for the Constant Year 2000 Composition scenario of the IPCC (2007a).

The projected warming for Mk3L therefore lies within the IPCC (2007a) ranges for the respective scenarios, and does so across all four scenarios. This gives confidence in the model. However, Mk3L consistently lies within the lower half of the IPCC ranges. There are a number of possible reasons why this might be the case. The list of forcing agents excludes the long-lived halocarbons, which have a positive warming effect. Aerosols are also excluded; most IPCC modelling studies assume declining concentrations of aerosols over the 21st century, which would also have a positive warming effect.

The transient climate response (TCR) is a measure of how the global mean surface air temperature in a climate model responds to a prescribed forcing. Specifically the TCR is the change in global surface air temperature in a 1% per year CO_2 increase experiment at the time of atmospheric CO2 doubling. The TCR of Mk3L has been found to be 1.6°C (2006a). The 5-95% range for the TCR from the IPCC model suite is 1.2-2.4°C, with a mean value of 1.76°C (Meehl et al. 2007). The response shown by Mk3L under the SRES simulations is therefore consistent with its transient response, as quantified by the TCR. The TCRs of different GCMs vary, reflecting differences in the model structure and component formulation.

The right panel of Figure C2 shows the projected change in surface air temperature for the Australian land surface only. This illustrates two key aspects of the climate system; first that the temperature change over a restricted region is more variable than that of the global mean, and is therefore more uncertain. This can be attributed to the inherent consequences of natural variability on the simulated climate of a specific region. Second, that the projected warming for Australia is significantly greater than the global mean for all of the scenarios considered. This is because the active heat capacity of the ocean is greater than that of the land masses, resulting in greater warming of the land masses relative to the oceans and, therefore, relative to the global mean.

Patterns of surface warming

The global-mean change in surface temperature only gives a broad insight into the response of any GCM. Figure C3 shows the spatial pattern of global warming over the 21st century for each of the four scenarios considered – these can be compared to the IPCC composites given by Meehl et al. (2007, Figure 10.8). Note that not all of these changes would be statistically significant when referenced to the variability of the simulated climate over the period 1751-1800.

Four key features are apparent from these figures. First, the pattern of warming is largely consistent between the scenarios and over time (not shown). There is therefore no evidence of a threshold aspect to the simulated climate, or of a bifurcation of the simulations. Second, the largest warming occurs in the polar regions, especially in the Arctic. This is the result of the well-known 'albedo feedback' whereby melting snow and ice exposes the darker ocean or land surface beneath; these surfaces absorb more solar radiation, leading in turn to further and more rapid warming. This feature is most apparent in the strong warming projected for the region north-east of Scandinavia, the Barents Sea, where the sea ice cover is thinnest. Third, the land surface warms more in general than the oceans, due to the lower active heat capacity. Finally, the response of the model is muted in the North Atlantic, with cooling projected under all three of the SRES scenarios considered. This region is significantly influenced by the surface ocean currents associated with both the Gulf Stream and the Atlantic section of the thermohaline circulation. These currents act to warm this region of the globe significantly relative to other regions at the same latitude. In many GCM climate change studies these currents are projected to weaken, thereby reducing their warming influence upon the North Atlantic region. In similar transient simulations conducted using Mk3L, the thermohaline circulation slows with increasing atmospheric carbon dioxide concentrations and global warming (Phipps 2006a).

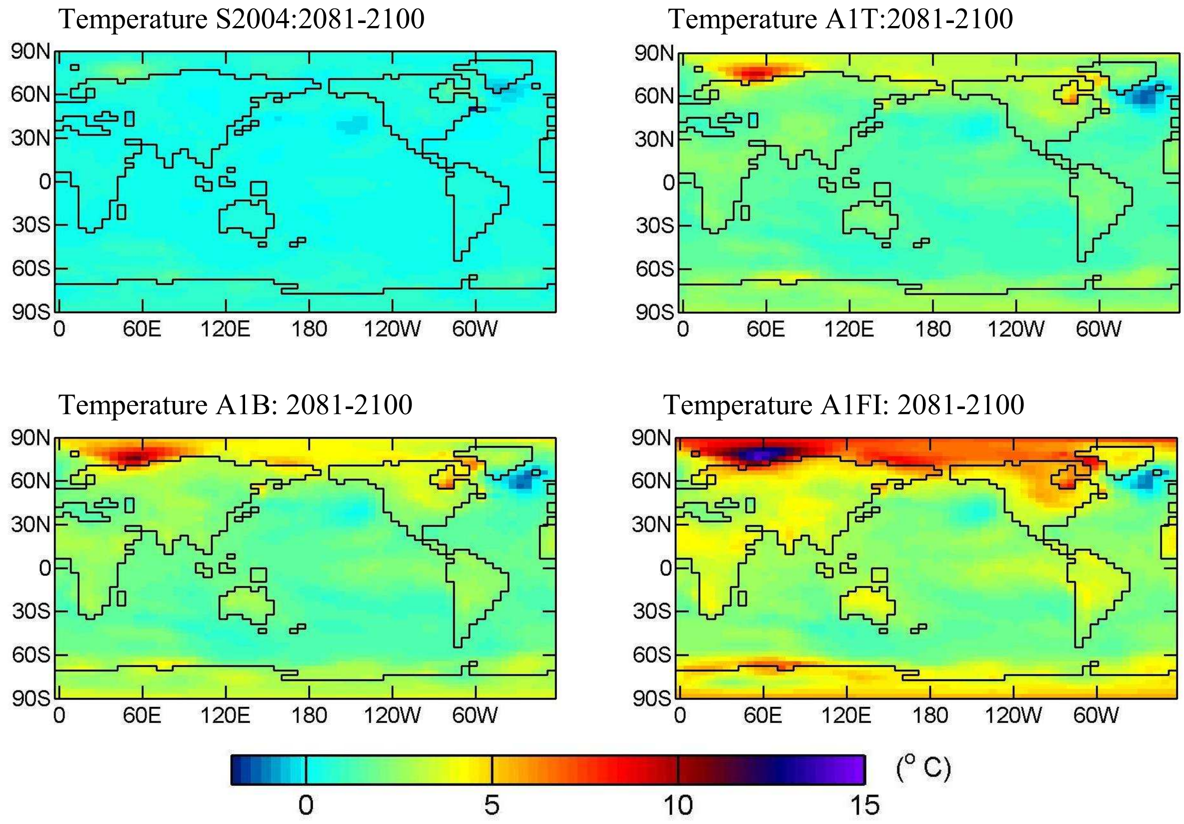

Figure C3. Projected change in the surface air temperature between 1991-2000 and 2080-2100 as simulated by Mk3L for the S2004 stabilisation scenario and for the three SRES scenarios considered. The temperature changes are not necessarily statistically significant.

Both the strong warming in the Barents Sea, and the muted response in the North Atlantic, are seen in the multi-model composite of surface warming given by the IPCC (2007a, Figure TS.28) albeit to a lesser degree.

Other metrics

There are many other climate variables which are important in an economic sense, and which may be expected to change under anthropogenic climate change. Figure C4 shows the projected changes in four variables - global-mean precipitation, surface evaporation and run off, as well as the estimated global-mean sea level change - as simulated by Mk3L under the four scenarios. All scenarios show an increase in both global precipitation and evaporation over the 21st century. For the A1B scenario, this change represents a ~3.5% increase in precipitation; this compares to the IPCC best estimate of a 5% change over the same period (Meehl et al. 2007). The difference is understandable given the generally lower warming exhibited by Mk3L. Globally averaged run off, a surrogate for river flow, is highly variable, with no significant change projected for the 21st century. Significant changes, do however, occur in precipitation, evaporation and run off at the regional scale (not shown).

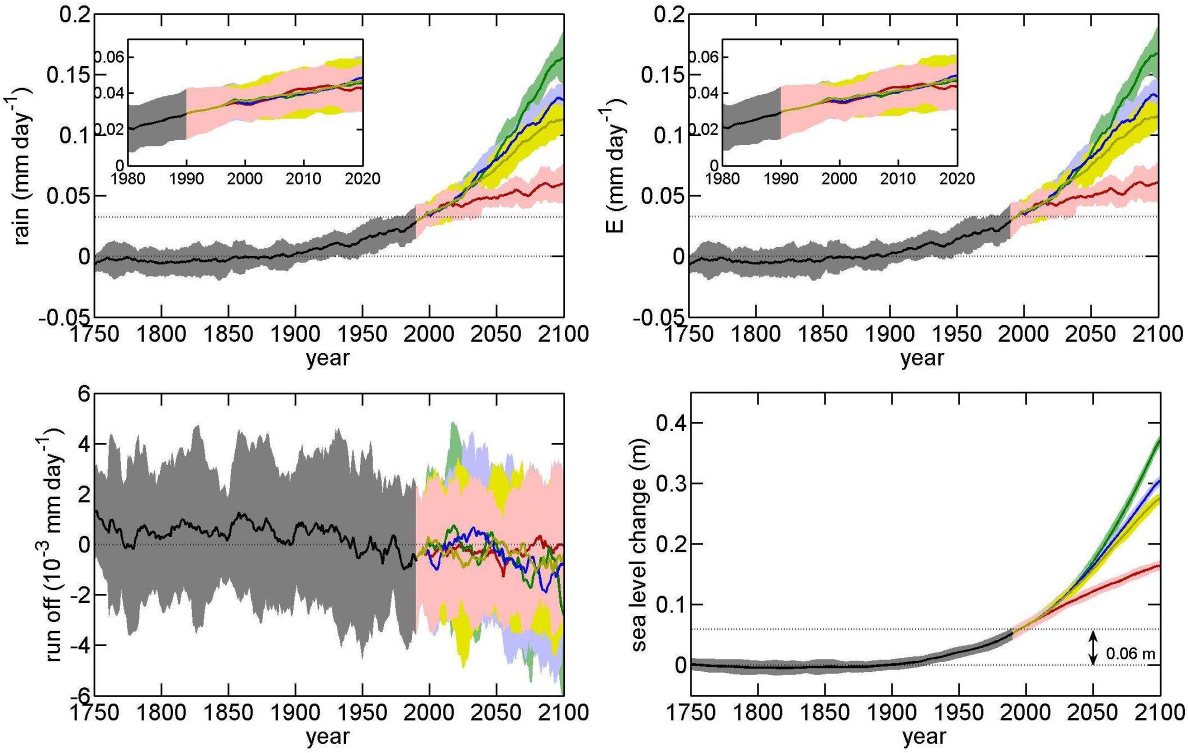

Figure C4. Projected evolution of the change in global-mean precipitation (upper left), evaporation (upper right), surface run off (lower left) and inferred sea level rise (lower right) as simulated by Mk3L. Lines give the 9-year running mean of the ensemble average, with the shaded area giving the 95% confidence interval around the mean. Simulated historical changes given in black; SRES marker scenarios for A1FI are given in green, for A1B in blue, for A1T in orange and for the S2004 stabilisation scenario in red.

Mk3L does not explicitly simulate changes in sea level. However it is possible to derive estimates from the changes in temperature and salinity, and therefore the density, of the ocean. This estimate incorporates the changes due to thermal expansion of the oceans and the melting of sea ice and land-surface snow. It does not include any changes due to the melting of ice sheets or glaciers. Estimates of the global mean sea level rise over the 20th century due to thermal expansion are approximately 0.04±0.01m of the estimated total 0.17±0.05m rise in sea level (IPCC 2007a). The sea level rise over the 20th century as estimated from the output of Mk3L is 0.06m. This is slightly greater than the observational estimate, which is consistent with the slightly greater than observed warming of Mk3L over the 20th century.

The Mk3L estimates of additional sea level rise over the 21st century are 0.32m for the A1FI scenario, 0.24m for the A1B scenario and 0.22m for the A1B scenario. These estimates lie well within, but at the lower end of, the 5-95% ranges given by the IPCC (2007a) of 0.26-0.59m for A1FI, 0.21-0.48m for A1B, and 0.2-0.45m for A1T. Given the differences in experimental design, unequal measures and the generally smaller temperature change simulated by Mk3L, these differences are to be expected.

Overall, Mk3L has been shown to be able to reproduce the observed changes in the global climate over the period from the pre-industrial era to the present day. The simulated global-mean temperature change is consistent with the IPCC estimates, though in the upper half of the range of uncertainty. This is a likely consequence of the omission of the impacts of aerosols within the current study.

The changes in the global climate over the 21st century, as projected by Mk3L under forcing by the SRES scenarios, have also been shown to be consistent with the projections of other models. The global-mean temperature changes lie within the ranges derived from the IPCC (2007a) model suite, although in the lower half of the range of uncertainty. This is a likely consequence of the omission of the impacts of the long-lived chloro- and fluoro-carbons and the impacts of aerosols in the current study.

D: The response of Mk3L under the Garnaut Review scenarios

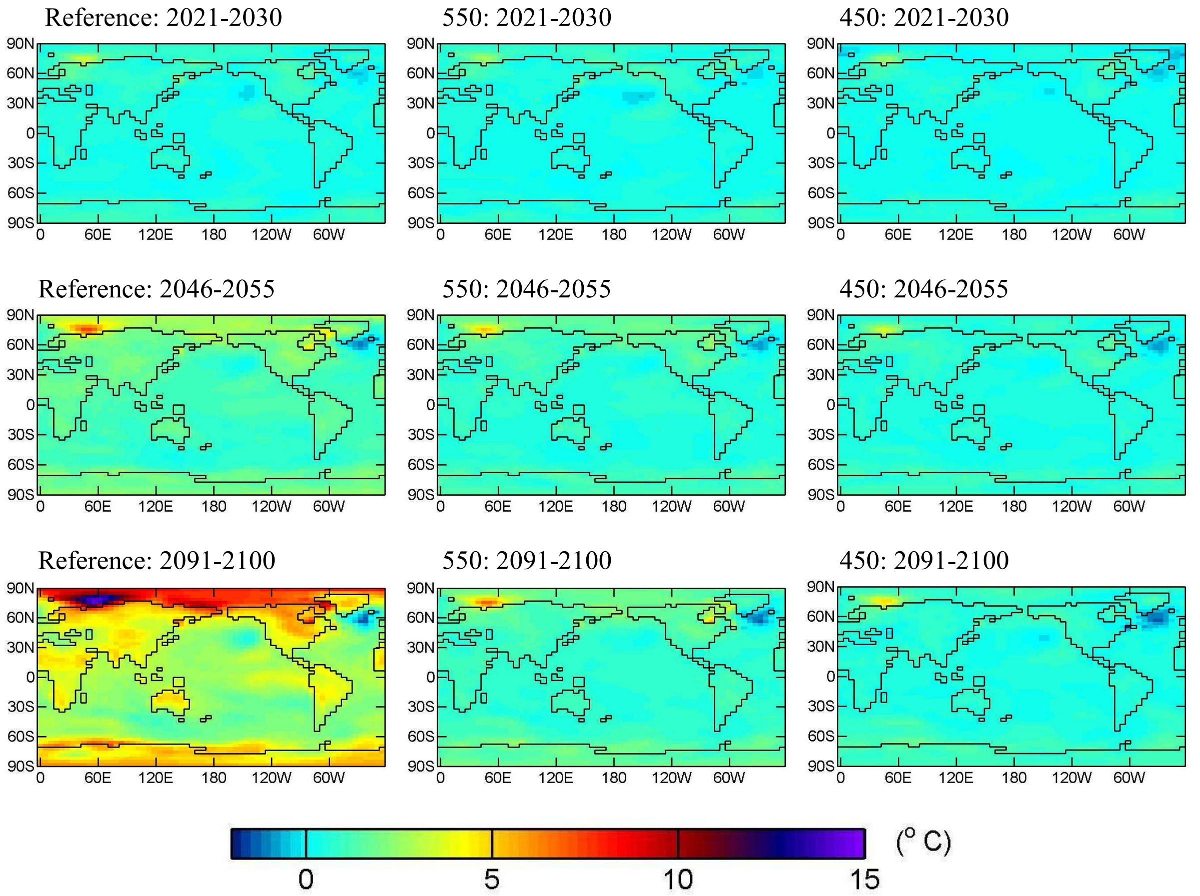

Figure D1. Projected change in the mean surface air temperature over the 21st century as simulated by Mk3L for the three Garnaut Review scenarios (with climate impacts included). Temperature changes are the difference between 1991-2000 and the period given above each panel. The temperature changes are not necessarily statistically significant.

Within GIAM, only the mean change in surface air temperature for each region is used to calculate the economic impacts associated with climate change. However, Mk3L simulates many more climate variables than simply the surface air temperature; this includes other economically-relevant variables. Figure D1 shows the change in surface air temperature for three periods in the 21st century (see also Figure C3). Under the reference scenario with climate impacts, the temperature changes exhibit a similar spatial pattern to those experienced under the A1FI scenario (Appendix C). However, the magnitude of the changes is generally larger. In particular, the dry regions of the land surface warm significantly more under the reference scenario than under A1FI, with some parts of northern Australia projected to experience increases in mean temperature of more than 6°C.

Conversely, the mitigation scenarios (450 and 550) show a more uniform response, with the overall magnitude of the temperature changes lying in between those exhibited under the constant concentration (S2004) and A1T scenarios. Outside of the Arctic, warming is restricted to around 1°C (1.8°C above pre-industrial values) for the 450 scenario and 1.5°C (2.3°C above pre-industrial values) for the 550 scenario. These are somewhat below the IPCC estimates of 2°C and 3°C (IPCC 2007a) respectively, although this is consistent with the characteristics of Mk3L. Interestingly, there are regions where for the 450 and 550 scenarios warming halts, or even reverses, in the second half of the 21st century.

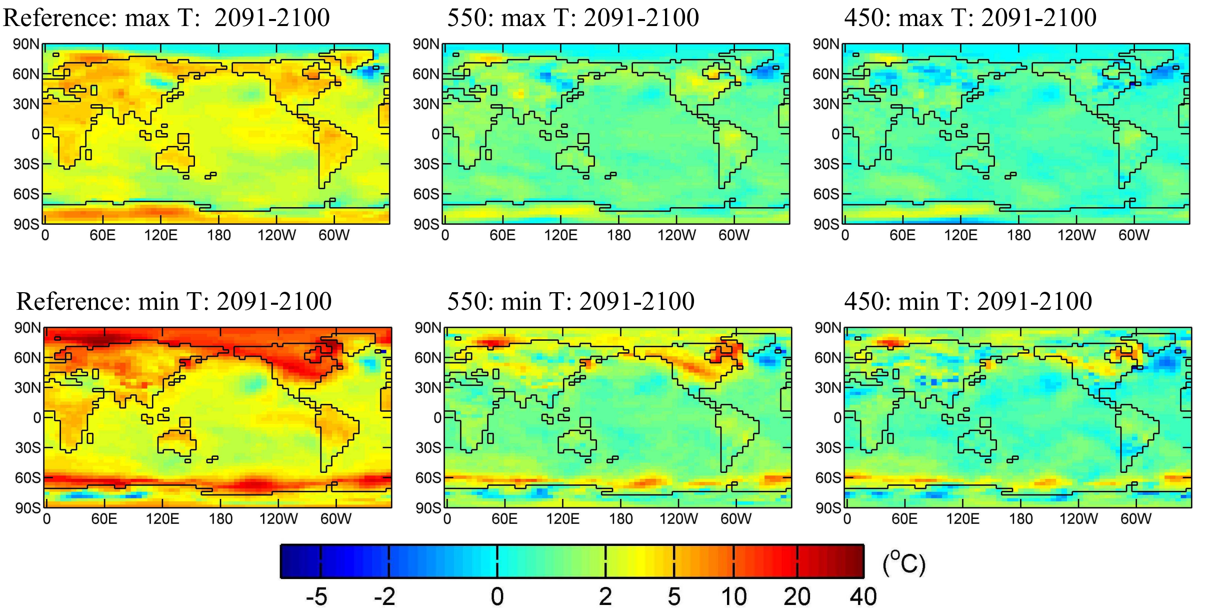

Figure D2. Projected change in the annual warmest maximum surface air temperature (upper panels) and annual coldest minimum surface air temperature (lower panels) as simulated by Mk3L for the three Garnaut Review scenarios (with climate impacts included). The changes shown are the difference between 1991-2000 and 2091-2100. The changes are not necessarily statistically significant.

There are many other climate variables which can be important economically. For example, extremes of temperature can play an important role in health and work force productivity. Extremes in temperature, wind and the hydrological cycle can also impact the design requirements and building costs of infrastructure. Projections of the extremes of any climate variable are more sensitive to the model characteristics than changes to the mean quantities. These results should therefore be treated as being indicative only.

Figure D2 shows the projected change in the annual warmest maximum and coldest minimum temperature over the 21st century. The coldest minimum temperatures are projected to increase substantially more than the warmest maximum temperatures. However, the spatial pattern of the increases in the coldest minimum and warmest maximum temperatures is broadly consistent with that of the change in the mean temperature (Figure D1). Away from the polar regions and northern land masses, the changes in both the coldest minimum and warmest maximum temperatures are approximately equal to the changes in the regional mean temperature. This indicates that changes in annual extremes (such as summer maximum temperatures) are projected to increase in a manner which is broadly consistent with the changes in the mean temperature.

The significant increases in the coldest minimum temperature can be traced to the loss of sea ice and snow cover in a warming world. Melting sea ice exposes the ocean surface beneath. This reduces the surface albedo, resulting in a large mean warming; however, it also increases the active heat capacity of the surface. This second effect acts to decrease the amplitude of the diurnal and annual cycles of surface temperature. In the case of the minimum temperature the mean warming and decrease in the amplitude of the annual cycle of temperature reinforce each other leading to large changes in the coldest minimum temperature. This effect can be dramatic; over open ocean the surface air temperature is broadly constrained to be above the freezing point of seawater (-1.8°C), whereas over sea ice the surface can cool much further (~-40°C). In the case of the warmest maximum temperature the two effects counteract each other, leading to the smaller changes seen in Figure D2.

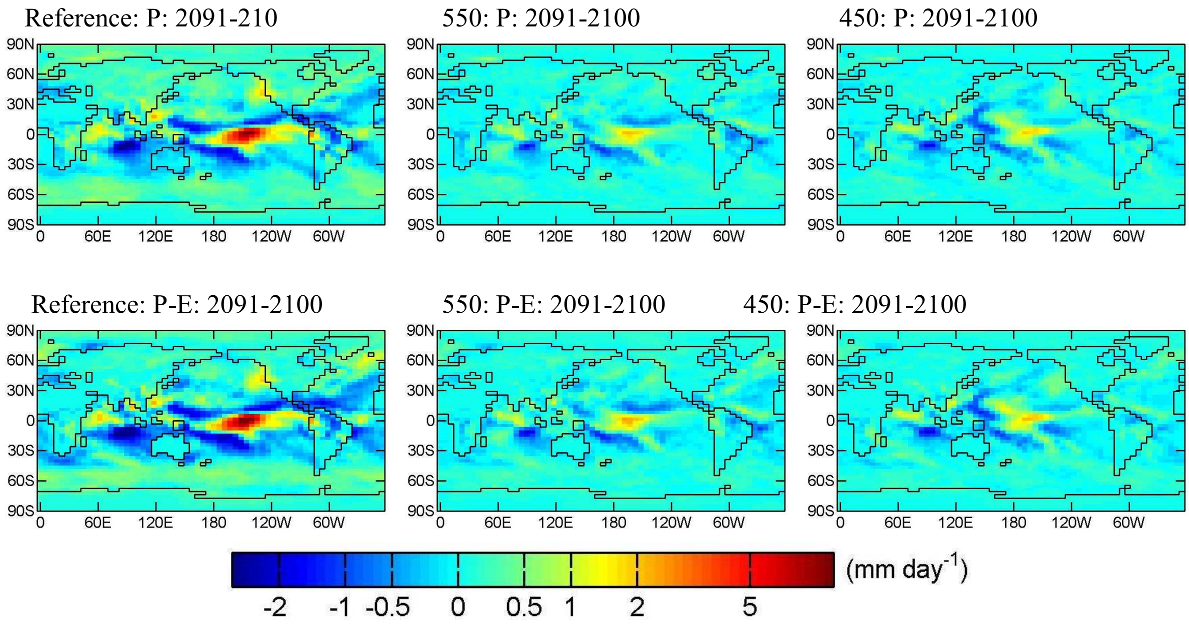

Figure D3. Projected changes in mean precipitation (P), and precipitation minus evaporation (P-E) as simulated by Mk3L for the three Garnaut Review scenarios (with climate impacts included). The changes shown are the difference between 1991-2000 and 2091-2100. The changes are not necessarily statistically significant.

Water is critical to society, the economy and to the environment – indeed water availability is probably more important than temperature for many aspects of global development. Mk3L, like all GCMs, includes representation of the hydrological cycle, and hence information is available concerning projections for future regional precipitation, evaporation, and other terms in the water balance. However, many of the physical processes which are important in the hydrological cycle occur at spatial and time scales which are finer than the resolution of most GCMs. Furthermore, there remains some uncertainty in the representation of some of the physical processes involved in the hydrological cycle. Consequently, the projections of future precipitation and the hydrological cycle are much more uncertain than those for temperature (IPCC 2007a).

Figure D3 shows projections from Mk3L of future precipitation (P) and precipitation minus evaporation (P-E) over the 21st century for the three Garnaut Review scenarios. Some features in the projections are common to those from other GCMs; there are increases in precipitation over much of the tropics and polar regions, together with decreases in precipitation over the sub-tropics and the Mediterranean region (Meehl et al. 2007, Fig. 10.12). However, the dominant signal in both variables is the large increase in precipitation over the central Pacific. This appears to be a specific characteristic of Mk3L.

The net difference between precipitation and evaporation is economically important because it quantifies the water available at the surface (in the absence of significant storage). Over the land areas, the change in P-E is generally of the same sign as that in P, but smaller in magnitude, illustrating that changes in evaporation are generally acting to offset the changes due to precipitation.

An important example of this occurs over Australia. All three scenarios give rise to a small but significant reduction in Australian precipitation. However, the mean change in P-E over the continent is negligibly small. There are two associated economically-important aspects of the Australian climate. First, the Australian water balance is predominantly characterised by water limitation, not energy limitation. This implies that, on average, the amount of precipitation is the controlling influence on the continent's water balance – the projections indicate that there will always be sufficient energy (radiation) to evaporate any available water. Australia is therefore likely to remain predominantly dry. Second, the Australian water balance, more so than many regions, is presently characterised by significant, irregular and individual events. This presents a real challenge for any climate model or IAM, given that these events are much harder to accurately represent and predict than the mean climate.

Given the difficulties in representing the hydrological cycle accurately, it is appropriate to concentrate on temperature changes as the metric of climate change at this time. This aspect of the economy-climate system, however, clearly demonstrates the need for continued development of the biophysical aspects of climate science.

E: Tables

Table E1. Percentage change in per capita GDP in the reference scenario, relative to the reference scenario without impacts.

	Deviation from the reference scenario without impacts (%)				
	2005	2025	2050	2075	2100
United States	0.0	-0.1	-0.7	-2.6	-5.8
EU25	0.0	-0.1	-0.6	-2.2	-5.2
China	0.0	-0.1	-1.0	-3.5	-8.1
Former Soviet Union	0.0	-0.1	-1.1	-4.8	-10.3
Japan	0.0	0.0	-0.2	-0.7	-2.2
India	0.0	-0.2	-1.4	-4.7	-13.4
Canada	0.0	-0.1	-0.9	-5.1	-10.7
Australia	**0.0**	**0.0**	**-0.4**	**-1.8**	**-5.4**
Indonesia	0.0	-0.2	-1.5	-4.5	-12.2
South Africa	0.0	-0.1	-0.8	-2.2	-7.4
Other Asia	0.0	-0.1	-0.7	-2.0	-6.1
OPEC	0.0	-0.1	-1.0	-3.3	-9.1
Rest of World	0.0	-0.1	-0.9	-3.1	-8.5
World	**0.0**	**-0.1**	**-0.9**	**-3.1**	**-8.0**

Table E2. Regional and global greenhouse gas emissions (Mt CO_2-e) for the reference scenario with climate impacts.

	Global greenhouse gas emissions excluding LUCF emissions			Global LUCF emissions			Global greenhouse gas emissions including LUCF		
	2005	2050	2100	2005	2050	2100	2005	2050	2100
USA	7220	9886	8940	-54	-560	-972	7165	9327	7968
EU25	4941	5563	5918	-8	-128	-224	4933	5436	5695
China	7233	31436	31977	-55	-244	8	7178	31192	31985
Former Soviet Union	3289	5639	6934	5	-166	-229	3294	5473	6706
Japan	1361	1113	1079	-0	-6	-5	1361	1107	1074
India	1893	11640	23944	-85	-17	10	1808	11623	23954
Canada	764	1160	1477	0	0	0	764	1160	1477
Australia	534	907	1524	54	49	45	588	956	1569
Indonesia	475	2094	3413	320	121	22	794	2215	3435
South Africa	449	1340	2092	50	30	23	499	1370	2115
Other Asia	1750	4523	6283	-56	-871	-1159	1695	3652	5124
OPEC	1729	6033	11578	94	97	89	1823	6131	11668
Rest of World	4693	19797	45657	2543	2239	1900	7237	22036	47557
World	**36332**	**101133**	**150817**	**2807**	**544**	**-491**	**39139**	**101676**	**150326**

Table E3. Contribution of each commodity to changes in Australia's terms of trade for the reference scenario with climate impacts relative to the reference scenario without climate impacts at 2100.

	export price (%)	import price (%)	terms of trade (%)
Coal	–0.47	–	–0.47
Oil	–0.01	–0.07	0.06
Gas	–0.31	–	–0.31
Petroleum and coal products	–0.04	–0.02	–0.02
Electricity	–	–	–
Iron and steel	–0.05	–0.01	–0.04
Nonferrous metals	–0.07	–0.03	–0.04
Chemicals, rubber, plastics	–0.04	–0.08	0.04
Other mining	–1.28	–0.01	–1.27
Nonmetallic minerals	–0.01	–0.02	0.00
Manufacturing	–0.12	–0.15	0.03
Other transport	–0.06	–0.04	–0.02
Water transport	–0.03	–0.01	–0.03
Air transport	–0.12	–0.02	–0.10
Crops	–0.27	–0.01	–0.26
Livestock	–0.12	–	–0.11
Fishing, forestry	–0.02	–	–0.02
Processed food	–0.26	–0.06	–0.20
Services	–0.26	–0.06	–0.20
Total change - Australia (%)	**–3.54**	**–0.60**	**–2.95**

Note: Contribution of an individual commodity is estimated as the product of the share of the commodity in total export or import value and the projected change in the export or import price of the commodity. Hence, the contributions of individual commodities are additive.

Table E4. Projected change in temperature by region under different scenarios, relative to 2000 (ºC)**.**

	Reference scenario without climate impacts		Reference scenario		Reference scenario with higher climate impacts		550 scenario		450 scenario	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
USA	1.7	4.4	2.0	4.6	2.1	4.1	1.2	1.3	0.9	0.4
European Union 25	1.7	4.1	1.6	4.0	1.9	3.5	1.2	1.5	0.9	0.6
China	1.7	4.4	1.8	4.3	1.8	3.8	1.0	1.0	0.7	0.5
Former Soviet Union	1.8	4.8	1.8	4.8	1.9	4.3	1.1	1.5	0.8	0.5
Japan	1.3	3.4	1.4	3.5	1.5	3.1	0.8	0.9	0.5	0.5
India	1.6	4.6	1.7	4.6	1.8	4.2	1.0	1.1	0.7	0.7
Canada	2.2	5.7	2.0	5.5	2.4	5.0	1.3	1.5	0.7	0.3
Australia	**1.4**	**3.9**	**1.5**	**4.2**	**1.6**	**3.8**	**0.9**	**0.9**	**0.7**	**0.6**
Indonesia	1.3	3.5	1.4	3.6	1.3	3.3	0.8	0.9	0.6	0.5
South Africa	1.4	4.3	1.6	4.2	1.7	4.0	0.8	1.1	0.7	0.5
Other Asia	1.4	3.6	1.5	3.7	1.4	3.5	0.8	0.9	0.6	0.4
OPEC	1.6	4.2	1.7	4.2	1.6	4.0	0.8	0.9	0.6	0.5
Rest of world	1.5	4.0	1.5	4.0	1.5	3.7	0.8	1.0	0.6	0.5
World	**1.2**	**3.4**	**1.3**	**3.3**	1.3	3.0	**0.7**	**0.9**	**0.5**	**0.5**
World (land only)	**1.7**	**4.4**	**1.7**	**4.4**	**1.7**	**4.0**	**1.0**	**1.2**	**0.7**	**0.6**

* The climates of the reference scenario without, with and with higher climate impacts are sufficiently close that the variability in the regional climate, as simulated by Mk3L, dominates over the small change in the global climate. Larger regional temperature changes under the scenarios with climate impacts than the scenario without climate impacts for some of the regions can therefore be expected.

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