

global integrated assessment model

a new analytical tool for assessing climate change risks and policies

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- *Much of the analysis on climate change in Australia has focused on the costs of mitigation policies. Analysis of the benefits of these policies in terms of reduced climate change impacts has been limited. The currently available analytical tools have a limited capacity to estimate both the economic impacts of climate change and the potential to reduce likely economic damages through either mitigation or adaptation.*
- *abare in collaboration with CSIRO has developed a preliminary version of a 'global integrated assessment model' (GIAM) to fill this gap in analytical capacity. GIAM allows feedbacks and interactions between climate and economic systems and has the capacity to provide detailed information about the physical and economic impacts of climate change.*
- *Development of this analytical capacity is particularly relevant as Australia and many other countries are moving or planning to move toward policy measures designed to address the impacts of climate change, including emissions trading schemes and adaptation measures.*
- *Using GIAM, an illustrative long run 'reference case' (to 2100) of global and regional economic activity with climate change impacts, in the absence of mitigation and planned adaptation measures, is developed.*
- *It is important to recognise the preliminary and illustrative nature of the analysis reported here. Additional work is needed to understand better the extent of climate change impacts and to further improve the analysis.*

An understanding of the potential costs and benefits of alternative policy approaches is needed in order to develop an appropriate response to the economic and environmental challenges presented by climate change. In Australia, much of the analysis of climate change has tended to focus on the costs of mitigation policies, rather than also considering the benefits of these policies in terms of reduced climate change impacts. This is primarily because the analytical tools to estimate both the economic impacts of

climate change and the potential to reduce any likely economic damages through either mitigation or adaptation have been underdeveloped. This is particularly the case with the representation of Australia in currently available analytical frameworks.

integrated assessment models

To overcome these limitations, abare and CSIRO (Commonwealth Scientific and Industrial Research Organisation) are currently developing Australia's first integrated assessment model — named the 'global integrated assessment model' (GIAM) — which will allow both the costs and benefits of climate change policy approaches to be assessed. In this article, a preliminary version of the core of GIAM — the economic and climate modules — is described and a long term illustrative 'reference case' or 'business as usual' scenario that incorporates estimated climate change damages is developed.

The development of a reference case that incorporates climate change damages is fundamental for assessing the costs and benefits of alternative policies as policy options are generally compared against a reference case.

The development of an Australian focused integrated assessment model is now particularly relevant as Australia and many other countries are moving or planning to move toward potentially significant policy measures designed to deal with the impacts of climate change. Such measures include emissions trading schemes, carbon taxes, research and development schemes to encourage energy efficient cleaner technologies, sectoral technology standards and adaptation.

This analysis extends previous abare efforts (abare 2006; Pant and Cao 2005a,b, 2006; Pant et al. 2005) by incorporating CSIRO's Mk3L coupled atmosphere–sea ice–ocean general circulation model and accounting for regional changes in temperature.

what are integrated assessment models?

One of the principal tools used in developing responses to environmental science, technology and policy problems like climate change is the integrated assessment model (IAM). Integrated assessment models used in climate change policy analysis are multiple equation, computer simulated models (Weitzman 2007) that capture the climate change cause and effect chain by incorporating the feedbacks between dynamic economic and scientific systems. Such models usually comprise many submodels adopted from a wide range of disciplines so that the impacts of climate change and the relevant responses to it can be analysed. For a discussion of the full range of IAM approaches, see Schneider (1997). Most integrated assessment models that have been developed so far concentrate on the economic cost-benefit analysis of climate change and GIAM falls into this class. In the rest of this article, therefore, references to integrated assessment models refer to

models of this type. It should be borne in mind that other approaches that attempt to balance other values also contribute to climate change response policy formation. A comprehensive integrated assessment model would incorporate the full climate change cause and effect chain, with information on the feedbacks between the socioeconomic drivers of greenhouse gas emissions, atmospheric greenhouse gas concentrations, climate forcing, climate change and the impacts of these changes on economic activity, ecosystems, food production, water supply, the environment and other aspects of socioeconomic 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). However, none of these models explicitly or adequately represent Australia.

what are integrated assessment models used for?

Integrated assessment models provide insights into the potential economic and environmental impacts of climate change as well as adaptation and mitigation responses at the regional and global level. Information generated with these models can be used by policy makers either to evaluate certain policy options more effectively (policy evaluation models) or to identify optimal policy approaches (policy optimisation models), given the current understanding of the uncertainties surrounding the underlying drivers of greenhouse gas emissions and the likely impacts of climate change and adaptation and mitigation responses. An illustrative discussion on assessing the costs and benefits of alternative climate change mitigation policies is presented in box 1.

Once fully developed the GIAM framework could be used as either a policy evaluation or policy optimisation tool. For example, the net physical, ecological and socioeconomic impacts of alternative policies, such as implementing a given carbon penalty or restricting emissions to achieve specified concentration levels, can be assessed at the economywide level. Alternative and efficient climate change response policy approaches that optimise the estimated value of key policy control variables (for example, carbon penalties, emission reductions) to achieve given policy goals (for example, welfare maximisation or minimal cost mitigation) can also be identified using integrated assessment models (Weyant 2003).

Some of the key policy questions that can be analysed using a comprehensive integrated assessment model 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?

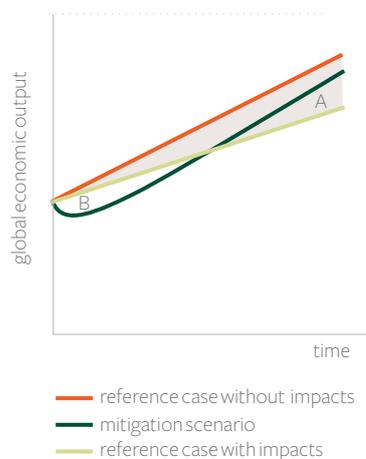
GIAM

- what is the least cost way of achieving 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 increasing the amount of energy sourced from biomass crops place on food or fodder production?

challenges in developing and using integrated assessment models

These models represent complex socioeconomic and biophysical climate systems and their interactions. Considerable uncertainties remain about virtually every relationship in the climate change cause and effect chain (Weyant 2003). However, a range of insights into the potential net impacts of alternative climate change response policy approaches can still be gathered using

illustrative representation of economic output with and without climate change impacts and mitigation responses



box 1 benefit–cost analysis of policies to reduce greenhouse gas emissions

In order to achieve an economically efficient response to any environmental externality such as climate change, the present value or discounted future streams of the net benefits of the mitigation policy (after adaptation) — that is, the benefits of reduced climate change damages less the economywide costs of the policy — should be maximised.

In the diagram, this concept is presented graphically using an illustrative case. The reference case without impacts line represents a ‘best guess’ of the future pathway of global economic output without incorporating the potential impacts of climate change. In contrast, the reference case with impacts line gives insights into the future pathway of global economic output if no action is taken to mitigate climate change damages. A limited amount of autonomous adaptation to climate change is assumed to be incorporated into this pathway. Conceptually the area between these two lines — the shaded area — is the economic damages (in net present value terms) associated with climate change in the reference case without impacts scenario.

The mitigation scenario line is a ‘best guess’ of the pathway of global economic output after accounting for the costs of mitigation and the net reduction in climate change damages (after accounting for autonomous and planned adaptation).

The pathway of global economic output under the mitigation scenario diverges from the reference case with impacts scenario immediately as action to mitigate emissions imposes costs on the global economy — for example, through the uptake of more expensive lower emission technologies. However, over time, as the (growing) costs of climate change in the reference case with impacts scenario are reduced, the rate of yearly economic growth in the mitigation scenario exceeds that in the reference case with impacts

continued...

these models, based on the best information that is currently available and on plausible assumptions.

Alternatively a range of options, including sensitivity analysis and statistical methods, are available that either allow the importance of different assumptions in the models to be tested or that probabilistically account for uncertainties (Kann and Weyant 2000; Kelly and Kolstad 1998; van der Sluijs 1996). 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. Furthermore, in GIAM, uncertainty relating to key economic and climate variables can be analysed through scenario and sensitivity analysis.

GIAM framework

abare has been developing its Australian focused integrated assessment modelling capacity over several years. Since 2007, abare has been working

box 1 benefit–cost analysis of policies to reduce greenhouse gas emissions *continued*

scenario until eventually total yearly economic output in the mitigation scenario exceeds that in the reference case with impacts scenario.

Under an economically efficient mitigation policy the discounted stream of benefits of that policy should exceed the costs. That is, the net present value of area A should exceed the net present value of area B in the diagram. The optimal global climate change response policy is that which maximises the difference between area A and B. Integrated assessment models are particularly useful for calculating these economic outcomes as they can account for both reductions in damages and the cost of climate change response policies. Adaptation policies must also play a role in any economically efficient response to climate change.

There are a great number of complexities in calculating the net benefit and cost streams over time under different scenarios using an integrated assessment model. For example, there are uncertainties over the long term relating to the reference case economic growth path, climate change impacts, reduction in damages (both market and nonmarket) as a result of mitigation and the actual costs of mitigation policies.

The choice of discount rate used when comparing costs and benefits of alternative policy approaches is also very important, particularly when undertaking analysis of long term issues such as climate change. The choice of a lower discount rate, such as used in Stern (2006) (primarily to account for intergenerational equity), increases the relative importance of climate change damages occurring into the distant future, relative to higher discount rates. The discount rate will also influence the optimal level of adaptation and mitigation responses. For example, if some adaptation measures yield net benefits more rapidly than mitigation then these will be favoured under higher discount rates.

GIAM

collaboratively with CSIRO to develop a preliminary ‘proof of concept’ integrated assessment model. abare and CSIRO have developed a preliminary version of GIAM (using best available data, information and plausible assumptions) that incorporates economic and climate modules that allow for the determination of long run economic activity and greenhouse gas emissions and the resulting regional temperature increases. The modules are then solved iteratively to determine the resulting impacts of climate change on economic activity and greenhouse gas emissions.

economic module

The economic module of GIAM is a long run version of abare’s global trade and environment model (GTEM), which is a multiregional and multisectoral general equilibrium model of the global economy (Pant 2007). The economic module allows projections of the major human induced factors influencing climatic conditions (such as greenhouse gas emissions) to be developed after accounting for regional and global production and consumption decisions and international trade.

In essence the economic module of GIAM represents, in a stylised fashion, the interactions between ‘agents’ in a multicountry, multi-industry and dynamic world economy in which people living in each region produce, trade and consume goods and services across countries and regions. The ‘agents’ of the model are assumed to be economic optimisers: given their resources and preferences they maximise benefits and minimise costs over goods and services in a given time period. To improve their welfare they innovate, invest, change technologies and use natural resources, labour and other human produced tools (capital) efficiently, subject to national and international policy constraints and the natural environments that they face. These human activities produce greenhouse gas 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.

The economic module of GIAM currently allows for analysis across nine regions, 28 commodities, four primary factors and six greenhouse gas emissions (table 1).

representation of energy technologies

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

Given that electricity accounts for about 30 per cent of global anthropogenic (human induced) greenhouse gas emissions, low emission technologies in this sector will be particularly important. The economic module of

GIAM incorporates cost and emissions characteristics of fourteen electricity generation technologies, which include six conventional technologies (brown coal, steaming 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 brown coal, steaming 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 and biomass and waste.

climate module

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

1 regional, commodity, primary factor and greenhouse gas emissions coverage in GIAM

regions	commodities	primary factors	greenhouse gases
united states	brown coal	capital	carbon dioxide
europaean union 25	coking coal	land	methane
china	steaming coal	labor	nitrous oxide
russian federation	oil	natural	hydrofluorocarbons
india	gas	resources	perfluorocarbons
japan	petroleum and coal products		sulfur hexafluoride
south korea	electricity		
australia	biofuels		
rest of world	iron and steel		
	nonferrous metals		
	chemicals, rubber and plastics		
	other minerals		
	uranium ore		
	uranium enrichment		
	bauxite		
	alumina		
	primary aluminium		
	nonmetallic minerals		
	manufacturing		
	other transport		
	water transport		
	air transport		
	livestock		
	crops		
	forestry and fishing		
	food		
	services		
	wood, pulp and paper		

GIAM

calculation of atmospheric greenhouse gas concentrations

A '5-box' model of the carbon cycle (based on Maier-Reimer and Hasselman 1987) is used to determine the atmospheric concentration of greenhouse gases over time. This module uses the projected emissions (of carbon dioxide, methane and nitrous oxide) from the economic module of GIAM to update atmospheric stocks of these greenhouse gases each year and then to calculate their atmospheric concentrations.

The only anthropogenic greenhouse gas explicitly treated by Mk3L is carbon dioxide. The greenhouse gas concentrations calculated by the box model therefore need to be converted into equivalent concentrations of carbon dioxide (CO₂-eq). A simple approach (as used by IPCC 2001) is used to derive the CO₂-eq values, based on the respective impacts of each greenhouse gas on the global radiation balance.

calculation of regional changes in long term temperatures – the csiro mk3L climate system model

In order to calculate regional changes in long term temperatures, the CSIRO Mk3L climate system model (Phipps 2006) 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 gridbox 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 timesteps 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.

translating regional temperature changes into regional economic impacts

Climate change is expected to be associated with a wide range of impacts on economic and environmental systems. For example, climate change is expected to have an impact on human health; labour productivity; demand for, and production of, a range of goods and services; agriculture; ecosystems and environmental services. In GIAM, to estimate the potential economic damages associated with climate changes, a stylised damage function is implemented in the economic module. The damage function estimates and translates regional changes in temperature through time to changes in factor productivity at the economywide level in each country or region of GIAM.

Regional climate change damages 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 terms of differences in gross domestic product (GDP) per person relative to a benchmark economy (the United States) and aims to capture the notion that the relative economic impacts of climate change for a given change in temperature will be higher in developing countries than in more developed economies.

The damage function used in GIAM allows economic damages (both market and nonmarket) to increase gradually for small changes in temperature before increasing more rapidly until the catastrophic temperature is reached (box 2). The damage function also allows for a catastrophic reduction in all economic activity beyond a specified temperature.

box 2 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 climate change induced nonmarket damages function used in the integrated assessment model, MERGE (model for evaluating the regional and global effects of greenhouse reduction policies) (Manne and Richels 2004). In GIAM, although nonmarket damages are not explicitly modelled they are recognised by assuming that loss of nonmarket environmental entities would also contribute toward a reduction in factor supplies and/or factor productivity.

The damage function used in GIAM is specified as:

$$(1) \quad \Lambda_r(t) = \begin{cases} \{1 - [\Delta AT(t)/\Omega]^\delta\}^{\mu_r(t)} & \text{if } |\Delta AT| < \Omega \\ 0 & \text{if } |\Delta AT| \geq \Omega \end{cases}$$

where:

- $\Lambda_r(t)$ is the region specific climate change induced economic loss factor (ELF) in year t
- $\Delta AT(t)$ is the region specific average surface temperature change in year t from the reference year (2000)
- Ω is the catastrophic change in average surface temperature from the reference year (2000) at which economic activity is reduced to zero
- δ and $\mu_r(t)$ are parameters to measure the severity of damage for a given temperature change.

Based on the parameterisation in MERGE, Ω is currently specified to be 17 degrees Celsius and δ is set at 2. This implies that if the actual temperature rises by 17°C above the reference year (2000) level, economic activity is reduced to zero. For all temperature increases below that number, 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 significantly only near the catastrophic value of the temperature change.

The time variant parameter $\mu_r(t)$ is set equal to 2 for all time only for the reference (or the richest) region which is assumed here to be the United States. For other regions, $\mu_r(t)$ is further defined as below 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:

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

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 considered in commensurable units
- σ s are adjustable parameters to measure the effect of difference in real income affecting the vulnerability to temperature changes.

continued...

box 2 a stylised climate change damage assessment function in GIAM *continued*

In the current analysis (following MERGE), it is assumed that: $\sigma_1 = 1$ and $\sigma_2 = 1$. The vulnerability of regions to climate change is measured relative to that of the United States. It follows that $\mu_r(t) \geq \sigma_1$ for each region r as $I_{ref} > I_r$.

The region specific economic loss factor, $\Lambda_r(t)$, 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 primary factors in the region. This can also be viewed as losses in factor supplies as well or a combination of both the losses in factor productivity and factor supplies.

In the current implementation of GIAM, a rise in average temperature means a loss in economic wellbeing through a decline in factor productivity across all sectors in a region. A positive value of σ_2 in equation 2 means that the losses are higher for poorer regions than for richer regions.

choice of parameterisation and functional form

The functional form and the parameterisation of the damage function will heavily influence the resulting economic damages from climate change as projected by GIAM. There is currently a high degree of both economic and scientific uncertainty and limited quantitative estimates about the nature and magnitude of long term climate change impacts across countries and sectors. As more information becomes available about the potential market and nonmarket economic impacts of climate change, substitutability of ecosystem services, ability to adapt and any threshold impacts, both the functional form and parameterisation of the damage function can be revised. The current functional form and parameterisation of the damage function in GIAM is derived from the best available information in the current literature.

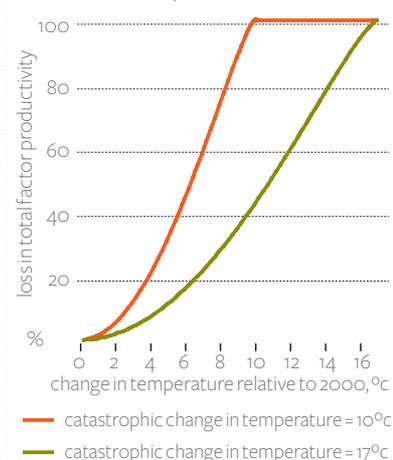
The shape of the damage function aims to represent the notion that the growth in the relative economic damages from climate change will generally increase at a greater rate as temperature increases until the catastrophic temperature is reached. This functional form is consistent with much of the literature on damage functions and with those currently being employed in integrated assessment models.

The parameterisation of the damage function aims to represent the current understanding about climate change damages, the vulnerability of economies to climate change and the catastrophic temperature at which economic activity will fall to near zero.

In the diagram opposite, the importance of key parameter values of the damage function is demonstrated by changing Ω or the 'catastrophic' change in average surface temperature. For example, if Ω is set equal to 10°C, and assuming other relationships are unchanged, the loss in total factor productivity for a 4°C change in temperature in Australia is estimated to be about 20 per cent, whereas when Ω is assumed to equal 17°C, the associated loss is estimated to be about 7 per cent.

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estimates of australia's loss in total factor productivity for different values of the catastrophic temperature illustrative example



box 2 a stylised climate change damage assessment function in GIAM *continued*

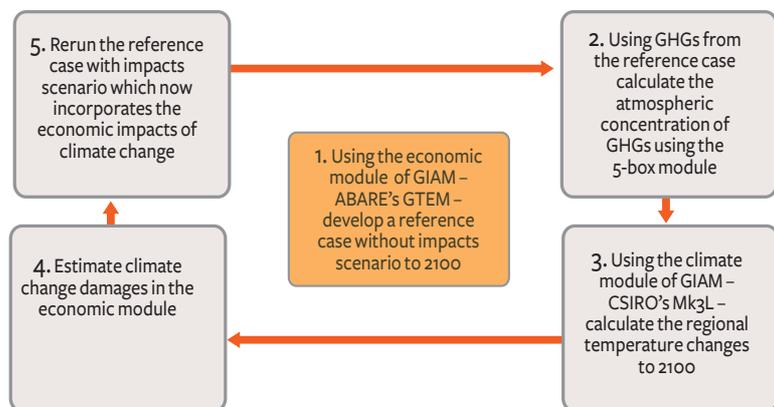
ongoing developments to the damage function

A number of developments are being considered to enhance the capability of the damage function to project the economic damages from climate change. First, both the functional form and parameterisation will be revised as better information becomes available on the nature and magnitude of climate change damages. For example, in some regions, such as the Russian Federation, small increases in temperature are likely to be associated with positive economic impacts (Mendelsohn et al. 1998; Nordhaus and Boyer 2000). Second, the damage function will also be extended to explicitly and individually account for the economic impacts associated with changes in sea level and precipitation rather than aggregating these impacts as a function only of changes in temperature. Third, attempts will be made to identify the appropriate functional form and parameterisation of the damage function for key sectors in key regions.

illustrative application of the ‘proof of concept’ GIAM

To prove the concept of this coupled modelling framework and to demonstrate the importance of accounting for the feedbacks between economic and climate systems, an illustrative reference case incorporating climate change damages has been developed using GIAM. The reference case is a regional representation of the future of economic growth, production and consumption and international trade after accounting for climate change damages. No mitigation or planned adaptation measures are assumed to take place. The process of applying the ‘proof of concept’ model is described in the following text and in figure a.

a schematic presentation of developing a reference case with climate change impacts



key steps in developing a reference case scenario with climate change impacts

- 1 develop a reference case scenario of the world economy to 2100 without climate change impacts using the economic module of GIAM – GTEM
- 2 using the resultant emissions pathway from the reference case, determine the stock and atmospheric concentration of greenhouse gases to 2100 using the 5-box carbon cycle module
- 3 calculate the associated changes in regional temperature to 2100 using the climate module of GIAM – CSIRO’s Mk3L model
- 4 use the damage function in the economic module of GIAM – GTEM – to determine the regional damages or proportional loss in regional factor productivity that result from the projected changes in regional temperature to 2100
- 5 rerun the economic module of GIAM to 2100 after incorporating climate change damages as a reduction in regional total factor productivity — this will generate a new regional economic pathway or ‘reference case with impacts’ scenario
- 6 repeat steps 1 to 5 to account for the feedbacks in the economic and climate systems until an appropriate level of convergence between changes in global mean temperature and changes in gross domestic product (GDP) is reached. Appropriate statistical measures are used to determine whether successive iterations of the model have converged. The resulting economic pathway after convergence is the final reference case with climate change impacts scenario.

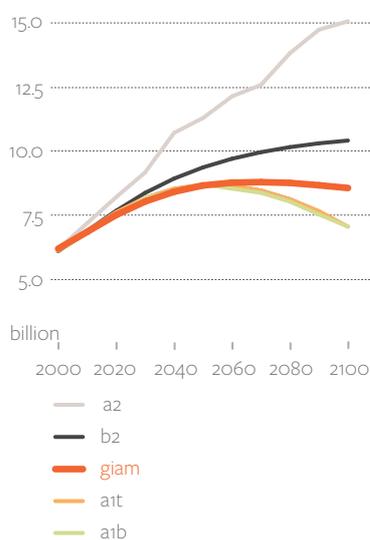
developing a reference case without climate change impacts

To estimate the potential economic impacts of climate change, a reference case without impacts scenario of the global economic and emissions pathway to 2100 is first developed in which the impacts of climate change are not considered. The emissions resulting from this scenario are used to determine the atmospheric concentration of greenhouse gases; the resulting change in regional temperatures and eventually the economic impacts of climate change.

The reference case without impacts scenario is an illustrative indicator of potential changes in economic growth, population, industry growth, productivity improvements, energy consumption and greenhouse gas emissions between 2001 and 2100. The key drivers of energy consumption and greenhouse gas emissions in the reference case without impacts scenario are population growth, economic growth and the uptake of energy efficient and lower emissions technologies and energy sources. Changes in these key determinants to 2100 are based on historical trends, best available

GIAM

b global population projections



information, expert opinion about changes in relevant variables through time and a range of underlying economic relationships.

population growth

In the reference case without impacts scenario, global population is expected to increase from about 6.2 billion in 2001 to about 8.7 billion in 2050. Global population is expected to peak in about 2070 as below replacement rate fertility levels result in an aging and eventually declining population in key regions, including China. In general, populations are expected to peak first in the more developed regions. By 2100, global population is projected to be about 8.6 billion. In Australia, population is projected to increase from about 19.4 million in 2001 to about 27.0 million in 2050 and 30.5 million in 2100.

In figure b, a range of global population projections in the literature, including scenarios from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC 2000), are presented. Population projections in GIAM are well within the range presented in the literature.

economic growth

Growth in economic output in GIAM is determined by growth in labour productivity and labour supply. GDP growth is expected to decline slowly over the projection period in most regions as a result of declining population growth rates, which occur because of declining and below replacement fertility rates in many regions. In rapidly developing economies, productivity growth per worker is also assumed to slowly decline over the projection period as income per person in these regions converge toward developed economy levels. Despite flat and declining regional per worker productivity assumptions over the long term and a peak and decline in global population levels, global GDP growth is projected to be relatively strong to 2100 (table 2).

2 regional economic activity

average annual growth in gdp in the reference case without impacts scenario

	2001 -2050	2050 -2100	2001 -2100
	%	%	%
united states	2.6	1.9	2.3
european union 25	1.7	1.5	1.6
china	5.3	3.6	4.5
russian federation	3.5	2.3	2.9
japan	1.5	1.2	1.3
india	5.8	3.9	4.8
australia	2.5	2.0	2.3
korea, rep. of	2.8	1.3	2.0
rest of world	3.8	3.3	3.5
world	3.0	2.8	2.9

energy consumption and changes in fuel mixes and technologies

The amount of greenhouse gases produced in an economy is influenced strongly by the level, type and emissions intensity of energy consumed (as well as by the production of fugitive emissions in agriculture, industry etc). Globally, consumption of primary energy is expected to increase from about 9.1 Gtoe (billion tonnes of oil equivalent) in 2001 to about 22.3 Gtoe in 2050 and 42 Gtoe in 2100. Much of this growth is projected to be driven by urbanisation in key developing economies. In Australia, consumption of primary energy is expected to increase from about 105 Mtoe (million tonnes of oil equivalent) in 2001 to about 181 Mtoe in 2050 and 237 Mtoe in 2100.

A range of global energy consumption projections in the literature are presented in figure c. Energy consumption projections in GIAM are well within the range presented in the literature.

By 2100 the efficiency of energy consumption in individual technologies across the global economy is projected to be well above 2001 levels, given assumed improvements in technology. These assumed improvements are consistent with forecasts by the International Energy Agency, the US Energy Information Administration and various other literature and government sources to about 2030. Beyond 2030, expert opinion is used to develop the underlying technological development assumptions.

There is also expected to be a significant increase in renewable technologies in the long run as technological advances reduce the relative cost and increase the technical efficiency of these technologies. In table 3 the percentage contribution of different fuel types to primary energy consumption in the GIAM reference case is presented.

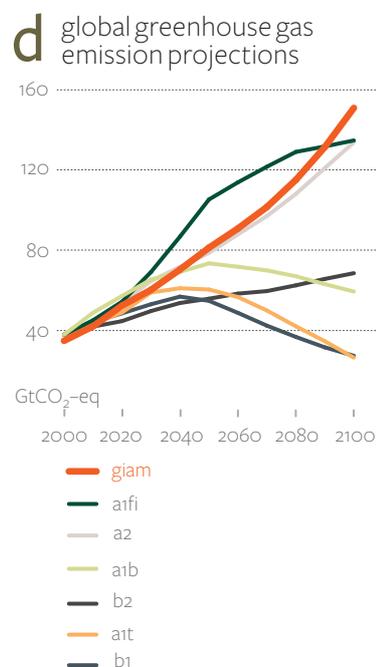
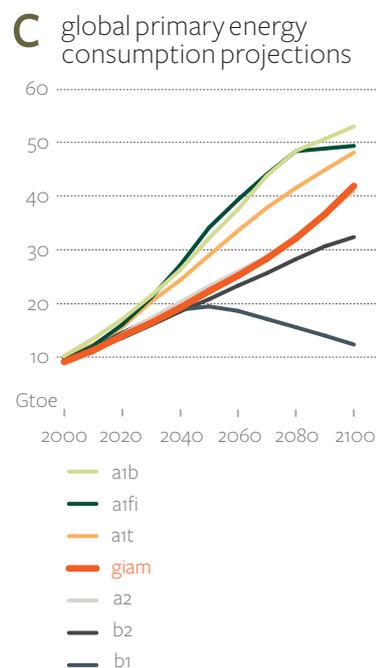
greenhouse gas emissions

Global greenhouse gas emissions, excluding those from land use change and forestry, are expected to increase from about 35 Gt CO₂-eq (billion tonnes of carbon dioxide equivalent) in 2001 to about 81 Gt CO₂-eq in 2050 and 151 Gt CO₂-eq in 2100. In Australia, greenhouse gas emissions, excluding those from land use change and forestry, are expected to increase from about 500 Mt CO₂-eq (million tonnes of carbon dioxide equivalent) in 2001 to about 744 Mt CO₂-eq in 2050 and 907 Mt CO₂-eq in 2100.

A range of global greenhouse gas emission projections in the literature is presented in figure d. Emission projections in GIAM are at the higher range of the estimates in the literature as a result of stronger growth in key sectors such as transport.

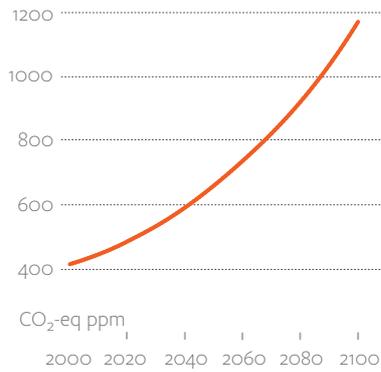
3 contribution of different fuel types to primary energy consumption GIAM reference case without impacts

	2001	2020	2040	2060	2080	2100
	%	%	%	%	%	%
world						
coal	26	29	26	24	24	25
oil	37	32	32	32	31	31
gas	26	28	28	27	26	24
nuclear	8	6	7	8	7	7
hydro	2	3	2	2	2	2
nonhydro renewables	1	3	4	6	9	12
australia						
coal	46	44	40	36	30	26
oil	27	26	27	27	27	27
gas	25	27	28	27	26	24
nuclear	0	0	0	0	0	0
hydro	1	1	1	1	1	1
nonhydro renewables	0	2	4	9	16	23

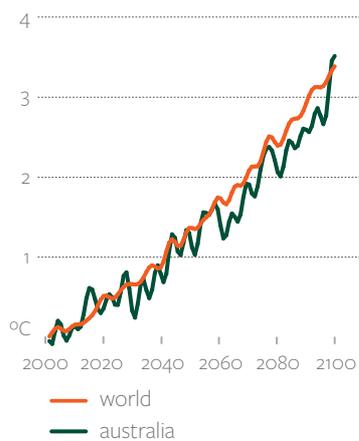


GIAM

e global atmospheric concentration of greenhouse gas emissions



f increase in average surface temperature, relative to 2000



long term atmospheric concentration

As discussed earlier, in the GIAM reference case without impacts scenario the atmospheric concentration of greenhouse gas emissions is projected to increase from about 411 ppm (parts per million) in 2001 to about 1172 ppm in 2100 (figure e). The increase in the atmospheric concentration of greenhouse gases is expected to drive changes in regional temperature such that by 2100 the average surface temperature in Australia is expected to increase by about 3.5 degrees Celsius in 2100 relative to 2000 levels. The increase in average global surface (global land – only mean) temperature is expected to be about 3.4 degrees Celsius at 2100, relative to 2000 levels (figure f).

The regional projected increase in temperatures in the reference case without impacts scenario is presented in table 4. There are noticeable differences between the temperature changes for the various geographic regions. A number of physical mechanisms account for these differences. In particular, the very large heat capacity of the oceans, relative to that of land, causes them to act as a heat sink. The temperature changes over the ocean are therefore smaller than those over land and, as a consequence, maritime regions experience less warming than continental regions.

Other significant phenomena include ice–albedo and snow–albedo feedbacks at high latitudes. The increased surface temperatures cause the ice and snow cover to retreat, exposing the darker land that lies beneath. This absorbs a greater fraction of the incident solar radiation, amplifying the original warming. In contrast, a steady reduction in the strength of the Gulf Stream limits the magnitude of the warming over Europe. It is important to recognise that climate is intrinsically variable so that quasi-random variations about the underlying warming trend occur, as is clear in figure f.

4 increase in average surface temperature, relative to 2000 reference case without impacts scenario

	2020 °C	2040 °C	2060 °C	2080 °C	2100 °C
united states	0.9	1.2	2.3	2.6	3.3
europaen union 25	0.2	1.6	2.2	2.1	3.1
china	0.7	1.1	2.1	2.3	3.0
russian federation	0.4	1.5	1.7	2.4	3.9
india	0.8	0.9	2.0	2.8	3.7
japan	0.3	1.0	1.2	1.8	2.1
korea, rep. of	0.6	1.2	1.8	1.8	2.2
australia	0.5	0.7	1.4	2.1	3.5
rest of world	0.5	0.8	1.7	2.4	3.3
global average (land only – mean)	0.5	0.9	1.7	2.4	3.4

developing a reference case with climate change impacts

In this section the long term effects of incorporating the economic impacts of climate change on the global and Australian economies are assessed.

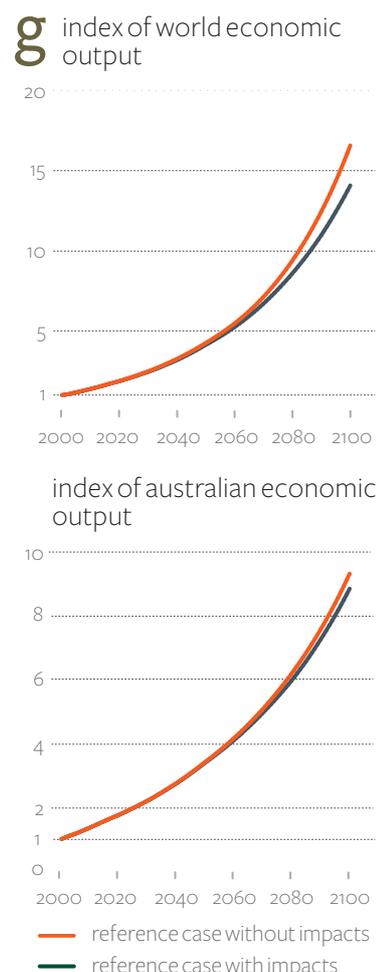
long term climate change damages reduce economic growth

The inclusion of climate change damages and the associated losses in total factor productivity across all sectors is projected to reduce potential regional and global economic growth pathways. As temperatures begin to increase over time and ecosystem and economic system thresholds are reached, the economic impacts of climate change are expected to increase at a faster rate. The estimated indexes of economic output for the world and Australia are illustrated in the reference case with and without climate change impacts scenarios in figure g. It is important to recognise the tentative and preliminary nature of these estimates. Hence, caution needs to be exercised in interpreting them.

A clear divergence in economic potential is projected to occur from about 2050 as climate change impacts are expected to have a material effect on regional economies. Globally, climate change damages are projected to reduce economic output by about 1.4 per cent in 2050 and 11.4 per cent in 2100, relative to the reference case without impacts scenario (see box 3 for comparison with other estimates). As a result, global economic output in the reference case without impacts scenario is estimated to grow by about 16.6 times over the period 2001–2100 compared with 14.1 times in the reference case with impacts scenario.

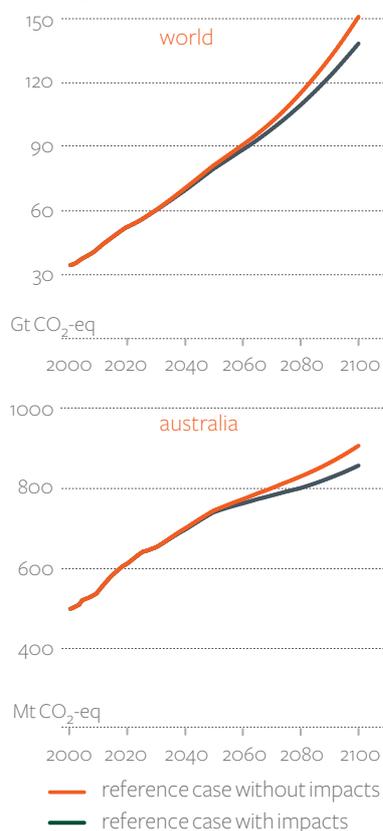
At 2050, Australia's economic output is estimated to be reduced by about 0.6 per cent, relative to the reference case without impacts scenario, as a result of climate change damages. By 2100 the reduction in Australia's economic output as a result of climate change damages is estimated to increase to about 5.0 per cent, relative to the reference case without impacts scenario. In 2100, Australia's economic output is estimated to be about 9.3 times higher than in 2001 in the reference case without impacts scenario. However, when climate change damages are included, economic output in 2100 is estimated to be reduced such that it is 8.8 times higher in 2100 than in 2001.

In Australia, economic output is assumed to grow on average by about 2.3 per cent a year in the reference case without impacts scenario over the period 2001–2100. A 5 per cent reduction in economic output at 2100 as a result of climate change impacts reduces average growth in economic output by about 0.1 percentage points, to 2.2 per cent a year. It is important to recognise that the impacts associated with unmitigated climate change will grow over the long term with the potential for cumulative effects and stepwise changes.



GIAM

h pathways of greenhouse gas emissions



climate change damages tend to lower the emissions pathway

The economic losses associated with climate change damages are expected to dampen economy wide demand for goods and services. As a result greenhouse gas emissions (which are associated with the production of goods and services throughout the economy) are projected to be lower when climate change damages are accounted for (figure h).

box 3 other estimates of the economic impacts of climate change

There are few studies in the literature that have estimated the economy-wide economic impacts of climate change. Most of these estimates focus on the economic costs of climate change for a 2.5°C temperature increase and vary widely on a regional and global basis. Estimates in the literature of the global cost of a 2.5°C temperature increase range from about a 1 per cent increase in global economic output to a 2 per cent decline, relative to what would otherwise be (Mendelsohn et al. 1998; Nordhaus and Boyer 2000; Pearce et al. 1996; Stern 2006). Estimates from GIAM currently project a decline of about 6 per cent in global economic output in response to a 2.5°C temperature increase, relative to the reference case without impacts scenario.

It is important to recognise that estimates presented in the literature were generated using different integrated assessment models and remain highly speculative given long run uncertainties in the underlying drivers of climate change and climate change impacts represented in the analytical tools. Results differ markedly between studies as a result of differences in assumptions about emission levels, adaptation and the inclusion of nonmarket, market and potentially catastrophic impacts (Tol 2005). However, they provide indications of the potential differences in climate change related impacts based on the best available understanding, data, information and plausible assumptions.

The relatively higher economic damages projected by GIAM are driven by two main factors: first, the current specification of the GIAM damage function does not allow economic benefits from small changes in climate that may occur in countries such as the Russian Federation and the United States (Mendelsohn et al. 1998; Nordhaus and Boyer 2000) and second, planned adaptation in response to climate change damages are not currently taken into account. Both of these factors will be incorporated into GIAM in the future.

Widely quoted estimates of the economic impacts of climate change reported in Stern (2006) of a 'now and forever' reduction in global GDP of 5–20 per cent are based on estimates of the net present value of potential climate change impacts into the very long term (beyond 2200) and for a temperature increase well in excess of 2.5°C. Such estimates are not directly comparable with those presented earlier.

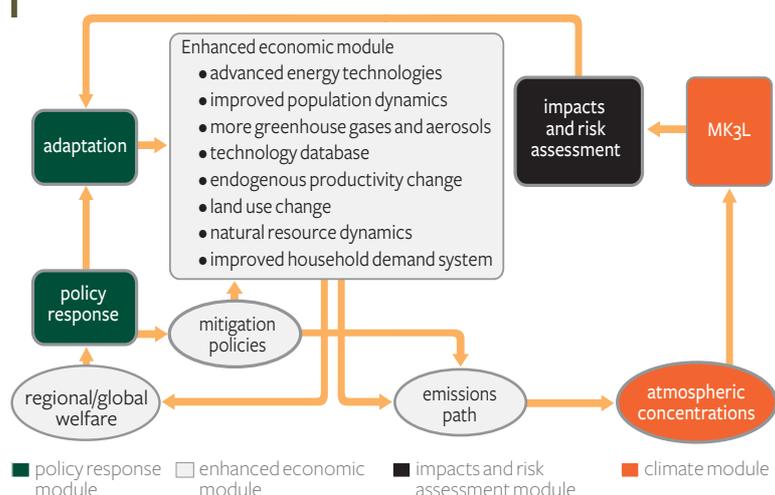
Globally, greenhouse gas emissions are projected to decline by about 8.3 per cent in 2100 as a result of climate change damages, falling from 151 Gt CO₂-eq in the reference case without impacts scenario to about 138 Gt CO₂-eq in the reference case with impacts scenario (excluding emissions from land use change and forestry).

In the reference case without impacts scenario, Australia's greenhouse gas emissions (excluding those from land use change and forestry) are projected to increase from about 500 Mt CO₂-eq in 2001 to about 907 Mt CO₂-eq in 2100. However, after accounting for climate change damages and the associated decline in economic activity, growth in Australian greenhouse gas emissions are projected to decline such that by 2100 they reach 858 Mt CO₂-eq — a decline of about 5.5 per cent — in the reference case with impacts scenario.

way forward

In this article, an illustrative reference case incorporating the economic impacts of climate change has been developed to demonstrate a 'proof of concept' version of GIAM that will eventually allow the benefits and costs of climate change policy to be examined at the economywide level. A range of areas for further development have been identified, including the need for in-depth, multidisciplinary research into the economic damages associated with climate change at the country level (figure i and box 4). Further, such economywide analysis should be supplemented by more micro assessments, particularly in relation to the assessment of the costs and benefits of mitigation and adaptation efforts.

i structure of the planned global integrated assessment model



box 4 further developments

The divergence between the emissions and GDP pathways in the reference case scenarios (with and without climate change impacts) indicate the importance of accounting for the interrelationships between economic and scientific systems. When analysing the costs and benefits of undertaking alternative mitigation pathways it is fundamental to have a reasonable understanding of the costs and benefits of climate change impacts and mitigation and adaptation responses.

It is paramount that an Australian focused integrated assessment model is developed that would allow a complete assessment of the costs and benefits of climate change and mitigation and adaptation responses. In figure 1, the structure of the proposed and more advanced GIAM, incorporating adaptation and policy response modules, is illustrated. These modules, which have not yet been developed, are discussed below.

adaptation module

The purpose of this module is to explore the possible ways of adapting to climate change. The adaptation module will provide information to the economic module on changes in factor supply, including labour supply and migration, productivity and consumption patterns resulting from adaptation measures.

policy response module

The policy response module will use information from the economic, climate and adaptation modules to endogenously determine the optimal level of adaptation and mitigation given the environmental and economic tradeoffs between reducing climate change damages and the costs and benefits of alternative policies.

A range of other developments could also be undertaken in GIAM to enhance the robustness and relevance of the insights. These include:

- enhancements to the damage function to represent climate change impacts at a sector level and in response to changes in rainfall, water availability and sea level rises
- recalibrating the damage function to allow for economic benefits for small changes in climate in some regions
- quantifying the “distribution” of climate change impacts at a country level
- the inclusion of social processes, biophysics and economics within the generalised surface scheme of an Earth System Model
- direct linking of the model components to allow the climate and economic modules to be solved simultaneously rather than the current iterative approach.

references

- abare 2006, *Development of an Integrated Assessment Model for Analysing Climate Change Policy: Phase 1*, abare Report, Canberra, March.
- IPCC (Intergovernmental Panel on Climate Change) 2000, *Special Report on Emissions Scenarios*, Nakicenovic, N. and Swart, R. (eds), Cambridge University Press, England.
- IPCC 2001, *Climate Change 2001: The Scientific Basis*, Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ and D. Xiaosu D. (eds), Cambridge University Press, England, pp 944.
- Kann, A. and Weyant, J. 2000, 'Approaches for performing uncertainty analysis in large scale energy/economic policy models', *Environmental Modeling and Assessment*, vol. 5, pp. 29-46.
- Kelly, D.L. and Kolstad, C.D. 1998, 'Integrated assessment models for climate change control', in Folmer, H. and Tietenberg, T. (eds) 1999, *International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues*, Cheltenham, England.
- Maier-Reimer E. and K. Hasselman 1987, 'Transport and storage of CO₂ in the ocean – an inorganic ocean-circulation carbon cycle model', *Climate Dynamics* vol. 2, pp. 63-90.
- Manne, A.S. and Richels, R.G. 2004, *MERGE: An Integrated Assessment Model for Global Climate Change*, Stanford University, Stanford, California (stanford.edu/group/MERGE).
- McGuffie, K. and A. Henderson-Sellers 1997, *A Climate Modelling Primer*, second edition, John Wiley and Sons.
- Mendelsohn, R.O., Morrison, W.N., Schlesinger, M.E. and Androva, N.G. 1998, 'Country specific market impacts of climate change', *Climatic Change*, vol. 45, nos 3-4, pp. 553-69.
- Nordhaus, W.D. and Boyer, J.G. 2000. *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, Massachusetts.
- Pant, H. 2007, *GTEM: Global Trade and Environment Model*, abare Technical Report, Canberra, June.
- and Cao, L. 2005a, 'Modeling energy technologies in the global economy, trade, environment and climate (GETEC) model', GETEC Technical Paper 3, abare, Canberra.
- and — 2005b. 'Modeling population dynamics in the global economy, trade, environment and climate (GETEC) model', GETEC Technical Paper 2, abare, Canberra.
- and — 2006. 'Concentration targets and technological responses in the global economy, trade, environment and climate (GETEC) model', GETEC Technical Paper 4, abare, Canberra.

GIAM

- , — and Fisher, B.S. 2005, The global economy, trade, environment and the climate system (GETEC) model and a reference case for climate policy analysis, abare conference paper 05.7 presented at the 8th Annual Conference on Global Economic Analysis, Lübeck, Germany.
- Pearce, D.W., Cline, W.R., Achanta, A.N., Fannkhauser, S., Pachuri, R.K., Tol, R.S.J., and Vellinga, P. 1996, 'The social costs of climate change: greenhouse damage and the benefits of control', in Bruce, J.P., Lee, H. and Haites, E.F. (eds), *Climate Change 1995: Economic and Social Dimensions – Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, pp. 179–224.
- Phipps, S. J. 2006, The CSIRO Mk3L Climate System Model, *Technical Report 3*, Antarctic Climate & Ecosystems CRC, Hobart, Tasmania, Australia, 236pp., ISBN 1-921197-03-X
- Schneider, S. H. 1997, 'Integrated assessment modeling of global climate change: transparent rational tool for policy making or opaque screen hiding value-laden assumptions?' *Environmental Modeling and Assessment*, vol. 2, pp. 229–.
- Stern, N. 2006, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge and New York.
- Tol, R. 2005, 'The marginal damage costs of carbon dioxide emissions: an assessment of uncertainties', *Energy Policy*, vol. 33, pp. 2064–74.
- van der Sluijs, J. 1996, *Integrated Assessment Models and the Management of Uncertainties*, International Institute for Applied Systems Analysis, Austria.
- Weyant, J.P. 2003, Integrated environmental assessment: an overview and assessment, Paper prepared for the OECD Workshop on Environment and Economic Modelling, 9–10 October, Ottawa.
- Weitzman, M.L. 2007, A review of the Stern review on the economics of climate change, *Journal of Economic Literature*, vol. XLV, pp. 703–24.