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## D Economic modelling and adaptation to climate change

Economic modelling has been used to examine climate change impacts and how adaptation (and mitigation) to climate change may affect the economy as a whole. Integrated assessment models (IAMs), computable general equilibrium (CGE) models and partial equilibrium (PE) models have been used for these purposes (box D.1).

Modelling approaches could be used to assess adaptation reform options if they can assist in answering one or more of the following questions.

- What are the costs and benefits of adaptation options?
- What types of adaptation should be pursued, and in which sectors?
- What is the optimal timing of adaptation?

However, modelling results need to be treated with appropriate caution. The uncertainties and long timeframes associated with climate change may limit the conclusions that can be drawn from modelling results. The use of sensitivity analysis and ranges can highlight the implications of uncertainty for the modelling results.

Section D.1 describes models that have been used to estimate the impact of climate change, and section D.2 looks at models that have been used to estimate the costs and benefits of adaptation. Section D.3 outlines the strengths and shortcomings of the modelling approaches in assessing climate change adaptation options.

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## Box D.1 Types of models

Economic models used to assess the impacts of climate change, and adaptation responses, use mathematical equations to represent economic and physical processes. These equations are used to simulate how various sectors and activities might respond to changes to the environment, economy or policy settings.

### Partial equilibrium models

Partial equilibrium models focus on how changes affect a particular firm or sector. These models are used to estimate the direct impacts of a change to the economy on that sector, and offer a more detailed representation of a sector than general equilibrium models. However, they are not designed to capture the flow-on effects on other sectors of the economy. An example of a partial equilibrium model is the model of the urban water sector developed by Barker, Murray and Salerian (2010).

### Computable general equilibrium (CGE) models

CGE models are used to analyse how changes or impacts on one sector of the economy flow through to the rest of the economy. Examples of CGE models include the Monash Multi-Regional Forecasting model and the Global Trade Analysis Project model.

Within CGE models, the economy is represented by a system of equations representing production, consumption and investment. A number of sectors or regions can be represented, and factors of production are free to move to sectors where returns are highest.

These models are calibrated using real-world data, and a 'baseline' scenario is estimated. Variables are then altered — referred to as a 'shock' — and the model is re-run to examine the impact of the 'shock' on the economy. For example, the impact of climate change on agriculture may be represented as a reduction in agricultural productivity. The model provides estimates of the effects of the shock on other sectors. In some cases, model results could be broken down by region.

CGE models can be either 'dynamic' or 'comparative static' (as can other types of models). Comparative static models compare the model before and after the shock to examine its impact. Dynamic models explicitly include the time dimension into the model, to examine how the impacts of the shock play out over time.

### Integrated assessment models

Integrated Assessment Models 'simulate the key human and natural processes believed to be driving climate change and estimate the socioeconomic impacts' (Baker et al. 2008, p. 29). Integrated assessment models contain both a model of the economy, and a model of the climate. Economic activity produces greenhouse gas emissions, which lead to climate impacts. These climate impacts influence the economy (for example, by reducing output) through a climate damage function.

*Sources:* Baker et al. (2008); Barker, Murray and Salerian (2010).

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## D.1 Modelling the impacts of climate change

### Australian studies

#### *Garnaut Review (2008)*

The largest exercise to estimate the impacts of climate change on the Australian economy was undertaken in 2008, as part of the Garnaut Review (Garnaut 2008b). The Garnaut modelling attempted to estimate the economic impacts of climate change on areas including:

- primary production — cropping and livestock
- human health
- critical infrastructure — water supply, electricity transmission and distribution, coastal buildings and ports
- residential buildings (due to increased cyclone intensity)
- international trade.

‘Shocks’ were estimated based on detailed reports of the physical impacts of climate change on each of these sectors, which were provided to the Garnaut Review by expert groups. These ‘shocks’ were incorporated into the Monash Multi-Regional Forecasting (MMRF) model — a dynamic multi-sector CGE model of the Australian economy. For example, in the case of coastal buildings, the costs associated with upgrading or relocating homes and businesses were modelled as an increase in capital costs for dwellings and commercial buildings.

The review modelled impacts for a range of climate scenarios. These included a ‘no mitigation’ scenario and two scenarios with mitigation stabilising atmospheric carbon dioxide equivalent concentrations at 550 parts per million and 450 parts per million. These were compared to a reference case of no human-induced climate change. The temperature rises estimated ranged from 1.5–4.5°C by 2100.

Some limited adaptation responses were included in the analysis. In particular, the MMRF model allows for adaptive responses such as producers switching to another industry if there is a loss of productivity in the industry they were originally in (which is a general feature of CGE models). Other, more specific, adaptation responses were also incorporated into the analysis. For example, the infrastructure analysis considered the effects of planning and building standards that increase the resilience of buildings. These responses were assumed to reduce the magnitude of the shocks that were incorporated into the model.

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### *Other Australian studies*

Other studies that have attempted to estimate the impacts of climate change on the Australian economy include those by Gunasekera et al. (2007, 2008). Gunasekera et al. (2008) used an IAM — the Global Integrated Assessment Model (GIAM) developed by ABARE and the CSIRO — to develop indicative estimates of the impacts of climate change to 2100. The GIAM model combines ABARE's Global Trade and Environment (GTEM) CGE model with a climate model used to estimate the average change in regional temperatures.

Gunasekera et al. (2007) used the GTEM and Ausregion CGE models to examine the impacts of climate change on agricultural productivity. They assumed that climate change would reduce agricultural productivity. By incorporating this shock into the model, Gunasekera et al. estimated the impact on agricultural production and trade flows globally.

### *Key results*

The Garnaut Review estimated that in 2100, unmitigated climate change would reduce GDP by 5.9 per cent, relative to what it would have been without climate change. Other Australian studies have reported similar figures — though in the case of Gunasekera et al. (2007), this is despite their model only considering impacts on the agriculture sector (table D.1).

**Table D.1 Economic impacts of climate change on Australia**

<i>Study</i>	<i>Model</i>	<i>Sector</i>	<i>Year</i>	<i>Temperature rise</i>	<i>Impact on GDP</i>
				°C	%
Garnaut (2008b)	MMRF	National	2100	4.5	-5.9
Gunasekera et al. (2008)	GIAM	National	2100	3.5	-5.0
Gunasekera et al. (2007)	GTEM/Ausregion	Agriculture	2050	0.8–2.8	-5.0

*Sources:* Garnaut (2008b); Gunasekera et al. (2007, 2008).

The Garnaut Review provided further detail on the economic impacts of climate change, broken down by sector. The impacts on infrastructure were estimated to have the most significant effect: an estimated 2.4 per cent reduction in GDP in 2100. Impacts on agriculture (-2.1 per cent) were also estimated to be significant. As a result of reduced demand for Australia's exports (such as coal and other mining products), a decline in the terms of trade resulting from climate change was also estimated to have a significant impact (-1.4 per cent).

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The Review also considered the impacts of climate change on each state and territory. Queensland and the Northern Territory were estimated to experience more than a 10 per cent fall in gross state product due to climate change by 2100 relative to what it would have been without climate change. Western Australia (around 9 per cent) and South Australia (around 7 per cent) were also expected to be significantly impacted. Both Tasmania and Victoria were projected to experience a 4 per cent reduction in gross state product, New South Wales a 2 per cent decrease, and the ACT estimated to experience minimal economic impact.

Finally, the modelling for the Review produced projections for 58 industries. Output was projected to fall in the majority of industries. The two most adversely affected were agriculture (over a 20 per cent decrease in output by 2100 relative to the no climate change scenario) and mining (a 13 per cent decrease in output by 2100).

### **International studies**

A series of studies was undertaken by the Fondazione Eni Enrico Mattei, modelling the impacts of climate change on tourism (Berrittella et al. 2006), human health (Bosello, Roson and Tol 2006) and coastal property (Bosello, Roson and Tol 2007). The studies used the Global Trade Analysis Project (GTAP) model of the global economy. First, datasets for the future world economy were compiled — including labour, capital, land, natural resources and productivity. Shocks were then incorporated into the model to simulate the effect of climate change in each of the sectors.

- In the case of tourism, data were obtained from a previous study which considered the changes in tourism flows resulting from climate change. Based on these data, two sets of variables were shocked — first, consumer spending on hotels, restaurants and recreation activities (assuming that foreign tourists increase expenditure on these). Second, changes in international income transfers associated with foreign tourists were modelled.
- In the case of coastal property, two scenarios were run. In the first case, no coastal protection was built — modelled as a reduction in the amount of land. In the second scenario, the land was fully protected by levees — modelled as a shock in the value of investment.
- Finally, the impacts on human health were modelled as shocks to labour productivity and expenditure on health services.

Eboli, Parrado and Roson (2010) extended this work using the Inter-temporal Computable Equilibrium System (ICES) model — a dynamic CGE model derived from the GTAP model. In addition to the shocks described above, Eboli, Parrado

and Roson included impacts on agriculture and energy demand. Agricultural impacts were modelled as a shock to the productivity of land, while energy demand impacts were modelled as increases or reductions in the demand for natural gas, oil and electricity. The modelling assumed an increased temperature of 1.5°C by 2050.

The economic impacts of climate change have also been modelled using a CGE approach in other sectors, including forestry (Rive, Aaheim and Hauge (2005) using the GRACE model) and agriculture (Bosello and Zhang (2005) using the GTAP model).

A range of international studies have also used IAMs to estimate the economic impacts of climate change. Examples include PAGE (Stern 2007), RICE (Nordhaus 1998) and WIAGEM (Kemfert 2002).

### Key results

The international models report a wide range of estimates for the impacts of climate change on GDP (table D.2). The estimates for 2100 range from a fall of 0.9 per cent of GDP (Stern 2007) to a fall of 11.4 per cent of GDP (Gunasekera et al. 2008). These variations may be due to a range of factors in the models, including their treatment of adaptation (for example, the PAGE2002 model assumes a proportion of the damages can be mitigated by low-cost adaptation options), catastrophic impacts and non-market impacts; the temperature rise considered; and the general uncertainty surrounding the impacts of climate change.

**Table D.2 Economic impacts of climate change globally**

<i>Study</i>	<i>Model</i>	<i>Sector</i>	<i>Year</i>	<i>Temperature rise</i>	<i>Impact on GDP</i>
				°C	%
Stern (2007)	PAGE2002	All	2100	3.9 (mean)	-0.9
Stern (2007)	PAGE2002	All	2100	4.3 (mean)	-1.2
Gunasekera et al. (2008)	GIAM	All	2100	3.4	-11.4
Kemfert (2002)	WIAGEM	All	2050	0.25	-1.8--0.9
Nordhaus (1998)	RICE	All	2115	2.5	-0.5
Bosello, Roson and Tol (2006)	GTAP	Health	2050	Unclear	-0.1--0.08 <sup>a</sup>
Bosello et al. (2007)	GTAP	Sea-level rise <sup>b</sup>	2050	Unclear	-0.03--0 <sup>c</sup>

<sup>a</sup> -0.1 refers to the region 'rest of world'; 0.08 refers to the region 'rest of Asia'. <sup>b</sup> For the 'no protection' scenario, assuming that coastal land is not protected. <sup>c</sup> -0.03 refers to the region China and India; 0 refers to the region 'Rest of Annex 1 countries'.

*Sources:* Bosello et al. (2007); Bosello, Roson and Tol (2006); Gunasekera et al. (2008); Kemfert (2002); Nordhaus (1998); Stern (2007).

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Some modelling exercises have broken down the impacts according to:

- sector — for example, estimates by Bosello et al. (2007) suggested that the impacts of sea-level rise may have significant effects on the rice sector in the region ‘rest of Asia’ (losing up to 0.6 per cent of output). Sea-level rise was estimated to have negligible impact on some other sectors, such as electricity
- region — though these are often relatively aggregated. For example, the GTAP model used by Bosello, Roson and Tol (2006) contains 8 regions — Energy Exporting Countries, the United States, China and India, Rest of Annex 1 Countries (which includes Australia), Japan, Eastern European and former Soviet Union countries, European Union, and Rest of World. It was found that the estimated impacts on health have the most pronounced effect on GDP in the Rest of World region (-0.1 per cent impact on GDP), with other regions such as the Rest of Annex 1 Countries and the European Union receiving a net GDP increase as result of the health impacts of climate change.

## **D.2 Modelling the costs and benefits of adaptation**

Modelling exercises may be of use in examining the costs and benefits of adaptation — whether for an economy as a whole, for sectors or regions, or for individual adaptation options. In addition, such models may be able to provide some insights into the optimal timing and types of adaptation.

However, to date, few studies have examined the costs and benefits of adaptation together, within a modelling framework. Of these studies, the majority have used integrated assessment modelling, which can provide an overview of the costs and benefits of adaptation responses. A small number of studies have considered more specific adaptation options within a cost–benefit framework. The use of CGE or PE modelling has been limited.

### **What models have been used?**

#### *Cost–benefit studies*

Some studies have used a cost–benefit framework to consider adaptation responses. These studies typically identify the potential risks using climate models and risk analysis, identify a range of adaptation options, and then use a range of approaches to analyse the costs and benefits of these options.

A suite of studies by AECOM used a cost–benefit framework to assess flooding in the Narrabeen Lagoon in New South Wales (AECOM 2009), adapting Victoria’s

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rail network (AECOM 2011) and adapting water supplies in Victoria's Central Highlands (AECOM 2010). These studies used Monte-Carlo analysis (an approach that involves running multiple simulations with random values picked from a probability distribution) and a range of climate scenarios to assess the impacts of climate change. Monte-Carlo analysis was also used to assess the potential for adaptation responses to reduce these impacts.

In general, the AECOM studies found that a portfolio of adaptation options is the most appropriate response.

- In the Narrabeen Lagoon study, options that passed the cost–benefit test included opening the lagoon entrance, building a levee, installing flood-warning systems and using land-use planning regulation. Two other levees did not pass the cost–benefit test.
- In the Victorian rail study, implementing regenerative braking and replacing cabling in overhead lines were estimated to have net benefits. Other options, such as replacing the current wooden sleepers with concrete sleepers did not pass the cost–benefit test.
- The Central Highlands water study estimated that accepting a lower reliability of water supply would reduce the costs of supplying water, and that implementing scarcity pricing would also reduce costs. However, restricting household connections to the water network was estimated to be a high-cost approach.

The Economics of Climate Adaptation Working Group (2009) undertook a range of cost–benefit studies examining possible climate change adaptation responses. One scenario considered the risk of flooding (both coastal and riverine) and wind damage in the UK city of Hull. The study considered a range of responses to the risks, including flood-protection measures, flood-awareness campaigns, flood proofing existing buildings, insurance, and improved drainage systems. The costs of the measures included capital and operating expenditures, and were extrapolated from current costs. The study considered benefits including a reduction in the severity of the expected hazard, a reduction in assets at risk, and a reduction in the vulnerability of assets (the expected damage to assets as a result of a given event).

The most cost-effective options were found to be flood awareness campaigns (cost–benefit ratio of 0.01<sup>2</sup>), sea and river defences (0.03–0.13), training staff for emergency management (0.28), and flood proofing floors of new buildings (0.49). Costly options included flood proofing the floors in existing buildings (3.30), sandbagging buildings (2.15) and reducing insurance premiums for small businesses (1.67).

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<sup>2</sup> A cost–benefit ratio of less than 1 indicates that the benefits of the option exceed the costs.



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A study by BRANZ (2007) considered the costs and benefits of retrofitting housing in New Zealand to deal with the impacts of climate change. The study considered adaptation options, including increasing the number of nails in roofs, increasing insulation, using stronger steel, installing water tanks, and moving housing inland. For each option, the cost of the option per house was calculated, and multiplied by the number of houses assumed to be at risk of extreme weather events, to estimate the total cost of the measure. Benefits were estimated by making assumptions about the damage reductions resulting from the adaptation measure.

The study estimated that the total cost of adaptation measures would be NZ\$2 billion, while the total benefits would be NZ\$4 billion. Most of the benefits (NZ\$3.6 billion) resulted from increasing the use of insulation, while other measures that were found to have benefits exceeding the costs included additional nails in roofs, and moving houses inland. Using higher quality steel was found to have costs exceeding the benefits.

Finally, some environmental impact assessments have included an analysis of adaptation options (Agrawala et al. 2010b). These assessments generally include an assessment of climate change risks and potential options to manage these risks. For example, the environmental impact assessment for the installation of an electrical substation in the ACT considered climate change risks to the investment. However, the assessment suggested that there were minimal climate change risks associated with the investment in the short term, and thus minimal benefits from proceeding with adaptation measures in the short term (Purdon Associates and AECOM 2010).

### *Integrated assessment models*

Few IAMs incorporate adaptation as an explicit variable. However, there are some studies that use IAMs to consider the costs and benefits of adaptation.

Hope, Anderson and Wenman (1993) were the first to consider adaptation as an explicit variable in an IAM framework. They used the PAGE model, in which adaptation was considered to:

- increase the temperature rise that can be considered ‘tolerable’
- reduce damages for temperature rises above the ‘tolerable’ level.

Two scenarios were assessed — one with no adaptation, and one with an assumed package of adaptation responses such as seawalls and land-use planning — to estimate the costs and benefits of adaptation. The adaptation package was assumed to make a 2°C temperature rise tolerable, and reduce the damage from temperature rises above this level by 90 per cent.

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Hope (2009) also used the PAGE model to consider adaptation. Hope modelled two scenarios — one with adaptation, and one without — to estimate the costs and benefits of adaptation. The scenario with adaptation incorporated assumptions used in the Stern review (Stern 2007) — that in developed countries, 100 per cent of the economic impacts of the first 2°C of temperature rise, and 90 per cent of the economic impacts of temperature rises beyond this level, could be managed by low-cost adaptation options.

The costs and benefits of adapting to sea-level rise were considered by Tol (2007) using the FUND model. Several scenarios were modelled, including scenarios with and without coastal protection, to determine the cost–benefit ratio of coastal protection adaptation responses.

Recent studies by Agrawala et al. (2010a), Carroro, Bosello and de Cian (2009) and de Bruin, Dellink and Agrawala (2009) have attempted to incorporate adaptation as an explicit variable within the RICE, DICE and WITCH IAMs (box D.2). In these models, adaptation was considered as a continuous dynamic variable, and the amount of adaptation within the model was optimised over time. A range of data sources was used to calibrate these models. For example, in calibrating the WITCH model, Agrawala et al. (2010a) used previously published climate change damage functions and studies on the costs of adaptation, including those published by the UNFCCC (2007).

Brown et al. (2011) used the DIVA model (a global model of coastal systems) to consider the costs and benefits of adapting to sea-level rise in the European Union. The study examined the risks associated with a 0.18–0.46 metre sea level rise by 2080. The adaptation responses considered included sea and river dikes, and beach nourishment.

### *Key results*

Modelling approaches have typically concluded that adaptation offers large net benefits. The studies using the PAGE model have estimated benefit–cost ratios in excess of 30, with the other studies generally estimating a ratio in the region of 2 (table D.3). (The large difference between the PAGE model and the other models is due to the differences in assumptions between the models — the PAGE model assumes that low-cost adaptation options can reduce much of the damages associated with climate change.) The optimal amount of adaptation in the models varies significantly, depending on the assumptions regarding the climate, the benefits of adaptation, and the model used.

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## Box D.2 **Incorporating adaptation into integrated assessment models**

In many IAMs, including DICE, RICE and WITCH, the climate change damage (reductions in global output) functions are purely a function of temperature increases. Adaptation is not included as a variable in these models. However, some recent studies have attempted to incorporate climate change adaptation responses into an IAM framework.

de Bruin, Dellink and Agrawala (2009) incorporated adaptation as a variable into the DICE and RICE models. Adaptation was included in the damage function and was assumed to reduce the economic damages associated with climate change, with adaptation costs increasing as more effective adaptation options are used up. The optimal level of adaptation is chosen every 10 years, and is modelled as a flow variable — adaptation in one period has no impact in the following periods (which is unlikely to be a realistic representation of investment in assets such as levees).

Agrawala et al. (2010a) built on the work of de Bruin, Dellink and Agrawala (2009), by expanding the RICE and DICE models to consider adaptation as both a stock and flow variable — allowing investment in adaptation in one period to have an impact on climate damages in future periods.

Carroro, Bosello and de Cian (2009) incorporated adaptation responses into the WITCH model. Adaptation was modelled as a sequence of constant elasticity of substitution functions, and was considered to be either anticipatory, information-based (modelled as stock variables), or reactive (modelled as a flow variable). A range of adaptation approaches were considered, including coastal protection, early-warning systems, and agriculture and health responses.

Some of the models also offer insights into the optimal timing of adaptation. Both models used by Agrawala et al. (2010a) (in particular the WITCH model) suggested limited adaptation will take place until 2025, due to limited temperature changes up to that point. Carroro, Bosello and de Cian (2009) produced similar results, with relatively little adaptation taking place until 2050 in their model.

The models also led to some conclusions about which types of adaptation may be optimal. Much of the adaptation modelled by Agrawala et al. (2010a) is anticipatory (such as coastal protection) or aimed at enhancing adaptive capacity, with limited implementation of reactive adaptation until the latter half of the century. On the other hand, reactive adaptation plays a bigger role in Carroro, Bosello and de Cian's (2009) model, and very little research and development expenditure on adaptation occurs.

**Table D.3 Key results — integrated assessment models**

<i>Study</i>	<i>Model</i>	<i>Sector</i>	<i>Period</i>	<i>Adaptation costs</i>	<i>Adaptation benefits</i>
Hope, Anderson and Wenman (1993)	PAGE	Global	1995–2100	0.5tr (ECU) <sup>a</sup>	17.5tr (ECU) <sup>a</sup>
Hope (2009)	PAGE	Global	2000–2200	6tr (USD)	350tr (USD)
Agrawala et al. (2010a)	DICE	Global	2005–2100	0.28% GDP	0.51% GDP
Agrawala et al. (2010a)	WITCH	Global	2005–2100	0.19% GDP	0.38% GDP
Carroro, Bosello and de Cian (2009) <sup>b</sup>	WITCH	Global	2010–2105	270tr (USD)	695tr (USD)
Carroro, Bosello and de Cian (2009) <sup>c</sup>	WITCH	Global	2010–2105	10tr (USD)	16tr (USD)
de Bruin, Dellink and Agrawala (2009)	RICE	Global	2025–2055	151tr (USD)	792tr (USD)
Brown et al. (2011)	DIVA	Sea-level rise (EU)	1995–2080	€0.3–€1.6bn (annual)	€5bn–€21bn (annual)

<sup>a</sup> European Currency Unit, the precursor to the Euro. <sup>b</sup> High climate change damage with low discount rate scenario. <sup>c</sup> Low climate change damage with high discount rate scenario.

Sources: Agrawala et al. (2010a); Brown et al. (2011); Carroro, Bosello and de Cian (2009); de Bruin, Dellink and Agrawala (2009); Hope (2009); Hope, Anderson and Wenman (1993).

### *CGE and PE models*

CGE and PE models have not been widely used to assess the costs and benefits of climate change adaptation. (However, these models can also be useful for highlighting the flow of resources through the economy in responses to climate change — a form of autonomous adaptation.)

Some studies have examined the benefits (though not the costs) of adaptation within the agricultural sector in developing countries. Calzadilla et al. (2009) used the IMPACT PE model and the GTAP model to assess the impacts of adaptation responses in sub-Saharan Africa. First, climate change was modelled as a reduction in agricultural productivity. Then, two adaptation scenarios were run.

- The first considered an increase in irrigated land. This scenario resulted in a small increase in GDP, with limited impacts on agricultural production aside from wheat.
- The second considered an increase in agricultural productivity. This scenario led to a substantial increase in GDP (1.5 per cent), with large increases in agricultural production in sub-Saharan Africa.

Further, a study by Nelson et al. (2009) used the IMPACT model linked to a crop model to estimate the agricultural productivity improvements that would be required to reduce estimated child-malnutrition levels in Africa in 2050 to

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pre-climate change levels. This study suggested that the cost of increasing productivity would be between US\$7.1 billion and US\$7.3 billion annually.

### **D.3 The strengths and limitations of modelling climate change adaptation**

To be relevant for this inquiry, modelling exercises need to provide insights into the costs, benefits and optimal timing of adaptation options. However, the usefulness of the models considered in this appendix is qualified by their considerable limitations. These can include adaptation-specific limitations, such as the handling of climate change within the models, or general limitations, such as the need for appropriate assumptions and good data.

#### **Where are these approaches most useful?**

At a broad level, IAM and CGE modelling can provide some insights into the impacts of climate change. In particular, such models indicate which sectors and regions may be most severely affected by climate change, providing some focus for policy makers.

IAMs can provide useful insights into the optimal timing of adaptation responses. Studies using these types of models have typically found that it is optimal for the majority of adaptation to occur after 2025, with minimal investment required in the early part of the century.

However, the costs and benefits of adaptation estimated by IAM exercises are less useful for this inquiry. These results tend to be highly aggregated at both the country and sector level, and thus provide limited focus for policy makers as to appropriate adaptation policies.

While CGE and PE approaches have not been widely used for assessing specific adaptation options, they are useful for highlighting market-driven responses to climate change. Such models can estimate how the allocation of resources within the economy may change in response to ‘shocks’ associated with climate change (for example, a reduction in agricultural productivity).

Cost–benefit studies have generally analysed sets of adaptation investments in specific regions. These studies are important for analysing specific adaptation options, but offer only limited insights for broader adaptation policy.

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## What are the limitations of these approaches?

The modelling approaches outlined in this appendix have a number of shortcomings, which limited their potential usefulness for the inquiry. These shortcomings include:

- dealing with the uncertainty associated with climate change
- the quality of assumptions and data
- difficulties valuing non-market outputs such as ecosystems
- uncertainty when modelling over long time periods
- incorporating climate change impacts.

### *Modelling is data and assumption driven*

Modelling in general is data and assumption driven. The accuracy of the results of modelling exercises depends on the accuracy of the data used, and the extent to which the modelling assumptions approximate the real world.

To model the costs and benefits of adaptation, assumptions need to be made as to the cost of adaptation options, how effective they are at mitigating climate change impacts and what level of climate change impacts there will be in the future. The assumptions used can have a significant impact on the modelling results.

For example, the modelling exercises considered in this appendix assumed that adaptation is effective at reducing climate change impacts, and that the money used for adaptation is well spent. If this is not the case in reality, the models would overestimate the benefits of adaptation.

The effect that assumptions can have on the results is highlighted with the contrasting approaches taken in the PAGE and WITCH models. The PAGE model used by Hope (2009) estimated a benefit–cost ratio for adaptation of around 60. On the other hand, the WITCH model used by Agrawala et al. (2010a) estimated a much smaller benefit–cost ratio of around 2.

This may be due to a range of assumptions included in the modelling exercises, such as assumptions regarding the nature of adaptation, the timing of climate change and the damages of climate change. For example, the PAGE model assumes that a large proportion of the damages associated with climate change can be avoided by low-cost adaptation options (Hope 2009). On the other hand, the WITCH model used by Agrawala et al. (2010a) drew on adaptation cost data from a range of sources, such as the UNFCCC (2007).

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### *Uncertainty when modelling over long time periods*

Due to the long time periods associated with climate change, modelling of adaptation is conducted generally at least to 2050 and often to 2100 and beyond. However, most models assume behavioural responses determined by:

... parameters and data that have been derived from recent history. These responses will not necessarily still hold far into the future, or for step changes that are outside of recent experience. (Garnaut 2008a, p. 14)

Past experience suggests that people will adapt, and behavioural assumptions in the model probably do not accurately describe the way people will deal with climate change into the future.

### *Uncertainty of climate change*

The severity and timing of climate change is uncertain. There is uncertainty about the level of future greenhouse gas emissions, the sensitivity of the climate to greenhouse gas emissions, and how climate change will affect particular regions and activities (chapter 2). As a result, the ability to predict future climate change impacts over the next 100 years and beyond is limited.

To estimate the costs and benefits of adaptation, it is necessary to make a set of assumptions about the physical impacts of climate change, and how these will affect the economy. According to Weitzman (2009), most IAMs are based on a central forecast of damages, which is assumed to be certain, and limited sensitivity analysis is undertaken.

Some researchers have attempted to take a more sophisticated approach that incorporates uncertainty. For example, key climate variables used in the PAGE model (Hope 2009) are expressed as probability distributions. Similarly, as noted earlier, AECOM (2009) used Monte-Carlo analysis for uncertain variables.

However, there are limitations to these approaches to dealing with uncertainty. These approaches do not take account of risk aversion. In addition, such modelling does not deal well with the risk of catastrophic climate change. According to Jotzo (2010), the low probability of catastrophic climate change could be the main driving factor relevant to economic decision making regarding mitigation. Similar arguments apply to adaptation — the risk of catastrophic climate change could drive very different adaptation responses than those considered in existing models.

Ultimately, where there is uncertainty, modelling results need to be reported in ranges. While the ranges can highlight the implications of the uncertainty, the

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presence of uncertainty limits the conclusions that can be drawn from these results (both the ranges and the point estimates).

### *Valuing non-market outputs*

Not all of the impacts of climate change can be easily captured in economic terms. These non-market outputs include environmental goods such as biodiversity and ecosystem ‘services’, and human health.

Non-market impacts are of particular importance in the context of climate change adaptation. Many adaptation options are likely to have both market and non-market impacts — for example, the installation of an air conditioner has a market cost (the price of the air conditioner) but non-market benefits (increased comfort). In addition, in Australia, the impacts of climate change on ecosystems, such as the Great Barrier Reef, are of great significance.

However, standard economic modelling often excludes non-market outputs. This includes most IAM models.

... RICE, as well as AD-WITCH and many other [integrated assessment] models, only partially captures non-market impacts, which are confined to the recreational value of leisure. Important climate related impacts on biodiversity and ecosystem losses or on cultural heritage are not part of the damage assessment. (Carroro, Bosello and de Cian 2009, p. 21)

Some studies attempt to incorporate ecosystem impacts into IAMs, but these approaches are often limited. For example, the FUND model bases the value of ecosystems on the ‘warm glow’ effect, whereby the value people place on ecosystems is largely dependent on their income, and is largely independent of any real change on ecosystems.

These issues are also relevant to cost–benefit studies. For example, the Narrabeen Lagoon study (AECOM 2009) was unable to take account of a range of costs and benefits, including the impacts on the recreational use of the lagoon, ecological impacts and the visual amenity impacts of levees.

### *Treatment of climate change impacts*

Most IAMs adopt a simplistic approach to estimating the costs associated with climate change. In these models, an increase in temperature affects output in each sector through a damage function. Such an approach may fail to fully capture the complex impacts of climate change — indeed, parts of some sectors may be positively affected by climate change.



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Through the use of ‘shocks’, CGE models may be better suited to considering more detailed climate change impacts. However, where these are used, they tend to consider only a subset of climate change impacts. For example, the Garnaut Review (Garnaut 2008b) modelled climate change impacts on five sectors. However, impacts such as an increase in defence and aid expenditure, and damage to residential buildings due to extreme events, were not modelled.