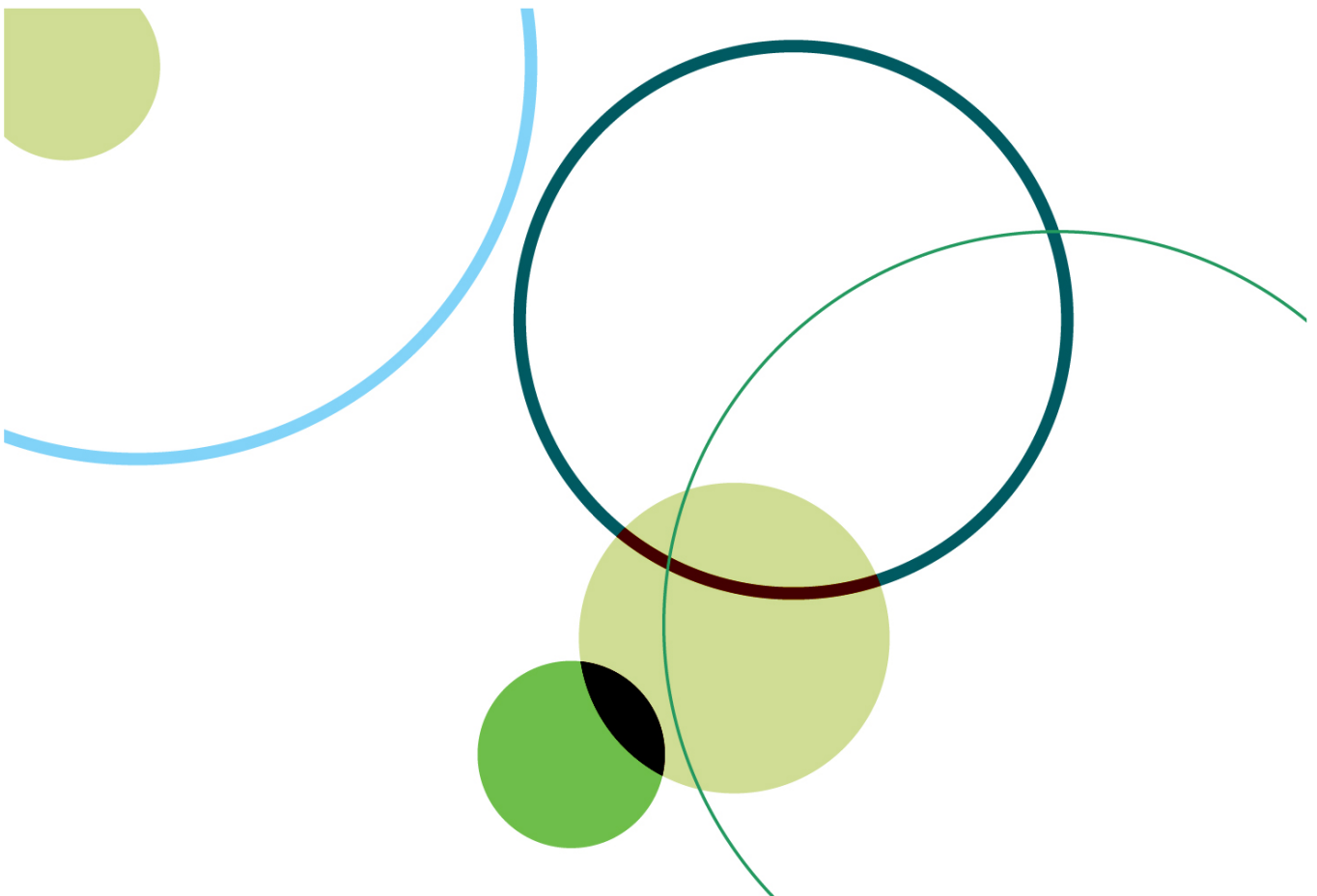


The macroeconomics of climate change

Report prepared for Defra

Final Report
May 2013



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Executive Summary

The macroeconomics of climate change is a nascent topic of study; policy questions are not yet clear and models currently find it hard to meet broad criteria of fitness

The aim of this report is to provide a review of the current techniques that exist to model the macroeconomic impact of climate change with and without adaptation and with a focus on the UK. To this end, the report suggests a framework for understanding the macroeconomics of climate change and provides a checklist of issues that future studies could aim to cover. The literature on the macroeconomics of climate change is reviewed with a focus on bottom-up, sector-specific studies, Integrated Assessment Models (IAMs), adaptation-IAMs (AD-IAMs), multi-sectoral models, including Computable General Equilibrium (CGE) models, and studies on the impacts of extreme weather events. The strengths and weaknesses of each of these modelling techniques are evaluated. The report ends with a set of recommendations on how to best direct future work on the macroeconomics of climate change.

There is a difference between the macroeconomics of climate impacts and the macroeconomics of climate policy instruments and the focus of this report is on the former. The modelling techniques reviewed in this report focus on the macroeconomics of climate impacts and do not consider the costs of climate policy instruments in a sophisticated way. The main difference between the two issues is that climate impacts affect a small number of sectors in the economy directly and can do so acutely, while policy instruments to encourage mitigation and adaptation, such as taxes and subsidies, directly change relative prices across a large number of sectors.

The macroeconomics of climate change has nine key dimensions. These nine dimensions are presented in Table 1 and developed in Section 1.3. These nine dimensions give rise to a checklist of questions against which the fitness of modelling techniques is assessed.

Non-market, direct climate impacts and cross-border spill overs are two of the most poorly understood dimensions. Modelling of non-market, direct climate impacts, such as those to ecosystem services, biodiversity and the dis-amenity to households of a changing climate, is poor or non-existent. Analysis of cross-border spill overs is currently limited to trade. However issues such as financial flows, migration and socially contingent events could be important. Modelling these missing elements is a significant challenge. Frameworks for their analysis in the absence of climate change are often not robust, although financial flows can be modelled using state-of-the-art macroeconomic techniques. Yet if these dimensions remain poorly understood then serious gaps will remain in estimates of the macroeconomic impact of climate change.



Table 1. **A framework of nine dimensions along which climate change can have a macroeconomic impact is used to structure the report and provides a checklist of questions against which current and future studies could be assessed**

| Dimensions | Question to consider when assessing studies |
|---|--|
| Direct climate impacts | Which direct climate impacts are covered and which are omitted? What is the quality of impact estimates? |
| Representation of cross-sectoral interactions | Are indirect, higher-order macroeconomic effects covered, and how? |
| Time | What is the temporal scale of the study? |
| Growth | Does the study model the effect of direct climate impacts on long-run growth prospects via investment? |
| Space | Can the study be used to produce spatially resolved, even UK-specific, estimates of impact and how? |
| Cross-border spill overs | Are the impacts on the UK of climate change outside the UK accounted for, including through trade, financial flows and migration? |
| Uncertainty | Is uncertainty about changes in long-run climate averages accounted for and how complete is the assessment, for example are tipping elements included? |
| Extreme weather | Are the impacts of extreme weather accounted for? |
| Vulnerability and adaptation | Does the study model changing vulnerability and does it explicitly account for adaptation? |

Source: Vivid Economics

Recommendations for defining a future research programme

There are three major recommendations concerning fundamental issues that will need to be resolved if a future research programme is to be useful to policy makers. The purpose of this report is to take stock of the current literature and assess its ability to speak to broad dimensions of the macroeconomics of climate change. A key finding is that research to improve upon current knowledge is warranted. However some fundamental issues should be addressed before research is undertaken. These issues are: connecting policy questions to the evidence, choosing modelling strategies and quality assurance.

Connecting policy questions to the evidence: current modelling techniques do not perform particularly well against the nine dimensions of the macroeconomics of climate change and so their performance against specific policy questions is generally worse. Further research would benefit from being led by the challenge of answering well-defined policy questions rather than policy attempting to adapt to the outputs of models that are often designed to further the academic literature.



Choosing modelling strategies: several modelling strategies can be envisaged, from a single, consistent but complex model, to a suite of simpler models, or a hybrid option where simple models can be coupled. There are advantages and disadvantages to each approach. Incorporating all relevant dimensions into a single model offers a consistent framework, however the model will become more difficult to use and understand as a consequence. Simple models may not provide consistent answers and this requires policy makers to interpret which results are most important, but this must be balanced with the gain in ease of use and explanatory power that comes from abstracting away from all but the most crucial mechanisms that affect the problem at hand. In addition, in a context where debates persist about the best way to represent dimensions such as growth, there is value in preserving model diversity.

Quality assurance: there has been little work on quality assurance and independent scrutiny; transparency regarding model assumptions and input data is often poor. Unless these issues are resolved current models will not be fit for use in policy decisions. Ways of resolving these issues may be more inter-model comparison, validation against empirical evidence and a requirement that models used to inform policy meet high standards of quality and transparency. Resolving these issues should be a high priority; for while a model may appear to cover many of the dimensions of interest, if the quality of the approach is questionable then model results will not provide a good basis on which to make policy decisions.

Conclusions on current modelling techniques

In general, current modelling techniques tend to specialise. This means they tend to answer different questions from each other and can rarely be seen as alternate methods to answer the same question. It also means that no model does well across all dimensions, suggesting that further research is needed before a full understanding of the macroeconomic impacts of climate change can be developed. This report provides a number of recommendations for improving current modelling techniques. Many of these would not require significant investment, such as the updating of direct impact estimates, while some would be harder, such as incorporating features of state-of-the-art macroeconomics into current models.

Bottom-up, sector-specific studies are indispensable for policy appraisal as they provide the direct costs and benefits of policy action or inaction, and this data is often used as an input by other modelling techniques. However there can be great difficulties in using several different bottom-up, sector specific studies as inputs into other modelling techniques. As a consequence, research programmes that estimate bottom-up, sector-specific impacts for several sectors within a coherent framework are particularly useful.

IAMs are the most flexible models for exploring the impact of climate change on GDP-equivalent, the central macroeconomic indicator, but they suffer from concerns about the quality of data used for calibration. IAMs are relatively simple models and have been adapted to explore a large number of the different dimensions of the economics of climate change, including uncertainty. However, IAMs do have some significant drawbacks. The results of IAMs are sensitive to input data choices, which are not always transparent and rarely reflect the latest available information; quality assurance and an update of input data are two key recommendations for improving IAMs. IAMs are also unable to explicitly model cross-sectoral interactions and cross-border spill overs, and GDP-equivalent may be too narrow an indicator for policy makers.



AD-IAMs, which extend IAMs to include adaptation, have provided valuable insights, but only at the very broadest level. AD-IAMs model adaptation at a very high level and so they are only suitable for answering very broad questions about adaptation, such as the profile of adaptation spending over time and the interaction of adaptation and mitigation. Therefore the suitability of AD-IAMs to answer policy questions should be judged only once clear policy questions have been developed.

Multi-sector models are currently most useful in understanding cross-sectoral interactions. Cross-sectoral interactions generate indirect effects which may counter the direct impacts of climate change, for some regions and sectors, while exacerbating them for others. The direction, magnitude and distribution of indirect effects is still an open research question and answering it would indicate whether economic analysis of climate change should be mainly concerned with direct impacts or whether macroeconomic analysis is warranted.

The macroeconomic impacts of extreme weather events in a changing climate are poorly understood and the literature is thin. The research challenges in this area are formidable. Not only is the physical science of how climate change will affect extreme weather events poorly understood, but the impacts of and vulnerability to extreme weather events is unevenly distributed in a manner which is hard to capture in an aggregate model. As a result, the impacts of extreme weather events should continue to be analysed separately and case studies may be more informative than macroeconomic analysis.

Recommendations for improving the current state of modelling techniques

There are a number of recommendations for improving each of the five modelling techniques reviewed. The justifications for these recommendations are provided in Section 3.1.

Recommendations for bottom-up, sector-specific studies:

- programmes of consistent bottom-up, sector-specific studies should continue to be supported and used as inputs for other modelling techniques. For example the outputs of the AVOID programme could be used in a multi-sector model;
- understanding of how sector specific economic responses vary over geography could be improved so that bottom-up studies need not be so aggregated; this could improve the spatial resolution of IAMs and multi-sector models, although significant uncertainty over changes in climatic variables at local levels will still remain.

Recommendations for Integrated Assessment Models:

- direct climate impact estimates in IAMs could be brought up to date;
- the transparency of IAMs could be improved, especially regarding the data used for damage function calibration;
- state-of-the-art stylised macroeconomic models could be adapted to explore endogenous growth and also climate impacts on simple financial assets, although currently only DICE/RICE could be modified with relative ease;
- IAMs could be run considering multiple dimensions altogether, such as an endogenous growth IAM with uncertainty explored via a Monte Carlo simulation.



Recommendations for AD-IAMs:

- AD-IAMs are not currently suited for answering policy questions about adaptation except at the most general level;
- future development of AD-IAMs for policy analysis requires a clear articulation of policy questions; although questions of a more detailed nature would, at best, require a great deal of model development and, at worst, could be infeasible.

Recommendations for multi-sector models:

- multi-sector models could be run with an updated and greater set of direct climate impacts included;
- multi-sector models could be run with worst-case scenarios as a precursor to running them probabilistically;
- economic interactions with physical sectors could be explicitly represented if physical sectors were included in multi-sector models. The GTAP-W model, which incorporates water, is an example of this;
- an inter-model comparison of multi-sector models could be conducted to ascertain the significance of indirect effects;
- state-of-the-art multi-sector macroeconomic models could be adapted to explore endogenous growth, financial assets, public finance and sophisticated representations of trade.

Recommendations for extreme weather event studies:

- the impacts of extreme weather events should continue to be analysed separately;
- the distributional impacts of extreme weather events may deserve more focus than the aggregate macroeconomic impacts, especially for extreme weather events in developed economies;
- the impact of worst-case extreme weather events on particularly vulnerable areas could be analysed.



How to read this report

The reader should bear in mind that this is a non-technical report for policy makers that aims to provide a foundation for future work. Macroeconomics and climate change are enormous topics in themselves and so providing a framework in which both issues can be analysed coherently in a non-technical manner has required trade-offs in detail that may not appeal to all members of the broad readership of this report. On other hand, a large amount of detail is still contained within this report, not all of which will be relevant to each reader depending on the reader's prior level of knowledge.

The first sentence of every paragraph, in bold, gives the key message of the paragraph. The remainder of the paragraph explains and supports the message in the first sentence. Therefore some readers may wish to focus on the first sentences of paragraphs and only read further when more explanation is required.

In the following guide to the report recommendations are made about selective reading: *sentences in italics suggest which types of reader need, or need not, read the section.*

Section 1 develops a theoretical framework for the macroeconomics of climate change. This is achieved by providing an introductory guide to climate change and macroeconomic modelling and identifying salient dimensions of both.

- Section 1.1 provides an introduction to climate change;
 - *readers with knowledge of climate change may pass over this section.*
- Section 1.2 provides an introduction to macroeconomic modelling;
 - *readers with knowledge of macroeconomic modelling may pass over this section.*
- Section 1.3 provides the framework for the macroeconomics of climate change;
 - *all readers should at least familiarise themselves with Section 1.3.1, as this is where the dimensions of the macroeconomics of climate change are introduced and assessment criteria for models are presented.*

Section 2 presents the key findings of the literature review. Five modelling techniques are reviewed according to the nine checklist criteria developed in Section 1.3.

- *Section 2 need only be read by readers who are interested in understanding the characteristics of the modelling techniques in depth;*
- *other readers may go straight to the assessment of modelling techniques in Section 3.1.*

Section 3 presents the conclusions of the report. *It is recommended that all readers consider the conclusions, which are presented in two parts:*

- Section 3.1 provides an assessment of modelling techniques and recommendations for improvement;
- Section 3.2 provides a set of recommendations concerning fundamental issues that will need to be resolved if a future research programme is to be well-defined;

Three annexes provide greater detail on the literature reviewed in Section 2. *These need only be read by the most interested readers.*



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1 A Theoretical Framework

Key dimensions of climate change and of macroeconomics combine to give a framework for the macroeconomics of climate change

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Introduction

This section introduces aspects of climate change with macroeconomic relevance and key dimensions of macroeconomic modelling and then, from this foundation, develops a framework for the macroeconomics of climate change along the following dimensions:

- direct climate impacts,
- representation of cross-sectoral interactions,
- time,
- growth,
- space,
- cross-border spill overs,
- uncertainty,
- extreme weather,
- vulnerability and adaptation.

Readers who are informed about climate change may wish to pass over Section 1.1 and readers who are informed about macroeconomic modelling may wish to pass over Section 1.2.



1.1 The aspects of climate change with macroeconomic relevance

There are substantial gaps in our understanding of the macroeconomic impacts of climate change

1.1.1 The relationship between climate change and macroeconomics

The economy and the climate co-exist in a feedback loop. Economic activity gives rise to greenhouse gases (GHGs) as a by-product, which accumulate in the atmosphere, causing radiative forcing, increases in temperatures and changes in other climatic variables, such as precipitation and winds. Climate change in turn has impacts on the real economy as well as other environmental, financial and social assets and processes that have economic value. Finally, these impacts affect GHG emissions, thus constituting the feedback loop. However, in the academic literature on climate change it is often convenient to abstract from the feedback and think of a linear causal process linking GHG emissions and climate impacts, as given here in Figure 1.

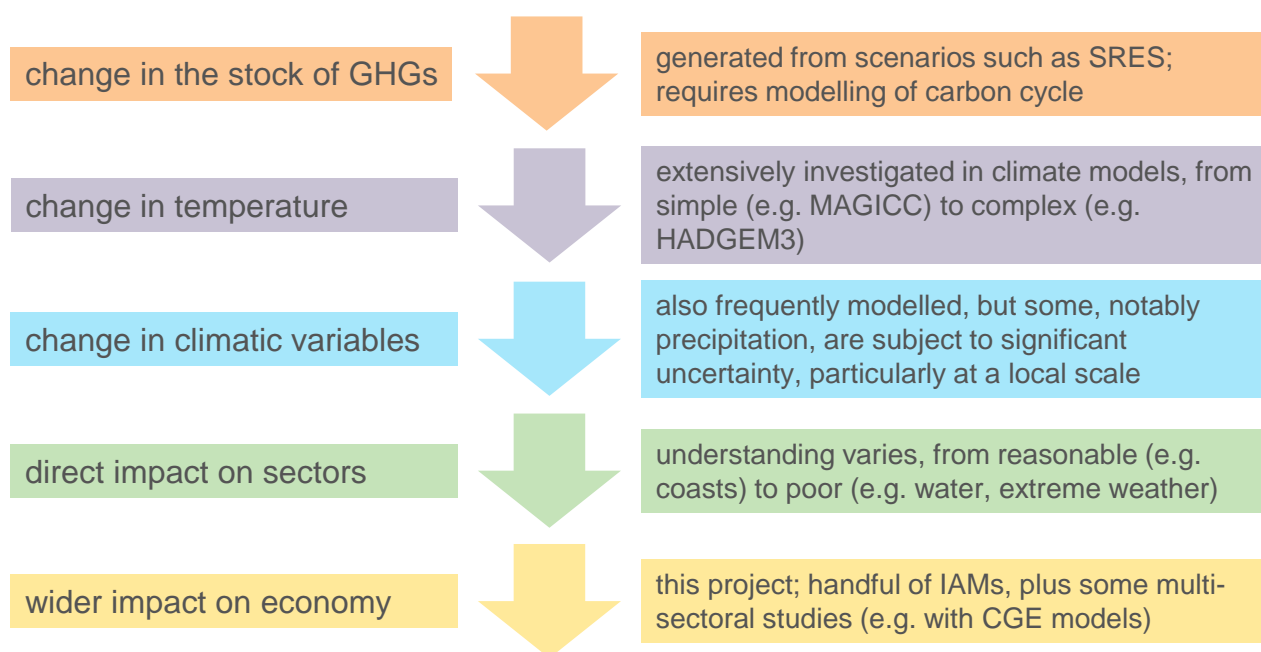
Macroeconomics can be defined as the branch of economics concerned with aggregates, such as national income, consumption, and investment (Collins, 2009). This implies a focus on two key aspects of the economic impacts of climate change. First and rather obviously, it implies a focus on climate impacts at the whole-economy level. Therefore, if, for instance, the costs of climate change on the agricultural sector are under consideration, the analysis is at the national level rather than the farm level. Second, it also implies a focus on the indirect effects of climate change on the economy, not just the direct impacts, for it is the hallmark of a good macroeconomic analysis to recognise that when there is an impact on production in one part of the economy, it should not be assumed that everything else remains unchanged. So, for instance, when the impact of climate change on agricultural production is quantified, it is recognised that agricultural products are an input into many other production processes, which will also then be affected. Indeed, there are many other such inter-linkages that could be mentioned.

This report sets out a conceptual framework for understanding the macroeconomic impact of climate change and surveys existing research to understand how clear a picture we have. Its focus is on advanced economies, especially the UK, and it includes an analysis of how adaptation can help to manage these impacts. As such, the report needs to concern itself with every link in the chain characterised in Figure 1: it must ask, on the one hand, what climatic changes could have an impact on the economy and, on the other hand, what are the characteristics of those economic impacts.

The climate is not, as standard, included in mainstream macroeconomic models. Figure 1 summarises the specific research fields that inform understanding of each link in the chain. While it cannot be denied that much more research is required on all links given the prominent role of uncertainty in setting current climate policies, it is arguably the case that the wider, macroeconomic impacts of climate change have received proportionately less attention to date.



Figure 1. The macroeconomic impact of climate change has been neglected relative to climatic changes themselves



Source: Vivid Economics

1.1.2 Key policy concerns in the macroeconomics of climate change

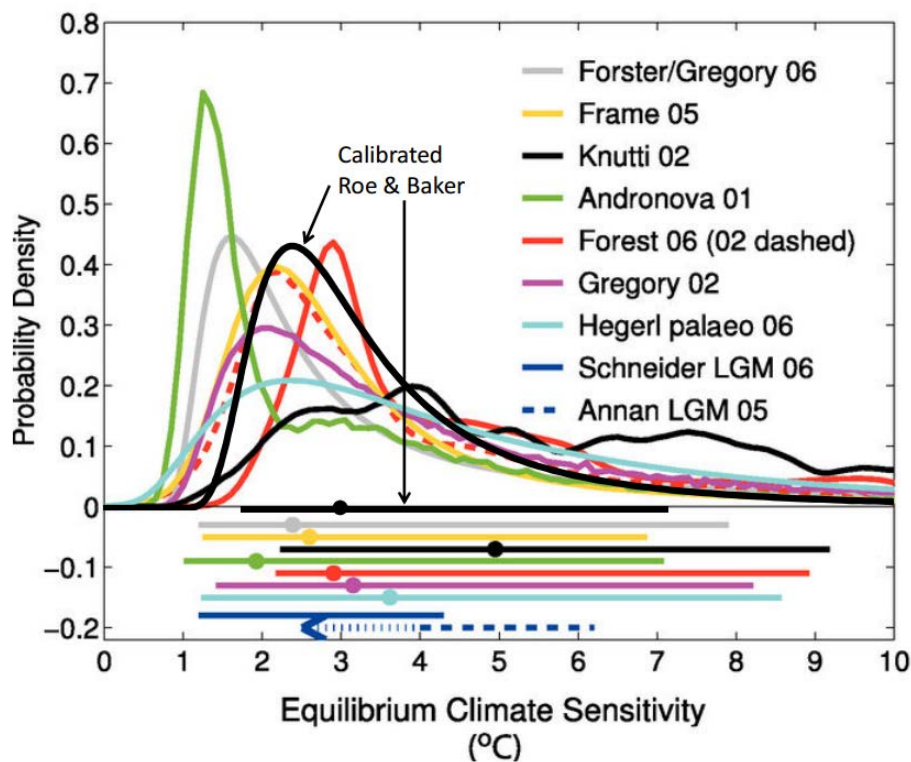
Projections of changes in climatic variables are still subject to large uncertainties. The range of possible climate outcomes is very broad, even at the global level where local-scale uncertainties may be finessed. For instance, a conservative estimate of the range for global mean temperature in 2100 is 1.1–6.4°C above the 1980–99 level (Intergovernmental Panel on Climate Change, 2007) and there are reasons to believe that this is an underestimate of the range of possible temperatures. Furthermore there may be ‘tipping points’ in the climate system that if passed could result in irreversible, qualitative changes to how the climate system functions at the global scale, with correspondingly large impacts on economic and social systems that are not adapted to them (Lenton et al., 2008).

The possibility of very large changes in climate is significant because it is widely thought that economic impacts increase more than proportionately as the climate changes, but at the same time uncertainty about impacts also increases. Motivated by the debate around the Stern Review there have been a number of studies on the economics of ‘dangerous’ climate change, for example (Ackerman, Stanton, & Bueno, 2010; Dietz, 2011; Pycroft, Vergano, Hope, Paci, & Ciscar, 2011). These studies have focused on the probability distribution describing the increase in global mean temperature (usually they specifically look at the climate sensitivity, which is the increase in temperature that would follow a doubling of the atmospheric stock of GHGs, in equilibrium), as a proxy for a wider set of climatic changes. A key feature of this probability distribution is that it is thought to contain a ‘fat tail’ of very high values with a very low, but non-

negligible, probability. Figure 2 illustrates the fat upper tail evident in the many estimates of the probability distribution of the climate sensitivity.

Given the possibility of very large but uncertain changes in the climate, decision-making should be supported by tools that can explore the full range of possible climatic changes and their impact on the economy. In tandem with the need for policy makers to explore uncertain outcomes and understand the costs of uncertainty to society, policy makers also need to understand the sensitivity of models to uncertainty so that results can be interpreted correctly.

Figure 2. Climate sensitivity, which drives temperature change and so economic impacts in IAMs, is thought to have a fat upper tail, which means that an unusually large amount of probability density is found at high values



Note: The 'Calibrated Roe & Baker' distribution is the preferred probability density in the source report.

Source: (EPA, 2010)

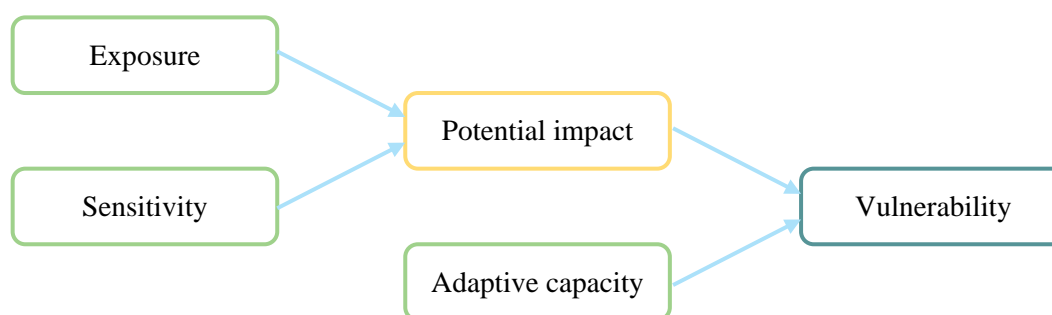
Projections of changes in climatic variables tend to focus on changes to average values but variations around averages, leading to extreme weather, also matter. The importance of considering short-run variation around long-run averages is highlighted by the impact of extreme weather events. For instance, the economic cost of Hurricane Sandy has been estimated at up to USD 50 billion (EQECAT, 2012). Extreme weather events result in costs directly associated with the event and also indirect costs, which affect the wider economy. However, while there is a mounting body of evidence on the costs of past extreme events, understanding of how the frequency and intensity of extreme events will change in the future as the climate



changes remains weak, as emphasised by the recent IPCC assessment (Intergovernmental Panel on Climate Change, 2012). In part for this reason, there has not yet been a comprehensive economic assessment of the future cost of extreme weather due to climate change. As a result, the macroeconomic impact of extreme weather is a policy concern in need of further analysis.

Adaptation can reduce vulnerability to climate change. Vulnerability to climate change is often taken to be a function of the economy's (i) exposure, (ii) sensitivity, which together determine the potential impact of climate change, and (iii) adaptive capacity, shown in Figure 3. While exposure and sensitivity are usually considered to be beyond the direct influence of climate policies, adaptive capacity is something that governments can boost investment in.

Figure 3. **The three constituents of vulnerability, exposure, sensitivity and adaptive capacity will change with economic development**



Source: (Intergovernmental Panel on Climate Change, 2001)

The benefit of adaptation may go beyond the sectors that adapt. Assessments of the costs and benefits of adaptation have predominantly been conducted at a local level. However, due to the interdependent nature of an economy, adaptation in one sector may benefit other sectors whilst vulnerabilities in a sector may put other sectors at risk; that is, adaptation could reduce systemic risk from climate change. Furthermore, there is some benefit in calculating, within a consistent framework, an aggregate estimate of the benefits of adaptation in much the same way that IAMs provide useful estimates of the benefits of mitigation. As yet, there has been only limited work carried out on the macroeconomics of adaptation, such as (Agrawala & Fankhauser, 2008) and further analysis is needed to understand the ways in which adaptation can be understood to reduce the wider economic impacts of climate change.

In summary the macroeconomics of climate change is relatively understudied and there is a need from policy makers to advance understanding both in general and in particular areas. Uncertainty is significant and should be recognised, explored and its presence valued. In addition the impact of extreme weather is unknown and therefore an area of interest and the macroeconomic benefits of adaptation require some method of estimation.

1.2 A guide to macroeconomics

Time, the representation of interactions, growth, sectors, space, cross-border spill overs and uncertainty are all major aspects of the macro-economy

1.2.1 A brief introduction to macroeconomics

Modern macroeconomics attempts to explain the behaviour of aggregate variables through the microeconomic behaviour of agents in the economy. Aggregate variables include Gross Domestic Product (GDP), investment, unemployment and so on. Consumers and producers are the main agents in an economy and governments are often, although not always, also considered.

Economic agents make choices, subject to constraints, with the purpose of achieving their objectives. The objective of consumers is to maximise utility and the objective of firms is to maximise profit. The aggregate of utility and profit is known as welfare, which is described in more detail in Box 1. Agents are free to make choices about some variables, such as consumption and employment, and are constrained by other variables, such as the quantity of factors of production available.

Factors of production are stocks of assets that can be transformed, via technology, into outputs. Land, labour and physical capital are the most basic factors of production. Human capital is often explicitly considered a factor of production and land is sometimes explicitly split into stocks of energy and other natural resources.

The price of an item describes the consumption that could be enjoyed if the resources required to produce the item were put to other means. Prices can be understood as exchange rates, they are the rates at which agents are willing to swap items. For example, a wage describes the rate at which an employee and an employer mutually agree to swap time for consumption goods.

In a model of the macro-economy variables can be either exogenous or endogenous. The value of an exogenous variable is not determined within the model but is an input to the model. Assumptions must be made about the value of exogenous variables and these values will not be affected by a shock to the model. The value of an endogenous variable is determined by choices made by agents within the model. These values will be affected by a shock to the model, which is the changing of a value of an exogenous variable in the model from some baseline level.

So the basic narrative of a macro-economy is that households choose how to allocate, according to prices, scarce factors of production across technologies, operated by firms, to provide a set of outputs that will maximise utility. This narrative can be made more complex; in particular, factors of production are stocks and the level of stocks can change over time, either endogenously, for example through investment in physical capital, or exogenously, through increasing population. In addition technologies can become more



productive, a process which is the foundation for many theories of growth. Or, in a dynamic macro-economy, the time horizon over which households maximise utility can vary; for example, there may be different generations. There may also be uncertainty about future conditions and this can influence decisions as households look to maximise utility over all periods. Producers can be differentiated by sector and actors in general can be identified by region and trade between regions can be modelled. Financial assets and unemployment are also very important in dynamic macro-economies. However, incorporating financial assets and unemployment requires modelling techniques that are significantly more sophisticated than the techniques currently employed in the macroeconomics of climate change. Furthermore, the impact of climate change on the UK financial sector is unlikely to be significant (Silver, Cox, & Garrett, 2010). Therefore, while these are important issues to be considered, they are not focused on in this report as there are more fundamental issues to be considered first.

1.2.2 Structural differences between macroeconomic modelling approaches

Macroeconomic models often focus on one area of complexity and take other areas as given. Many models aim to investigate just one facet of an economy and so make simplifying assumptions about the complex extensions described above. Often the behaviour of those parts of the economy that are not under analysis is taken as given.

Structural divisions between models focus on the treatment of time, either static or dynamic, and on the concept of equilibrium employed: general equilibrium, partial equilibrium or Keynesian. More minor, although still significant, differences between models concern the variables treated as exogenous or endogenous, the representation of growth, the level of differentiation between producers, households and regions as well as the modelling of trade and the inclusion of random processes, known as stochastic processes and agents' responses to the uncertainty these processes generate.

Time in a macroeconomic model is composed of periods and these are defined by the change in the state of a variable. Consider a savings account that receives an interest payment at the end of each month. The savings account has twelve periods in a year as the value of the account changes twelve times; days have no representation.

A static model does not have any variables that change state over time. If the values of variables in a static model do change, for example due to a policy shock, then it is as if we are viewing an alternative reality rather than viewing the same reality at a different time; such comparison is called 'comparative statics' and it is the mode of analysis of static Computable General Equilibrium (CGE) models.

A dynamic model has variables that vary exogenously or endogenously over time. In some dynamic models variables change state exogenously. For example, in some Integrated Assessment Models (IAMs), GDP per capita and GHG emissions change exogenously. In other dynamic models agents make choices in the current period that influence the state of variables in the future. When agents make choices that affect the future they must have some expectation about what the future will be like as they are trying to maximise their objective over all time periods. Expectations can take a number of different forms, such as adaptive



expectations, where the future is expected to look, in some way, like the past, or rational expectations, where agents make choices on the basis of their beliefs about the future.

In a general equilibrium all markets must clear. This means that consumption equals the production of consumption goods and savings equals investments and so on. Prices adjust so that agents maximise their objectives and markets clear. As agents have the same objective in every time period an ideal economy will be the same in every period. So a dynamic model in a general equilibrium will be in a steady-state across time periods. If a dynamic economy is not in a steady-state, for example due to initial conditions below the optimum or shocks, then it will move along an equilibrium path, which is a sequence of choices leading to a steady-state. The conditions to which a static general equilibrium model is calibrated are assumed to be the steady-state values of the economy that the model is representing.

In partial equilibrium a sub-set of the economy is considered independently from the rest of the economy. A central idea embodied in the concept of a general equilibrium is that all markets are linked and so if prices change in one market then all markets will be affected. A partial equilibrium model assumes that the market of analysis is independent of all other markets and seeks equilibrium only in the market of analysis. Such an approach is justified if there is a negligible effect in other markets due to a shock in the market of analysis. A partial equilibrium approach is often far more tractable than a general equilibrium analysis.

In a Keynesian macro-economy prices do not adjust instantaneously. It is not the purpose of this report to go into the fine distinctions between schools of macroeconomic thought, but, broadly-speaking, in a general equilibrium prices adjust instantaneously in response to changes in the ‘real’ value of a variable, for example the relative value of labour will fall if the labour supply increases; while in a Keynesian economy prices can lag changes in ‘real’ variables, so the wage may not decline when the relative value of labour does.

Real variables are items that generate utility or profit and they can have a real value and a nominal value. Real variables are items such as labour or consumption goods. They can be valued in ‘real terms’, which means they are valued relative to each other. Real values can be contrasted with ‘nominal’ prices, which is the quantity of money a real variable is worth. In a Keynesian macro-economy nominal prices can remain rigid for some periods after a change in real values. As agents make decisions on the basis of nominal prices a Keynesian economy need not be in equilibrium, although nominal and real values should converge over time. Keynesian policy makers view macroeconomic aggregates as important in themselves, rather than just a function of microeconomic decisions, as these aggregates can influence nominal price levels, which in turn affect microeconomic decisions.

1.2.3 Other differences between macroeconomic modelling approaches

Temporal and equilibrium assumptions result in structurally different models while issues of growth, detailed representations of production, trade and uncertainty, though not trivial, can be seen as extensions to standard modelling approaches. Incorporating these issues does lead to distinct classes of



models, such as endogenous growth models, CGE models, open-economy models and stochastic models respectively, but classes of models share common structural assumptions.

Growth in an economy can be generated by increases in factors of production or increases in productivity, so that more output is made from the same inputs. Agents must make a trade-off between consumption in the present and investing for greater consumption in the future. Increasing stocks of factors of production can increase the output of an economy. Alternatively factors can be made more productive. This latter process is represented by factor-augmenting technologies. As these technologies improve a greater output is achieved for a given input.

Factor stocks will only be accumulated up to a point if production is assumed to exhibit diminishing returns, and this limits growth. Diminishing returns mean that the percentage increase in output is less than the percentage increase in input. If the economy is subject to diminishing returns as a whole, which is known as decreasing returns to scale, then eventually it will no longer be worth increasing stocks of factors and so the economy will enter a steady-state. If the stock of factors, or the productivity of factors, is assumed to grow exogenously then the economy will not achieve a steady-state, where the values of endogenous variables are constant, but will instead achieve a balanced growth path, where the growth rates of the values of endogenous variables are constant. However the empirical facts of growth do not necessarily support the assumption of decreasing returns to scale nor do they support the assumption that agents in the economy cannot influence the growth rate beyond simple factor accumulation through endogenous savings.

Endogenous growth theory assumes that agents can influence the growth rate via investments in factor-augmenting technology. A number of mechanisms through which agents can improve productivity have been suggested in the literature, for example from knowledge spill-overs, research and development or improvements in human capital. Regardless of the mechanism, agents in an endogenous growth model maximise their objective as usual, but savings are channelled towards both accumulating factor stocks and increasing their productivity. Returns to scale are still important in endogenous growth models. For example an endogenous growth model with decreasing returns to scale would find a balanced growth path and so outcomes could be replicated by an appropriately calibrated exogenous growth model.

An economy that exhibits increasing returns to scale is only compatible with an endogenously determined growth rate. Decreasing returns to scale mean that at some point it is no longer worth increasing factor stocks and so the economy achieves a steady-state. However in an economy with increasing returns there is always a gain from investing and, as economies evidently do not put all their income into investment, there must be a choice being made to not invest more. Hence endogenous growth models go hand-in-hand with theories of increasing returns to scale. Indeed the mechanism by which agents choose the growth rate is identified as the way in which an economy can move from decreasing to increasing returns to scale.

A detailed representation of production in an economy does not fundamentally change a model but quantitative results will be more subtle due to a greater number of interactions. There are a large number of final consumption goods and these are the product of a long supply-chain of intermediary production. Such complexity is only embraced in a macroeconomic model if the impact of shocks on specific



sectors is of specific interest, for example CGE models are used to assess the distribution of impacts on firms of changes in taxation policy. The interdependency of firms in a supply-chain is often modelled through nested production functions. This means that the production of cheese, for example, is a function of cheese-specific technology, labour and milk, where milk is a function of milk-specific technology, labour and cows. So shocks to a specific sector affect other sectors in the supply-chain. Such shocks also affect all other products because they change the relative prices of final consumption goods and so cause consumers to change their demands. Models with a detailed representation of production do not use a different modelling technique, they are merely more fine-grained.

Spatial differences are represented in a similar way to time periods. Geography does not tend to be a defining characteristic in the macro-economic treatment of space, where space should be understood as a dimension in which objects have a location. Instead areas are grouped into regions on the basis of stocks of factors of production or the productivity of technology or to conveniently match definitions in data used for calibration. Some multi-regional models do not consider interactions between regions, in the same way that some models do not consider dynamic effects. Other multi-regional models do consider links between regions and have to make assumptions about trade. Despite the similarity in the representation of space and time, there is a difference in how private agents in the economy respond to time and space. Agents are directly concerned about their utility over time but they are not directly concerned about the utility of other agents in the same, or in another, region; so private agents maximise their objectives over time but not over space.

Multi-regional models often make assumptions about the elasticity of substitution between imported and domestic goods. The basket of goods consumed by households will contain some domestically produced goods and some imported goods. Empirical evidence suggests that demand for an imported substitute often has a smaller response to a given price change than a domestic equivalent. This is incorporated into multi-regional models with trade via an ‘Armington’ elasticity for each product. This elasticity drives the changes in trade due to shocks in such models.

Multi-regional models must also consider the mobility of factors of production. Consider that savings can be invested in some, but not all, countries other than the country where the savings were originally made. This ability to invest internationally is described as the mobility of capital. Labour is also mobile to some degree but land is not, although natural resources from the land can be traded. The representation of, and degree of, mobility of factors of production can have a significant influence on responses to shocks. For instance if a country suffers a sudden decrease in physical capital, say due to a storm, then, if reconstruction can be financed by foreign investment, the affected country will not have to save so much to replace the capital stock. This means that the welfare impact in the country will be lower as less consumption will have to be forgone.

Uncertainty must be considered from two perspectives: the uncertainty of assumptions made by the macroeconomic analyst and the response to uncertainty of agents in the model. An analyst must make choices about the structure of the model, as well as values to assign to initial conditions and exogenous variables. The structure of the model does not tend to be subject to uncertainty analysis, but analysts do tend to explore uncertainty about initial conditions and other exogenous variable values through scenarios,



sensitivity analysis or Monte Carlo methods. In the same way that an analyst wants to consider the range of possible outcomes, it can be desirable to understand how agents in the model respond to uncertainty. Dynamic Stochastic General Equilibrium (DSGE) models provide the framework for such analysis. In DSGE models agents believe that the future is described by a pre-determined probability distribution and make choices according to the set of possible futures and their preferences over risk.

1.2.4 A summary of the key issues in macroeconomic models

The basic concepts in modern macroeconomics are:

- agents want to maximise their objectives given their available resources; the aggregate quantity resulting from maximised objectives is known as welfare, which is explain in more detail in Box 1;
- factors of production are stocks of assets that can be transformed, via technology, into outputs that are used to satisfy objectives;
 - so the level of factor stocks and their rate of change, productivity and its rate of change, and the nature and time-horizon of agents' objectives greatly influence macroeconomic outcomes.
- variables can be either exogenous or endogenous:
 - the value of an exogenous variable is not determined within the model but is an input to the model;
 - the value of an endogenous variable is determined by choices made by agents within the model.
- a shock to a model is just the changing of a value of an exogenous variable in the model from some baseline level.

There are seven major aspects of a macro-economy that expand the scope of models beyond the basic macroeconomic concepts:

- **time:** models can be either static or dynamic and variables in dynamic models can vary exogenously or endogenously over time; the trade-off between consumption and saving is very influential in dynamic models;
- **representation of interactions:** economies can either move to an equilibrium influenced solely by micro-decisions or there can be nominal rigidities which also influence the economy and prevent it from achieving a general equilibrium;
- **growth:** growth can be generated by increases in factor stocks and productivity. Endogenous growth models allow households to choose the growth rate while exogenous growth models have a fixed rate of growth and the economy moves along a balanced growth path;
- **sectors:** production supply-chains can be represented and shocks to any part of the supply-chain affect other connected sectors. This will change the relative price of final goods in any connected supply-chain and this will change the composition of consumer demand, which will affect all sectors of the economy;
- **space:** regions do not have an explicit geographical representation but are abstractly represented, in a similar way to time periods;
- **trade and international financial flows:** domestically produced and imported goods are not perfect substitutes and the degree to which a region chooses imports over domestic products is determined by an Armington elasticity; the representation of, and degree of, mobility of factors of production is very important in determining the response of a region to a shock;
- **uncertainty:** uncertainty must be considered from two perspectives: uncertainty about the structure of the model and its parameterisation, and the response of agents in the model to uncertainty.



Box 1. Measuring the state of the economy: welfare, GDP and well-being

Welfare is an economist's core measure of the success of an economy and encompasses market and non-market sources of value. Welfare is the aggregate of the utility obtained by households in the economy, which derives from consumer surplus and profit. Utility is an abstract unit of account that describes the strength of preferences a household has over a set of items. Households can be represented as having preferences over non-market items such as culture and so if there is an impact to a non-market item then the welfare of households will change.

The challenge of including non-market impacts into macroeconomic models is that the strength of preference of households for non-market items must be estimated. Such estimation is difficult as there is no market to provide data. However methods do exist and have been employed in major sector-specific studies, such as (TEEB, 2010) and the inclusion of non-market services in CGE models is common. For the purposes of this report it is enough to note that methods exist to provide data for non-market items and that non-market impacts can be incorporated into macroeconomic models if necessary.

Welfare and GDP are not the same. GDP is the output of an economy, some of which is investment and some of which is for consumption. Welfare is generated by the consumption of outputs and non-market items. A change in GDP does not necessarily lead to the same change in welfare. For instance if investment increases to repair the damage of an extreme weather event then GDP will increase, as investment contributes to GDP, but welfare will fall because households are forgoing consumption they would enjoy in favour of investment and they may also have lost some non-market items that they had previously enjoyed.

Welfare can be expressed as GDP-equivalent. Welfare is an abstract modelling concept and so cannot be observed in reality. It is therefore problematic to express welfare impacts in a meaningful way. However, since within a model the exchange rate of welfare and real values can be observed, welfare impacts can be normalised to money units and expressed as a percentage of GDP. This is known as a GDP-equivalent impact. Models of the impact of climate change often use the concept of GDP-equivalent, so when results are reported as, for instance, a percentage of GDP, this does not necessarily imply that non-market impacts are not considered.

Welfare is not the same as 'well-being'. Welfare is a utilitarian concept and the human concept of value is arguably far richer than that. Well-being is an umbrella-term for the results of attempts to enrich the economic concept of value. However, departing from the utilitarian framework entails leaving aside many of the tools of macroeconomics and so to make such a departure is beyond the scope of this report. Furthermore, as explained above, welfare is a broad concept that should suffice in most cases. However that is not to say that well-being should be ignored in the context of climate change. Indeed, it has been argued that the impacts of climate change may be underestimated precisely because climate change can affect many dimensions of well-being and this has a greater effect in the whole than the summation of welfare losses (Vivid Economics, 2011).



While welfare is the ultimate measure of a macro-economy other metrics can be considered.

Other metrics can be considered either as policy goals in themselves, although this may be incompatible with standard welfare economics, or other metrics may provide early-warning signals of the effects of climate change on welfare. For example, changes in the savings rate or the terms of trade can be measured and indicate that levels of welfare are changing.



1.3 A framework for the macroeconomics of climate change

Climate change interacts with the macro-economy along nine key dimensions

1.3.1 The interaction of climate change and the macro-economy

Climate change has an impact on the macro-economy in two basic ways:

- by affecting factor stocks and productivity and the growth rates of both;
 - for example floods may damage infrastructure or labour productivity may decline due to increased temperature.
- by affecting the way in which agents maximise their objectives;
 - for example demand for healthcare or air-conditioning may increase, as may uncertainty over future states of the world which affects how households plan, or climate change may affect non-market items that households value such as biodiversity.

The dimensions through which climate change has an impact on the macro-economy can be considered along similar, but not identical, lines to the major aspects of the macroeconomic theory summarised in Section 1.2.4. The dimensions along which climate change can have an impact on the macro-economy are explained in more detail in Sections 1.3.2–1.3.10. They are summarised in Table 2, along with a checklist of questions against which current studies are assessed and which future studies could aim to cover. These checklist questions provide the basis for the assessment of the strengths and weaknesses of studies reviewed in Section 2.

1.3.2 Direct climate impacts

The impact of climate change on the economy varies by sector and a small subset of sectors is directly sensitive to the climate. The following are typically the focus in economic studies: agriculture, forestry, energy, water, economic activities in coastal zones, healthcare and tourism.

The non-market impacts of climate change are important although measuring the value of non-market sectors can be difficult. A non-market item is an item that is not traded in an economy but still has value to some agents in the economy. Biodiversity and cultural items are examples of non-market items and the change in health outcomes, mortality and morbidity, is a non-market impact often considered in the context of climate change. In a model non-market items can be represented, via a measure of welfare, as having value in the same way as a market item. Market and non-market value can be aggregated into GDP-equivalent. The concept of welfare is explained in more detail in Box 1. As described in Box 1 the difficulty in representing non-market sectors lies in determining the value to assign to the sector but techniques do exist.



Table 2. **Climate change can have a macroeconomic impact along nine dimensions and this provides a checklist of questions against which current and future studies could be assessed**

| Dimensions | Question to consider when assessing studies |
|---|--|
| Direct climate impacts | Which direct climate impacts are covered and which are omitted? What is the quality of impact estimates? |
| Representation of cross-sectoral interactions | Are indirect, higher-order macroeconomic effects covered, and how? |
| Time | What is the temporal scale of the study? |
| Growth | Does the study model the effect of direct climate impacts on long-run growth prospects via investment? |
| Space | Can the study be used to produce spatially resolved, even UK-specific, estimates of impact and how? |
| Cross-border spill overs | Are the impacts on the UK of climate change outside the UK accounted for, including through trade, financial flows and migration? |
| Uncertainty | Is uncertainty about changes in long-run climate averages accounted for and how complete is the assessment, for example are tipping elements included? |
| Extreme weather | Are the impacts of extreme weather accounted for? |
| Vulnerability and adaptation | Does the study model changing vulnerability and does it explicitly account for adaptation? |

Source: Vivid Economics

Most research into climate impacts focuses on one or a small number of sectors in isolation. Relatively few studies aggregate over many sectors and these are almost entirely economic analyses since money provides a convenient numéraire. Studies across multiple sectors still rely on more detailed, sector-specific work for calibration and the sectoral coverage of such studies varies. A review of key bottom-up, sector-specific studies that calculate the direct impacts of climate change is presented in Section 2.1.

1.3.3 Representation of sectoral interactions

Macroeconomic analysis is concerned with the wider impact of a direct shock and so the representation of interactions between sectors is important for capturing indirect and higher-order effects. The set of indirect, higher-order effects is diverse. Examples include:

- direct impacts to agriculture can change the terms of trade for economies where agriculture generates a large proportion of income;



- changes in heating and cooling requirements can change the price of energy, which affects all sectors that use energy as an input;
- direct health impacts can affect labour productivity, which directly affects income and the productivity of all other sectors.

A multi-sector economic model is required to analyse indirect and higher-order effects. The most common multi-sector models are Computable General Equilibrium (CGE) models and these are reviewed extensively in Section 2.4. However, there is no reason in principle why a non-equilibrium macroeconomic model could not be used for this purpose, although, to our knowledge, no such model with sectoral disaggregation has been used to consider the impacts of climate change.

The key issue when considering sectoral interactions is the magnitude and direction of indirect effects relative to direct effects. Indirect effects could oppose, and indeed reverse, direct effects for some regions and sectors. So if there was a negative direct effect then the indirect effect would be positive and the net change would also be positive. Addressing this issue is important as it indicates how misleading a narrow, but more tractable, focus on direct effect is.

1.3.4 Time

Climate change is a dynamic process and so static models will not capture all the effects. Therefore the temporal scale of a study is an important issue since GHG emissions today have impacts spanning several centuries. It should also be noted that the way in which some models estimate the economic impact of climate change appears dynamic, in the sense that in each time period there is an estimate of what costs or benefits the economy faces due to climate change, but the representation is actually static as the impacts in each time period are isolated and have no knock-on effects. This isolation of temporal effects means that the impacts of climate change on economic growth are not captured. This is considered as an issue in its own right in Section 1.3.5.

The length of time steps is relevant from a policy perspective. The longest policy timeframes are a small number of decades, for example a 2050 target, and most policy timeframes are much shorter. So studies that have multi-decadal time steps will be less able to inform current policy debates.

1.3.5 Growth

Climate change may affect the growth rate of an economy by changing either output today or returns that may be earned in the future. If output today falls, for example if productivity falls or there is a negative shock to a factor of production, then this will slow the pace at which capital can be accumulated as the economy has a lower amount of output overall and so absolute investment will be lower. This is known as the capital accumulation effect. Climate change may also reduce the savings rate by reducing the return on investments, for example by reducing productivity. This is known as the savings effect. When less investment occurs the economy cannot increase output by as much in the next period and so growth is lower.



In an endogenous growth model, lower investment will also reduce improvements in productivity and so growth will also be lower.

As the effect of a change in the growth rate is compounded over time the welfare loss from a change in the growth rate can be greater than the direct impacts. Models that do not consider the effect of impacts in the current period on future capital accumulation will underestimate the cost of climate change in the long-run.

Fankhauser & Tol (2005) explore the impact of climate change on the growth rate according to a variety of models. The authors modify the DICE model so that it resembles four different growth models and then simulate the impacts of climate change to see how the magnitude of total costs varies according to the representation of growth described by each of the four models. The results are shown in Figure 4. The four growth models considered, and their key assumptions in (Fankhauser & Tol, 2005) are:

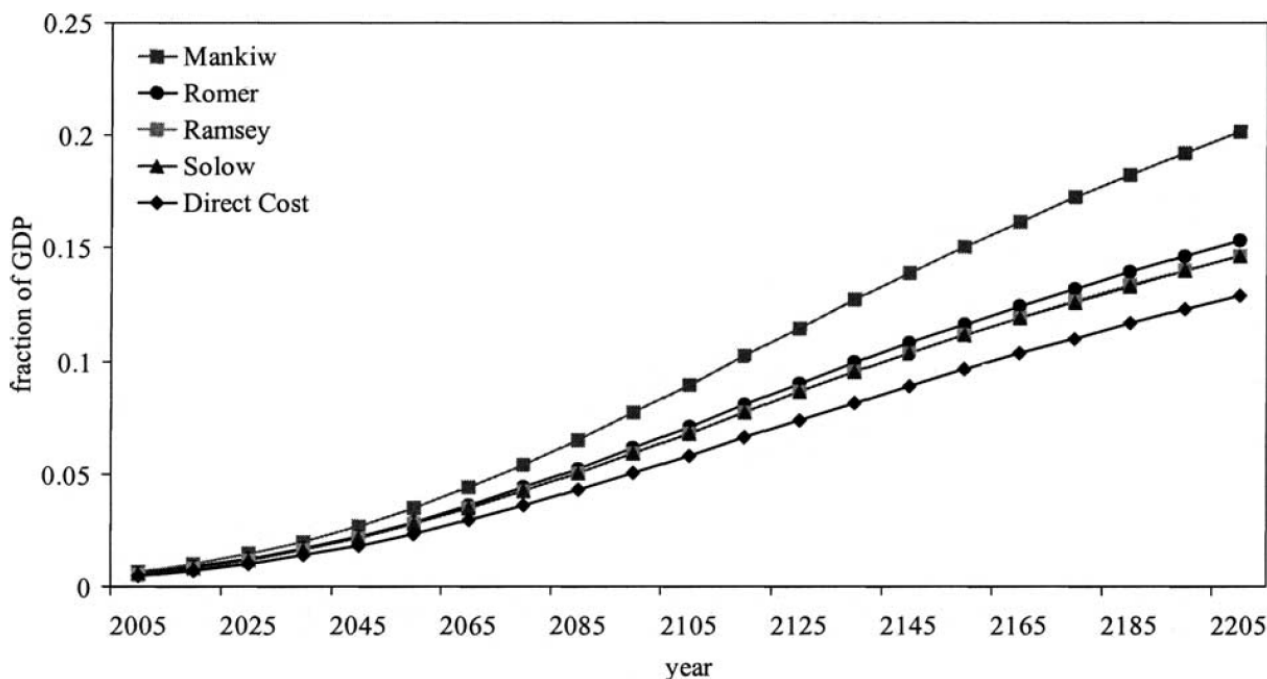
- **Solow model:** the savings rate and the productivity growth rate are exogenous;
- **Ramsey model:** the savings rate is endogenous while the productivity growth rate is exogenous, this is the normal specification of DICE;
- **Romer model:** the savings rate is exogenous while the productivity growth rate is endogenous and is a function of the output of an R&D sector in the economy;
- **Mankiw model:** the savings rate is exogenous as is the productivity growth rate but investment can be used to increase human capital, which augments production.

Fankhauser & Tol (2005) find that the capital accumulation effect is greater than the savings effect. So the authors find that lower investment due to lower income is more important than lower investment due to a decline in the return to investment. This can be seen by the difference in outcomes between the Solow and the Ramsey model in Figure 4. In endogenous growth models, where lower investment also reduces the productivity growth rate, the impacts of climate change are greater and are most significant in the Mankiw model.

Only some studies of the impacts of climate change will partly capture these effects. Fankhauser & Tol (2005) explore the impacts of climate change using stylised models and a specific level of climate impact to illustrate the relative importance of models of growth on estimates of climate impact. Only some macroeconomic models used in more realistic assessments of the impacts of climate change have explicit savings and investment decisions. These are DICE/RICE, ICES and ENVISAGE. None of these models are endogenous growth models.



Figure 4. Fankhauser & Tol (2005) is the only study, to our knowledge, that explores the impact of climate change on the rate of change in productivity growth



Note: Models are run assuming that a global mean temperature increase of 3°C causes 5 per cent GDP damage. 'Mankiw' and 'Romer' are endogenous growth models.

Source: (Fankhauser & Tol, 2005)

Over the past few years much attention has focused on the concept of 'green growth'. Green growth has a range of interpretations, from weak to strong. Green growth is economic growth which also achieves significant environmental protection, where significant protection is least controversially understood to be at least a greater level of protection than is delivered by business as usual patterns of growth (Jacobs, 2012). The weak version of green growth argues that benefits of significant environmental protection outweigh the costs and so economic growth will be higher compared to business as usual as net damages will be lower. The strong version of green growth makes the case that environmental protection not only protects the economy but stimulates it as well. There are at least three types of strong green growth according to Jacobs (2012):

- a Keynesian argument that government stimulus in a recession will increase growth and that an environmental stimulus will boost growth the most;
- a growth theory explanation where environmental policy corrects market failures, particularly the mispricing of natural capital;
- a comparative advantage and technological revolution narrative in which greater environmental protection generates new industries and gives first-mover economies a comparative advantage. In its strongest version environmental protection drives the next industrial revolution.



1.3.6 Space

The impacts of climate change differ by region and so studies that do not consider a spatial dimension may not be adequately describing the impact of climate change. Most macroeconomic studies of climate change are globally aggregated or else they are disaggregated to large world regions, such as Europe. Few models with a global or regional outlook disaggregate to the level of the UK, although from a policy perspective this would be highly desirable.

Drawing implications from global or regional models for the UK requires some form of downscaling. Regional disaggregation tends to be limited by the granularity of information on region-specific climate change impacts; therefore any downscaling risks giving the impression of artificial accuracy as no more is known about a downscaled impact than is known about the regional impact. That said, rigorous techniques for downscaling physical changes in climate have been developed and these may be transferable to the downscaling of economic impacts.

1.3.7 Cross-border spill overs

The impacts of climate change on the UK economy may come from outside the UK as much as inside. These effects are principally in the form of effects on trade flows, the terms of trade and national account balances, and also the effects on migration, political stability and global governance. The European Commission has recently started funding for a major collaborative study of what they term the ‘spill over impacts’ of climate change on the EU and the UK Foresight programme considered the international dimensions of climate change in 2011 (Foresight, 2011).

Effects on trade flows can be simulated using a multi-country macroeconomic model. However, for the analysis to be sensible it would need to be disaggregated to quite a high resolution in terms of commodities traded. Only some models, such as the World Bank’s ENVISAGE model, are currently capable of this. An important component of trade flows is the international mobility of factors of production as this affects the degree to which factor prices in a country will change in response to a climate shock.

Some sectors, but not all, are sensitive to both climate change and trade. For example agricultural commodities are widely traded and so such trade will be sensitive to climate impacts but health impacts will not directly influence trade. The relationship of some sectors to trade may be quite subtle but also quite important, for instance water is effectively traded via the trade in products that are produced using water and so impacts to water supply may affect trade.

Modelling the effect of climate change on areas other than trade is a significant challenge. Issues, such as migration, require an entirely different modelling approach to macroeconomic analysis, while political issues are not suitable subjects for quantitative modelling. There is, at present, little if any detailed literature in these areas.



1.3.8 Uncertainty

A full picture of the macroeconomic impact of climate change must account for uncertainty about both climate and economy. Both climate and economic forecasts are notoriously uncertain. The inter-linkages between the two are also uncertain. Therefore the outcomes of a model require uncertainty analysis and policy makers should also consider how different modelling approaches influence results. Probabilistic studies on the economics of climate change show that overall results greatly depend on low-probability, high-impact outcomes and so the specification of the tails of probability distributions matters.

Exploration of uncertainty is often insufficient. Most studies ignore uncertainty and just run the model once with best guesses for the values of all the model's parameters. While this is difficult to justify when making recommendations on policy, most of the studies in the macroeconomics of climate change aim to contribute to the academic literature in other ways and therefore uncertainty analysis is not a central priority. However, all the models considered are capable of incorporating uncertainty, although the most complex models can only do so simplistically through, for example, sensitivity analysis or scenarios.

Studies that do account for uncertainty do so in three ways. These ways are:

- **sensitivity analysis on parameter values:** this is usually based on an a priori assumption about what parameters are most important, or else on what parameters are of interest. Only very recently have methods of global sensitivity analysis been applied, for example (Anderson, Borgonovo, Galeotti, & Roson, 2012);
- **scenario analysis:** a set of scenarios describe a set of possible narratives that are considered plausible. Uncertainty about GHG emissions is often handled in this way;
- **Monte Carlo simulation:** this yields probabilistic estimates of economic impact. In this method key parameters are described by probability distributions which must be pre-specified. Parameter choice is again a priori.

Uncertainty also affects how people make decisions and this can be incorporated into a model, although it has not been included in climate change studies so far. Issues of uncertainty discussed so far concern the uncertainty of a policy-maker. Agents within a model economy also face uncertainty and this affects decisions. For example an agent who is risk-averse will invest less in agriculture if there is uncertainty over future productivity than if there were no uncertainty. So far, to our knowledge, no operational model has incorporated uncertainty induced by climate change into agent's expectations.

1.3.9 Extreme weather

Extreme weather events can be significant disasters with complex impacts that often appear large in the short-term but insignificant in the long-term. Extreme weather can cause acute distress and damage to a locality but often the scale of such disasters relative to the economy is small. From a macroeconomic perspective concerns should therefore be focused on the costs in the short-run, during which the economy returns to its long-run equilibrium, and any changes induced by the disaster in the long-run equilibrium. Economic analysis of both short-run and long-run phenomena within a coherent model is very challenging. The welfare outcomes of recovery and the extent to which these may be different to GDP outcomes are also



relevant. From an adaptation perspective it is important to identify the characteristics of an economy that make it more or less vulnerable to extreme weather events. These issues are considered in the literature review in Section 2.5 but the framework for understanding the impacts of extreme weather events is described in this section.

Disasters can cause a variety of types of losses. All of these types of losses are relevant from a macroeconomic perspective:

- **direct losses:** these are losses caused by the immediate impact of the disaster;
 - direct market losses: loss of output, such as agriculture in a drought, and loss of assets;
 - direct non-market losses: loss of life and damage to natural and cultural assets.
- **indirect losses:** these are not caused by the disaster itself but by secondary effects, they are also losses incurred after the time period of the disaster;
 - indirect market losses: loss of output over time due to business disruptions and loss of capital;
 - indirect non-market losses: losses due to ill-health and discomfort and losses of ecosystem and cultural services.

There can also be indirect gains as well as losses. For indirect effects to be fully understood, price changes, output in unaffected sectors and any productivity effect must be considered:

- **price changes:** large natural disasters may change the prices of some goods and services, meaning that it is inappropriate to simply multiply the quantity of lost output by pre-disaster prices;
 - costs can increase if prices rise in sectors that have suffered damage, for example the price of housing may go up so the welfare cost of lost housing services also goes up;
 - price changes can also incentivise reconstruction which dampens costs, for example higher construction wages attract more construction workers and this increases the pace of reconstruction.
- **output in unaffected sectors:** output from capital that was not directly affected by the disaster can:
 - decrease if it depends on goods and services supplied by damaged sectors. The effect on transportation and utilities is often important here;
 - increase if it can compensate for lost output elsewhere, or contribute to reconstruction. This depends on substitution patterns and whether there is spare capacity in the economy.
- **productivity effect:** since natural disasters destroy capital, there can be a productivity effect:
 - it has been argued that, by replacing old, damaged capital with new capital, productivity is increased. This, coupled with the reconstruction stimulus, may explain why some studies have suggested that disasters boost growth in the medium/long term, assuming these studies have robust statistics;
 - however, the notion of a positive productivity effect rests on quite strong assumptions about it being economic to replace old capital with new capital. Hallegate & Przulski (2010) provide a summary of this discussion.

There are significant difficulties in estimating the costs of disasters. Non-market costs and indirect costs evolve over time and are hard to separate from normal economic changes. In addition the replacement value of lost market assets may not equal the market value if the economy is in disequilibrium, which may be the case after a large disaster. Price changes due to a disaster will also influence estimates of replacement costs. Also, some lost market assets, such as infrastructure, may provide public benefits which are not captured in replacement cost estimates. Furthermore, disasters may lead to bankruptcy for firms due to illiquidity rather



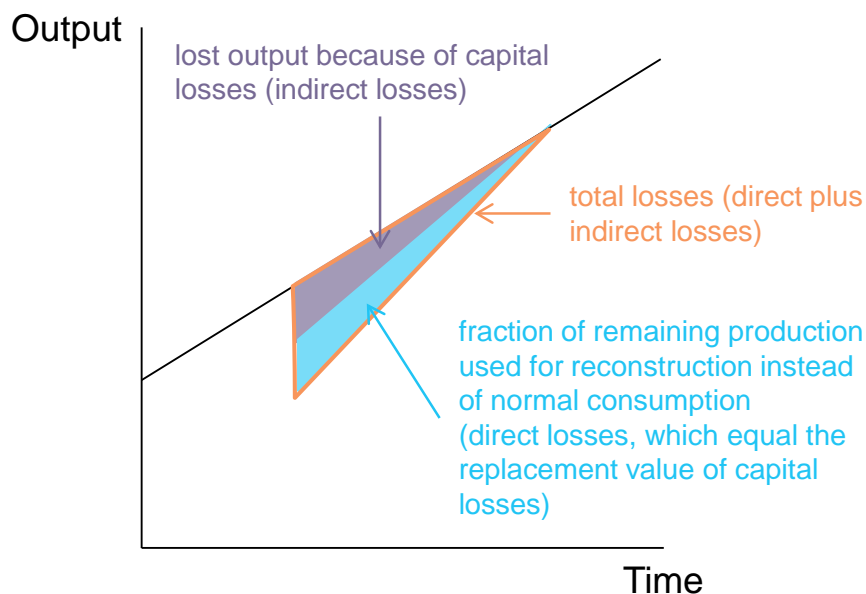
than insolvency and this means that output will decrease to a greater extent than the asset level of the economy would imply.

The welfare outcome of a disaster and subsequent recovery can be different from the GDP outcome.

The main components of GDP are consumption and investment while the main driver of welfare is consumption. A natural disaster diverts output from consumption to investment. It also reduces the level of output in the economy by destroying capital and by reducing productivity, although this may be balanced by an increase in the productivity of unaffected capital. Therefore, as consumption falls more than GDP, the welfare impacts of a disaster will be greater than the GDP impacts.

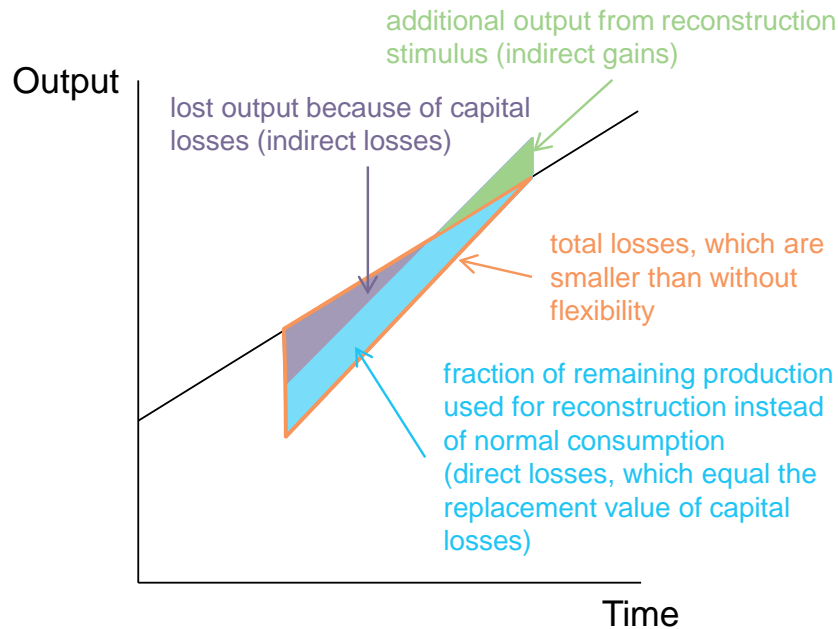
The extent to which GDP can increase as a result of a disaster depends on flexibility of production in the economy. If production levels are not flexible then investment in replacement capital will crowd out normal consumption, as shown in Figure 5, and so GDP will not increase. However, GDP can increase if production levels are flexible and so output from unaffected capital can increase to compensate for the loss of output from destroyed capital, as illustrated in Figure 6.

Figure 5. When production levels are not flexible reconstruction crowds out other economic activity, which leads to greater total losses than if production levels were flexible, as shown in Figure 6



Source: (Hallegate & Przulski, 2010)

Figure 6. If production levels have some flexibility then unaffected capital can increase its own production to compensate for output lost due to destroyed capital and so while there is still some crowding out there is also a stimulus effect



Source: (Hallegate & Przulski, 2010)

1.3.10 Vulnerability and adaptation

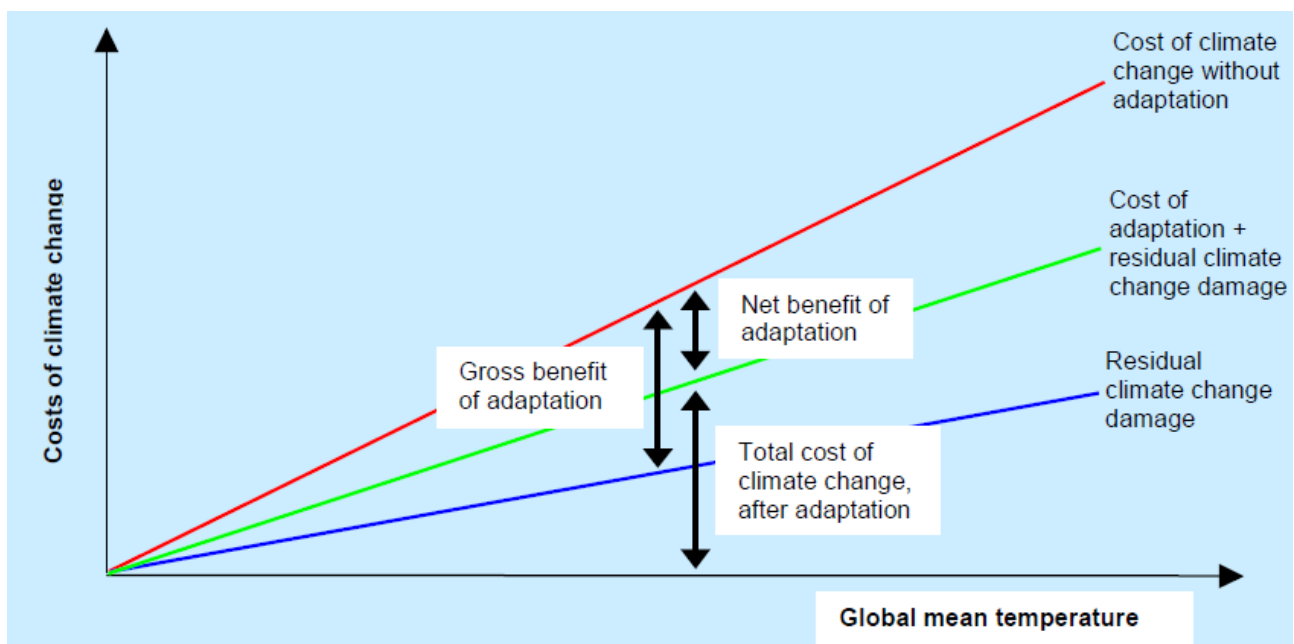
The role of adaptation is to reduce the vulnerability of an economy to the climate. From an economic perspective, adaptation should be undertaken up to the point where net benefits are zero. Studies show economically optimal adaptation is positive, but it does not pay to adapt all the way up to the point where all economic activities are ‘climate proofed’. The way that adaptation interacts with the costs of climate change is illustrated in Figure 7.

Not all adaptation requires policy intervention. Unlike mitigation, it will at times be in the private interest of agents to adapt to climate change. This is because adaptation does not face as significant an externality as mitigation. However, there is an open question as to the level of private adaptation that will occur and whether this level is socially desirable. Much work has been done on the barriers to effective climate change adaptation, for example (Cimato & Mullan, 2010; Frontier Economics, Irbaris, & Ecofys, 2013), which include:

- **market failures:** conditions that prevent markets from achieving the most efficient allocation of resources. Examples include the ‘public good’ characteristics of information on climate change impacts, and infrastructure that provides resilience such as flood protection walls;

- **regulatory barriers:** regulations that inhibit effective adaptation. For example, a lack of integration of building and planning regulation could lead to gaps in the regulatory framework;
- **governance and institutional barriers:** governance arrangements that impede coordination between government authorities, reduce accountability or lead to authorities being allocated responsibilities for which they do not have sufficient capacity to carry out effectively;
- **behavioural barriers:** ways people process information and make decisions, which could act as a barrier to effective adaptation. For example, individuals may be unable to respond optimally to risk and/or evidence or they may have high discount rates;
- **adaptive capacity:** the ability of groups of people to respond to climate change may be limited due to financial or other constraints;
- **natural capacity:** the environment may not have the ability to adapt to climate change if the pace of change is greater than natural adaptive capacity.

Figure 7. Adaptation reduces gross damages, leaving residual damages, but adds to the costs of adaptation



Source: (Stern, 2007)

A distinction can be made between ‘flow’ and ‘stock’ adaptation.

- **flow adaptation:** this is defined as providing costs and benefits in the short-run and so is limited to changes in variable inputs such as switching between available crop varieties;
- **stock adaptation:** in the long-run it is possible to also make investments that provide a stream of adaptation benefits, for example sea walls protect coasts from sea level rise for a number of years.

The great uncertainty in climate prediction is a challenge for adaptation, particularly stock adaptation. There is little macroeconomic work on this as yet, but in recent years much thought has been put into adaptation planning more broadly. It has been found that at times there is a tension between:

- a concern for robustness, usually operationalised as the need for an investment to perform well in all future scenarios and contingencies;
- a concern for flexibility and maintaining option value, for instance not committing irreversibly to investment when the pay-offs are unclear.

Whether or not this tension between robustness and flexibility exists depends on the characteristics of the problem. For the Thames Barrier, for example, it has been shown that flexibility should be built in (Environment Agency, 2012). However this will not be the case for all investments and so uncertainty about the performance of stock adaptations should be analysed using standard methods of project appraisal under risk, which vary along a spectrum of technical sophistication from sensitivity analysis through Monte Carlo simulation to real-options analysis.

Adaptive capacity is just one of the determinants of vulnerability, alongside exposure and sensitivity, and these tend to vary according to economic development. As illustrated in Figure 3, vulnerability to climate change can be thought of as depending on exposure and sensitivity, which together determine the potential gross damage, and adaptive capacity, which can reduce gross damages to residual damages plus adaptation costs. These potential net costs are the measure of an economy's vulnerability. All of these are linked to general economic development. For very poor countries, it is fairly clear that development reduces vulnerability at least by reducing sensitivity and increasing adaptive capacity. This is known as the 'Schelling hypothesis'. However, in industrialised economies like the UK, the relationship is unclear (Anthoff & Tol, 2012a).

Vulnerability will change over time and models should incorporate this. The economy that faces future impacts of climate change will be different from the current economy. Exposure of assets will change, for instance more economic activity may be concentrated on coasts or flood plains. Sensitivity will also change as, for example, a greater percentage of GDP may come from service sectors not directly affected by climate change. Adaptive capacity will change; it tends to increase with GDP. Overall, then, vulnerability will change and as it is vulnerability that ultimately determines the cost of climate change to an economy, if studies do not consider how vulnerability changes over time then the true costs may not be correctly estimated.



2 Literature Review

Five modelling techniques are reviewed against the nine checklist criteria of the framework

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Introduction

This section introduces each of the five modelling techniques reviewed in this report and describes the key findings from the literature review, organised by the nine checklist criteria developed in Section 1.3. This section organises current knowledge while Section 3.1 assesses it.

Readers who do not require a review of the modelling techniques against each of the nine dimensions but are interested in an overall assessment of the fitness of modelling techniques may wish to go directly to Section 3, in particular Section 3.1.

A set of annexes provide more detail on some of the modelling techniques reviewed:

- Annex 1 provides more detail on Integrated Assessment Models;
- Annex 2 provides more detail on multi-sector models;
- Annex 3 provides more detail on extreme weather event studies.



2.1 Bottom-up, sector-specific studies

The integration of these studies with macroeconomic models is the key issue of interest but the nature of the studies themselves is important to understand

2.1.1 Introduction to bottom-up, sector-specific studies

Bottom-up, sector-specific studies provide the estimates of direct impact that other modelling techniques build upon. The literature on bottom-up, sector-specific impacts is very large. Here the focus is on a few major studies, which constitute the state-of-the-art across the principal direct climate impacts. These are:

- the AVOID programme (AVOID, 2012);
- the PESETA programme (Ciscar et al., 2009);
- the ClimateCost programme (Watkiss, 2011);
- the IMPACT model for agriculture (International Food Policy Research Institute, 2012);
- the DIVA model for coasts (Hinkel, 2005);
- health impact studies based on (McMichael, 2004).

Bottom-up, sector-specific studies do not add much to our understanding of the macroeconomics of climate change by themselves. Using bottom-up, sector-specific studies, it is possible to build a picture of the sum of direct climate impacts on various parts of the economy, including agriculture, water, energy and coastal zones. However, by their nature such studies ignore many of the macroeconomic effects of interest.

2.1.2 Key findings from the review of bottom-up, sector-specific studies

Direct climate impacts

The wider literature covers the range of direct impacts. However the robustness with which some impacts are estimated can be low. The studies considered represent the state-of-the-art in impact estimation and the impacts considered by these studies define the set of easily estimable impacts. The direct impacts the studies cover are:

- **AVOID:** water, river flooding, drought, crop productivity and energy demands;
- **PESETA:** agriculture, river floods, coasts, tourism, health;
- **ClimateCost:** coasts, health, ecosystems, energy, agriculture and infrastructure;
- **IMPACT model:** demand, supply, prices and trade of agriculture commodities;
- **DIVA model:** coasts;
- **Health impact studies:** heat and cold related mortality and morbidity, vector-borne diseases, malnutrition, mortality and morbidity due to floods.



Representation of cross-sectoral interactions

Bottom-up, sector-specific studies do not consider cross-sectoral interactions. It is in the nature of these studies to only consider the impacts of climate change on specific sectors and so higher-order macroeconomic effects are not analysed.

Time

Studies must balance the long timescale of physical change in the climate and the shorter timescale of economic activity. AVOID, PESETA and ClimateCost consider some impacts over short timescales but provide results at key representative dates over the next century, such as 2020, 2050 and 2080. IMPACT provides annual estimates over 50 years and DIVA has five year time steps to 2100. Health studies consider impacts to be a function of climatic changes and exposure rather than time and so while climatic variables and exposure change with time the studies themselves are not dynamic.

Growth

Bottom-up, sector-specific studies do not consider impacts on growth. It is in the nature of these studies to only consider the impacts of climate change on specific sectors and so macroeconomic impacts, such as impacts on growth, are not considered. The effect of exogenous growth on vulnerability is often considered and is dealt with under that dimension.

Space

Impacts can be estimated to a very high resolution by considering the response of regional impact models to local climatic changes. AVOID, PESETA and the IMPACT agriculture model estimate changes in climatic variables for 0.5° latitude by 0.5° longitude grid cells. ClimateCost uses similarly high resolution grid cells. Impacts are then aggregated to suitable regions, for instance the IMPACT model has 281 'food-producing units' which overlay onto geo-political regions and DIVA considers impacts for linear coastal segments that can be aggregated by country. PESETA and ClimateCost focus on Europe while all other studies considered impacts globally with varying degrees of aggregation.

Cross-border spill overs

Only the IMPACT agriculture model considers trade. In the IMPACT model agricultural commodity prices are determined on world markets and therefore regional production is traded to satisfy regional demands. The representation of trade is relatively simple with only the net position of each region being considered.

Uncertainty

Bottom-up, sector-specific studies face uncertainty along a number of dimensions. There is uncertainty over socio-economic and emissions pathways, which is often explored using scenario analysis. There is also uncertainty over the economic response to a physical impact, however this is rarely addressed. There is also uncertainty over the changes in climatic variables. Major bottom-up studies of sector-specific impacts use complex climate models called General Circulation Models (GCMs) as these provide the detailed information necessary for bottom-up estimates. Different GCMs give different changes in climatic variables for a given concentration of GHG emissions. This occurs for two main reasons: different GCMs have different structures, as the nature of the climate system is not known, and the climate is a very complex



system and so a large number of runs from a model will only provide a sample of some of the possible outcomes. To deal with this uncertainty studies use an ensemble of GCMs and consider impacts across the range of possible climate outcomes. These uncertainties still affect models that use the data from bottom-up, sector-specific studies but these uncertainties become implicit when the analysis moves to the next part of the impact chain introduced in Figure 1, while in bottom-up, sector-specific studies the uncertainty can be directly explored.

Extreme weather

Some studies consider river floods but only consider direct impacts and do not always monetise them.

AVOID, PESETA and (McMichael, 2004) consider the direct impact of floods. The impacts considered focus on mortality and morbidity from floods and the population at risk of more frequent flooding.

Vulnerability and adaptation

Adaptation is considered to a limited and inconsistent extent. Adaptation is often considered as a costless reduction in gross damage. The degree to which gross damage is reduced is often determined through appeal to findings in the literature and is not consistent across studies. Adaptation is most often considered in agriculture and coastal studies. In agriculture, adaptation maintains yields at a level above that implied by climatic changes. In coasts, adaptation is largely based on the measures available in the DIVA database, which are sea walls and beach nourishment.

Changes in vulnerability are captured but treatment varies across studies. Due to the high resolution of spatial analysis, vulnerability can be assessed with some detail, for example estimates of the current geographic distribution of population can be coupled with downscaled estimates of changes in climatic variables to consider the number of people directly affected by drought. However, changes in the geographical distribution of population over time are not projected meaning changes in such vulnerability over time are not considered. When changing vulnerability is considered it is often modelled as changing as incomes change, for example heating and cooling demand in AVOID changes as incomes rise. As with adaptation, approaches to considering vulnerability are not consistent across studies.



2.2 Integrated Assessment Models

IAMs are flexible enough that most dimensions have been explored, although some only in a highly reduced form, however they are rarely, if ever, run with all dimensions considered at once

2.2.1 Introduction to Integrated Assessment Models

IAMs integrate climate science and economics, using simple, linked models of the relevant systems, to perform a wide variety of numerical simulation exercises, in particular quantifying the total economic impact of climate change. Many IAMs have been built over the years. In this report attention is limited to those used to quantify the total cost of climate change, of which there are now three principal exponents, FUND, PAGE and DICE/RICE. Other IAMs exist in this category, but they have tended to either fall out of use, or else their impacts modules, which are of primary interest to this study, are derived from DICE/RICE and hence their inclusion adds little, although the WITCH model is mentioned where relevant.

This literature review does not review extensively the workings of IAMs but focuses on their application to the macroeconomics of climate change. IAMs have been extensively reviewed, for example (EPA, 2010; Fussel, 2010; Warren et al., 2006), and are among the most familiar tools for the quantitative analysis of the impacts of climate change. Therefore the structure of the models is only briefly described and the key findings focus on the strengths and weaknesses of IAMs against the checklist of criteria developed in Section 1.3.

A description of the IAMs reviewed can be found in Annex 1.

2.2.2 Key findings from the review of Integrated Assessment Models

Overall, IAMs are useful for framing the debate about the potential consequences of climate change as they provide a formalised, quantitative forum for debating the overall level of global ambition on emissions reductions. The usefulness of IAMs in providing consistent estimates of aggregate impacts in a relatively parsimonious way is not to be underestimated and they are flexible enough to explore most of the checklist dimensions. However they do not consider cross-sectoral interactions explicitly and are weak on vulnerability and adaptation. There is also low confidence in their overall results due to uncertainty and the quality of calibration data.

Direct climate impacts

IAMs model direct climate impacts through a damage function, which gives a level of damage for a given temperature change. This relationship is calibrated to data from bottom-up, sector-specific studies. Damage functions are often calibrated to only a couple of data points and the shape of damage functions at high temperature changes, for which calibration data does not exist, is largely based on expert opinion.



Coverage of direct climate impacts in IAMs is comprehensive relative to most other studies in this report and improving as new impacts are added, although there remain key gaps and questions over data quality. Only FUND has sector-specific damage functions, for example one for each of agriculture, energy and so on. PAGE is partially aggregated, comprising damage functions for economic and non-economic impacts, sea level rise and discontinuity (catastrophe) impacts. These impacts are calibrated to damage estimates developed in other studies, including FUND and DICE/RICE, so PAGE does not constitute an independent set of estimates. DICE/RICE represents all production as a single sector and imposes impacts via a single, aggregated damage function. This damage function is calibrated to impact estimates across a range of sectors, which is known as a ‘reduced form’ model. It should be noted that concerns have been expressed about the age of some of the data used to calibrate IAMs (Warren et al., 2006).

Both the magnitude of damages and the relative importance of direct impacts vary considerably across IAMs, while there are potentially important impacts that no models include. There remain substantial differences between IAMs in their overall estimates of damage from climate change and in the composition of these estimates, as Figure 8 and Figure 9 show.

There are potentially important impacts that IAMs do not include, either directly or via their calibration. These include most kinds of extreme weather events and socially contingent effects, such as migration and conflict (Stern, 2007). However, given the reduced form of the damage function in PAGE and DICE/RICE, it is unclear whether such impacts are in fact reflected in assumptions made by these two models about the slope of the function at higher temperatures. Therefore it is not straightforward to conclude that such models underestimate the cost of climate change, as some have argued.

Representation of cross-sectoral interactions

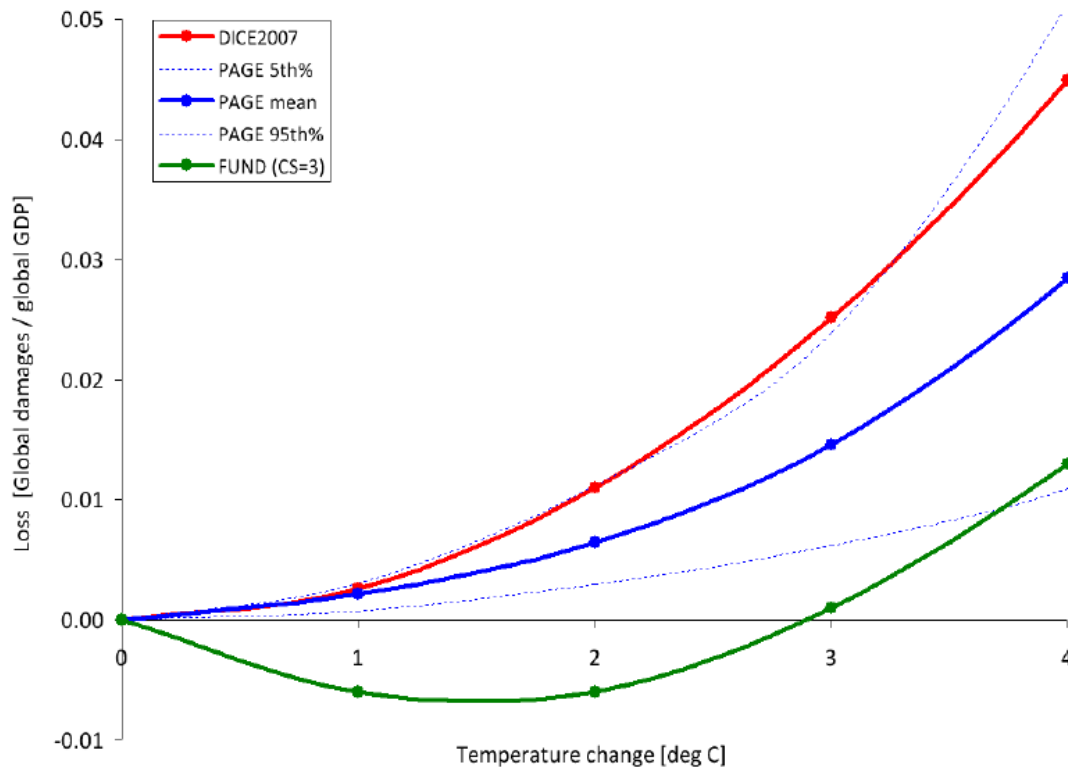
IAMs do not explicitly represent interactions between sectors. FUND and PAGE lack micro-foundations and so there are no interactions between sectors and GDP is exogenous. DICE/RICE is a version of the Ramsey growth model and so has micro-foundations. However production is highly stylised; there is only one representative production sector and therefore no scope for explicit sectoral interactions. Nonetheless the data used to calibrate damage functions in IAMs may have come from a model that did consider cross-sectoral interactions. Indeed, ClimateCost (2012) calibrated the damage function of WITCH, an IAM based on DICE/RICE, to the outcomes of ICES, a dynamic CGE model that explicitly represents cross-sectoral interactions, when ICES was shocked with the direct impacts that would have originally been used to calibrate the WITCH damage function.

Time

IAMs cover long time frames, often with short time steps. IAMs require long time frames, in the hundreds of years, to properly evaluate the economic cost of GHG emissions, which last for a very long time in the atmosphere. Yet economic analysis is often focused on the period to 2100. FUND has yearly time periods; DICE/RICE has decadal time steps while PAGE has decadal time steps to 2050 and then 25 year time steps to 2100 and 50 year time steps to 2200. The time dimension is important as the majority of climate impacts tend to occur in the far-off future and as a result IAMs are famously, or even notoriously, sensitive to assumptions regarding the discount rate.



Figure 8. Annual consumption loss as a fraction of global GDP in 2100 due to an increase in annual global temperature varies across DICE2007, PAGE2002 and FUND (2.9 or later)



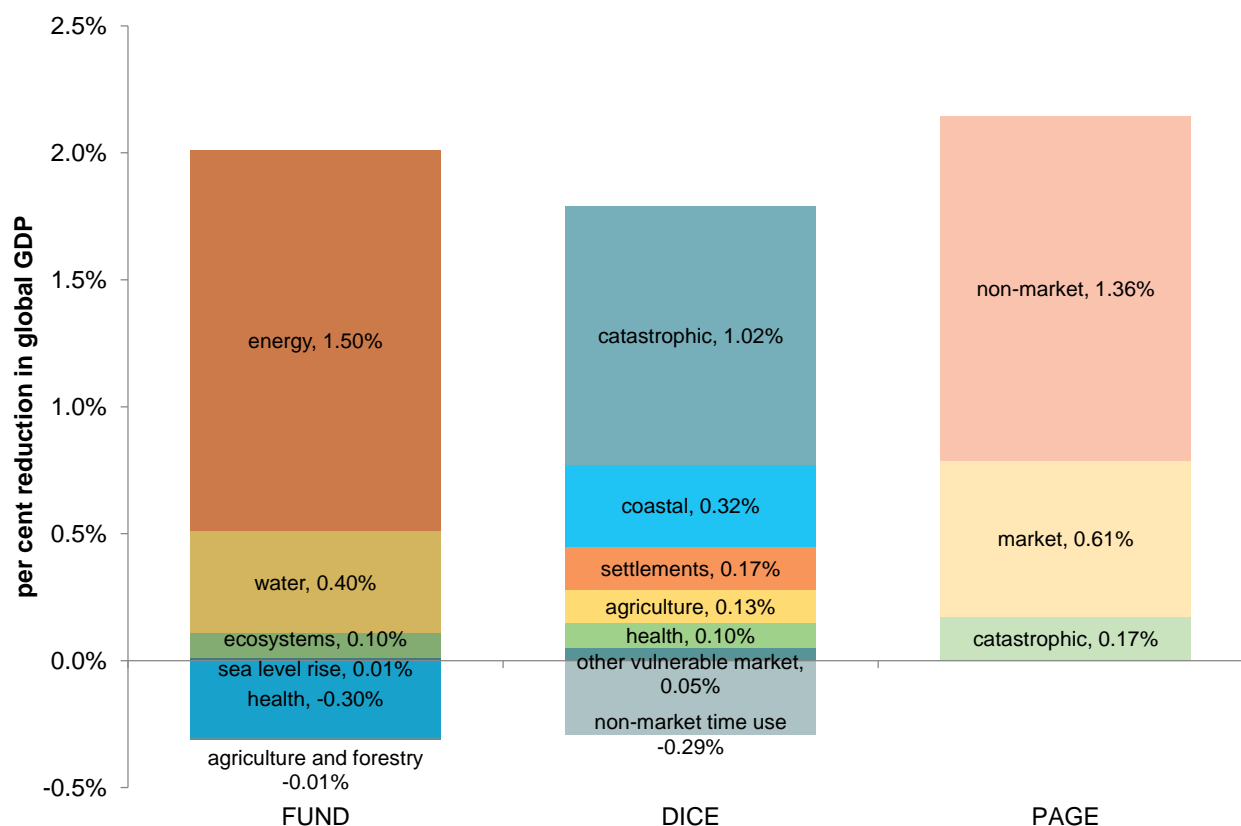
Note: Models are run using modeller's default scenarios and mean input assumptions. Version of FUND is not stated but coverage of impacts is consistent with version 2.9 or later.

Source: (EPA, 2010)

Growth

Only DICE/RICE can capture the impact of climate change on growth in the long-run, as investment is endogenous. DICE/RICE is a modification of the Ramsey growth model. Technological change is exogenous and so the impact on growth comes via reduced investment, due to lower income as a result of current climate shocks, and/or lower expected returns as a result of future climate shocks. This has some impact on economic growth, but as Fankhauser & Tol (2005) show, and as is illustrated in Figure 4, the growth impact is relatively small compared to the direct impact of climate change. Nonetheless, Fankhauser & Tol (2005) show that the growth impact could be significantly larger in a model where productivity growth is endogenous. While this result comes from an extension of DICE/RICE, endogenous growth is not a standard feature of the model, so other literature does not include it.

Figure 9. 2.5°C of warming relative to 1990 results in a similar magnitude of damage across IAMs but in each IAM the damage occurs in different sectors; note that this data is for old model versions



Note: Data from FUND 2.9, DICE-99 and PAGE2002. FUND 2.9 and PAGE2002 specify that 2.5°C of warming relative to 1990 occurs by 2080. FUND and PAGE use the SRES A2 scenario and DICE endogenously produces a scenario between SRES A2 and B2. Negative GDP impacts are gains and the chart shows gross impacts, i.e. the net impact for FUND is 2.01% - 0.31% = 1.7% damages and the net impact for DICE is 1.79% - 0.29% = 1.5% damages. The mean output value of net impact for PAGE is 2.14% damages. The 5th percentile output value of net impact for PAGE is 0.21% damages and the 95th percentile output value of net impact for PAGE is 6.56% damages. DICE and PAGE global estimates are aggregated from regions using output weights, which tend to give a lower damage estimate than population weights. The method of aggregation for FUND was not specified.

Source: Vivid Economics based on (Warren et al., 2006)

Space and cross-border spill overs

IAMs are regionally disaggregated, but not sufficiently so to explicitly identify the UK, and there is no representation of trade. FUND has 16 regions, RICE has 12 and PAGE has eight, while DICE is a globally aggregated model. The UK typically sits with Europe, or Northwest Europe. Regional disaggregation is limited due to limited knowledge on region-specific changes in climate and region-specific vulnerabilities. The regional weights used in IAMs are at best averages for the region and sometimes extrapolations from studies of impacts in a single region. Attempts at simple down-scaling from regional estimates has been attempted, for example (Ward et al., 2012). While these estimates are useful for illustrative purposes, more sophisticated statistical downscaling techniques have been developed, for example in the literature on physical climate impacts. To the best of our knowledge, these techniques have yet to be applied and there are some concerns about their robustness (Lopez, Smith, & Suckling, 2011). Regions do not explicitly interact in



IAMs and so the impacts of climate change on trade cannot be reported and such impacts will only be considered if they are accounted for in the studies that provide data for the calibration of damage functions.

Uncertainty

IAMs are well-suited for exploring uncertainty over key assumptions, in particular climate sensitivity and the responsiveness of damages to changes in temperature. A large amount of work has been done to test the sensitivity of outcomes in IAMs to key assumptions. PAGE is designed as a probabilistic model and FUND and DICE have been run as probabilistic models too.

Extreme weather

Only FUND explicitly considers extreme weather. The representation of extreme weather in FUND is described in Annex 1.

Vulnerability and adaptation

Neither vulnerability nor adaptation is well represented in standard IAMs. PAGE considers adaptation in a relatively simplistic way by increasing, for a cost, the temperature below which no impacts are felt. This representation is considered arbitrary and difficult to calibrate (Agrawala et al., 2011). FUND explicitly considers adaptation in agriculture and coastal protection. The degree of adaptation is exogenous. Otherwise adaptation in FUND and DICE/RICE is only incorporated to the extent that it is considered in the studies that provide data for the calibration of damage functions. In DICE/RICE the calibration of the damage function takes some account of how impacts as a percentage of GDP change as GDP increases. This crudely accounts for some elements of dynamic vulnerability. In FUND damage functions take changing vulnerability into account by considering how demand for products from directly affected sectors changes with GDP growth. PAGE represents the maximum vulnerability of an economy by imposing a limit on damages and this limit can change over time. Adaptation IAMs, considered in Section 2.3, explicitly incorporate adaptation into IAMs.



2.3 Adaptation Integrated Assessment Models

Adaptation IAMs yield useful findings about optimal adaptation policy, but so far only at a very high level

2.3.1 Introduction to Adaptation Integrated Assessment Models

Two principal adaptation-IAMs (AD-IAMs) have been developed so far: AD-WITCH and AD-DICE/RICE. AD-WITCH is described in (Bosello et al., 2010) and AD-DICE/RICE is described in (De Bruin et al., 2007). WITCH is based on the DICE/RICE framework, with the addition of a detailed energy production sector and some other features. So the models have a common damage function structure, based on (Nordhaus & Boyer, 2000). To incorporate adaptation the damage function is modified in both models so that damage is the sum of adaptation costs and residual damage, where residual damage is a function of gross climate damages minus protection afforded by adaptation.

In both AD-IAMs adaptation is modelled as a stock and a flow variable, to represent anticipatory and reactive adaptation respectively. AD-WITCH also distinguishes between generic and specific investments in adaptive capacity. A generic investment in adaptive capacity would be an investment in healthcare while a specific investment would be increased R&D into adaptation. Adaptation costs and benefits are essentially represented by adaptation functions, similar to damage functions. These region specific functions are calibrated to data from studies of adaptation costs. The optimal level of adaptation is determined endogenously in the models.

AD-IAMs explore macroeconomic questions about adaptation to climate change. The types of macroeconomic questions considered so far are:

- how does adaptation complement or substitute mitigation efforts?
- what is the order of magnitude of adaptation expenditure?
- what is the distribution of adaptation costs across regions?
- what is the optimal profile of expenditure in adaptation over time?
- what proportions of expenditure do different types of adaptation consume?

2.3.2 Key findings from the review of Adaptation Integrated Assessment Models

AD-IAMs share the strengths and weaknesses of the standard IAMs they are based on. However they add the ability to explicitly consider vulnerability and adaptation, while at the same time they have so far not been run probabilistically. As AD-IAMs are modifications of standard IAMs, organising the key findings from the review of AD-IAMs according to the checklist is not as informative as it is for other modelling techniques, as only the dimensions of uncertainty and vulnerability and adaptation vary significantly from standard IAMs. Therefore other dimensions are briefly summarised while uncertainty and, particularly, vulnerability and adaptation are explored in more detail.

AD-IAMs seem useful in framing the debate over the type, level, timing and distribution of adaptation required. From the perspective of the checklist the major improvement of AD-IAMs over standard IAMs is



that they explicitly incorporate adaptation as an endogenous choice. This means that they can provide insights into the optimal balance between adaptation versus mitigation and between flow and stock adaptation. However the conclusions that can be drawn from the results of AD-IAMs can only be broad, in much the same way that standard IAMs provide broad conclusions on mitigation needs that must be followed up with more detailed studies if an actionable policy is to be produced.

The findings for AD-IAMs across a number of dimensions are similar to the findings for standard IAMs:

- **Direct climate impacts:** current AD-IAMs are based on the damage function of DICE/RICE, although in principal other IAMs, with different coverage of direct climate impacts, could be converted to AD-IAMs
- **Representation of cross-sectoral interactions:** like IAMs, AD-IAMs do not explicitly represent interactions between sectors
- **Time:** AD-IAMs focus on the period 2100 in time steps of five and ten years for AD-WITCH and AD-DICE/RICE respectively
- **Growth:** current AD-IAMs capture the impact of climate change on growth via investment as they are based on DICE/RICE
- **Space:** AD-IAMs are regionally disaggregated but face the same limitations as IAMs, along with the additional constraint that regional adaptation cost estimates are required. AD-WITCH has 12 regions and AD-RICE has 13 regions while AD-DICE is globally aggregated
- **Cross-border spill overs:** as is this case with standard IAMs, regions do not explicitly interact and so the impacts of climate change on trade or other cross-border spill overs cannot be reported and such impacts will only be considered if they are accounted for in the studies that provide data for the calibration of damage functions
- **Extreme weather:** extreme weather is not considered in current AD-IAMs although in principal it could be considered in AD-IAMs

Uncertainty

AD-IAMs do not consider uncertainty beyond testing scenarios of economic growth. AD-IAMs are a relatively new class of IAMs and have not been built for probabilistic runs so far. Yet the relatively simple structure of AD-IAMs makes them suitable for probabilistic analysis, such as has been done using standard IAMs.

Vulnerability and adaptation

Adaptations in the sectors that the DICE/RICE damage function is calibrated to are currently considered. These sectors are agriculture, other vulnerable markets, coasts, health, non-market time use, catastrophes and settlements. Adaptation is considered in these sectors as follows:

- agricultural adaptation is a flow variable in AD-WITCH but both a flow and stock variable in AD-DICE/RICE;
- other vulnerable markets includes energy adaptation as a flow variable for increased cooling and water adaptation as a stock variable for improved infrastructure;
- health adaptation focuses on general improvements to healthcare to reduce the burden of vector-borne diseases;



- adaptation in non-market time use is not modelled as more regions experience a benefit due to climate change;
- adaptation to catastrophes is limited to the benefit of early warning systems;
- adaptation in settlements is a stock variable in AD-WITCH while AD-DICE/RICE considers adaptation in human settlements and ecosystems. Human settlements are assumed to be able to adapt more than ecosystems, although neither can adapt cheaply. There is a greater adaptation potential in developing countries than in developed countries.

Adaptation costs are driven by assumptions regarding damages. As adaptation is an endogenous decision within current AD-IAMs the level of adaptation over time in a region is determined by the profile of damages that the region faces. The higher the damages the higher the adaptation costs to achieve a certain level of protection. Furthermore, higher damages induce greater investment in stock adaptation, and indeed greater investment in mitigation. While these are obvious responses to high climate impacts they highlight the importance of assumptions about damage functions; the results of AD-IAMs will only be as robust as these assumptions.

Current AD-IAMs agree on the broad division of regional adaptation costs but not on the magnitude. Current AD-IAMs find that India and sub-Saharan Africa face the largest adaptation costs as a percentage of GDP. However AD-WITCH finds that both regions face adaptation costs of 1.5 per cent of GDP in 2100 while AD-RICE finds adaptation costs for the regions to be half that. These findings should be treated with caution as there have only been a few studies conducted so far and these studies rely on similar data and models, so results may not be independent.

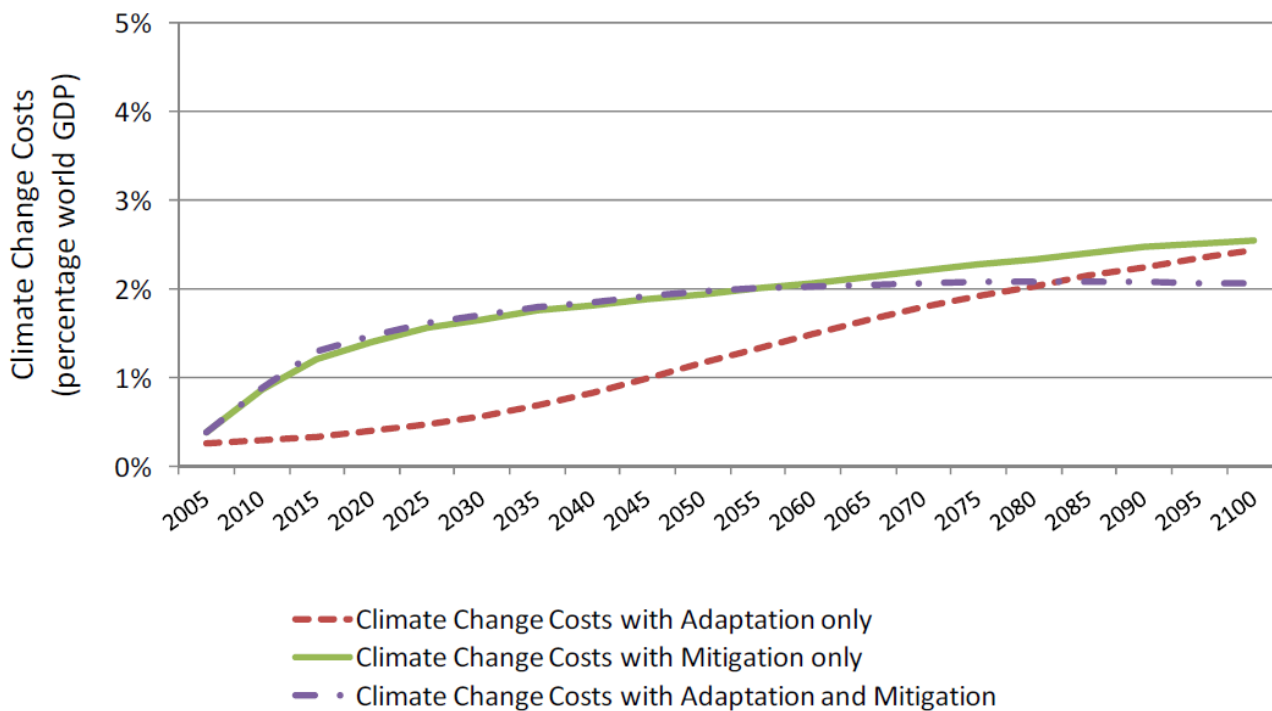
Adaptation costs rise over time. For instance costs in AD-WITCH are 0.5 per cent and 0.4 per cent in 2050 for India and sub-Saharan Africa respectively but 1.5 per cent in 2100. Adaptation costs for Western Europe rise from low levels in 2050 to 0.4 per cent and 0.8 per cent in AD-RICE and AD-WITCH respectively.

Stock adaptation dominates costs. This is because stock adaptation investments tend to be more costly than flow adaptations. This finding is particularly relevant as government may have a greater role in investment in stock adaptation than it will in flow adaptation. AD-IAMs may be useful in gauging the fiscal impact of adaptation although such analysis has not been done so far.

Adaptation appears to be a complement to mitigation. A regime of both adaptation and mitigation appears to have the lowest costs. However adaptation alone may have a lower Net Present Value to 2100 as adaptation costs can be incurred later in the century than mitigation costs. Such a conclusion is reached by the AD-WITCH model, as shown in Figure 10, but not by AD-DICE. Beyond 2100 adaptation alone becomes insufficient to reduce damages and so over long time frames mitigation is important.



Figure 10. **AD-WITCH suggests that adaptation alone is the lowest cost policy over the next century although that may not be the case over the next two centuries and beyond**



Note: Climate change costs are the sum of residual damages (gross damages minus adaptation benefits) and adaptation costs.

In the source, AD-DICE finds adaptation only to have the same, if not slightly worse, time profile of costs as an adaptation and mitigation policy.

Source: (S. Agrawala et al., 2010)

Representing adaptation as a function of regional damage may not be the ideal approach but is reasonable given the constraints on data. The adaptive response of economies to potential impacts is the product of a decision process with a large number of factors and so a simple functional representation of the response may not be sufficient. While the optimal adaptation decision of an economy, given its constraints, should theoretically be contained in the calibration data, the data on which adaptation costs and benefits are currently estimated is not sufficiently robust. Furthermore, policy makers may want to control for other more realistic components of adaptation decision-making in the model, for example capital or fiscal constraints. However, despite these issues, AD-IAMs are a good option for establishing broad results on adaptation given the lack of alternative approaches.

2.4 Multi-sector models

Multi-sector models suggest that indirect effects from cross-sectoral interactions can change the outcomes implied by direct effects

2.4.1 Introduction to multi-sector models

All multi-sector models in the review are General Equilibrium (GE) models. The GE models considered in this review, GTAP-E(F), GEM-E3, ICES, ENVISAGE and under development in (Krusell & Smith, 2009) and (Krusell & Smith, 2012) encompass the range of possible forms of GE models. In principle it would be possible to build a non-equilibrium multi-sector model in the Keynesian tradition but this has not yet been attempted.

An economy can be highly disaggregated or represented in a stylised way. Regions and production sectors can be highly disaggregated in some GE models known as Computable General Equilibrium (CGE) models. CGE models require computation because the representation of many sectors and regions make analytical solutions intractable. GTAP-E(F), GEM-E3, ICES and ENVISAGE are all CGE models. GE models can also be stylised, which means that they are not disaggregated. IAMs, such as DICE/RICE, WITCH and the models of Fankhauser & Tol (2005), are in fact stylised GE models, as is the DSGE model under development in (Krusell & Smith, 2009, 2012). Such models often make a trade-off between having a detailed representation of the economy and describing a complex phenomenon, such as the interaction between the climate and the economy or the impact of climate change on economic growth across a set of theories of growth.

GE models can be static or dynamic. Dynamic CGE models are more complicated to build and interpret than static CGE models but they have the advantage of modelling how an economy changes over time as explained in Section 1.3.4. ICES and ENVISAGE are dynamic CGE models while GTAP-E(F) and GEM-E3 are static CGE models.

Impacts of climate change tend to be implemented in CGE models in three ways. The magnitude of impacts for a scenario of temperature change consistent with the GHG emissions of the model economy are estimated from sector-specific studies. Impacts are implemented by changing the value of exogenous variables accordingly. Three types of variable can be changed:

- **factor stocks:** land, capital and labour can all be subject to impact. For example sea level rise reduces land and capital, and health impacts reduce labour via increasing mortality. Capital stocks are usually determined endogenously in GE models and so such impacts require capital stocks to be made exogenous;
- **productivity:** climate change can reduce the productivity of agriculture and forestry while there can also be productivity shocks via health impacts and floods. Implementing the necessary shocks is relatively easy;
- **household demands:** climate change can affect energy demands, demand for health and tourism services, and enforce ‘obliged consumption’, which is used to proxy for the disruption costs of floods. Household



demands are normally determined endogenously and so such impacts require the affected demands to be made exogenous.

Dynamic Stochastic General Equilibrium (DSGE) models allow uncertainty to be incorporated directly into the economy. The way in which variables, such as the productivity growth rate or the global average temperature, will change over time is often uncertain and this uncertainty affects how agents in the economy plan for the future. A DSGE model explicitly represents uncertainty in the economy by treating uncertain variables as stochastic processes, which means that the value of the variable in the future is taken from a set of possible values, each of which has a probability of occurring. Treating uncertain variables as stochastic processes improves the realism of a model and also allows the impact of uncertainty on agents to be estimated. To our knowledge, no DSGE model incorporating the impacts of climate change has so far been operationalised, although Per Krusell and Anthony Smith are developing such a model.

A description of the multi-sector models reviewed can be found in Annex 2.

2.4.2 Key findings from the review of multi-sector models

Direct climate impacts

CGE models do not have as comprehensive coverage of direct climate impacts as IAMs. Despite this a relatively large number of direct impacts have been considered, including tourism, which has not been considered in standard IAMs so far. CGE models have tended to use similar sources for estimates of direct climate impacts, in particular coasts, where the DIVA model is commonly used. However studies using GEM-E3 and GTAP-E(F) have tended to draw on independent impact estimates.

The direct climate impacts that studies consider are:

- **GEM-E3:** agriculture, river floods, coastal systems and tourism (J.-C. Ciscar, Szabó, Regemorter, & Soria, 2012);
- **GTAP-E(F):**
 - tourism (Berritella, Bigano, Roson, & Tol, 2006);
 - health (Bosello, Roson, & Tol, 2006);
 - sea level rise (Bosello, Roson, & Tol, 2007);
- **ICES:**
 - health, agriculture, tourism, energy demand and sea level rise (Eboli, Parrado, & Roson, 2010);
 - sea level rise, energy demand, agriculture, tourism, forestry, floods and thermal discomfort (Bosello, Eboli, & Pierfederici, 2012);
- **ENVISAGE:** agriculture, sea level rise, water, tourism, energy demand, human health and thermal discomfort (Roson & Mensbrugge, 2012).

The need to explicitly model the pathway of a sector impact in a CGE model limits the range of direct impacts that can be included. Climate impacts can only be included if they can be made to connect with the existing structure of the model, for example an agricultural impact acts by reducing the productivity co-efficient of the production function in the agricultural sector. In contrast, the flexible, reduced form of IAM damage functions means that more impacts can be included through calibration.

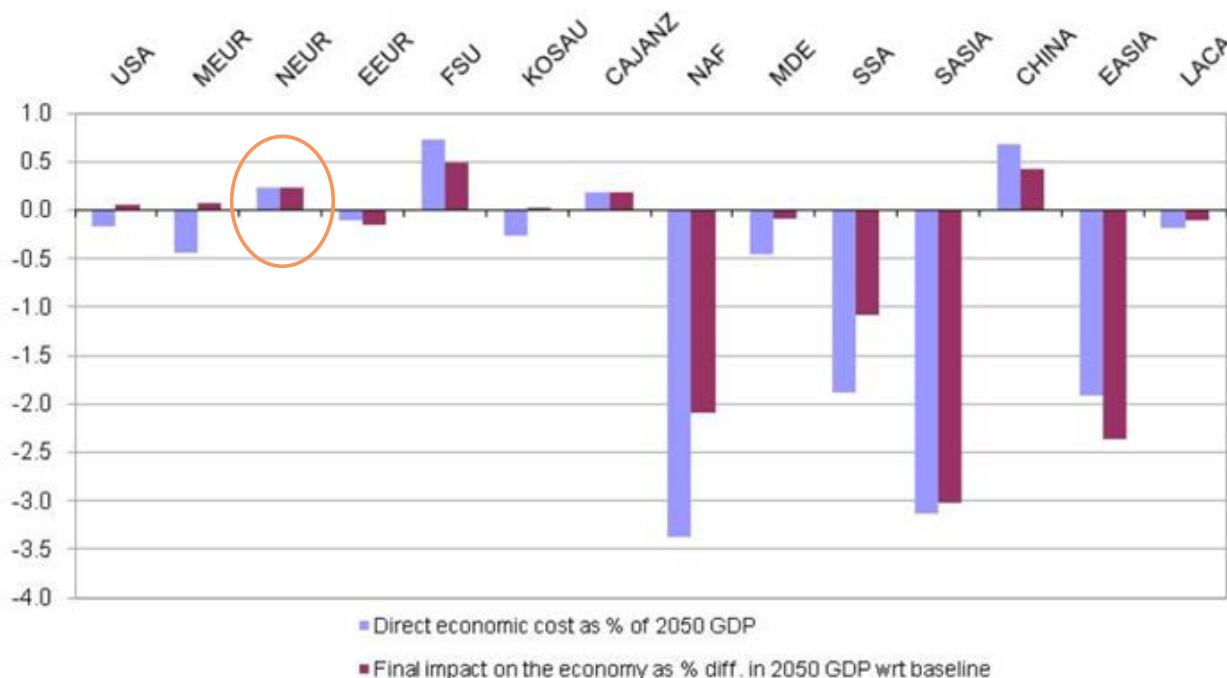


Representation of cross-sectoral interactions

CGE models have a large number of sectors and so can capture cross-sectoral interactions relatively comprehensively. GEM-E3 has the fewest sectors, with 18. GTAP-E(F), ICES and ENVISAGE are all based on the GTAP database and so have 57 sectors, although these are almost always aggregated in modelling exercises.

The main insight from multi-sector models is that, in equilibrium, indirect effects on GDP may be significant and may dampen the negative effect of direct impacts, even resulting in a net benefit occurring in some regions and sectors. There is limited analysis of this effect and so conclusions are inevitably tentative. Studies based on the ICES model show significant indirect effects that can dampen or even reverse the direct, negative impact of climate change (Bosello et al., 2012; Eboli et al., 2010). This is illustrated in Figure 11, which shows direct and final economic costs of climate change in the agricultural sector; here the USA and MEUR, Mediterranean Europe, face negative direct economic costs but positive final impacts. However other studies do not find such significant indirect effects. For example, as Figure 12 shows, Berrittella et al. (2006) find, using GTAP-E(F), a static version of ICES, that the welfare impacts from tourism come largely from the change in income from changing tourism rather than second-order effects such as changes in the terms of trade.

Figure 11. Modelling using ICES shows that indirect impacts may often reduce, and even reverse, the impacts of climate change on crop productivity, and the same is true for tourism and sea level rise



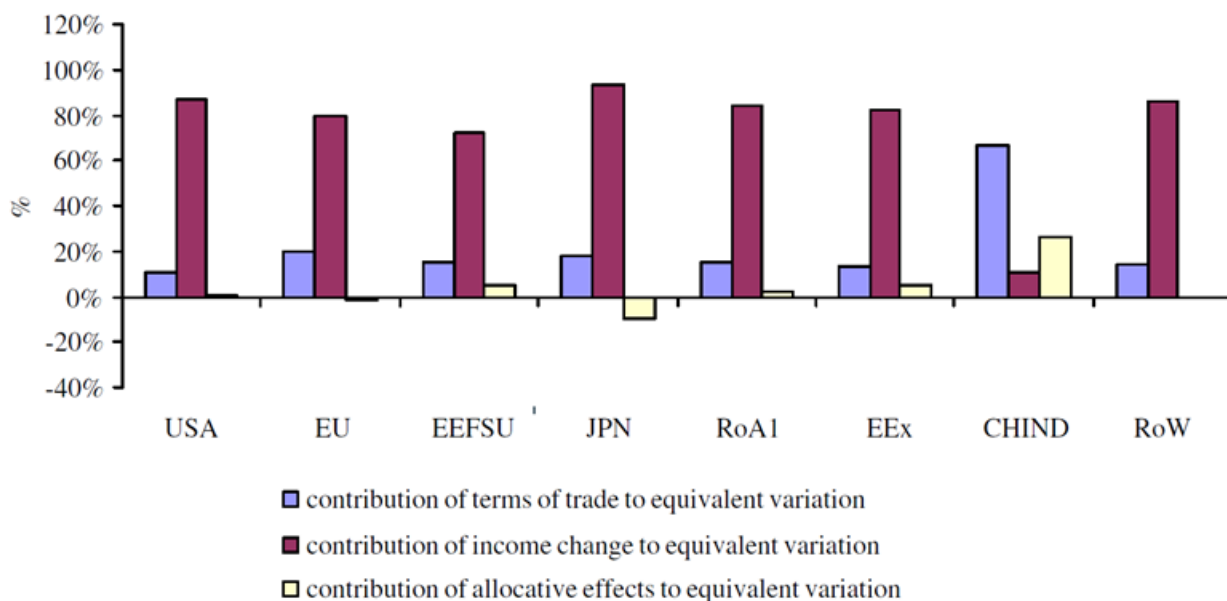
Note: Figure is for impacts in the agricultural sector. Northern Europe is highlighted with an orange circle.

Source: (Bosello et al., 2012)

The fact that opposing indirect effects are more pronounced in ICES, a dynamic CGE model, than in static CGE models, suggests that over time the economy adapts to climate change via structural change. Such long-run structural change is not possible in static CGE models but is a natural part of dynamic models as investment in affected sectors can change over time.

The sign and magnitude of indirect effects warrants further study as they imply that direct impacts do not provide a complete picture of the effects of climate change. Table 3 provides a comparison between the regional impacts of climate change according to ICES for a 1.92°C temperature change and the regional impacts of climate change according to the direct impact data for the same temperature change that is used to calibrate the DICE/RICE damage function. While other features of the modelling approach will contribute to the difference in results between the two sets of impacts, cross-sectoral interactions will have a significant impact. Given the differences in outcomes across the models, and the increased variation in damages between developed economies and developing economies in ICES, further research could be required to test the robustness of these findings.

Figure 12. **The welfare decomposition of the equivalent variation for the impact of climate change on tourism in 2050 in the static CGE model GTAP-E(F) shows that most of the impact comes from changes in income due to changes in tourism levels, except in China and India**



Note: Equivalent variation measures the level of income change, at constant prices, which would have been equivalent to the simulation outcome, in terms of the utility change of households.

Source: (Berritella et al., 2006)



Table 3. The outcomes in ICES and the damage function calibration data for DICE/RICE in Nordhaus (2007) are quite different, with impacts in ICES for developed economies decreasing while increasing in developing economies

| Region | Percentage change in real GDP, relative to no temperature increase, due to market impacts of a 1.92°C temperature increase | | Percentage change from Nordhaus (2007) to ICES |
|-----------------------------|--|-----------------|--|
| | ICES | Nordhaus (2007) | |
| United States | 0.17 | 0.12 | 42% |
| Mediterranean Europe | -0.15 | -0.25 | -40% |
| Northern Europe | 0.18 | -0.25 | -172% |
| Eastern Europe | -0.21 | 0.15 | -240% |
| Former Soviet Union | 0.81 | 1.78 | -54% |
| Korea, S. Africa, Australia | 0.09 | 0.48 | -81% |
| Canada, Japan, New Zealand | -0.09 | 0.02 | -550% |
| North Africa | -2.67 | -0.97 | 175% |
| Middle East | -0.83 | -0.64 | 30% |
| Sub Saharan Africa | -1.50 | -0.97 | 55% |
| India and South Asia | -3.10 | -0.77 | 303% |
| China | 0.20 | -0.12 | -267% |
| East Asia | -2.82 | -0.60 | 370% |
| Latin and Central America | -0.71 | -0.58 | 22% |

Note: Nordhaus (2007) impacts are rescaled linearly from 2.5°C to 1.92°C temperature increase. Regions and direct impact sectors do not match perfectly. In particular river flood impacts in ICES are contrasted with impacts to settlements in Nordhaus (2007) and data for river floods and health is only considered in Europe. ICES also considers impacts on forestry.

Source: (ClimateCost, 2012)



The method of allocating investment across regions has a significant influence on the magnitude of GDP impacts in both static and dynamic models. Impacts can increase the marginal rate of return on capital in a region, either by destroying capital and so making it scarcer or by increasing demand for capital for adaptation investments, such as sea walls. If savings are internationally mobile then foreign investment will flow to impacted regions to take advantage of the relatively higher rates of return. This will increase the GDP of the impacted region and allow it to smooth the cost of the impact over time. This latter effect occurs because foreign investment is equivalent to a debt, which allows investment today, alleviating the cost to the impacted region of having to save first, but which must be paid off over time. GTAP-E(F) and ICES, which share the same investment allocation model, reflect the effect of internationally mobile savings. The ENVISAGE model, a dynamic CGE model where investment is largely influenced through domestic savings, has much higher impacts, although the authors do not explore the relevance of savings mobility.

Growth

Dynamic CGE models show that the impacts of climate change on growth are significant and theory suggests that not all growth effects are considered. As described in Section 1.3.5, Fankhauser & Tol (2005), using a set of stylised GE models, show that the impact of climate change on GDP growth can be greater than the direct impact. Impacts on growth can occur via a capital accumulation and a savings effect, as explained in Section 1.3.5. ICES and ENVISAGE only incorporate the capital accumulation effect and, while the authors do not provide much explicit analysis, the impact over time is much greater for regions whose incomes are significantly impacted and so whose savings are lower. As noted above, impacts are worse in ENVISAGE where capital is less internationally mobile and this suggests that impacts to growth due to reduced capital accumulation are significant and worthy of further investigation.

Cross-border spill overs

The representation of trade in CGE models is important as price changes in international markets have important consequences for the distribution of impacts. Climate change can reduce the production of an item and the resulting increase in scarcity can lead to higher prices. The increase in price can compensate countries that do not experience significant output loss but not those countries where the affected sector provided a large percentage of GDP. This has the effect of improving the terms of trade for the least physically impacted countries, thus welfare in the most impacted countries can fall further. Agriculture and energy are two key markets where this effect is relevant. Agriculture tends to dominate the economies of developing countries and this effect compounds the disproportionate direct impacts they suffer. Energy demand is found to decline due to climate change in ICES and ENVISAGE as heating needs decrease more than cooling needs increase. This means that energy-exporting countries suffer worsening terms of trade and are among the worst impacted countries in these models.

Vulnerability and adaptation

Multi-sector models capture autonomous adaptation, although static models do not include key considerations such as changing vulnerability and adjustment costs. Changes in vulnerability are not explicitly considered in any of the studies reviewed. Studies using GTAP-E(F), ICES and ENVISAGE consider the future impacts of climate change on future, that is economically more developed, economies. However there is no accounting for changes in vulnerability in the implementation of impacts. Ciscar et al. (2012) impose forecast climate impacts in 2080 on the current economy so as to avoid adding uncertainty over the future economy to uncertainty over climate impacts. Adaptation is only explicitly considered in the



case of sea walls and the level of protection is always an exogenous choice. Autonomous adaptation, in the form of sectoral adjustment away from impacted sectors, can be captured in CGE models and is noted in (Bosello et al., 2012), however results from static CGE models ignore adjustment costs.

Other dimensions of the macroeconomics of climate change

In addition to these main points the remaining issues on the checklist are as follows:

- **Time:** time is not relevant in static CGE models while ICES has time periods of one year and ENVISAGE has time periods of ten years;
- **Space:** regions tend to be relatively aggregated although this is not due to constraints on the standard economic data. GTAP-E(F), ICES and ENVISAGE are calibrated to the GTAP database, which has 129 regions, although to model the impacts of climate change ENVISAGE is aggregated to 15 regions, ICES to 14 regions and GTAP-E(F) to 8 regions while GEM-E(3) is just used for Europe, which is aggregated into 5 regions. Regions may be aggregated for computational or presentational purposes or because direct impact data is not sufficiently disaggregated;
- **Extreme weather:** the impacts of extreme weather are not accounted for in any of the multi-sector models reviewed and CGE models are not suitable for such analysis because they cannot model the short-run effects of extreme weather events;
- **Uncertainty:** uncertainty is explored via scenario analysis for GEM-E3 and is not explored in any meaningful way in other modelling exercises. Krusell and Smith are developing a DSGE model, which would incorporate uncertainty into the model, but, as explained in Section 2.4.1, this is still a work in progress.



2.5 Extreme weather event studies

Extreme weather impacts appear to be qualitatively worse for developing economies

2.5.1 Introduction to extreme weather event studies

The impacts of extreme weather require novel estimation methods. While there are numerous studies analysing the impact of specific extreme weather events, a synthesis assessment of the macroeconomic impacts of all kinds of extreme weather nationally or globally requires a systemic study that looks at common mechanisms of impact and the general magnitude of impacts. There is then the further challenge of analysing how these impacts change as the climate changes. As a result the selection of robust literature is relatively thin.

A diverse set of studies is considered here, including econometric analysis, a disequilibrium model and the inclusion of cyclones in FUND. The IPCC's recent 'SREX' special report on extreme events (Intergovernmental Panel on Climate Change, 2012) provides a summary of knowledge on the physical impacts of extreme weather due to climate change. Dell, Jones, & Olken (2012) consider the historical relationship between temperature fluctuations and economic growth. Leiter, Oberhofer, & Raschky (2009) examine the impact of floods in Europe on firms' capital accumulation, employment growth and productivity. Martin, Muûls, & Ward (2011) consider the impact of extreme weather on exports and imports in the UK using firm level data. NEDyM, a Non-Equilibrium Dynamic Model, is used to analyse the impacts of extreme weather in (Hallegate, 2005) and (Hallegate, Hourcade, & Dumas, 2007). Finally the implementation and impact of tropical and extra-tropical cyclones in FUND is considered in (Narita, Tol, & Anthoff, 2009) and (Narita, Tol, & Anthoff, 2010) respectively.

A description of the extreme weather event studies reviewed can be found in Annex 3.

2.5.2 Key findings from the review of extreme weather event studies

Direct and indirect climate impacts

The main finding is that developed economies appear to be resilient to extreme weather while developing economies seem to suffer significant impacts in both the short-run and the long-run. The vulnerability of developed economies to extreme weather impacts seems to be qualitatively different from the vulnerability of developing economies and this may imply that different policy and modelling approaches could be necessary.

The indirect impacts of extreme weather events are important relative to the direct impacts. While there does not seem to have been enough work to agree on the magnitude of indirect impacts relative to direct impacts, studies so far indicate that indirect impacts are not negligible and may be greater than direct impacts. However this is more likely to be the case for developing economies than for developed economies. For example Hallegate et al. (2007) estimate that the economic amplification ratio is 1.6. This is the ratio of



total direct losses to total, undiscounted, indirect losses and if it is greater than one then indirect losses are greater than direct losses. They also find that the economic amplification ratio is increasing in constraints to reconstruction investment, which are more likely in developing economies. Dell et al. (2012) find, for developing but not developed economies, a negative, statistically significant, relationship between the change in annual average economic growth and the change in annual average temperature between 1970–1985 and 1985–2000. This is shown in Figure 13 and implies that the indirect effects from a loss of economic growth may be greater than the direct impacts.

The estimation of indirect impacts remains a challenge but the economic theory necessary to describe them is improving. Indirect impacts are difficult to distinguish from normal economic changes although studies such as (Dell et al., 2012) and (Leiter et al., 2009) attempt this using robust econometric methods. Analysing indirect impacts in an economic model is also hard, as indirect impacts occur over a range of time periods, during some of which the economy is arguably in disequilibrium. The NEDyM model provides a coherent although non-standard stylised macro-economic model for considering such situations and finds that the magnitude of indirect impacts is mainly a function of the pace of reconstruction.

Representation of cross-sectoral interactions

The composition of sectors in the economy can reduce vulnerability to extreme weather. Extreme impacts can reduce the productivity of weather-exposed sectors, such as water, agriculture and food security, forestry, health and tourism. It can also destroy physical capital. Therefore industries not in weather-exposed sectors and with high intangible capital are less vulnerable. Furthermore there is some evidence, in Leiter et al. (2009), that sectors with a high share of intangible capital increase investment in response to floods. This means that change in the sectoral composition of economies as they developed is an important consideration for models of the impact of extreme weather, although it should be noted that this is an important consideration for all impacts of climate change.

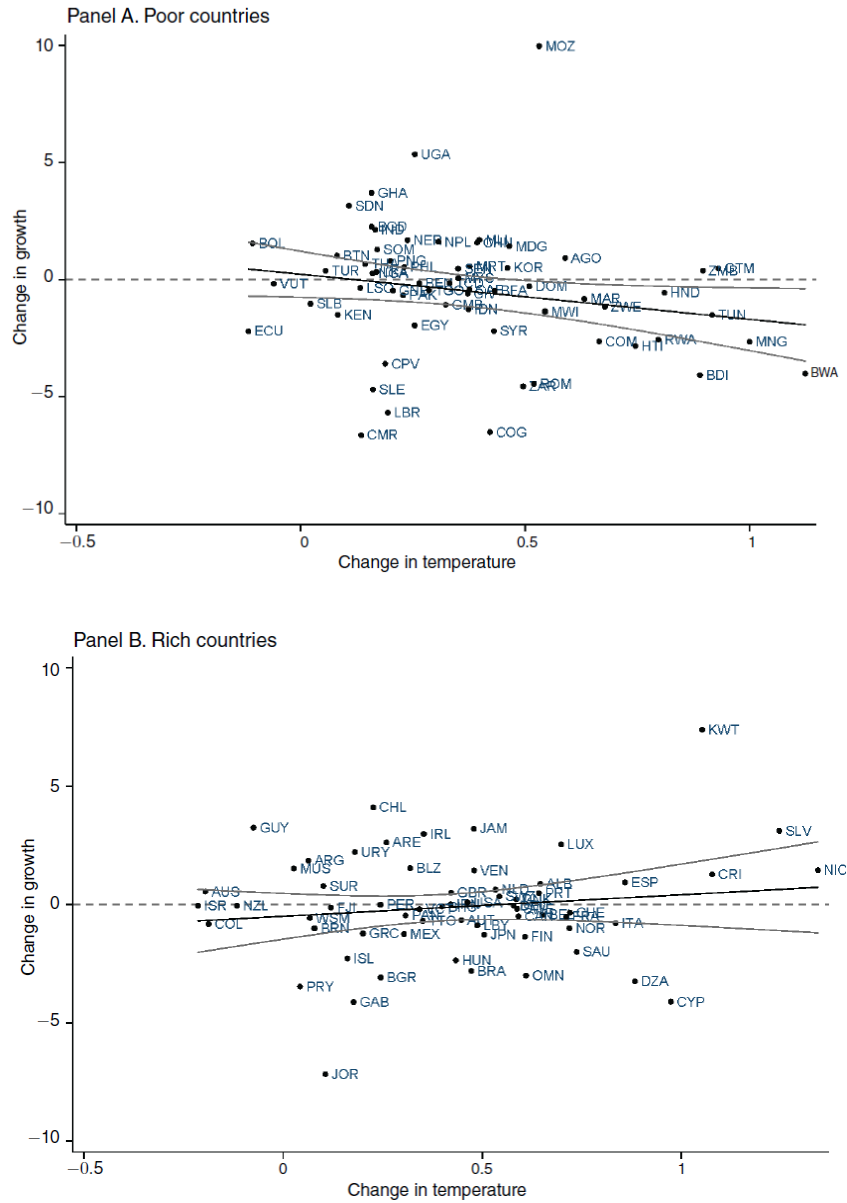
Growth

Extreme weather events can increase GDP, primarily due to increased investment for reconstruction, although this is less likely to be the case in developing countries where there are constraints on the pace of reconstruction. However an increase in GDP does not necessarily imply an increase in welfare as consumption will be forgone to fund the increased investment. Furthermore increased investment is not necessarily efficient as Leiter et al. (2009) show in an econometric analysis of flooding in Europe.

Developed economies may be resilient to reductions in growth due to extreme weather. There is limited analysis on this topic but both a modelling approach, using NEDyM, and an econometric approach, (Dell et al., 2012), which has already been discussed, both suggest that developed economies are more resilient to reductions in economic growth due to extreme weather events than developing economies. Analysis using NEDyM (Hallegate et al., 2007) finds that constraints to the quantity of investment that can be allocated to reconstruction has the greatest impact on GDP out of a set of issues that could increase indirect impacts of a disaster. The interaction between the impact on GDP and investment constraints is shown in Figure 14. If there is a reduction in GDP there will be an impact on GDP growth through the capital accumulation effect, as explained in Section 1.3.5. However developed economies are unlikely to face significant investment constraints.



Figure 13. For rich countries, Dell et al. (2012) find no statistically significant relationship between the change in annual average growth and the change in annual average temperature between 1970–1985 and 1985–2000, but they do find a statistically significant negative relationship for poor countries

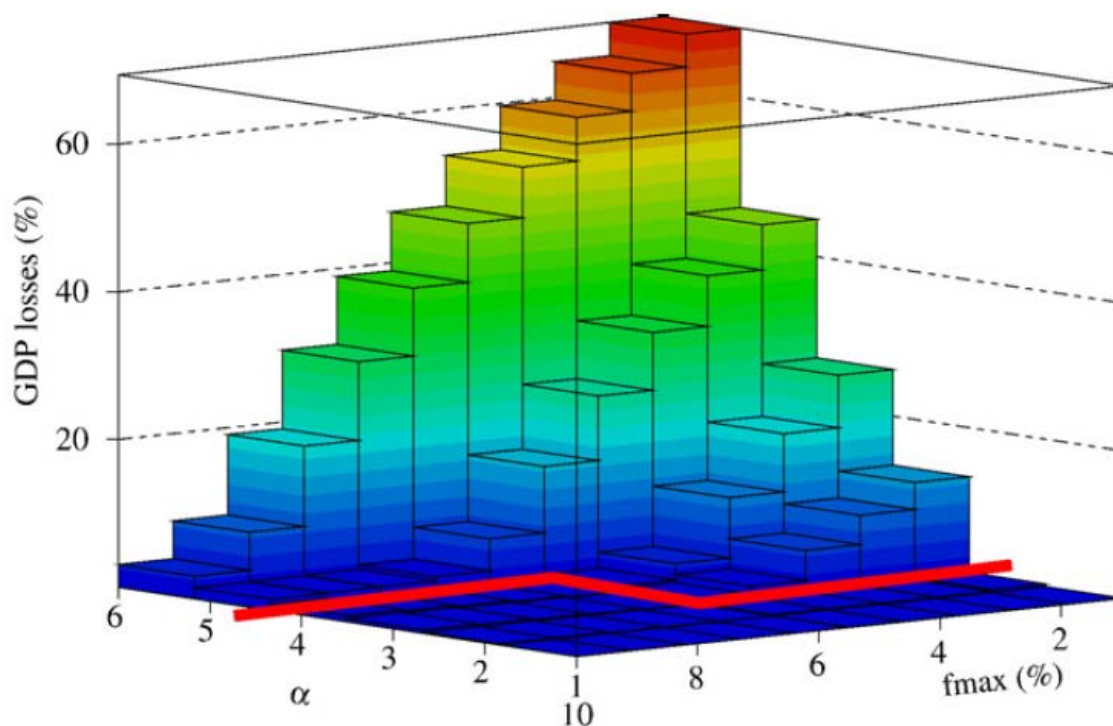


Note: The solid line shows a simple linear regression, and the lighter coloured line shows the 95 per cent confidence interval in the regression line. The relationship is statistically significant in poor countries but not in rich countries.

Source: (Dell et al., 2012)



Figure 14. Constraints to reconstruction investment appear to increase the indirect costs of extreme weather events but developed economies are unlikely to face such constraints



Note: GDP losses are the modelled annual production loss due to extreme weather, averaged over 100 years, as a function of the magnitude of the events, alpha, and the limit on investment, fmax, which is the percentage of total annual investment in the economy that can be invested in reconstruction.

Source: (Hallegate et al., 2007)

Time and space

Analysis of impacts over time and space is limited. There does not seem to be a consensus regarding the time scale over which to assess indirect impacts and attempts to reconcile short-run and long-run impacts within a coherent macroeconomic model are at an early stage. Detailed spatial analysis of extreme weather impacts is limited by data, particularly on projections of changes in extreme weather.

Cross-border spill overs

Extreme weather may have an impact on trade by affecting production either at home or abroad, and thereby changing the relative value of imports and exports. These trade effects are not well explored, with (Martin et al., 2011) being the only study reviewed, but they could be a topic for further investigation.

Uncertainty

Studies do not explore uncertainty over changes in extreme weather. This may be because studies are either econometric analyses of historical data or first-of-a-kind stylistic models and so are designed to prove a concept rather than explore outcomes. Furthermore, not much is known about average changes in extreme weather and so uncertainty around these averages is not bounded.

Vulnerability and adaptation

Increasing exposure due to economic growth is an important part of understanding the impacts of extreme weather. As economies grow the value of assets at risk increases in absolute terms and this must be controlled for in studies analysing the impact of climate change. This is done with the greatest care in econometric studies while modelling studies take exposure into account in a simple way and there is not much discussion of its relevance in results. Vulnerability may also increase due to a lack of economic growth as a result of repeated extreme weather events. These two effects suggest that vulnerability could increase for opposing reasons. Developed economies may have more to lose while developing economies may have less to defend themselves with.

There is some evidence that economies can adapt to changes in temperature in the long-run. For example Dell et al. (2012) find that the relationship between temperature variation and economic growth is smaller and weaker in the medium term than in the short term. However the changes in extremes due to climate change may be harder to adapt to as they will continue to evolve over time. As a result the benefits of adaptation may change over time.



3 Conclusions

The current literature does not provide adequate answers to policy questions but questions must be clearly articulated before studies can be improved

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Introduction

In the first part of the section, Section 3.1, the modelling techniques reviewed in Section 2 are assessed, both relative to each other and individually and recommendations for improving the current state of each modelling technique are presented.

In Section 3.2 a set of recommendations are presented concerning fundamental issues that will need to be resolved if a future research programme is to be useful to policy makers. The issues are:

- connecting policy questions to the evidence;
- choosing modelling strategies;
- quality assurance.

An expert workshop was held in which the findings of this report were debated. Salient points from the workshop are included in this section. The authors would like to thank the attendees for their valuable contributions to this report.

‘Current modelling techniques do not perform particularly well against the broad framework of assessment developed in Section 1.3. Their performance against more specific policy questions is generally worse.’



3.1 Assessment of modelling techniques

Studies struggle to meet all the challenges of modelling the macroeconomics of climate change

3.1.1 General assessment across techniques

Modelling techniques are best assessed relative to the objectives of modellers. This poses three challenges to an assessment of modelling techniques. First, while informed by high-level policy questions, much of the literature is motivated primarily by the aim to contribute to academic debate. As a result there is a difference between the answers that can be provided and the often specific answers required by policy. This issue is considered further in Section 3.2.1. Second, models tend to be designed to answer particular questions and this means that they do not cover all the dimensions of the framework developed in Section 1.3. However, the need for coherent policy across all the issues at hand suggests that a more fundamental debate about modelling strategies is required and the possible terms of this debate are presented in Section 3.2.2. Third, quality assurance and inter-model comparison may not currently meet the needs of policy makers. This is considered further in Section 3.2.3.

The aims of policy makers regarding the macroeconomics of climate change have not yet been clearly defined. This report takes stock of the current literature and assesses whether it can answer broad but important questions about the macroeconomics of climate change, presented in Table 2. The expert workshop organised for this report was strongly of the opinion that policy questions should be clearly articulated first and then tools should be sought to answer those questions. However, it was recognised that policy makers need some understanding of what answers they can realistically expect from the current literature and what barriers are in the way of more ambitious questions. This assessment is therefore against broadly-defined issues in the macroeconomics of climate change with the aim of characterising the state of current knowledge and it is not an assessment against particular policy questions. The ways in which policy questions may connect with the evidence are explored in Section 3.2.1.

Modelling techniques tend to be used for different purposes and can rarely be seen as alternate methods to answer the same question. Standard IAMs and multi-sector models are the most similar and the trade-offs between them are relatively simple. Multi-sector models allow the effect of interactions on outcomes to be considered, be they cross-sectoral interactions or trade interactions, while the parsimony of IAMs gives them the flexibility to explore other dimensions of interest, in particular that of uncertainty. Bottom-up, sector-specific studies are an input into other modelling techniques while AD-IAMs and extreme weather event studies analyse a particular topic.

No modelling technique is without significant weaknesses. This is a common view held by the attendees at the expert workshop and is supported by the literature review, as demonstrated in Table 4. Even in areas where models are designed to be strong there was a consensus that models are not complete. This suggests that there is important work to be done in defining the research programme as discussed in Section 3.1.



The value of impacts to ecosystem services, biodiversity and the dis-amenity to households of a changing climate were considered by the workshop to be key direct impacts that are either poorly dealt with or not considered in current models. These non-market impacts have not been sufficiently quantified as yet. Indeed the value of ecosystems and natural capital in the absence of climate change has not been quantified, although it has been recognised as an area of importance, as demonstrated by the recent formation of the Natural Capital Committee which is described further in Box 2. So while some models do consider non-market impacts, for example they feature in IAM damage functions, it is likely that their value is mis-estimated. The cost of these impacts could increase rapidly as temperatures increase. For instance the adaptive capacity of ecosystems could be relatively low in the face of high temperature changes.

Box 2. The Natural Capital Committee

The Natural Capital Committee (NCC) has not yet considered climate change as a specific issue.

The NCC was set-up in 2012 to help the Government better understand how the state of the natural environment affects the performance of the economy and individual well-being and advise the Government on how to ensure England's 'natural wealth' is managed efficiently and sustainably (Natural Capital Committee, 2012). While the impacts of climate change on the macro-economy could conceivably be considered by the NCC they have not been considered so far during the NCC's limited time in existence.

The NCC has so far focused on the degree to which ecosystems are at risk and on ways to account for natural capital. Such work could be useful for considering how climate change could impact non-market sectors but the resources of the NCC are such that it is likely to provide a framework for considering these issues rather than data.

The workshop thought that interactions within physical systems and feedbacks between economic and physical systems may be important but are not explicitly considered in any modelling techniques.

Climate change will induce changes in a number of physical systems, from the geographic range of agricultural pests to the types of vegetation growing in an area. These changes will be dynamic and humans will respond to these changes in ways that may compound the rates of change. Some of these impacts may be considered implicitly in the calibration data for impacts to sectors such as forestry but this is unlikely to capture dynamic feedback effects that could exacerbate costs.

The modelling of climate change impacts does not reflect state-of-the-art macroeconomics. There are a number of features of the economy that would be useful to include in climate change impacts modelling and that can be represented using state-of-the-art macroeconomic models. In particular dynamics, uncertainty within the model economy, endogenous growth, financial assets, public finance and sophisticated representations of trade can, in theory, be represented in different types of climate impacts modelling. No operational climate impacts models have incorporated these aspects although the Phoenix model (Sue Wing, Daenzer, Fisher-Vanden, & Calvin, 2011), which has been used to assess the costs of mitigation policy, has a public finance component as does Krusell and Smith's work in progress DSGE model (Krusell & Smith, 2009, 2012), which also considers uncertainty and basic financial assets.



The absence of endogenous growth in any modelling technique was considered in the workshop to be a significant issue. No operational modelling techniques consider the impact of climate change on endogenous growth despite this being a key issue in modern macroeconomics. The relevance of endogenous growth is greater than just considering whether the direct impacts of climate change will decrease the productivity growth rate. The impact of policy instruments to encourage adaptation and mitigation on the productivity growth rate must also be considered. There is a debate over whether these policy instruments will enhance productivity growth or diminish it. This issue is often described as ‘green growth’ and is discussed in more detail in Section 3.2.1.

International dimensions, including but also extending beyond trade, were considered important in the workshop as impacts in other countries could spill over to the UK. Alongside trade, international issues such as climate-impacted growth rates in developing economies, returns from overseas investments, constraints to flows of international finance, migration and other socially contingent events were identified as climate change related risks to the UK that are likely to be important but on which there is currently little research.

Distributional issues are relevant to policy makers but are hard to capture in macro-economic models. Aggregate impacts mask winners and losers within an economy. This is an area of concern for policy makers as climate change can have extreme local impacts, such as storms. However detailed distributional analysis requires models that are more disaggregated than standard macroeconomic models. It should be noted however that high-level distributional impacts are considered by some of the modelling techniques reviewed. For example IAMs have been central to the debate about how impacts should be distributed over generations and multi-sector models can describe the distribution of impacts over regions and sectors, although typically at a low resolution.

Table 4 describes how each modelling technique addresses each dimension of the theoretical framework. The major issues evident from this comparison are:

- **Direct climate impacts:** IAMs have the broadest coverage, while remaining relatively parsimonious, although impact estimates often do not reflect the latest science; non-market impacts are poorly considered in all models;
- **Representation of interactions:** only multi-sector models have any explicit representation of cross-sectoral interactions;
- **Time:** timescales of studies tend to be sufficient for policy makers, although some multi-sector models are static and so have no representation of time;
- **Growth:** only DICE/RICE and dynamic multi-sector models consider impacts to growth and no models consider impacts to endogenous growth;
- **Space:** most modelling techniques currently have a high level of geographic aggregation and so rarely consider impacts solely for the UK;
- **Cross-border spill overs:** analysis of trade impacts is relatively simple and only incorporated by the following modelling techniques: multi-sector models, some bottom-up sector-specific models and some econometric studies; none of the techniques considers the impact of climate change on financial markets or the possible impact of migration.
- **Uncertainty:** uncertainty is only sufficiently explored by some IAMs, despite the high level of uncertainty in climate change economics;



- **Extreme weather:** extreme weather events are rarely considered outside of specific studies on extreme weather events;
- **Vulnerability and adaptation:** methods of modelling changing vulnerability vary and this may reflect the difficulty of modelling a complex characteristic best understood at the micro level within an aggregate model. The same applies to adaptation: if adaptation is considered, the representation of the adaptation process does not reflect the key drivers of adaptation decision-making beyond the crude description that adaptation reduces gross climate damages for a cost.



Table 4. The modelling techniques reviewed address the dimensions of the macroeconomics of climate change in a variety of ways

| Dimension | Bottom-up, sector-specific studies | Standard IAMs | Adaptation IAMs | Multi-sector models | Extreme weather event studies | |
|--------------------------------|---|--|---|--|---|--|
| | | | | | NEDyM | Econometric studies |
| Direct climate impacts | Studies provide the basis for our understanding of direct climate impacts | Good coverage, especially of direct market impacts | Same potential as standard IAMs. Current AD-IAMs based on DICE/RICE impacts | Relatively small set of market impacts | Impacts are represented by a generic reduction to physical capital | Historical impacts are incorporated in the data |
| Representation of interactions | Not modelled | Not modelled | Not modelled | Modelled | Not modelled | Interactions are captured to the extent they are in the data |
| Time | The time frame tends to be this century and impacts from major studies are presented for key representative dates while other studies have short time periods | Several centuries with time steps as small as one year | Several centuries, with time steps of five to ten years; focus on period to 2100 | GEM-E3 and GTAP-E(F) are static while ICES and ENVISAGE are dynamic, with time steps of one and ten years respectively | NEDyM considers a short, post-shock timescale of up to a few years in time steps of weeks | Data ranges from a few years to a few decades |
| Growth | Not modelled | Only DICE/RICE can consider some growth effects | Incorporated as based on DICE/RICE | ICES and ENVISAGE can consider some growth effects | NEDyM can consider some growth effects | Growth effects are analysed, particularly in (Dell et al., 2012) |
| Space | Changes in climatic variables can be estimated to a very high resolution but impact responses tend to be regional so results are aggregated | From 16 regions in FUND to DICE, which is globally aggregated; trade is not explicitly represented | 13 regions in AD-RICE, 12 in AD-WITCH and AD-DICE is globally aggregated; trade is not explicitly represented | Possibility of high disaggregation, but aggregated from 15 regions globally to 5 regions in the EU | Not modelled as NEDyM is a stylised model | Data ranges from a number of regions to a global scope |
| Cross-border spill overs | Only considered in the IMPACT agriculture model | Not explicitly modelled, although may feature in calibration | Not explicitly modelled, although may feature in calibration | Explicitly modelled and governed by assumptions over Armington elasticities | Not modelled | Trade is considered in (Martin et al., 2011) |

| Dimension | Bottom-up, sector-specific studies | Standard IAMs | Adaptation IAMs | Multi-sector models | Extreme weather event studies | |
|------------------------------|--|--|--|--|--|---|
| | | | | | NEDyM | Econometric studies |
| Uncertainty | Uncertainty in climate projections is well analysed but uncertainty in economic responses is not | Uncertainty analysis can be conducted in the IAMs reviewed | Currently not incorporated | Currently limited to scenario analysis | Currently limited to scenario analysis | Considered as per standard econometrics |
| Extreme weather | Impacts of river floods are considered to a limited extent | Only FUND considers the impacts of cyclones to a limited extent | Not modelled | Not modelled | Modelled | The subject of study |
| Vulnerability and adaptation | Adaptation is considered to a limited and inconsistent extent, primarily in agriculture and coasts. Current vulnerability can be well described but changing vulnerability is often not considered | PAGE models adaptation, but in an unsophisticated way. FUND considers changing vulnerability. Adaptation may be implicit in calibration data | Explicitly incorporated as an endogenous choice via an adaptation function | Sensitivity is captured and autonomous adaptation is implicit in structural change. All models but PESETA consider changes in exposure | This is considered explicitly via the modelling of reconstruction capacity | This is captured to the extent that it is in the data |

Source: Vivid Economics

In the following Sections 3.1.2–3.1.6, recommendations for improving the current state of each modelling technique are presented in Box 3 to Box 7.

3.1.2 Bottom-up, sector-specific studies

Box 3. Recommendations for bottom-up, sector-specific studies

- programmes of consistent bottom-up, sector-specific studies should continue to be supported and used as inputs for other modelling techniques. For example the outputs of the AVOID programme could be used in a multi-sector model;
- understanding of how sector specific economic responses vary over geography could be improved so that bottom-up studies need not be so aggregated; this could improve the spatial resolution of IAMs and multi-sector models, although significant uncertainty over changes in climatic variables at local levels will still remain.

These studies are indispensable for policy appraisal as they provide the direct costs and benefits of policy action. However they do not provide indirect costs and benefits and must be aggregated to provide a more full account of total impacts. As a result bottom-up, sector specific studies cannot by themselves provide a macroeconomic analysis of climate change.

Bottom-up, sector-specific studies provide a foundation for other modelling techniques. Therefore their quality and consistency is very important. However there is often a lack of consistency between studies, particularly regarding adaptation, which makes aggregation of impacts difficult.

Studies that estimate bottom-up, sector-specific impacts for several sectors within a coherent framework are particularly useful. Studies such as AVOID, ClimateCost and PESETA are peer-reviewed, consider uncertainty and are designed with their use in other modelling techniques in mind. This helps mitigate problems regarding quality assurance and aggregation.

The spatial resolution of economic responses to changes in climatic variables is generally low and this limits the geographic disaggregation of modelling techniques reliant on bottom-up, sector-specific studies. Climate scientists have developed methods to provide forecasts of changes in climatic variables at a relatively high resolution, but economic damage estimates can, currently, only be provided at a relatively low resolution. This in turn limits the regional definitions of models that use the impacts data of bottom-up, sector-specific studies. Therefore to increase the resolution of economic impact estimates work is required to improve knowledge of local economic responses, although the robustness of local climate projections will remain limited for the foreseeable future.



3.1.3 Integrated Assessment Models

Box 4. Recommendations for IAMs

- direct climate impact estimates in IAMs should be brought up to date;
- the transparency of IAMs could be improved, especially regarding the data used for damage function calibration;
- state-of-the-art stylised macroeconomic models could be adapted to explore endogenous growth and also climate impacts on simple financial assets, although currently only DICE/RICE could be modified with relative ease;
- IAMs could be run considering multiple dimensions altogether, such as an endogenous growth IAM with uncertainty explored via a Monte Carlo simulation.

IAMs are in principal a good way of exploring the total economic impacts of climate change. IAMs are relatively simple models with a great deal of flexibility. This allows them to be used to explore many of the checklist dimensions but also means that calibration is very important.

Current coverage of direct climate impacts is broad but quality should be scrutinised. Current IAMs tend not to reflect the latest science or be particularly transparent. There are notable inconsistencies between IAMs on direct impacts at the sector level and on aggregate impacts at temperature changes of more than 3°C.

More direct climate impacts could be considered but this will require new bottom-up, sector-specific research. There is in principal no reason why damage functions cannot be calibrated to consider a fuller set of climate impacts, as long as calibration data is of good quality and well documented.

Cross-sectoral interactions and trade are dimensions that IAMs cannot explicitly consider. The extent to which these higher-order impacts are important has yet to be determined but if they are important then IAMs will be misrepresenting final impacts. An option would be to calibrate IAM damage functions to the output of a multi-sector model that has been shocked with climate impacts as has been done in (ClimateCost, 2012).

The case for climate change policy may be best made using a range of metrics but IAMs only provide one, GDP-equivalent. While GDP-equivalent is a measure of welfare and so is broader than just GDP as Box 1 explains, IAMs do not provide any other macroeconomic indicators, such as changes to the terms of trade, or indicators of physical change, such as biodiversity loss.



3.1.4 Adaptation Integrated Assessment Models

Box 5. Recommendations for AD-IAMs

- AD-IAMs are not currently suited for answering policy questions about adaptation except at the most general level;
- future development of AD-IAMs for policy analysis requires a clear articulation of policy questions; although questions of a more detailed nature would, at best, require a great deal of model development and, at worst, could be infeasible.

The extension of IAMs to include adaptation has provided valuable insights, but only at the very broadest level. AD-IAMs essentially disaggregate the damage function in IAMs in order to explicitly estimate adaptation benefits and costs, the optimal mix of flow and stock adaptation, and the optimal mix of adaptation and mitigation. However, the results are at a very high level of abstraction. Moreover there are significant concerns about their robustness given present uncertainties. These concerns include those that apply to standard IAMs, and the additional difficulties inherent in forecasting adaptation benefits and costs.

The use of AD-IAMs depends on the questions of policy makers. For example if the focus is on the extent to which adaptation is a substitute or complement to mitigation then AD-IAMs in their current form may be sufficient. However, if the policy question is more specific, such as ‘how can adaptation spending be prioritised across sectors’ or ‘what are the wider macroeconomic benefits of a specific adaptation?’, then AD-IAMs are unlikely to be sophisticated enough to provide a satisfactory answer. For example, they do not include explicit sectoral disaggregation, so they cannot be used to identify sectoral priorities.

AD-IAMs do not currently analyse uncertainty. AD-IAMs are a recent advance and they have yet to be designed to run probabilistically. While this may change in the future it is a significant drawback, especially as the introduction of adaptation adds another layer of uncertainty.



3.1.5 Multi-sector models

Box 6. Recommendations for multi-sector models

- multi-sector models could be run with an updated and greater set of direct climate impacts included;
- multi-sector models could be run with worst-case scenarios as a precursor to running them probabilistically;
- economic interactions with physical sectors could be explicitly represented if physical sectors were included in multi-sector models. The GTAP-W model, which incorporates water, is an example of this;
- an inter-model comparison of multi-sector models could be conducted to ascertain the significance of indirect effects;
- state-of-the-art multi-sector macroeconomic models could be adapted to explore endogenous growth, financial assets, public finance and sophisticated representations of trade.

The key strength of multi-sector models is in the analysis of indirect effects. Indirect effects are an important component of the impacts of climate change that is not widely considered (Watkiss & Hunt, 2012) and this makes multi-sector models useful. However it should be noted that modelling a multi-sector economy is complex and requires a large amount of data, which can introduce error and so increase uncertainty about results.

Work on multi-sector models is at an early stage and so there is not enough evidence to judge the importance of indirect effects. Some evidence suggests that indirect effects on GDP may be significant and may dampen the negative effect of direct impacts, even resulting in a net benefit occurring in some regions and sectors. This is because, in CGE models, changes in relative prices induce agents to substitute away from goods and services that have become more expensive due to climate change. However this result may not be very robust (Watkiss & Hunt, 2012). Furthermore multi-sector models do not consider all the impacts of climate change and inclusion of previously unconsidered impacts may lead to more negative indirect effects.

At present the set of direct climate impacts considered in multi-sector models is narrow but more impacts could be included. Multi-sector models consider a smaller set of direct impacts than IAMs and this could be expanded relatively easily. The primary difficulty in incorporating a direct impact into a multi-sector model is that the impact pathway must be explicitly described, for example a health impact lowers labour productivity, while in an IAM impacts are implemented as a simple reduction in generic output.

Uncertainty analysis in multi-sector models is limited; in particular they have not yet been used to consider worst-case scenarios. Multi-sector models are difficult to run probabilistically due to their complexity, which, given the level of uncertainty in climate change economics, is a significant drawback. In particular, it is possible that the character of indirect effects changes fundamentally when the economy suffers very high damages from climate change. As the full range of uncertainty is hard to explore, emphasis could be placed on considering worst-case scenarios in multi-sector models as this would then bound the



upper end of expected damages. Such knowledge would then make it clear how important it would be to determine the probability of the worst-case occurring.

The response of the economy to the stream of climate damages over time is not fully described. The majority of the multi-sector modelling that has been done to date has used static CGE models which do not allow for an analysis of how sectors react to the stream of damages that climate change will deliver over time. The dynamic multi-sector models that are in use assume adaptive expectations, which means that agents do not take into account all information currently available on the stream of future damages. This lack of dynamism is at odds with both the needs of policy makers and with modern macroeconomic methods.

Multi-sector models provide the best representation of international dimensions of climate change but this is still a limited representation. Current multi-sector models only model trade via Armington elasticities. More sophisticated models of trade exist, though there is debate about whether they add much. There are also a number of other international dimensions of climate change, such as climate impacted growth rates in developing economies and migration that are of interest to policy makers but are not considered in any of the models reviewed.

3.1.6 Extreme weather event studies

Box 7. Recommendations for extreme weather event studies

- the impacts of extreme weather events should continue to be analysed separately;
- the distributional impacts of extreme weather events may deserve more focus than the aggregate macro-economic impacts, especially for extreme weather events in developed economies;
- the impact of worst-case extreme weather events on particularly vulnerable areas could be analysed.

The impacts of extreme weather events in a changing climate are poorly understood and the literature is thin. The research challenges in this area are formidable, including a weak understanding of how climate change will affect the frequency and intensity of extreme weather, and the sheer diversity of extreme weather types and locations that could be affected.

Econometric studies capture all the impacts of past extreme weather but they may not provide good predictions of future impacts if vulnerability changes. The impacts of extreme weather should be recorded in the data that econometric studies use and so econometric analysis gives a full assessment of the costs of extreme weather for the sample of past events considered. However the costs incurred in the past may not reflect the costs incurred in the future if more assets become exposed or if an economy increases its adaptive capacity. Therefore, while a reduced form econometric model may currently be more complete than a structural simulation model, an econometric model does not enable us to understand how impacts will change if the structure of impact pathways and responses change.

Simulation studies face the challenge of describing how impacts evolve as the economy moves from extreme weather event to reconstruction to recovery. Developing coherent modelling techniques that can



represent an extreme weather shock and have an economy that moves from disequilibrium in the aftermath to equilibrium in the long-run is a significant methodological challenge. However the limited work that has been done suggests that such models provide insights that other techniques cannot provide and so continuing to focus on extreme weather event specific models may a good way forward.

Evidence suggests that the macroeconomic impacts of extreme weather are likely to be small relative to the macro-economy of large developed countries but this will mask devastation in some regions and sectors. Developed economies are large enough and extreme weather events are infrequent enough that impacts are likely to be relatively small. However, while impacts will be small when averaged over the whole economy, costs will be concentrated in specific regions and sectors, such as cities on coasts or in flood plains and sectors with high levels of exposed physical capital. These costs can be shared across an economy through policy but there is unlikely to be full cost sharing and so climate change may drive inequality between regions. If regions become less habitable then assets may be stranded and there may be costs of migration and these costs are likely to be borne privately. Such issues are not considered in an aggregate macroeconomic analysis and so more disaggregated modelling or case studies may be warranted.

The workshop considered whether repeated extreme weather events may weaken an economy and whether this could be balanced by the learning and adaptation that may occur if the frequency of events increases. Climate change is likely to increase the frequency of some types of extreme weather events (Intergovernmental Panel on Climate Change, 2012) yet there has been little analysis on whether repeated events compound damages. It can be argued that an economy will learn how to adapt to increased extreme weather and this may prevent damages from compounding. It is an open research question as to whether the rate at which extreme weather events increase will be greater than the rate at which an economy can adapt.



3.2 Defining the research programme

Fundamental questions on purpose and methods need to be answered before modelling work can be taken forward

3.2.1 Connecting policy questions to the evidence

Current evidence is rarely useful in answering specific policy questions. Current modelling techniques do not perform particularly well against the broad framework of assessment developed in Section 1.3. Their performance against more specific policy questions is generally worse.

There is a difference between the macroeconomics of climate impacts and the macroeconomics of climate policy instruments. Climate impacts affect a small number of sectors in the economy directly and can do so acutely, there then may be significant indirect effects but the direct impacts drive the macroeconomic analysis. Policy instruments such as taxes and subsidies can change relative prices across a large number of sectors and so the macroeconomic narrative is one of distortions and whether the costs of introducing a distortion to the economy are greater or less than the benefits the policy instrument delivers. The modelling techniques reviewed focus on the macroeconomics of climate impacts and do not consider the costs of climate policy instruments in a sophisticated way.

Suggestions can be made as to how key areas of policy concern fit within the macroeconomics of climate change and how they could connect with current literature. These areas are project appraisal for adaptation, the understanding of specifically macroeconomic effects, impacts on long-term investments and rates of return and the interaction of adaptation and growth, all of which are discussed in more detail below.

Project appraisal for adaptation

Adaptation policy is likely to often need project-specific cost-benefit analysis. Adaptation is, in many ways, a micro-level issue where a very high level of local detail is required, as is the case in the Thames Estuary 2100 project (Environment Agency, 2012). Therefore top-down macroeconomic models will not be able to identify the costs and benefits of adaptation unless they are calibrated to extensive bottom-up studies. In this case much of the difficult work will have been done and care will be needed to aggregate and monetise the results of a complex project-specific analysis so that it can be integrated with a macroeconomic model. Therefore bottom-up, project-specific cost-benefit analysis should be the first tool of adaptation policy appraisal with macroeconomic models providing secondary analysis.

It is important to distinguish between adaptation that has no co-benefits, contingent co-benefits and absolute co-benefits and this is best done at the level of individual projects. Respective examples are sea walls, disaster risk reduction and improved healthcare. Co-benefits are important as they provide benefits regardless of the degree of climate change that comes to pass and therefore can be good projects even in the face of significant uncertainty. The value of co-benefits often depends on the local context of the investment and so project-specific analysis is required.



The risks of maladaptation need to be identified and this again requires careful analysis at the local level. Maladaptation is adaptation that actually increases vulnerability to climate risks, often either from climate risks other than the original focus of adaptation or from risks that evolve as the climate changes. Modelling how different types of climate risks interact at a specific site cannot be captured by an aggregate model. Furthermore models that solve for optimal adaptation levels, such as AD-IAMs, do so given current knowledge about the path of climate change. It is as if all future adaptation had to be planned today and the plan could not be changed if new information suggested that the original plan would lead to a maladaptation. Given these issues macroeconomic models are unlikely to be the best tools for adaptation policy appraisal.

Understanding of specifically macroeconomic effects

Macroeconomics is concerned with the effect of shocks on economic aggregates and so all indirect effects must be taken into account. Direct impacts to a sector can have impacts throughout the economy as sectors are linked. Policy questions should be interested in whether climate shocks have an effect that is significant beyond these direct impacts as this indicates where the economic risks of climate change lie and whether the macro-economy can autonomously adjust to climate impacts or not.

Multi-sector models are the only modelling technique that explicitly considers indirect effects and the interactions that generate them. These models have not been extensively used in the macroeconomics of climate change and so there is likely to be considerable room for improvement. In particular current multi-sector models do not incorporate many features of state-of-the-art macroeconomic models, such as endogenous growth, financial assets, public finance and sophisticated representations of trade.

Observed data on aggregates should reflect values taking into account all interactions. Such data can be used by reduced form models. For example it can be used to calibrate damage functions in IAMs or it can be used in econometric analysis. Therefore while these models are ‘black boxes’ their results should reflect all of the processes that occur within the economy. However if there is not enough good quality data then there is a risk that the sample of data does not show the true effects.

Impacts on long term investments and rates of return

Concerns over the impact of climate change on the financial sector are best understood as concerns over the performance of long term investments, which are consider only a subset of the costs of climate change. The financial sector is a significant component of the UK economy and so concerns over the impacts of climate change on the viability of the sector are well motivated. Four pathways through which climate change could impact the sector have been identified in (Silver et al., 2010). These are: agriculture, forestry and ecosystems; water resources; human health and industry; and settlement and society. These are a subset of the direct climate impacts that can affect an economy. Silver et al. (2010) argue that the financial sector is most vulnerable to secondary effects of climate change, arising due to lower growth prospects in developing economies and changes in relative prices. These are some of the main concerns of the macroeconomics of climate change.

Investors are only directly concerned with the impacts of climate change on investable assets and so only market impacts are directly relevant, while policy makers should consider all impacts. Investors



only invest in market assets while policy makers have a broader sphere of concern. As a result, current modelling techniques meet the concerns of investors better than they meet the needs of policy makers, although non-market impacts may affect market sectors as discussed below.

The extent to which non-market impacts may undermine market sectors is an important and unresolved question. Some market sectors use ecosystem services and so if there are non-market impacts there will be indirect effects in market sectors. The pathways, let alone the magnitude, of these effects are not well known but may be important as described in Section 3.1.1. Further research is required in this area but if the linkages between non-market sectors and market sectors are very strong then investors should be concerned about non-market impacts as well.

The time scales of climate change are longer than those of investors. Most strategic asset allocations are made with a time horizon of around 10 years (Mercer, 2011) while the impacts of climate change will evolve over centuries. This means that there is a mismatch between current modelling techniques and the needs of investors but this may work in the favour of investors as more is known about the near future than is known about the distant future.

Financial assets are not currently included in climate impact modelling but DSGE models could be a useful tool for future analysis. Macroeconomic models that consider financial assets are more sophisticated than models employed to date but in principal there is no reason why a DSGE model with a representation of the financial sector that incorporated climate impacts could not be developed, although it would not be a minor undertaking. Even then, some macroeconomic variables, such as nominal inflation, cannot be satisfactorily modelled.

Adaptation and growth

The benefits of adaptation can outweigh the costs, so economic growth can be higher with adaptation compared to business as usual as net damages will be lower. A standard growth argument can be made for adaptation. When adaptation is cost-effective it protects incomes relative to the counterfactual of bearing full climate damages. As incomes are higher than in the counterfactual, investment will also be higher. Given that investment leads to growth, adaptation has a growth effect in the same way that any action that increases incomes relative to the counterfactual will have.

The standard growth argument for adaptation can be described as a weak version of ‘green growth’, but there is a possibility of strong green growth effects from adaptation. Green growth is economic growth that also achieves significant environmental protection, where significant protection is least controversially understood to be at least a greater level of protection than is delivered by business as usual patterns of growth (Jacobs, 2012). Green growth is explained in more detail in Section 1.3.5. The strong version of green growth makes the case that environmental protection not only protects the economy, as argued above, but stimulates it as well.

Adaptation is unlikely to deliver green growth in its strongest sense. Adaptation provides net benefits and so could deliver the weaker form of green growth. However adaptation does not correct market failures to the extent that mitigation may and so a growth theory explanation is unlikely. In addition some of the



technology for adaptation is already well known, such as that incorporated in sea walls and water reservoirs, and so the scope for growth from a technological revolution may be low. A Keynesian argument could be made in the short-run but it is contingent on a number of issues, such as a recession, the magnitude of Keynesian effects and the relative return to adaptation versus other economic activities.

The current literature provides little evidence with which to consider the growth effects of adaptation. AD-IAMs alone provide a framework for assessing the growth benefits of adaptation and only the weak form of green growth can be explored due to the structure of the models. Furthermore the incorporation of adaptation may not be sufficiently robust for reliable claims to be made regarding the growth effects of adaptation.

3.2.2 Choosing modelling strategies

Several modelling strategies can be envisaged, from a single, consistent but complex model, to a suite of simpler models. There are advantages and disadvantages to each approach. Incorporating all relevant dimensions into a single model offers a consistent framework, however the model will become more difficult to use and understand as a consequence. Simple models may not provide consistent answers and this requires policy makers to interpret which results are most important, but this must be balanced with the gain in ease of use and explanatory power that comes from abstracting away from all but the most crucial mechanisms that affect the problem at hand. In addition, in a context where debates persist about the best way to represent dimensions such as growth, there is value in preserving model diversity.

The debate over modelling strategies is not unique to climate change. For instance the Bank of England has defended its use of a suite of models (Vickers, 1999). There are a number of dimensions to this debate beyond the concerns of the analyst, such as quality assurance and inter-model comparison, discussed in Section 3.2.3, as well as the ease of communicating methods and results to non-experts. However this must be balanced by the fact that the economics of climate change is complicated and so a complex model may be needed to just crudely capture the key processes and that the capability to code and run complex models is rapidly improving.

Policy makers will use their own implicit model when interpreting results from a suite of models.

Policy makers face the challenge that ultimately a decision must be made and therefore all evidence must be weighed and a judgement made. A single consistent model makes the aggregation of relevant factors explicit, although the aggregation is unlikely to be satisfactory due to quantification issues. A suite of models places the burden of aggregation onto policy makers, who may well be best placed to weigh fuzzy issues but who are also likely to suffer bias. Ultimately, which ever strategy is taken some discussion regarding how the various dimensions of analysis can be considered together cannot be avoided.

A compromise may be to focus on a set of specialised models, which can, individually, be used to answer specific questions, but which can also be formally linked to consider larger problems. The various models in the set could even work on different geographical and temporal scales. There are many attractions to such an approach, although extreme care must be taken to ensure consistency of assumptions.



The OECD Environment Directorate is taking such an approach in its latest work on modelling the impacts of climate change and other environmental threats.

3.2.3 Quality assurance

There has been little work on quality assurance of models according to the expert workshop but this will be vital if models are to be used to inform policy. Quality assurance is needed in two areas: the assumptions made and calibration data used in setting up models, and the quality of the code in the model programs. Without adequate quality assurance results may not stand up to scrutiny or pass the standards needed for inclusion in government impact assessments.

Quality assurance may be improved through more inter-model comparison, validation against empirical evidence and a requirement that models used to inform policy meet high standards of quality and transparency. Resolving these issues should be a high priority; for while a model may appear to cover many of the dimensions of interest, if the quality of the approach is questionable then model results cannot provide a good basis on which to make policy decisions.

There may be lessons to learn from the work on the modelling of physical changes to the climate, especially regarding using inter-model comparison to improve models. Models of the physical changes to the climate are very complex and an effort has been made to understand the differences between models and the need to run them under similar conditions to see how results differ. Such inter-model comparison has been undertaken for economic models of climate change, mainly IAMs, for example (S. Agrawala et al., 2010; Energy Modeling Forum, 2009; EPA, 2010; Warren et al., 2006) but these efforts do not seem to have resulted in significant improvements, while physical climate models have improved.



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Annex 1

Literature review for Integrated Assessment Models

FUND

FUND, currently in version 3.6, takes an exogenous population, GDP, energy efficiency improvement and carbon efficiency improvement scenario. GHG emissions are then calculated from these according to the Kaya identity. Emissions may also be reduced via policy. Mitigation policy is represented by a function calibrated so that emissions costs vary according to the carbon-intensity of a region and so that a 10 per cent emission reduction in 2003 would cost the least emissions-intensive region 1.57 per cent of GDP. The temperature increase and sea level rise due to emissions is then calculated using a simple climate model. There are 16 regions in FUND and the model runs from 1950 to 3000 in time-steps of a year, although post-2300 economies are assumed to be in a steady-state other than climate impacts. FUND is used in a number of papers but the primary reference for the model structure is (Anthoff & Tol, 2012b).

A series of sector specific damage functions transforms changes in temperature and sea level into welfare losses in terms of 1995 USD. The damage functions are designed to reflect the sensitivity of damage in each sector to changes in climatic variables and also to changes in vulnerability due to changes in demand for products and services from directly impacted sectors as GDP per capita increases. Damage functions have regional weights to reflect varying degrees of impact. Damage functions are calibrated to bottom-up, sector-specific studies from a wide range of sources. Not all damages are market damages and such damages are multiplied by a monetary estimate of the welfare cost of the impact, such as the value-of-statistical life, to give impacts in GDP-equivalent.

The sectors that face impacts from climate change are:

- agriculture;
- forestry;
- water resources;
- energy consumption;
- dryland and wetland loss due to sea level rise;
- ecosystems;
- human health (diarrhoea, vector-borne diseases, cardiovascular and respiratory mortality);
- extreme weather (tropical and extra-tropical storms).

PAGE

PAGE, currently in version PAGE09, takes an exogenous scenario of population, GDP and emissions growth rates. Emissions may be reduced via a policy choice, incurring a cost determined by a marginal abatement cost curve calibrated to best estimates. Temperature change is calculated as a function of unabated emissions via a simple climate model. Economies can tolerate a level of climate change and this can be increased, for a cost, via an adaptation policy choice. There are eight regions in PAGE and the model runs

from 2010 to 2200 in decadal time steps to 2050 and then 25 year time steps to 2100 and 50 year time steps to 2200. The primary references on the structure of PAGE are: (Hope, n.d.-a, n.d.-b, 2011, 2012).

Damage functions for economic, non-economic, sea level rise and discontinuity (catastrophe) impacts are calibrated to best estimates. Damage is not felt for temperatures below a tolerable threshold, which can be raised by adaptation. Damages also reach a saturation point, which can vary over time. This caps damage and so represents the maximum vulnerability of an economy to the impacts of climate change.

DICE/RICE

RICE is a version of DICE with the world disaggregated into 12 regions and so the two models share a common micro-founded framework based on the Ramsey model. The innovation of DICE/RICE on the Ramsey model, which is a standard neo-classical growth model, is to consider concentrations of GHGs as negative natural capital and emissions reductions as investments that raise the quantity of natural capital. This means that the two key endogenous variables are the savings rate and the emissions-control rate, both of which are a function of the rate of return on capital. The rate of return on capital is defined by the 'Ramsey equation', where the return on capital is equal to the pure rate of time preference plus the product of the elasticity of consumption and the growth rate. All the parameters of the Ramsey equation are determined exogenously. The pure rate of time preference and the elasticity of consumption are preference parameters that determine the preference for consumption over time and space respectively. The growth rate is determined by the rate of technological progress which, in DICE/RICE, is exogenous. The damage function in DICE/RICE is calibrated to impact estimates across a range of sectors and directly reduces output. The primary reference for DICE is (Nordhaus, 2008) and for RICE is (Nordhaus, 2010).



Annex 2

Literature review for multi-sector models

GTAP-E(F)

GTAP-E(F) is a modification of the GTAP-E model, which itself is a modification of the GTAP model.

The Global Trade Analysis Project (GTAP) have developed and maintained a static CGE model and calibration database for a number of years. GTAP-E makes changes to the production structure of the original GTAP model so that energy is equivalent to a factor of production and can be substituted with physical capital. GTAP-E(F) modifies GTAP-E to enable the study of climate change impacts. So far the impacts on tourism, health and the impacts of sea level rise have been studied.

An important feature of GTAP-E(F) is that regional savings are pooled and invested internationally so that expected rates of return are equalised across regions. The key implication of this is that domestic investment is not constrained by domestic savings, which are a constant fraction of GDP. So capital is internationally mobile. This means that foreign investment flows to any region where a shock increases the rate of return, either by making capital scarcer or by increasing demand for capital for adaptation investments, such as sea walls. However, because GTAP-E(F) is a static model, dynamic changes to investment are not captured.

Berrittella et al. (2006) consider the impacts of climate change on tourism using GTAP-E(F). Changes in tourism are based on an econometrically estimated simulation model of bilateral flows of tourists. Climate change impacts tourism by making a destination more or less attractive and also by making domestic tourism more or less attractive. A change in tourism is modelled as an income transfer to tourism sectors of the economy. The increase (decrease) in these sectors relative to the baseline has the effect, beyond the direct GDP impact, of increasing (decreasing) the relative importance of the service sector and so increasing (decreasing) demand for labour relative to capital. A relative increase in the importance of service sector also decreases imports although this effect is often negated by the increase in imports due to the increase in GDP. The magnitude of tourism impacts are in the order of tenths of a per cent of GDP in 2050.

Bosello et al. (2006) consider the impacts of climate change on health using GTAP-E(F). The impacts from changes in vector-borne, cardiovascular, respiratory diseases and diarrhoea are taken from the literature and implemented via two channels. Mortality and morbidity reduce labour productivity, as well as being valued as a direct welfare loss via multiplication with a value-of-statistical-life estimate. Demand for healthcare is the second channel. Indirect impacts follow the sign of direct impacts. So if there is a net increase in disease there will be a negative direct and indirect impact on the economy. However indirect impacts are significantly smaller than the welfare cost of mortality and morbidity. Price changes are more subtle because, while mortality and morbidity reduce labour productivity and so reduce wages, the increase in demand for healthcare services can increase wages. The magnitude of indirect health impacts are in the order of hundredths of a per cent of GDP in 2050.



Bosello et al. (2007) consider the impacts of sea level rise due to climate change using GTAP-E(F). The study only considers the impacts of erosion, inundation and coastal protection. Therefore there is no accounting for increases in storm surges and so on. The Global Vulnerability Assessment is used for direct impact data. This is the same database that underlies the commonly used DIVA model. Sea level rise of 25 cm by 2050 is considered. A scenario where there is no protection and a scenario where there is full protection are modelled. In the no protection scenario land is lost and this affects agriculture as it is the only sector that uses land as an input. Therefore the impacts are primarily felt by developing countries whose economies are agriculturally dominated and food prices rise. In the full protection scenario there is no land lost and so there is no direct impact. However the structure of final demand is changed to accommodate the increase in investment required. As investment is internationally mobile, countries with the greatest protection needs experience an increase in GDP as total investment is greater than domestic savings. The magnitude of sea level rise impacts are in the order of tenths to hundredths of a per cent of GDP in 2050 and total protection seems to be more costly than no protection.

GEM-E3

Sector-specific impact estimates in 2080 from the PESETA project were implemented in the GEM-E3 CGE model for Europe. A number of temperature scenarios were considered between 2.5–5.4°C. A scenario with 5.4°C of temperature increase plus high sea level rise of 88 cm was also considered. The EU welfare loss is estimated to be between 0.2–1 per cent depending on scenario and Southern Europe is the most vulnerable of the five regions. Four types of impact were simultaneously modelled. Agricultural impacts were implemented by changing sector productivity. Yield losses are small under most scenarios except for the 5.4°C scenario where yields fell by 10 per cent. River flooding impacts are split across sectors, with 80 per cent of costs borne by households and modelled as obliged consumption. The remaining costs are split between agriculture, commercial and industrial sectors and implemented as productivity or capital losses. Tourism was modelled as changes in the exports of the ‘market services’ sector. The impacts of sea level rise on coasts were taken from the DIVA model and implemented in two ways. Migration costs were modelled as obliged consumption and flood costs were implemented as capital losses borne by the whole economy.

ICES

ICES is a dynamic version of GTAP-E(F) with myopic expectations and endogenous capital accumulation. Dynamics in ICES are driven by changes in factor stocks, which are exogenous except for capital. Investment is represented in a similar way to GTAP-E(F) but modified to reflect the dynamic nature of the model. Regional savings are still pooled internationally and invested across regions to equalise growth rates but investment levels are adaptive, which means that they are also a function of past investments in the region. This means that ICES has myopic expectations as investment decisions are based on past states rather than future states. As in GTAP-E(F) domestic savings do not match total investment but, due to the dynamic nature of ICES, an economy has a stock of debt, which records the difference in flows of domestic savings and total investment. At a global level savings and investment must balance in each time period. Time periods in ICES are annual and run from 2002 to 2100. ICES is calibrated to the GTAP 6 database.

Eboli et al. (2010) use ICES to test whether the impacts of climate change have an impact on growth and the distribution of income globally. ICES is set-up with 17 industries across food, heavy industry and light industry, the latter including water and non-market services, and eight regions. The authors shock ICES



with impacts to agriculture, energy demand, human health, tourism and sea-level rise. Sectoral impact estimates are adapted from studies used as inputs in previous CGE modelling exercises. The authors find that the final impacts are mainly distributional and developing countries suffer the greatest impacts. Not all impacts are negative for all regions and sectors as changes in relative competitiveness and higher relative rates of return can lead to higher regional and sectoral incomes.

The dynamic nature of the analysis appears to have important implications for impacts. Impacts can cause economies to diverge over time, with economies that suffer initial shocks suffering progressively worse GDP impacts. This will be a function of the increasing magnitude of impacts over time and reductions in growth due to insufficient capital accumulation. However, the authors do not explore which feature is more significant. They do find that, because shocks increase over time, economies that suffer initial shocks and so attract foreign investment never cease to have a capital account deficit. Some such countries do experience greater growth rates relative to a baseline as they would not receive such levels of foreign capital investment in the baseline. The authors also find that for some regions and sectors the indirect impacts oppose the direct impacts.

Energy exporters and the ‘rest of the world’, which is composed of small developing countries, suffer the greatest losses of five and four per cent of GDP respectively relative to a baseline in 2100. Losses in other regions are limited to one per cent of GDP relative to a baseline in 2100 and some regions gain by up to three per cent. The most impacted sectors are forestry, fishing, gas, rice, energy-intensive and ‘other industries’. The major price changes are in agriculture, where prices rise, and energy, where prices fall.

Bosello et al. (2012) uses ICES in the ClimateCost project to estimate a new damage function for the WITCH model. The authors examine the economic cost of a 1.9°C temperature increase, which is consistent with the A1B SRES scenario. They consider impacts to energy demand, agriculture, tourism, net primary productivity of forests and the impacts of sea level rise and also river floods and thermal discomfort in Europe alone. They find that in 2050 there is a global GDP loss of 0.5 per cent, which is primarily driven by changes in crop productivity, the redistribution of tourism flows and the loss of land to sea level rise. The EU as a whole experiences a 0.01 per cent gain in GDP, with Northern European gains compensating for Southern European losses.

The authors find that indirect effects can oppose, and in some regions and sectors counteract, direct impacts. Such effects are particularly pronounced in agriculture in Europe, where price increases due to large global reductions in output compensate the lost revenue from small output losses in Europe. The authors suggest that this effect can increase over time as economies move away from impacted sectors in a form of private adaptation.

ENVISAGE

ENVISAGE is a dynamic CGE model developed and used by the World Bank. ENVISAGE is calibrated to the GTAP database and has 57 sectors and 112 regions and has ten year time periods. Factor stocks and productivity are dynamic although only capital accumulation is endogenous. Savings are adaptive, similar to ICES, but are not as internationally mobile as in ICES and are also a function of the youth and elderly dependency ratio. There is a distinction between vintages of capital, with capital invested in the current period enjoying a higher elasticity of substitution than capital invested in any prior period. ENVISAGE also



incorporates the simple climate model of DICE so that temperature change is determined endogenously as a function of GHG emissions. More detail on the structure of ENVISAGE can be found in (Mensbrugghe, 2008).

Roson & Mensbrugghe (2012) model the impacts of climate change using ENVISAGE and, with greater temperature change, find larger impacts than ICES, although with a similar regional distribution. The authors model the impact of climate change on agriculture, sea level rise, water, tourism, energy demand, human health and thermal discomfort. The impacts to GDP, for a 4.8°C increase by 2100, vary from a 3 per cent gain to a loss of 12 per cent from baseline GDP in 2100. The authors also find that the impacts to consumption, a better proxy for welfare than GDP, have greater variation between regions than impacts to GDP and in some cases there are worse impacts to consumption than GDP although globally impacts to consumption and GDP are similar.

Annex 3

Literature review for extreme weather impact studies

IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

The IPCC's recent 'SREX' report on extreme events and disasters (Intergovernmental Panel on Climate Change, 2012) summarises the state of knowledge on the impact of climate change on extreme weather events. The report finds that the physical changes to extreme weather events are as follows:

- the frequency of hottest days is likely to increase;
- heavy rainfall is likely to increase;
- it is likely that average tropical cyclone maximum wind speed will increase, although not in all areas;
- the global frequency of tropical cyclones is likely to either decrease or not change;
- there is medium confidence that the number of extra-tropical cyclones averaged over each hemisphere will decrease;
- there is medium confidence that droughts will intensify in some seasons and areas;
- climatic changes imply possible changes in floods although there is low confidence in projections of changes in fluvial floods;
- it is very likely that extreme coastal high water levels will increase due to sea level rise.

Aside from summarising the physical changes to extreme weather patterns the report makes a number of points relevant to the macroeconomics of climate change.

- developing countries have been worse affected by disasters in the recent past;
 - for instance, based on limited evidence, the report finds that during the period from 2001 to 2006, losses amounted to about 1% of GDP for middle-income countries, about 0.3% of GDP for low-income countries and less than 0.1% of GDP for high-income countries.
- the cumulative effect of a sequence of extreme weather events will increase vulnerability;
- the temporal and spatial dynamics of exposure are important as adaptation in one time and place may reduce vulnerability in the short-term but increase it in the long-term as extreme weather patterns change;
- extreme weather is likely to have the greatest impacts on sectors such as water, agriculture and food security, forestry, health and tourism. However climate change may not be the primary driver of change in these sectors.

Econometric analysis of the impact of extreme weather events

Dell, Jones, & Olken (2012) perform an econometric analysis of the historical relationship between changes in a country's temperature and precipitation and changes in its economic performance. The authors analyse year by year fluctuations so as to isolate effects from time-invariant country characteristics.

They find that poor countries experience large negative effects to growth due to higher temperatures. Poor countries suffer a reduction in economic growth of about 1.3 per cent in a year as a result of a 1°C



temperature rise in that year. Temperature rise has no robust, discernible effect on growth in rich countries. The effect on growth of changes in precipitation is relatively mild for both rich and poor countries.

There is some evidence that temperature increases affect not just the level of output in poor countries but the growth rate as well. As the impact of a reduction in the growth rate is compounded over time the magnitude of such impacts can be significant. The authors test the relevance of a number of variables to see if they have explanatory power regarding changes in growth rates due to increased temperature. They find reductions in agricultural output to be particularly important but impacts on industrial output are also relevant. However, impacts on industrial output are not widely considered in the literature. The impact on industrial output is lower in rich countries and the authors suggest this is because there is less weather-exposed employment in rich countries. Furthermore there is some evidence that higher temperatures lead to political instability in poor countries and this may influence growth rates.

The finding that the level and growth rate of incomes in poor countries is significantly more vulnerable than that of rich countries is a major conclusion given the robustness of the econometric analysis. The authors also note some other relevant points:

- the evidence suggests that the impact of temperature on GDP is roughly linear, although this conclusion is tentative;
- there is no significant effect of temperature on either the start or conclusion of conflicts;
- the short-term impacts of temperature changes are greater than long-term impacts would imply. This supports the hypothesis that in the long-run economies can adapt to changes in weather but they take some time to adjust.

Leiter, Oberhofer, & Raschky (2009) examine the impact of floods in Europe on firms' capital accumulation, employment growth and productivity. The key finding is that, in the short-run, companies in flood affected regions show on average higher growth of total assets and employment than firms in regions unaffected by flooding. However productivity declines for affected firms. Firms with a high share of intangible assets are less vulnerable to floods than firms with a high share of tangible assets. Firms with a large share of intangible assets do not suffer as great a decline in productivity. Furthermore floods decrease assets of firms with a high share of tangible assets but increase assets of firms with high intangible assets.

The authors reach their conclusions via econometric analysis of firm level data in Europe in 2000, a year of severe floods. The study is important because it uses firm level data and also because it controls for exposure by distinguishing between tangible capital assets, which can be flooded, and intangible capital assets, which cannot be flooded. The authors argue that the increase in assets in response to floods represents an attempt by firms to re-adjust toward optimal factor holdings and this may induce investment greater than the level required to just replace lost capital. They also note that the short-run decrease in productivity suggests that the adjustment is not initially successful although in the long-run the extra investment may raise productivity but the data considered does not allow for this to be analysed.

Martin, Muûls, & Ward (2011) consider the impact of extreme weather on exports and imports in the UK using firm level data. They find that UK summer heat waves have a robust negative impact on labour productivity. They also find that heat waves affect trade patterns. Heat waves in countries that produce intermediate goods for import to the UK reduce UK productivity while heat waves in countries that are destinations for UK exports result in an increase in exports. The authors also find that the impact of heat



waves in the UK affects the productivity of large firms while small firms appear unaffected. The cost of the 2003 UK summer heat wave is estimated at £400–500 million.

NEDyM (Non-Equilibrium Dynamic Model)

Hallegate (2005) introduces a stylised macro-economic model of an economy, called NEDyM, which can experience both short-run disequilibria and a long-run equilibrium. NEDyM is based on the Solow model but it is modified so that there are short-run price and wage rigidities that adjust over time to equilibrium levels. The resultant over or under production is stored as positive or negative inventory. As prices adjust to equilibrium levels the stock of products in the inventory will change to zero. So in the long-run NEDyM converges to the equilibrium of a Solow model but in the short-run it experiences a disequilibrium as the economy adjusts over time.

Hallegate, Hourcade, & Dumas (2007) use NEDyM to explore both the short-run and long-run impacts of extreme weather events. This study takes great care to realistically implement extreme weather impacts. Aside from the possibility of disequilibria in the short-run, three modifications are made to capture impacts that would not be captured in a standard macroeconomic model:

- **a given percentage reduction in capital reduces production by the same percentage:** this is not the case in standard models where the implicit assumption is that the least efficient capital is destroyed and so production will not fall by the same percentage. This is because production suffers from decreasing returns to capital;
- **there is a distinction between normal, productive investment and replacement investment:** in standard models there is no distinction between types of physical capital. However in this study the authors assume that investments are first made to replace destroyed capital;
- **there are constraints on the pace of the reconstruction process:** constraints to finance, organisation and skills in the reconstruction sector can slow down the pace of reconstruction but are not considered in standard models. The pace of reconstruction matters because the longer an economy goes without replacing capital the greater the compounded impact.

The authors analyse the effect of these modifications on the response of NEDyM to a negative shock to capital equivalent to a 2.5 per cent of GDP. They find that constraints on the pace of reconstruction have a large impact on outcomes while the other modifications are less significant. However constraints on the pace of construction do not have a persistent impact on growth rates unless the constraint is very tight, for example for the growth rate to still be reduced two years after the event the constraint must be that no more than 1 per cent of total investment in the economy can be focused on reconstruction. In all other cases the growth rate increases after the event as the economy increases investment, although welfare will be reduced as consumption is forgone.

The study also explores two other relevant points:

- the authors estimate that the economic amplification ratio is 1.6. This is the ratio of total direct losses to total, undiscounted, indirect losses and if it is greater than one then indirect losses are greater than direct losses. They also find that the economic amplification ratio is increasing in constraints to reconstruction investment;
- the authors argue that the position of the economy in the business cycle prior to a disaster is relevant. Specifically, if an economy is suffering underemployment of factors of production then the costs of



reconstruction will be low as the extra economic activity will not compete with normal economic activity to such a great extent.

Extreme weather events in IAMs

The direct economic impacts of tropical and extra-tropical cyclones enhanced by climate change are modelled in FUND from version 3.4 and 3.5 respectively. Tropical cyclones are considered in (Narita et al., 2009) and extra-tropical cyclones are considered in (Narita et al., 2010). In the base case the direct GDP impact in 2100 of tropical cyclones is 0.006 per cent and of extra-tropical cyclones is 0.0009 per cent. The only indirect impact considered is the increase in mortality, which is valued at 0.0014 per cent of GDP for tropical cyclones and 0.00016 per cent of GDP for extra-tropical cyclones. Tropical cyclones tend to be more powerful than extra-tropical cyclones. The direct economic impact of tropical and extra-tropical cyclones attributed to climate change is equal to a 100 per cent and a 38 per cent increase on current economic losses from such storms by 2100 respectively. However much of the increase in damages is due to the increase in exposure as GDP in 2100 is eight times the 2000 level. Economic damages are calculated via a damage function taking into account baseline storm damage, increasing exposure to absolute damage as GDP per capita increases, an elasticity of storm damage and a simple representation of the impact of temperature change on wind speed and the impact of wind speed on economic damage. Mortality impacts are calculated using the same functional form as the economic damage function and then mortality figures are multiplied by a value-of-statistical-life estimate.

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Company Profile

Vivid Economics is a leading strategic economics consultancy with global reach. We strive to create lasting value for our clients, both in government and the private sector, and for society at large.

We are a premier consultant in the policy-commerce interface and resource- and environment-intensive sectors, where we advise on the most critical and complex policy and commercial questions facing clients around the world. The success we bring to our clients reflects a strong partnership culture, solid foundation of skills and analytical assets, and close cooperation with a large network of contacts across key organisations.

