

# Scoping study: Modelling the interaction between mitigation and adaptation for decision making

## AVOID:

### Avoiding dangerous climate change

AVOID is a DECC/Defra funded research programme led by the Met Office in a consortium with the Walker Institute, Tyndall Centre and Grantham Institute

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## **Key outcomes / non-technical summary**

- **Adaptation and mitigation are complementary measures.**
- **Globally, one cannot trade the concept of ‘1 degree of mitigation’ with that of ‘1 degree of adaptation’, owing to the very different potential for adaptation in different sectors and regions, the issue of scale, the dynamics of the process, and incomplete information about the limits to adaptation. The concept of ‘reaching the 2 degree target’ under 3°C temperature rise with ‘1°C of adaptation’ is not realistic.**
- **Most non-complex integrated models mislead users by attempting to derive optimal tradeoffs between mitigation and adaptation based upon an incomplete and inadequate representation of the climate system, climate change and climate change impacts, and an incomplete representation of the adaptation process. Outcomes are dependent on subjective and sometimes non-transparent judgements. Hence they fail to properly account for the significant uncertainties that pervade climate policy questions.**
- **The integrated models are perhaps most misleading when considering policy options under extreme climate change.**
- **The PAGE09 model overcomes most, although not all, of these difficulties through its rigorous uncertainty analysis and other merits, and can yield useful insight.**
- **Physically based models have limited treatments of adaptation, with the exception of crop models. Representation of adaptation processes in models could be improved, e.g. through the representation of additional water storage and levels of flood protection, or through the representation of reduced demands and improved efficiency in resource use.**
- **Modelling adaptation requires consideration of non-climate influences as well as climate change, as illustrated in the review of coasts. The DIVA coastal model provides a good approach to begin such analysis for this sector.**
- **A new conceptual framework for modelling combinations of mitigation and adaptation using a risk assessment approach is put forward.**

## **SCOPING STUDY: MODELLING THE INTERACTION BETWEEN MITIGATION AND ADAPTATION FOR DECISION MAKING**

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## Executive Summary

The earth is already committed to further warming in the next few decades, to which some adaptation will be required. A certain amount of warming cannot therefore be avoided via mitigation perhaps at least 1.5C above pre-industrial levels. Meanwhile, risks of catastrophic climate change and more particularly dangerous climate change impacts become significant with larger increases in temperature. Since adaptation has limits, mitigation will be required to address this risk. Hence, combinations of mitigation and adaptation will be needed to avoid dangerous climate change.

In exploring these combinations, the question has been posed as to whether adaptation in a +3°C world could reduce impacts to the level that would have been incurred in a +2°C world (which may or may not already have implemented some adaptation measures). Adaptation, however, is a complex process, implemented by organisations and society, generally at the local or national scale. Its feasibility and costs differ greatly across sectors and regions, and even locally within regions. There are limits to adaptation: but a comprehensive assessment of such limits across regions, sectors and incorporating local scale issues is not feasible. Limits to adaptation include both immutable, physical limits and more mutable financial or societal limits that are inherently difficult to quantify. However, even if such information could be collated, the degree to which the +2°C world could be ‘restored’ would depend on the sector and region concerned. In particular, ecosystems have a very limited potential to adapt and so the differences between a +3°C and +2°C world in this sector cannot be removed through adaptation. The concept of ‘1°C of adaptation’ is thus very difficult to realise, owing to the extreme non-uniformity with which adaptation is applied in practise in different sectors, regions and individual locations.

The concept of an ‘optimal’ tradeoff between mitigation and adaptation is often considered. However, this report finds that such a concept is potentially extremely misleading, since ‘optimality’ is strongly influenced by subjective assumptions about the valuation of climate change impacts in disparate sectors and regions; assumptions about the discount rate; and importantly, by highly uncertain input data. Hence, as soon as knowledge about the benefits and costs of mitigation or adaptation improve (as they continually do), the ‘optimal’ solution becomes ‘suboptimal’ and so on. Hence, we rather recommend a risk assessment approach, in which the risk of occurrence of residual climate change impacts is analysed for different combinations of adaptation effort, mitigation effort, and climate change outcome. We suggest that such a study should address uncertainty, including how outcomes compare across different socioeconomic futures; should be multi-institutional, so that a full suite of impacts models can be included; and should incorporate both economic and physically based modelling approaches.

This paper assesses two sets of models which can provide information on the interaction between mitigation and adaptation: analysis at the global level with economics-based aggregated models; and analysis at the sector level with physical impact models. It cannot comprehensively review all types of impacts models available, but rather an overview is provided.

Global economic integrated assessment models (IAMs) (in theory) provide certain insights into the mix – or even the optimal combination of mitigation and adaptation policies, when viewed from an economic perspective. Common issues with many of these models include: inadequate or outdated representation of climate change, in particular relating to a lack of consideration of extreme weather events and catastrophic change; and oversimplified representation of climate change impacts and uncertainty, generally underestimating the climate change impacts and/or the damage that they cause, particularly those

associated with high levels of temperature rise. On the adaptation side, there are many aspects that are inherently difficult to capture in global scale simulations, for example local scale issues and the organisational and institutional contexts in which adaptation processes occur. Models fail to account for adaptation limits and the context-specific nature of adaptation, and often assume that societies are optimally adapted to their climates, whereas in fact many adaptation deficits currently exist, most obviously in developing countries, but also in developed ones. Model applications are also restricted by the evidence base available to them on the costs of climate damage – particularly from extreme climate change - adaptation investment costs and the economic benefits of adaptation at the global scale. This further compromises the ability of simple integrated models to accurately represent adaptation processes.

We conclude that certain limitations in simple IAMs' ability to capture all of the potential impacts of climate change, to represent inherent uncertainties, climate change impacts, adaptation processes and adaptation costs compromise the ability of simple integrated models to inform climate policy decisions about investments in mitigation and adaptation. Models tend to underestimate damage costs and adaptation costs, and to overestimate the potential for adaptation. However, we highlight in particular the PAGE IAM, which does have a good treatment of many uncertain factors and can provide useful input to help study such problems.

Unlike most IAMs, the PAGE model overcomes many of the above issues, by more accurately representing the latest climate change science, including catastrophic change, by not assuming that adaptation and mitigation are perfect substitutes, and by allowing for lags in adaptation time. Most importantly, PAGE has a comprehensive uncertainty analysis allowing for differences in the setting of the discount rate and other contentious parameters, as well as the asymmetric nature of climate change risk (that is, low probability high consequence outcomes). Although PAGE still unavoidably omits significant issues such as limits to adaptation, institutional processes and local scale issues, its carefully designed features allow it to provide useful insights, and we describe it some detail, as well as providing some suggestions for how the model could be further developed to enhance its capabilities in better representing impacts and adaptation.

Global scale physically based impacts models currently have a greater, yet still limited treatment of adaptation processes than IAMs, but there is considerable scope for improvement. For example, in water resources models it would be straightforward to represent water saving technologies and demand management practices through water use scenarios, but exploring the sensitivity to changes in demand may be more useful since the uptake and implementation of such measures is likely to be context specific. Supply side adaptation in the water sector is also likely to depend on local context, but is possible to represent to a certain extent in a generic way. In the agricultural sector, some crop yield models already include farm level adaptation measures such as planting date decisions, crop variety switching and irrigation implementation. It is more difficult to simulate adaptation effects on crop production, for which agro-economic models are typically required. In coastal models, climate-induced and non-climate induced sea level rise both have to be considered; adaptation has to consider both mean, and extreme, water levels; and it is important to include the dynamics of sea level rise and adaptation processes owing to the long time scales involved. A range of planned retreat, accommodation and protection adaptation options are available, and adaptation and mitigation complement in coastal areas, with mitigation being key in avoiding large sea level rise due to ice sheet loss. PAGE09 represents well the dynamic aspects of sea level rise impacts but like most models treats the coastal system as highly aggregate. Only two modelling teams have addressed adaptation in the coastal zone, the most advanced being the DIVA (Dynamic Interactive

Vulnerability Assessment) system which includes a series of internally consistent adaptation options and takes into account impacts on numbers of people flooded and wetland loss.

A new conceptual framework is introduced, based on a dynamic risk assessment of alternative future scenarios which combine alternative levels of mitigation effort and alternative levels of adaptation effort, under future combinations of climate change and socioeconomic futures. This matches the new scenarios process currently unfolding in the integrated modelling community, and it could help decision-makers deal with the uncertainty and complexity of interactions between mitigation and adaptation in climate policy.

## **Introduction**

In this report we review current thinking about how adaptation and mitigation interact in reality (section 1). We then examine the extent to which this is reflected in existing models, covering both integrated assessment models and physical impact models (section 2). We also suggest how models might be improved to better reflect reality, put forward a conceptual framework for thinking about the issue, and finish by suggesting potential ways forward, describing a small work programme and a potential medium sized work programme (section 3).

## **1 The interaction between mitigation and adaptation: substitutability, tradeoffs, limits, and uncertainties**

### **1.1 Global scale issues**

This paper identifies five policy-relevant questions:

1. Can mitigation and adaptation substitute one another?
2. If so, can tradeoffs be made between mitigation and adaptation?
3. Are there alternatives to mitigation/adaptation optimisation?
4. What are the limits to adaptation?
5. What are the uncertainties in projecting climate impacts and adaptation?

These questions are used in the following two sections to briefly discuss the nature of interactions between mitigation and adaptation in the design of climate change policy informed by modelling.

### ***Policy Question 1: Can mitigation and adaptation substitute one another?***

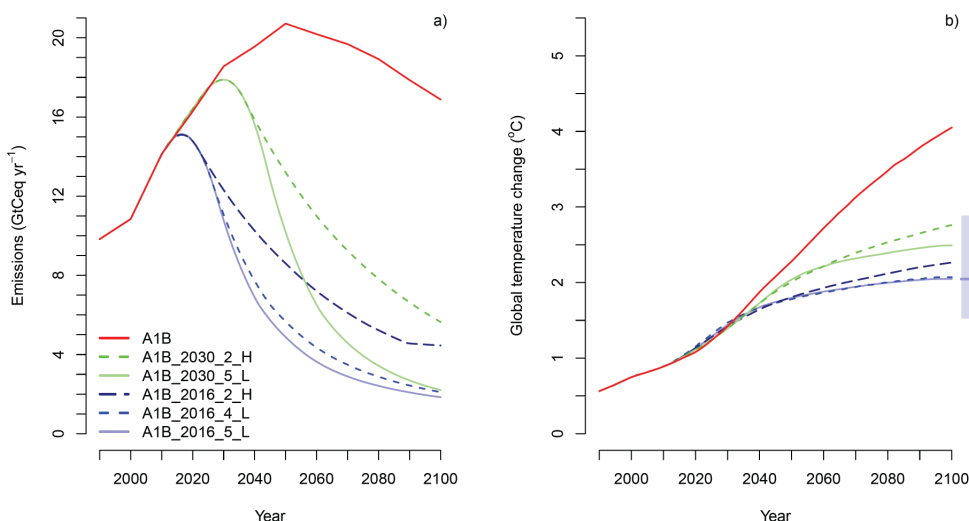
Mitigation and adaptation both serve to reduce the risks associated with climate change. But even the most stringent mitigation efforts can no longer stop climate change from happening; in fact, the first impacts of climate change can already be observed (IPCC, 2007). This then calls for adaptation, particularly to address near-term impacts. Even with the most aggressive mitigation scenarios, the next few decades of anthropogenic change are already locked-in to the system and will thus require early adaptation. As shown in the box below, the climate model projections from a medium-high 'business as usual' scenario and ambitious mitigation scenario, do not diverge until after 2040 (see Figure 1). This is because these early changes are already 'locked-in' to the climate system as a result of historical emissions. They cannot be altered by any mitigation action. Therefore, these early decades are a key priority for adaptation.

Yet mitigation also remains crucial: to rely on adaptation alone would lead to a level of climate change that presents insurmountable challenges to adaptation in the longer term. These include the potential risks of extreme or catastrophic events (e.g. global or regional discontinuities), that have recently come to the fore in the literature on tipping points (Schellnhuber et al, 2005) or tipping extremes<sup>1</sup> (Lenton et al, 2008), for example, the abrupt solid ice discharge from the West Antarctic Ice Sheet, a critical threshold temperature at which a complete disintegration of Greenland Ice Sheet is certain, etc. These events are only likely to occur after 2050 and probably after 2100, but they are a key element of the justification for mitigation.

A critical point to this debate is that the thresholds for these major events are not known precisely. Kriegler et al (2009) elicited potential probability intervals for a selection of tipping extremes, and Levermann et al. (2012) updated these most recently for Europe. In both cases, expert elicitation, or recent review, considers the risk of tipping of major climatic subsystems is significant especially for high warming scenarios, though they are still at significant probability even for a moderate temperature increase within this century. Many of these events could exceed the limits of adaptation, or adaptation would be possible only at very high social, economic and environmental costs. Successful action on climate change, therefore, must include both mitigation and adaptation (see Box 1).

**Box 1: Mitigation and adaptation**

Action on climate change can take the form of mitigation or adaptation. Mitigation refers to all policies and measures aimed at reducing emissions of greenhouse gases, such as carbon dioxide, or at capturing them in forests, oceans or underground reservoirs. Adaptation is the term used to describe all activities aimed at preparing for or dealing with the consequences of climate change, be it at the level of individual households, communities, and firms or of entire sectors and countries.



<sup>1</sup> Subsystems of the Earth system that are at least sub-continental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations.



Fig. 1. (a) Global greenhouse emissions and (b) projected annual global mean near-surface temperature rise (°C) (with respect pre-industrial levels) in the AVOID scenarios. Solid lines refer to median temperature rise, whilst shaded bars provide a 10-90% range. (Key to mitigation scenario names: A1B- xxxx-y-z where ‘xxxx’ refers to the year during which global greenhouse gas emissions peak, ‘y’ refers to the rate (%/year) at which emissions subsequently decline, and ‘z’ refers to whether the final emissions floor level is set to high (H) or low (L).

Whilst in practice, optimal combinations of mitigation and adaptation across the full range of outcomes are impracticable, there may remain some potential for the benefits of both approaches to be maximised through some combination of mitigation and adaptation in some parts of the future policy space. This is illustrated in the figure 2 below. Below a certain level (‘Temperature threshold A’) at the bottom of the figure (defined below as +2°C from pre-industrial, but plausibly somewhere between +1.5 and +2.5°C), mitigation is prohibitively expensive (and for +1.5°C, plausibly impossible due to historical emissions and forecast emission trends over the next decade). Mitigation also does not address impacts in the next few decades, because, as above, the future trends are already locked in until 2040. In contrast, adaptation is highly effective within both this level of change and timescale.

At the other extreme, above a certain level (‘Temperature threshold B’) which is as yet undefined, the risks of catastrophic climate change and tipping elements require mitigation, as major earth system perturbations are beyond the limits of adaptation, and have at least a risk of potentially unbounded impacts. Only mitigation can prevent these events.

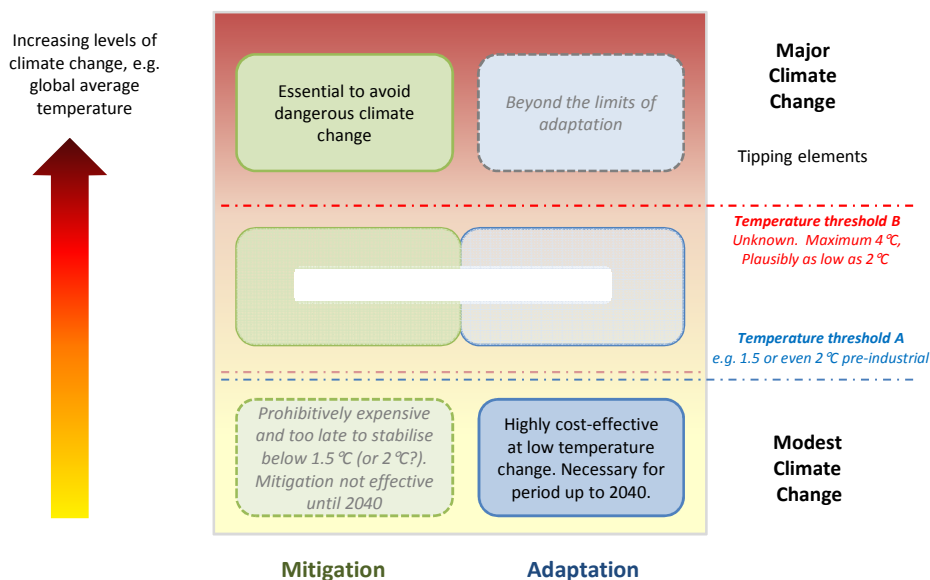


Fig. 2. Climate change and adaptation policy space. Source Watkiss, Benzie and Klein for this paper/WIRE.

Between these two areas there is an area where a mix of mitigation and adaptation can be explored using a risk assessment approach, for example using the conceptual framework outlined in section 3. [Note also that the unknown threshold B could turn out to coincide, or even potentially be lower than, the threshold A.

If future scientific endeavour reveals B to be lower than A, we would find ourselves in a situation where ‘infeasible’ (in the context of the above discussion) levels of mitigation and/or adaptation would be required].

**Mitigation and adaptation are thus complementary strategies.** And because both strategies serve to reduce climate risk, some analysts and policymakers regard them as policy substitutes (*e.g.* Tol, 2005; Buob and Stephan, 2011). If the marginal costs of adaptation fell, it would be rational to adapt more and mitigate less (Ingham *et al.*, 2005). Several IAMs and studies (Bosello *et al.*, 2008; De Bruin *et al.*, 2009) treat the two strategies as substitutes in order to find a balance or even an optimal mix. Their apparent substitutability does not, however, mean that trade-offs between the two are plausible or practicable (see policy question 2).

There may also be synergies or conflicts between mitigation and adaptation. On a regional scale, individual mitigation processes might be synergistic or in conflict with local adaptation, whilst individual adaptation schemes might compromise or enhance mitigation (Parry *et al.*, 2001; Klein *et al.*, 2007). That is, certain measures may reduce emissions and raise or reduce vulnerability at the same time. For example, reforestation schemes sequester carbon whilst also improving water management, soil stability and biodiversity. Such schemes may also support adaptation indirectly if their mitigation benefits are recorded in the form of certified emission reductions, which could be monetised and thus generate finance for adaptation. On the other hand, energy-based adaptation might increase emissions (*e.g.* water desalination or mechanical air conditioning), whilst various mitigation policies might increase vulnerability to climate variability and change (*e.g.* where renewable technologies rely on climate sensitive resources or conditions, such as bioenergy or reliable wind or water, see CCC, 2010). However, these synergies and direct conflicts are thought to be relatively small in the overall picture (Klein *et al.*, 2007).

### **Policy Question 2: Can trade-offs be made between mitigation and adaptation?**

Competition for scarce resources hints at the need to consider possible trade-offs between mitigation and adaptation at least for some areas of the policy space (*i.e.* IAMs are often used to analyse trade-offs at the aggregate global macro-economic level). But in fact, **adaptation does not necessarily occur at the expense of mitigation, and vice versa.**

In a limited set of circumstances mitigation and adaptation might indeed compete for the same resources, for example when national governments choose to invest in emissions reduction or in ‘facilitative’ adaptation (Tol, 2005). If they are considered public policies, mitigation and adaptation would compete for resources with all other public policies (*e.g.* education, public health, military spending) meaning that any trade-off exercise must involve several types of public policy, not only between adaptation and mitigation (an issue not treated by IAMs). But, only to a limited extent is climate policy a public affair. Decisions on adaptation and mitigation are taken by many different actors, operating across different sectors and on different scales and, importantly, managing different budgets.

Climate policy therefore does not involve allocating a single fixed budget to adaptation and mitigation, whereby increased spending on adaptation would mean that less money were available for mitigation (and vice versa). For example, investments by an energy-intensive industry to reduce its emissions will have very little effect on the resource availability of water companies to develop and execute drought-contingency plans, and even less on that of consumers to purchase water-saving shower heads.

The IPCC noted in 2001 that striking the appropriate balance between mitigation and adaptation would be a tedious process and the optimal mix of options will vary by country and over time, as local conditions and costs change (Tóth *et al.*, 2001). It is particularly challenging because of some unique characteristics of the problem: long time horizons, non-linear and irreversible effects, global scale, social, economic and geographical differences amongst affected parties, and the fact that institutions needed to address the issue have only partially been formed (Arrow *et al.*, 1996; Tóth *et al.*, 2001).

The IPCC Fourth Assessment Report chapter ‘Inter-relationships between adaptation and mitigation’ (Klein *et al.*, 2007) concluded that whilst mitigation and adaptation could be considered substitutes in macro-economic theory, the situation is often different in decision-making practice. Box 2 presents the relevant IPCC conclusions.

In addition, **uncertainty about climate and socio-economic change affects the outcome of any optimisation exercise**. As soon as new information becomes available, the optimal mix will be different (Lempert *et al.*, 2000): local conditions change, costs of adaptation and mitigation will be different, and knowledge about climate change and climate impacts evolves. Any optimal mix of mitigation and adaptation assessed today is therefore likely to prove suboptimal over time because it cannot be based on accurate assessments of future socio-economic and climate conditions, including (the dynamic effects of) extreme events and possible catastrophic levels of climate change. Specifically, even if a particular mitigation target is set and met, with a particular level of global climate change in mind, and an anticipated level of adaptation in mind, the actual level of global climate change experienced might be larger (or smaller), requiring much more (or less) adaptation than anticipated. Or a mitigation target may be set but not met, so that more climate change impacts ensue.

**Box 2: Relevant IPCC conclusions** (Klein *et al.*, 2007)

*Decisions on adaptation and mitigation are taken at different governance levels and inter-relationships exist within and across each of these levels (high confidence).*

The levels range from individual households, farmers and private firms, to national planning agencies and international agreements. Effective mitigation requires the participation of major greenhouse gas emitters globally, whereas most adaptation takes place from local to national levels. The climate benefits of mitigation are global, while its costs and ancillary benefits arise locally. In most cases, both the costs and benefits of adaptation accrue locally and nationally. Consequently, mitigation is primarily driven by international agreements and ensuing national public policies, possibly complemented by unilateral and voluntary actions, whereas most adaptation involves private actions of affected entities, public arrangements of impacted communities, and national policies.

Understanding the specific economic trade-offs between the immediate localised benefits of adaptation and the longer-term global benefits of mitigation requires information on the actions’ costs and benefits over time. Integrated assessment models provide approximate estimates of relative costs and benefits at highly aggregated levels, but only a few models include feedbacks from impacts. Intricacies of the inter-relationships between adaptation and mitigation become apparent at the more detailed analytical and implementation levels. These intricacies, including the fact that specific adaptation and mitigation options operate on different spatial, temporal and institutional scales and involve different actors with different interests, beliefs, value systems and property rights, present a challenge to designing and implementing

decisions based on economic trade-offs beyond the local scale. In particular **the notion of an ‘optimal mix’ of adaptation and mitigation is difficult to make operational, because it requires the reconciliation of welfare impacts on people living in different places and at different points in time into a global aggregate measure of well-being.**

***Policy Question 3: Are there alternatives to optimisation?***

The notion of an optimal mix is perhaps best understood as a heuristic device, useful for understanding some of the implications of policy choices, but not practical as an operational decision criterion to identify a policy that is ‘best’. A ‘justifiable’ mix of mitigation, adaptation and other policies will come from consultative and decision processes that are perceived as legitimate, even if flawed; not from globally aggregated estimates of benefits and costs, although aggregated estimates of costs and benefits can helpfully inform such decision making processes.

There is a need to better understand how to build and use capacity for mitigation and adaptation, as well as to know the ‘implementability’ of the options. To develop such understanding requires research on the relevant political, behavioural, cultural and other contexts of decision-making, in particular addressing limits and barriers to action. Research that better reflects the realities of climate policy implementation will enable decision-makers to make better assessments of how much mitigation and adaptation is possible, and thus be more instructive in answering the question of how to avoid dangerous climate change.

The fact that the danger of climate change is reduced not only when climate change is mitigated or when successful adaptation to the impacts takes place, but also when the living conditions for those experiencing the impacts are improved, raises three additional questions. First, how would climate policy best complement other types of public policy? Second, on which spatial and institutional scales would government action on climate change be most effective? Third, how would decision-making responsibilities between public and private actors best be divided? Current economic research on the links between mitigation and adaptation does not address these questions. Instead, it continues to focus predominantly on the perceived trade-offs between mitigation and adaptation, framing climate policy as a national or global cost-benefit question of optimality and zero-sum games (Klein, 2006).

***Policy Question 4: What are the limits to adaptation?***

Greater adaptation efforts will be required if mitigation is less effective or successful than envisaged.

**There are, however, limits to the extent to which adaptation could reduce the impacts not avoided by mitigation.** These **limits exist both in the natural world and in society**; some limits are absolute whilst other ones are mutable (i.e. subject to change). For example, the rate of sea-level rise determines whether or not healthy coastal ecosystems such as salt marshes and coral reefs can adapt by growing landwards and upwards. Beyond a certain rate these ecosystems will not be able to ‘keep pace’. To establish that rate (*i.e.* the adaptation limit) is not as straightforward as it seems, because ecosystem response is often influenced by many other factors. In the case of salt marshes, for example, coastal erosion or sediment starvation could impede marsh development, and coastal infrastructure (such as seawalls) could stand in the way of landward migration. Coral reefs may be damaged and polluted as a result of tourism and other human activities, whilst rising sea-surface temperatures add another climatic factor limiting coral growth.

Irrespective of whether or not these and other limits in natural systems can be assessed with any accuracy, they are absolute limits: once they are crossed adaptation is no longer possible and irreversible change occurs (see tipping elements discussion above - though adaptation limits also include a range of other individual thresholds for specific regions, countries or sectors). Other limits, especially in human systems, are not absolute. These limits can be considered as the points beyond which people can no longer meet their adaptation objectives, or where adaptation can no longer avoid a situation in which people's needs and values are compromised due to climate change. These limits are not the same around the world: a certain level of salt-water intrusion into groundwater could make land unsuitable for agriculture in some places, whereas in other places technology might be available to manage groundwater flows and thus avoid impacts. Limits may also be normative; for example, societies that have agreed on safe minimum standards and minimum levels of service provision (*e.g.* flood protection, water supply) might find that climate change limits their ability to meet these standards and levels. Climate change may provoke societies to reconsider and redefine such standards.

In 2006 the IPCC identified and discussed the following five types of limits (Adger *et al.*, 2007): physical and ecological limits, technological limits, financial barriers, information and cognitive barriers, and social and cultural barriers. The physical and ecological limits are the absolute limits referred to above. The other four types are mutable and therefore closely related to adaptive capacity. The fact that the latter three types are referred to as barriers already suggests the mutable nature of these limits; it is unclear why the same terminology has not been used to describe technological limits.

Knowledge about limits to adaptation could inform the level and timing of mitigation (Patt *et al.*, 2010) and might justify early mitigation action (De Bruin *et al.*, 2009). For example, if it becomes known that a society cannot adapt to sea level rise above a certain threshold (at acceptable social and environmental costs), the value of more stringent, early mitigation increases.

## 1.2 Local-scale approaches

Despite the substantial scientific knowledge base developed over the past two decades, adaptation research has had little impact on adaptation action at the local level. Adaptation researchers either fail to demonstrate to stakeholders the relevance of their findings, or stakeholders base their views and decisions on other kinds of information. A gap exists between adaptation research and action at all spatial levels, affecting public and private stakeholders alike. This gap can be explained by the existence of five bottlenecks to the use of adaptation research in policy and decision-making (Klein and Juhola, in prep.):

- Theoretical concepts and constructs developed and applied in adaptation research do not relate to the decision 'reality' of stakeholders;
- Uncertainty surrounding the potential impacts of climate change makes stakeholders inclined to wait and see rather than act;
- There is a mismatch between the local scale on which many stakeholders operate and the smaller-scale climate information provided by models;
- There is a mismatch between stakeholders' primary concern to manage current climate variability and the medium to long-term perspective of much adaptation research;
- Adaptation research often ignores the fact that adaptation is not the only priority for many stakeholders.

Much adaptation research builds on a conceptual foundation developed in the 1990s and summarised by Smit *et al.* (1999, 2000) and Füssel and Klein (2002, 2006). While this foundation has been useful and influential in structuring academic discourse and international policy on climate adaptation, it does not consider the strategic and operational levels at which stakeholders make actual adaptation decisions, nor that adaptation is a messy, complex process rather than a linear one. To many stakeholders, adaptation concepts developed and applied by academics appear overly theoretical and irrelevant to their day-to-day reality. This even concerns the very use of the word ‘adaptation’, which is not part of most stakeholders’ standard vocabulary and is therefore often interpreted as doing something new, rather than doing something better. Some researchers argue that reframing climate adaptation as climate risk management facilitated by organisational learning could help to link better between adaptation theory and practice (Jones, 2001; Storbjörk, 2007; Pelling *et al.*, 2008). However, this would further reduce the value of models in supporting adaptation decision-making.

As mentioned earlier, the projection of climate change impacts is uncertain for two broad reasons. First, scientists’ incomplete understanding of the way in which natural and social system dynamics affect climate change and climate impacts means that these dynamics cannot be captured fully within any kind of model. Second, it is impossible to predict with accuracy future demographic, technological and economic change, which will influence both greenhouse gas emissions (and thereby the level of climate change) and the emergence or reduction of people’s vulnerability to the impacts of climate change. While scientific progress will continue to yield better understanding of system dynamics, including at the local level, uncertainty will never disappear and stakeholders will always need to consider it in their adaptation decisions (Dessai and Hulme, 2004; Patt and Dessai, 2005; Patt *et al.*, 2005; Hall, 2007). Uncertainty is therefore an unavoidable, key component of local adaptation processes.

However, much adaptation research still conveys the impression that detailed knowledge of future climate conditions is indispensable for adaptation decision-making. But it is not sufficient merely to supply decision-makers with climate scenarios and other forms of climate information; it must be accompanied by targeted guidance to support its uptake, and there needs to be continuous dialogue to balance user requirements and expectations with the ability of the scientists to produce and deliver knowledge and information (Gawith *et al.*, 2009). Such dialogue would foster awareness that the production of climate information is a complex task that requires making compromises between the needs of science and policy (Hulme and Dessai, 2008). Regardless of uncertainty and complexity, however, the spatial resolution of climate projections does not match the scale of many adaptation interventions. Climate science has made great advances over the past years and the typical resolution of climate models has increased in recent years from around 500km<sup>2</sup> in 1990 (IPCC first assessment report) to 180km<sup>2</sup> (IPCC fourth assessment report) (see IPCC, 2007) and lower (e.g. the UK has climate projections at 25km<sup>2</sup> grid square), but spatial resolution is only one challenge: for example, successful adaptation requires an ability to cope with changes in the frequency, magnitude and spatial occurrence of extreme weather events, such as windstorms, floods and heat waves, which are extremely difficult to predict.

Related to the mismatch in spatial scales is a concurrent mismatch in temporal scales. The focus on adaptation to future climate conditions has distracted from the fact that many communities, firms and households are not well adapted to the current climate. In other words, there is an ‘adaptation deficit’ (Burton, 2004), which renders people vulnerable to weather-related hazards already now. Stakeholders may or may not be aware of this deficit and how it might affect them, but in many cases a good starting point for adaptation would involve better managing risks associated with today’s climate. Burton (2004) argues that

adaptation to future climate conditions is less likely to be effective when current adaptation deficits are not also addressed.

Adaptation research and modelling often ignores the fact that adaptation is not the only priority for many stakeholders. Storbjörk (2007) found that, particularly at the local level, adaptation has to compete with many other, often more immediate, concerns. The kinds of trade-off that need to be made at the local level are quite different from the ones being negotiated at the global level: adaptation at the local level may compete with priorities as diverse as traffic congestion, urban green spaces, playgrounds and so on. Experience in Sweden shows that while local decision-makers are keen to have access to the latest climate information, they do not consider climate and impact models helpful in justifying local investment in adaptation (Simonsson *et al.*, 2011).

The five bottlenecks lead one to question the value of current adaptation research and modelling in informing and supporting adaptation decision-making, especially at the local level. There has been a proliferation of adaptation research and modelling in the last ten years, yet much of it has been detached from the reality of decision-makers (Klein and Juhola, in prep.). Much research and modelling is done with an emphasis on scenarios and relative vulnerabilities, rather than on specific options available to stakeholders (Smit and Wandel, 2006; Eisenack and Stecker, 2012). Any attempt to represent (local) adaptation in models must therefore reflect the influence of complexity and uncertainty in the adaptation process if it is to be accurate and useful.

## 2. Models, adaptation and potential improvements

The analysis below is based on a review of the main literature critiquing integrated assessment models, for example (Watkiss, 2011; Patt et al, 2010; Fuessel, 2010; Ackerman et al, 2009; Stanton et al, 2009; De Bruin et al, 2009).

Some of this analysis does not apply directly to the PAGE model, which treats uncertainty and adaptation in different ways to many other IAMs, although some of the general critique is also relevant to PAGE

The PAGE model is described in detail below (see 2.5.1.1).

### 2.1 Integrated assessment models of the ‘cost-benefit’ type

Integrated assessment models (IAMs) of the ‘cost benefit’ type are commonly used to derive ‘optimal’ decisions about the timing of investments in mitigation, or in mitigation and adaptation, at the global scale. IAMs consider, either explicitly or implicitly, technological change, financial resource availability, and other factors determining adaptive (and mitigative) capacity, as well as physical and ecological impacts of climate change. Such models generally contain a simplified representation of climate change and its impacts (Denniss, 2012), and in some cases adaptation, whilst retaining a more detailed representation of the world economic system. Human decision making is represented by simple rules. The design of the models assumes certain parameters and takes certain patterns of behaviour to be universally representative of the agents included in the model (see Box 3).

IAMs are global economic models and therefore adopt an economic framework in their analysis. As a result they provide information from an economic perspective to decision makers at global and national levels wishing to design climate change policies. There is a concern however that a purely economic approach may not be valid when seeking to avoid dangerous climate change, which is likely to involve major ethical or moral choices and may justify more precautionary approaches to decision making.

**Box 3: Model assumptions**

The assumptions that underpin IAMs largely determine their results. Differences in reported results between models can be explained by their use of different assumptions as much as by structural differences (Watkiss, 2011). These assumptions should therefore be of critical interest to decision-makers hoping to use modelling insights to inform their decisions, but in reality users do not always understand the value-laden assumptions that underpin IAMs (Schneider, 1997). Key assumptions include (Watkiss, 2011):

- Climate damage functions
- Discount rate
- Time horizons considered
- Equity weights
- Sectoral and spatial coverage
- Considerations of uncertainty
- Risk aversion.

However, whilst a body of literature has investigated and reported on these issues (e.g. Tol, 2005; Watkiss and Downing, 2008; Hof, et al, 2008; Watkiss, 2011 and many others), there has been less focus on the assumptions underpinning adaptation, even though, according to Patt et al (2010) these involve just as many important issues and sensitive assumptions. As illustrations, the models include (and/or are often based on underlying literature that includes) important assumptions that affect adaptation costs, including:

- That adaptation will be optimal and optimally timed
- That adaptation agents will behave rationally, with access to perfect information,
- That adaptation costs and benefits in early time periods have no legacy issues on later decisions, ignoring inter-dependencies.
- That adaptation decisions are driven by climate change
- That adaptation will be uniform within regions, and that adaptation responses are equally transferable across all countries and regions.

The treatment of these assumptions in the PAGE model is markedly different to most IAMs. That is one reason why PAGE is explained in more detail below and why PAGE is considered suitable for further exploring the role of adaptation in integrated assessment modelling in the conceptual framework outlined below.

Uncertainty is not necessarily a barrier to decision making. Indeed, high uncertainty itself may present the most persuasive reason for taking precautionary measures to ‘insure’ against catastrophic climate change (Weitzman, 2010). However, uncertainty must be communicated to and understood by the decision makers



who intend to use model results. It is therefore important to identify the major uncertainties pervasive in climate change adaptation decision-making and to offer an initial assessment of how these are accounted for in integrated assessment models.

***Policy Question 5: What are the uncertainties in projecting climate impacts and adaptation?***

There are large uncertainties regarding the systems that influence adaptation options. These systems include the climate system, the natural and human systems that are impacted by climate change and the human and institutional systems that drive adaptation processes. The complexity of predicting how these systems will respond to future changes makes predictions, or model results based on assumptions of these dynamic systems, highly uncertain.

For example, the sensitivity of the global climate system to a doubling of greenhouse gas concentrations is not known. To illustrate, the IPCC AR4 (IPCC, 2007) reported that “equilibrium climate sensitivity is likely to be in the range 2°C to 4.5°C, with a best estimate value of about 3°C”, but also that values substantially higher than 4.5°C cannot be excluded, highlighting that probability density functions derived from different information and approaches (e.g. Stainforth et al, 2009) tend to have a long tail towards high values exceeding 4.5°C. The IPCC added that “Analysis of climate and forcing evolution over previous centuries and model ensemble studies do not rule out climate sensitivity being as high as 6°C or more.”. The behaviour of the climate system itself is therefore highly uncertain.

The behaviour of systems that will be affected by climate change magnifies this uncertainty because they are subject to additional layers of uncertainties. For example, the exact response of ecosystems to given changes in mean temperature is not known. Even less is known about responses to more complex changes in the amount or timing of precipitation, drought, flood, etc., the influence of multiple variables acting together, or to the possibility of the early loss of ecosystem species within complex ecological systems. Similarly, the response of urban systems to given changes in extreme events such as heat waves, floods and droughts is not known, particularly inter-dependencies and cross-sectoral linkages, the effects on critical infrastructure and the dynamics of complex human behaviour within urban systems, etc. The extent to which human decision-making processes will be capable of addressing the challenges posed by changes in climate, ecosystems or urban systems, for example, is therefore also highly uncertain, and yet predictions of the behaviour of these systems is crucial for modelling adaptation. Hence, the dynamics of these complex systems can at most be partially represented in models and then only if the model considers a wide range of uncertainty.

This section outlines some of the key areas of uncertainty relevant to decision making based on model results, namely uncertainties relating to climate change, climate impacts, complex systems, adaptation processes and the costs and benefits of adaptation.

### **2.1.1 Climate change**

In most cases, IAMs base their calculations of climate change on **central or average estimates of changes in global mean temperature (GMT)**, which are used to represent the level of climate change that will occur (Stanton *et al.*, 2009). For example the DICE/RICE models are based on GMT, whilst the FUND model includes other impacts that are assumed to change with GMT. Indeed, the FUND model has been

found to contain a weak relationship between global greenhouse gas emissions and climate change, with similar temperatures out to 2100 for all four SRES emission scenarios, resulting in climate projections that are inconsistent with those of the IPCC. This is due to the use of out of date science to represent the carbon cycle and of the temperature response to radiative forcing. FUND, which shows smaller temperature responses to reducing emissions than IPCC simulations on comparable timescales, will therefore underestimate the benefits of emission reductions and hence the calculated ‘optimal’ level of investment in mitigation. (Warren et al 2010) (More recently, FUND has been modernised).

Ackerman et al (2008; 2009) report that some current IAMs project modest changes in damages with temperature, even with very high temperature increases. They argue that such parameterization does not reflect the full range and upper values for uncertainty. This is because models based on GMT do not fully capture the important influences of extreme events and low probability, high magnitude scenarios, and thus exclude their importance in the consideration of subsequent adaptation benefits. Such low-probability high-magnitude scenarios may in fact dominate climate policy conclusions, given the potentially unbounded costs of climate catastrophes (Weitzman, 2009), though they do not seem to dominate the model results.

An important issue here is whether the models are run with central estimates, or consider some form of risk or uncertainty analysis. A number of the models (PAGE02; PAGE09; FUND) can be run with a Monte Carlo analysis. The inclusion of this functionality leads to radically different results to the central tendency values, i.e. mean values of estimated damages are much higher than median values, because of the inclusion of the higher end risks, and for some models (such as PAGE), the inclusion of catastrophes. The difference can be as much as a factor of five (Watkiss, 2011). Monte Carlo runs also normally produce some extremely large outliers, where the combination of upper parts of the probability density function are combined, leading to SCC values that can be easily in excess of \$1000 /tCO<sub>2</sub>. Such results offer decision makers a more accurate impression of the range of uncertainty inherent with climate policy.

The shape of probability density functions (PDFs) for various climate related projections could have important implications for decision-making in relation to extreme events. Changes in average temperatures cannot be used to determine shifts in the probability of catastrophic events. The so-called ‘fat tails’ in some probability density functions (PDFs) show a greater range of probabilities at the extreme end of future projections, implying greater sensitivity to extreme event occurrences under climate change scenarios (e.g. Ruff and Neelin, 2012). IAMs are very sensitive to the ‘tail fatness’ of PDFs for climate change (Weitzman, 2010). Failing to reflect the uncertainty implied by tail fatness in IAM results can therefore mislead decision makers about the implications of various policy choices.

Model results based on GMT will probably underestimate future climate damages and the omission of tipping points in much of the global climate economics literature implies a systematic under reporting of economic costs of climate change (Watkiss et al, 2005; Warren et al. 2006). Some IAMs (PAGE and DICE) do include some representation of major events (through a combination of tipping elements and higher sensitivity), but this coverage remains partial.

Even where sensitivity analysis sheds light on key parameters, models can send mixed messages as a result of over-simplifying assumptions. This can be shown with the results from De Bruin et al (2009), who used the AD-RICE model to investigate ‘optimal’ balances between investments in mitigating climate change, investments in adapting to climate change and accepting (future) climate change damages. The results indicate that short term optimal policies need to consist of a mixture of substantial investments in

adaptation measures, coupled with investments in mitigation, even though the latter will only decrease damages in the longer term. However, in their results, the higher the current value of damages, the more important mitigation become (compared to adaptation) and thus the relative mix of the two depends critically on the assumptions in the model (and input by the model author), notably in relation to the discount rate, the parameterisation of damages, etc. Perhaps the most relevant issue however is the large differences in the predicted optimal mix of De Bruin (2009) versus Bosello (2008), despite using effectively the same model. This difference is due to the time period of analysis considered (2100 vs 2200) and thus the relative importance of higher long-term mitigation costs. All of this cautions against the narrow over-simplistic application of the IAMs to such a complex issue and re-emphasises the need to clearly communicate the assumptions underpinning results to decision makers.

Another important point here is the rate of climate change, an issue that is not captured in any of the current generation of models. It seems fairly obvious that more rapid onset of higher temperatures and other climatic changes will increase impacts (relative to if they occurred over longer periods of time) and increase the challenge (and cost) of adaptation: this could be due to the rate of change being beyond ecosystems acclimatisation rates, or it could be due to the rate of change being quicker than asset turnover, thus requiring earlier replacement (i.e. more expensive adaptation). Similarly, this also has implications for the rate of autonomous adaptation and the effectiveness of planned adaptation. This issue is particularly important because it implies that climate change damages associated with higher emission scenarios, even given that they often omit the potential for major catastrophic changes, may be currently underestimated in the economic models.

### 2.1.2 Climate impacts

IAMs use numerical damage functions to translate different levels of climate change (*e.g.* GMT change) into output losses for the economy (though some models also estimate intermediate physical impacts for some categories). The damage functions used in IAMs in most cases are linear or quadratic functions (Stanton *et al.*, 2009). In fact impacts will likely be highly non-linear (IPCC, 2007) with tipping points and catastrophic climate change more likely at larger levels of temperature rise. However, the thresholds for these tipping points are poorly understood by scientists and therefore difficult to represent accurately in models.

Quadratic functions are not appropriate for representing tipping points; they can produce results that suggest welfare losses at unimaginably high levels of climate change are tolerable (*e.g.* ~50% welfare losses in a +18°C world, see Weitzman, 2010). The most commonly-used damage functions therefore underestimate damages from climate change impacts (Yohe *et al.*, 2007), particularly at higher levels of change.

Some IAMs attempt to include large-scale climate instabilities (mainly the breakdown of the thermohaline ocean circulation in various versions of the DICE model: see Füssel, 2010; Mastrandrea and Schneider, 2001; as well as the collapse of the West Antarctic ice sheet in FUND: Nicholls *et al.*, 2008). Some also include a generic category of discontinuities, such as the PAGE model (Hope, 2006). A critical issue here is that these events are projected to occur in the far future, post 2100, and thus their effects are significantly reduced through discounting. Anything other than a zero pure rate of time preference reduces the reported impact of these events (and conversely, the use of a zero or near zero pure rate of time preference dramatically increases damage costs). The issue of discounting has been the subject of considerable debate following the Stern review, but the critical element of this is that the major tipping elements are most

affected by this (recognised implicitly by Weitzman), such that catastrophic earth system change is subjected to marginal economic discounting.

Very recent IAM updates, for example the 2012 update of the CRED model (Ackerman *et al.*, 2012) have begun to consider the effect of non-quadratic damage functions and catastrophic climate change. The PAGE model also includes non-quadratic damage function (see section on PAGE below). But generally catastrophic climate events cannot be accurately included in the damage functions used in models, not least because the information on these events is as yet highly qualitative in nature. Furthermore, Watkiss (2011) points out how important local severities of climate change impacts are not captured in global or other large scale models. Some IAMs, with the exception of PAGE and FUND, also fail to acknowledge uncertainties relating to potentially positive impacts, where relevant (Watkiss, 2011).

Only some non-market damages are covered by the major IAMs, including health and to a limited extent biodiversity (Watkiss, 2011). Non-monetary metrics exist to measure climate impacts, and have been recommended in the literature (*e.g.* Parry *et al.*, 2001), but have not been taken up in IAMs.

In summary most IAMs do not accurately represent the impacts of climate change, particularly for high end scenarios, which brings into question the usefulness of the economic calculations that follow on the policy mix between adaptation and mitigation.

### 2.1.3 Adaptation processes

Adaptation is a process that is characterised by uncertainty. As a result there are various specific features that make it difficult to predict how much adaptation will actually occur, when, by whom and for what reasons. It is also uncertain whether adaptation will be effective. This uncertainty presents a huge challenge to modellers seeking to represent adaptation decisions.

Adaptation is best understood as a process (Brown *et al.*, 2011; Grothmann and Patt, 2005). **Models, however, tend to treat adaptation as a series of one-off, static decisions** that can be made at certain (optimal) points in time, for example, to build a dam when it becomes cost-effective to do so. It is relatively straightforward to accommodate this sort of behaviour in models, especially where there are clear investment requirements and definable threats (or damage costs to be avoided) – as is arguably the case with a theoretical dam investment decision. However, not all adaptation involves hard engineering solutions to a well-defined problem. The practice of adapting social processes, soft institutions and behaviours is too complex and context-dependent to be accurately recreated in simplified models, yet a vital part of reducing the damage costs of climate change. When adaptation is seen as a process and not a decision, the weakness of model-based adaptation simulations becomes more apparent. These weaknesses challenge the basic assumption common to most IAMs that adaptation will be ‘optimal’. In fact, there are several **reasons to expect that adaptation will be significantly suboptimal in terms of the amount of adaptation that occurs and the timing of adaptation, with implications for the way IAM results are used to support policy decisions.**

**There are current adaptation deficits.** Society is not always well-adapted to current climate. Models are considered to have a poor coverage of existing vulnerability (Watkiss, 2011). This is a particular issue for developing countries, which have large adaptation deficits (Parry *et al.*, 2009). This is likely to reduce the effectiveness of future adaptation. The assumption that future adaptation is overlaid on existing optimal protection does raise concerns whether the models are accurately capturing impacts properly, as well as

adaptation effectiveness. This assumption even occurs in some of the sectoral models, for example, it is assumed in the DIVA coastal model that current coastal protection is in place, and this influences the marginal adaptation costs, as well as the cost benefit analysis. This may even be an issue in developed countries. For instance, the UK is near the limits of coping with current climate variability in some sectors and could be ‘pushed over the edge’ as a result of climate change (ASC, 2011). Most IAMs would assume the UK is optimally adapted. The assumption that future adaptation will be optimal is based on an empirically weak foundation.

**There will be spatial variation in adaptation outcomes.** Local context will determine adaptation outcomes, and extrapolations of this local detail to the global level for modelling are highly uncertain (*e.g.* de Bruin *et al.*, 2009). Even within regions or countries that experience similar levels of climate change, different levels of adaptation will occur. Some countries or sub-national regions will have inherently high adaptive capacity – not simply in terms of available financial resources (income can be and is modelled) but in terms of human, social and ecological capacities (*e.g.* higher awareness of future climate change, stronger institutions, a higher variety of available adaptation options). Adaptive capacity and the variety of available adaptation options will influence the costs of adaptation (*e.g.* higher costs of sea defence if there is no room to migrate), but also the limits to adaptation (*e.g.* a heavily populated thin strip of land between coast and mountains). Numerous other local features will define adaptive capacity and thereby influence the spatial variation of adaptation outcomes, as well as the true costs and limits to adaptation. It is therefore inaccurate to assume that adaptation responses will be uniform across the different regions delineated in IAMs.

**Individual and organisational constraints apply.** The way in which adaptation challenges are framed by individual adaptation agents will vary, leading to a variety of adaptation outcomes. Proactive adaptation depends on decision-makers’ perception of climate risks and adaptation benefits. Perceptions and the frameworks used to understand and overcome adaptation challenges are key variables determining adaptation responses (Grothmann and Patt, 2005); they vary significantly between actors in ways that are difficult to model or replicate at regional or global scales. Simply assuming that these barriers and framing issues are not relevant does not produce robust simulations of how much adaptation will occur. Berkhout (2011) finds that assumptions about utility maximising behaviour in organisations (which are consistent with assumptions in most IAMs) are not accurate in the context of adaptation decisions; aspects such as perception, evaluation, enactment and learning are critically important. For example, adaptation agents with short-term time preferences faced with high uncertainties (and applying standard discount rates) will frequently shun opportunities to invest in long-term adaptation. Individual and organisations constraints apply, such that agents’ willingness to exercise available adaptation options will vary between organisations (Berkhout, 2011).

It is therefore inaccurate to assume that all adaptation agents will respond identically to climate stimuli, even if it were rational to do so. Organisational and individual contextual factors will determine how much adaptation will occur. **Models therefore need to better account for the variation of responses from adaptation agents.**

**Those who can adapt might not.** Adaptive capacity does not equal adaptation action. Whilst modellers can make use of improvements in the measurement of adaptive capacity, there is an emerging view that high adaptive capacity is not a sufficient criterion for implementing adaptation actions. Repetto (2008) provides examples from the United States of where capacity is theoretically high but adaptation and

learning do not occur, leading to higher damage costs from climate change than would be assumed. The Adaptation Sub-Committee (2011) state the UK is making slow progress in converting capacity into tangible adaptation actions. As a result of the disconnect between capacity and action, the ‘adaptation deficit’ may actually be growing in some countries, especially in those with lower capacity than the United States and the UK, as the climate begins to change before any adaptation is implemented. IAMs could be usefully used to explore the implications of different rates of adaptation on the relative timing and costs of mitigation, but it is difficult for such models to predict how well capacity will translate into action when this is not well understood empirically.

**‘Adaptations’ are not just about climate change.** Adaptation decisions are rarely motivated by a climate signal alone (Berrang-Ford *et al.*, 2011): other drivers unrelated to climate change will determine which decisions are selected as preferential and acceptable to local stakeholders, and will therefore determine the timing and amount of adaptation. For example, adaptation to improve the resilience of cities to high temperatures and pluvial flooding may be included as part of an urban regeneration programme, but this programme will be the outcome of protracted negotiations between various stakeholders and heavily influenced by non-climate drivers including local development, politics, demographic and land-use change, etc. Therefore it is inaccurate to assume that adaptation can be modelled as the direct response to a change in climate.

**Adaptation will not be linear.** The timing of adaptation is highly uncertain. Future adaptation may not keep step with changes in climate. Adaptation can be proactive (driven by perception of future change, *e.g.* from climate models) or reactive (in response to actual events). It is well recognised, for example, that extreme events are important triggers for adaptation (Berrang-Ford *et al.*, 2011). Whilst humanity has always adapted to climatic (and other) changes, this has mostly been in response to actual experiences; there are few examples of society effectively anticipating threats and adjusting decisions accordingly. If the same pattern is repeated with climate change, adaptation will lag behind emerging risks, creating at least a cyclical adaptation deficit before event motivate society to ‘catch up’ with its own changing climate. The more rapid the change in climate the less effective reactive adaptation is likely to be (Repetto, 2010). Therefore without being able to predict the occurrence of extreme climate events (which they cannot), it is difficult for models to provide useful information on when adaptation will occur and how quickly.

**Maladaptation will occur.** Despite best efforts to effectively reduce the impact of climate change through adaptation, early experience has revealed the potential for adaptive decisions to increase vulnerability: a consequence known as ‘maladaptation’. Barnett and O’Neill (2009) identify five types of maladaptation that they consider to be likely: increasing greenhouse gas emissions, disproportionately burdening the most vulnerable, high opportunity costs, reducing the incentive to adapt, and path dependency. The extent to which adaptation leads to maladaptation will depend on local context, but early examples suggest that maladaptation will be another constraint on society’s attempts to adapt optimally.

In summary, **the timing and amount of adaptation that can be expected in future is highly uncertain and therefore difficult to model robustly.** Research on climate impacts, vulnerability and adaptation undermines many of the simplified assumptions that underpin most IAMs, such as the accuracy of global climate damage functions, the existence of rational decision-makers and perfect information and the behaviour of adaptation agents under conditions of uncertainty. IAMs tend to misrepresent adaptation as a response to marginal changes to achieve optimal balance, when in reality it will be a frequently sub-optimal, non-linear response to non-linear changes, driven and restricted by a variety of non-climate

motivating factors. **Any assessment of limits to adaptation by IAMs is preliminary and of little use in informing decision-making, because of uncertainty about the existence and level of adaptation limits,** the mutable nature of these limits and the ambiguity of relevant definitions.

**IAMs will therefore tend to overestimate the level of adaptation that will occur in response to a given level of climate change, and/or its effectiveness, because they fail to take into consideration the constraints on adaptation agents in these real world local, institutional and psychological contexts** (all of which will serve to limit adaptation below the optimum).

#### 2.1.4 Adaptation costs

The aforementioned uncertainties also affect cost-benefit estimates (e.g. the level and rate of climate change, timing and amount of adaptation, etc.). In addition, there are various uncertainties that pervade attempts to model the costs and benefits of adaptation. These generally lead to certain adaptation costs being underestimated, and benefits being optimistic, and omitting many factors as a result of assumptions or missing empirical evidence or data sources.

At the most basic level, **some IAMs implicitly assume optimal adaptation and do not explicitly include any adaptation costs** at all (Füssel, 2010). This is equivalent to assuming that adaptation is free (e.g. autonomous adaptation at farm level in the agricultural sector).

As recently as 2007, the literature on the costs and benefits of adaptation was considered ‘quite limited and fragmented’ (Adger et al, 2007) and predominately constrained to a few sectors, notably coastal areas and agriculture (Agrawala and Fankhauser, 2008). The literature has progressed then, though still remains limited (Markandya and Watkiss, 2009, Watkiss and Hunt, 2010 for Europe).

Most of the models therefore take cost information from a few limited studies and extrapolate. This is inevitable given the scarcity of data, but it does raise questions of transferability. Some recent literature has surveyed the (limited) adaptation cost information (Agrawala et al, 2012), and concluded the assessments are in line with the available evidence. However, many of the existing estimates of adaptation are for low-cost measures that will be implemented in early years, e.g. low cost preventative health measures, or marginal increases in flood protection (see case study below), and these are unlikely to be sufficient for major climate change. They also rarely assess major investment associated with tackling higher levels of climate change or extremes, i.e. when the level of change moves beyond marginal tolerance limits and requires doing something different.

Some models have user-defined adaptation costs (e.g. PAGE), though the default settings are largely based on the previous UNFCCC Investment and Financial Flows (2007) study, and therefore are subject to the issues associated with that study (for a critical review of these estimates, see Parry et al, 2009).

As highlighted above, there is also the issue that many of the existing cost estimates define cost for a single scenario, or provide estimates on a ‘predict and optimise’ based approach, i.e. they assume that there is perfect knowledge on future impacts, and they do not consider the cost implications of a single response to future uncertainty.

Economic analyses of climate change rely on the assumption that marginal costs and benefits, as well as absolute costs and benefits, are finite. This is not necessarily the case as outlined by Tol (2003). As Weitzman identifies, the consideration of extreme outcomes leads to radically different conclusions for policy from the conventional advice from standard economic analysis and formalized CBA, and by implication, a different conclusion in looking to find an optimal sweet spot for the balance of mitigation and adaptation (see also Stern, 2006).

Since it is not easy to separate adaptation from current activities in reality, it is **difficult to say empirically what the actual costs of adaptation are** (e.g. what fraction of an investment in a new reservoir is to account for future climate-related water shortages?). It is therefore difficult to estimate and separate future adaptation costs from 'business as usual' costs.

**Very limited validation of adaptation cost data has been undertaken.** One exception is a review undertaken for sea level rise – reported in the box below. The findings are that the costs in the integrated assessment model (DIVA) appear much more optimistic than the detailed national studies, which are looking at practical adaptation within a framework of uncertainty, i.e. without perfect foresight. If this is true for other sectors – and exploring this would seem a priority – it implies that the current costs in the aggregate models are a systematic underestimate of adaptation costs, so much so that they could change the whole mitigation –adaptation debate.

#### **Box 5: An indicative verification exercise: DIVA**

The DIVA Model (Hinkel, 2005; Vafeidis et al., 2008; Hinkel and Klein, 2009; <http://diva-model.net>) is a global coastal model which can assess the impacts and economic costs of sea level rise, and the costs and benefits of adaptation. It is one of most widely cited models in the adaptation cost literature, and has been used in most of the recent global studies (UNFCCC, 2009, World Bank, 2010), at European scale (Brown et al, 2011; Nicholls et al, 2009) and even at country level.

Recent analysis in Europe, as part of the ClimateCost project (Brown et al, 2011) has found that the model reports that adaptation is extremely effective.

Coastal flooding in the EU, along with other impacts of sea-level rise (e.g. erosion), is estimated to lead to high economic costs. The annual costs in Europe are up to €11 billion (mid estimate) for the 2050s, rising to €25 billion by the 2080s (combined effects of climate and socio-economic change, based on current prices, with no discounting). However, the analysis finds hard (dike building) and soft (beach nourishment) adaptation greatly reduces these costs.. The cost of adaptation were estimated at €1.6 billion per year in the 2050s (EU, current prices, undiscounted), and achieves a benefit-to-cost ratio of 6:1 (A1B (I) mid scenario). The benefit-to-cost ratios increase throughout the 21st century. Further, even with a scenario of extreme sea level rise, with a projections of well over 1metre by 2100 (in which annual damage cost are estimated to rise to €156 billion (undiscounted) by the 2080s), adaptation is still projected to be extremely effective, and costs only rise slightly under this scenario, with even higher benefit to cost ratios. As Brown et al acknowledge, the DIVA Model assumes uniform responses to damage and adaptation, whereas in reality, coastal adaptation will be site and context specific. The benefit-to-cost ratio purely provides an economic assessment of the effects of sea-level rise immediately in the coastal zone, but adaptation can have a far more reaching benefit as inland areas also take advantage of the coast (e.g. supply chains, aquaculture products).



Nonetheless, while these sorts of assessment may take the model out of the context it was originally intended for, the estimates produced do not seem valid when compared to sea level protection costs in Europe. Evidence from the Netherlands with the Delta Commission (Delta Commissie 2008) and in the UK (e.g. Evans et al., 2008) implies much higher costs than DIVA. The estimated annual costs for future flood protection and flood-risk management in the Netherlands for the implementation of a comprehensive set of adaptation measures could be in excess of €1 billion/year and these imply higher costs at the whole European scale from DIVA. Similar costs were reported by Evans et al (2008) for the UK. Further, studies at the city level reveal that the costs for some individual projects can be very large. For instance, the Modulo Sperimentale Elettromeccanico barrier in Venice has a capital cost of €4.7 billion (Regione del Veneto, 2010) and the Thames Barrier in London (Environment Agency, 2010) cost £0.5 billion to build (completed in 1982, £1.4 billion at 2007 prices). Both of these projects use moveable barriers across an inlet or estuary.

The reasons for this difference are complex, but highlight issues with other cost estimates.

First, estimates in the Netherlands are much higher because a higher level of protection (acceptable level of risk) is being set, compared to DIVA: the Dutch have historically built to a 1 in 10 000 year level of protection, whereas DIVA assumes lower levels and optimality. In this case, the risk of extreme events has translated to higher adaptation costs. Second, the Delta Commissie is factoring the risks of major extreme sea level rise, potentially in excess of 1 metre by 2100, as is the UK in its' Thames Estuary 2100 project. These recognise the issue of uncertainty, and also the long life times involved in investment decisions to respond to these changes (noting TE2100 has conditional level of future building depending on how sea level rise actually transpires). In other cities, the issues may arise with existing deficits and low levels of protection, whereas the model assumes marginal coastal protection policy is needed, and only looks at the capital costs of dikes, rather than the operational and maintenance costs (which Brown et al highlight could be significant).

It has already been mentioned that societies often face current adaptation deficits. **Models based on assumptions of optimal adaptation fail to account for the shortfall costs associated with adapting to current climate variability** and the reduction in effectiveness of future adaptation when faced with this deficit. This is a particular issue when transferring estimates from developed to developing countries.

As highlighted by several commentators (Parry et al, 2009; Watkiss, 2011b), **the costs (and benefits) of adaptation are determined by the objectives and the framework of analysis**. The objectives of adaptation can be framed in many ways, but from an economic perspective, the critical issue is the trade-off between the original damage costs, the costs and benefits of adaptation, and the residual damage costs after adaptation. A critical issue is whether the aim is to adapt to the most economically efficient (optimal) point (where marginal costs and benefits are equal), consistent with a cost-benefit framework, or whether to maintain current levels of protection (or weaken or strengthen these) framed within a cost-effectiveness framework.

What is clear is that alternative objectives can dramatically alter the costs of adaptation, as evidenced by the difference in coastal and river protection levels. In many cases, the existing levels of protection have been set in policy (or in some cases, even in law), based on a risk based approach for reducing the risks of

major extremes, and thus implicitly have higher levels of adaptation required than the economic optimum (because the impacts of climate change often do not factor in the consideration of extremes – see discussion of IAM damage costs above).

Various **non-monetised values are relevant to adaptation investments**. For example, the cultural value assigned to certain crops by farmers or lifestyles by people who live in high-risk areas will have a significant influence on people's willingness to (and the timing and likelihood that they will) enact various adaptation responses that models assume will be rational. IAMs can in theory include non-market values where the economics literature provides robust evidence of what these are, but most currently do not.

Various adaptation processes will involve significant 'frictional' costs that are likely to influence the timing and acceptability of certain response (Patt *et al.*, 2010). For example, to implement a new spatial planning strategy that, among other things, is more resilient to climate impacts will involve negotiations between competing actors that are costly in relation to the actual additional costs of implementing the strategy. However, these **frictional costs tend not to be recognised**.

Also, **the costs of learning are frequently disregarded**. Ingham *et al.* (2005) argue that a crucial determinant of adaptation costs is the rate at which those who respond to climate change (*e.g.* householders, farmers, firms and local policymakers) can learn about their changing environment. Again, learning costs tend not to be recognised.

Most IAMs count **damage as losses to income, whereas climate impacts will affect capital stocks and productivity** as well (Füssel, 2010). Millner and Dietz (2011) include capital stock losses in their numerical modelling of climate change, but their model is not within the IAM framework. Their methods are not represented in current IAMs (but could be included in PAGE as outlined in section 3).

**Non-climate drivers will influence the costs** of adaptation. For example, underlying socio-economic trends will determine the value of capital stocks or number of people at risk. These same trends will influence the vulnerability of the population (*e.g.* changes in regional economic growth, income inequality, demography, social cohesion, infrastructure investment, migration patterns, etc.) and therefore the likelihood of impacts causing economic losses. These non-climate drivers are perhaps too diverse to be characterised and evidenced in ways that could provide model inputs. However, they could increase or decrease the potential costs of adaptation.

Even if the impacts of climate change were fully known and adaptation responses well understood (which sections above have argued to be far from true), the projection of adaptation costs and benefits would still be heavily influenced by **subjective choices on how to aggregate costs across space and time** (Füssel, 2010). Choices such as **discount rates and equity weights can dominate** IAM results (Watkiss, 2011; De Bruin *et al.*, 2009; see also Box 3). Various IAMs can and do test the sensitivity of results to these assumptions, but this is not always communicated clearly to or properly understood by decision makers when confronted with model results.

If total damage costs are underestimated in IAMs, then the potential benefits of adaptation will also be underestimated, provided that adaptation is not limited from reducing those 'additional' damage costs for any reason. **'Optimal' mitigation pathways can be highly sensitive to changes in adaptation costs and**

**benefits** (Patt *et al.*, 2010), making this an important consideration for decision-makers who use IAMs to inform strategy.

A final area here is the uncertainty in relation to adaptation functions in the IAMs and the effect it has in reducing aggregate economic cost estimates (see Patt *et al.*, 2009). Analysis of adaptation is far less explicitly covered in the models and is incorporated in different ways. The FUND model (Tol, 2002a; 2002b) assumes adaptation happens optimally (in the damage function specification), estimating residual damage and adaptation costs where possible. The PAGE2002 model (Hope, 2005) uses parameterized functions to represent how much adaptation can reduce impacts. Adaptation affects the rate and level of temperature change at which an onset of impacts begin and reduces the severity of these impacts. The AD-DICE model (de Bruin *et al.*, 2007; de Bruin *et al.*, 2009b) can disaggregate the damage function into adaptation costs and residual damages. However, the highly aggregated approach to adaptation in these models has been criticized (Lorenzoni and Adger, 2006; Ackerman *et al.*, 2009; Patt *et al.*, 2009). As highlighted above, the models do not include any technological detail, most (with the exception of PAGE) assume perfect foresight and optimal decisions – thus by their nature they do not consider uncertainty.

These criticisms have led to changes, at least in some of the recent model updates. The PAGE09 model assumes less adaptation than in PAGE2002, particularly in the economic sector, which was criticised for possibly being over-optimistic (Ackerman *et al.*, 2009). This has a significant effect in reducing the economic costs of climate change. The default adaptation assumptions in the PAGE09 model are in aggregate about half as effective as those assumed in the previous model.

A crucial issue here is whether adaptation has limits, and this makes a large difference to the substitutability argument – so for example – in PAGE09, adaptation in the economic sector is assumed to largely reduce impacts to zero up to +1°C of temperature rise from current, but above this it has declining effectiveness, only reducing impacts by 30%, and it is considered ineffective above +3°C above pre-industrial. Adaptation is also considered less effective for the non-market sectors, recognizing the challenges for ecosystems, and only reduces impacts by 15% for the first 2°C of temperature rise above pre-industrial levels.

This highlights a critical issue: while the literature has now effectively critiqued the damage functions, there is still little understanding of the adaptation functions, and whether they can be verified or validated by more detailed studies.

### 2.1.5 Concluding remarks

The current generation of IAMs have a poor representation of adaptation. The highly aggregated approach to adaptation in these models has been criticized (Lorenzoni and Adger, 2006; Ackerman *et al.*, 2008; Patt *et al.*, 2009) as the models do not include any technological detail, they do not reflect the real world constraints that face adaptation decision makers, autonomous adaptation is optimistic (and normally zero cost), and where models include planned adaptation, it is in a highly theoretical form. The models also adopt a predict-and-provide rational and optimal decision model, which assumes perfect foresight. To date,

the lack of evidence on the costs and benefits of adaptation has prevented better representation, but the growth in this literature means that improvements should be possible.

It is highlighted that even with these two areas addressed, these models cannot capture the rich complexity of the trade-offs and complementary/conflicts between mitigation and adaptation (as outlined above), but they would at least be able to focus in and provide commentary on the main areas where policy choices between the two might be inevitable.

Despite some recent improvements (see De Bruin *et al.*, 2009; Hope, 2011; etc.) the results from IAMs that do not explicitly consider uncertainty should generally be treated with significant caution until they can better account for climate change uncertainties, and can model a greater number of the total impacts. Partly as a result of underlying gaps in the literature, models still have a partial coverage of impacts and thus have a systematic under reporting of costs (Watkiss et al, 2005), with particular concerns on the omission (or incomplete consideration of) major catastrophic events and abrupt climate change. This is a particular concern because the exclusion of these effects encourages substitution.

In conclusion, **many of the uncertainties related to adaptation are not well accounted for in IAMs**, which oversimplify complexity in ways that ultimately misrepresent the nature of the decision-making problem. **As a result, IAMs tend to overestimate the level of adaptation that will actually occur.** IAMs also tend to **underestimate the damage of climate impacts** and **underestimate both the potential costs and benefits of adaptation.**

### 2.1.6 Incorporating adaptation into integrated assessment models

Future improvements to the current generation of IAMs might allow decision-makers to reflect on the implied timing of and balance between mitigation and adaptation efforts, especially if adaptation processes were better represented and uncertainties more appropriately reflected. The scale and urgency of the adaptation challenge would probably become more apparent.

PAGE02 (Hope, 2006), and the recent update PAGE09 (Hope, forthcoming) uses simple equations to simulate the results from more complex specialised scientific and economic models. It does this while accounting for the uncertainty that exists around climate change. It uses parameterized functions to represent how much adaptation can reduce impacts. Adaptation affects the rate and level of temperature change at which an onset of impacts begin and reduces the severity of these impacts. It is one of the most widely cited models, and was the primary model used in producing the headline estimates for the Stern review (Stern, 2006).

As such, PAGE09 addresses many of the problems noted in sections 2.1.1 to 2.1.5, and is described further in the next section.

#### 2.1.6.1 PAGE09

Probabilistic calculations are used in some IAMs to better account for uncertainty (*e.g.* PAGE09). Whereas previous versions of the DICE/RICE model group used damage estimates from a limited set of studies (mostly from the US), a wider range of references from different regions is now included. Recent models have been coupled with global or regional impact models (that are not part of the core model in most cases

– PAGE being one exception) to improve the representation of impacts across sectors, or even of non-climate sustainability issues such as pollution or land use (Füssel, 2010).

PAGE09 is an Integrated Assessment Model that uses simple equations to simulate the results from more complex specialised scientific and economic models. It does this while accounting for the profound uncertainty that exists around climate change. Calculations are made for eight world regions, ten time periods to the year 2200, for four impact sectors (sea level, economic, non-economic and discontinuities).

As in PAGE2002, all calculations are performed probabilistically, using Latin Hypercube Sampling to build up probability distributions of the results. The results for two policies and the difference between them are calculated in a single run of the model, so that the incremental costs and benefits of different abatement and adaptation policies can be found. A full description of the model including model equations can be found in Hope, 2011.

The PAGE09 models works with eight world regions, ten time periods to the year 2200, for four sectors (sea level rise, market, non-market and major discontinuities), and is able to examine the costs of climate change, as well as the costs of mitigation and adaptation. The update to PAGE09 takes account of the latest scientific and economic information, primarily in the 4th Assessment Report of the IPCC (IPCC, 2007). It also includes major improvements and updates to the climate, economic cost, mitigation and adaptation modules. The probability distributions for all inputs have been reviewed, and new ranges have been included where appropriate, which allows the model to take account of uncertainty. Additional features in PAGE09 include a specific category of sea level rise, explicit dependence of impacts on GDP per capita, smooth marginal abatement cost curves, and the reduction of costs through learning and technical change.

In PAGE09, adaptation policy is specified by seven inputs for each impact sector. The tolerable temperature is represented by the plateau, the start date of the adaptation policy and the number of years it takes to have full effect. The reduction in impacts is represented by the eventual percentage reduction, the start date, the number of years it takes to have full effect and the maximum sea level or temperature rise for which adaptation can be bought; beyond this, impact adaptation is ineffective. Both types of policy are assumed to take effect linearly with time.

An adaptation policy in PAGE09 is thus 7 inputs for 3 sectors (sea level, economic and non-economic) for 8 regions, giving 168 inputs in all.

As an illustration of how adaptation is modelled in PAGE09, the green line in Fig. 3 shows the tolerable temperature in an impact sector that results from an adaptation policy to increase the tolerable temperature to 2 degC, starting in 2020 and taking 20 years to implement fully. If the temperature rise is shown by the red line, there will be 0.5 degC of impacts in 2000, increasing to 1 deg C by 2020, and then reducing to 0 from 2030 to 2060 after which time the impacts start again, reaching 1 deg C by 2100.

The user is free to specify the start date, the plateau and the number of years to take full effect, to try to reduce the impact from climate change.

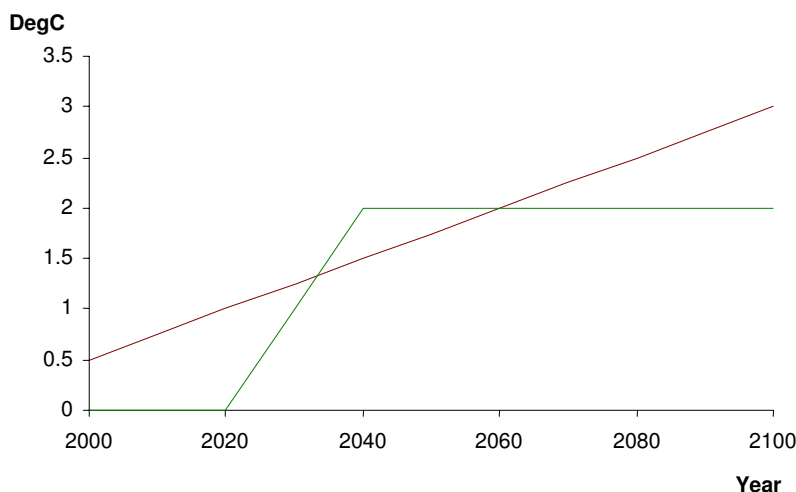


Fig. 3. Temperature and tolerable temperature by date in PAGE09

**Adaptation input values in the default PAGE09 model**

As the climate changes, there will be opportunities to adapt to the changes, either reactively, as the climate changes, or pro-actively, anticipating what future changes might occur. Table 1 shows the default assumptions about adaptation in the EU region (other OECD regions are similar, developing countries are less able to adapt).

Table 1 Adaptation policy input values in the default PAGE09 model for the EU

	<u>Plateau</u>	<u>Pstart</u>	<u>Pyears</u>	<u>Impred</u>	<u>Istart</u>	<u>Iyears</u>	<u>Impmax</u>
EU Sea level	0.25	2000	20	50	2020	40	1
EU Economic	1.0	2000	20	30	2010	20	2
EU Non-econ	0	2000	100	15	2010	40	2

The table is interpreted as follows:

For sea level rise, adaptation means that we will eventually be able to tolerate a 0.25 metre rise in sea level with no impacts. It is assumed that this adaptation was started in 2000 and will take 20 years to take full effect. If the sea level rises more than 0.25 metres, adaptation will not be fully effective, but will eventually be able to reduce impacts by 50%; this type of adaptation starts in 2020 and takes 40 years to reach its full effect. It only works for the first metre of sea level rise above the tolerable level (1.25 meters above pre-industrial); beyond that sea level rise adaptation is assumed to be ineffective.

In the economic sector, adaptation means that we will eventually be able to tolerate a 1 degC rise in temperature with no impacts. It is assumed that this adaptation was started in 2000 and will take 20 years to take full effect. If the temperature rises more than 1 degC, adaptation will not be fully effective, but will be able to reduce impacts by 30%; this type of adaptation starts in 2010 and takes 20 years to reach its full effect. It only works for the first 2 degC of temperature rise above the tolerable level (3 degC above pre-industrial); beyond that temperature rise adaptation is assumed to be ineffective.

In much of the non-economic sector, such as ecosystems, adaptation is harder, so there is no tolerable temperature rise, and the reduction in impacts is only 15%, starting in 2010 and taking 40 years to reach its full effect, which only applies for the first 2 degC of temperature rise above pre-industrial levels.

The evidence base for assumptions about adaptation is very thin, but the assumptions made here are consistent with the findings of deBruin et al (2009) that

“the optimal level of adaptation varies from 0.13 to 0.34, with an average of 0.27, that is 27 percent of gross damages are reduced due to adaptation.” (p15),

and their table 2 showing residual damages of about 85% of damages without adaptation in 2030, and 72% in 2100.

Parry et al, 2009, finds that “much damage will not be adapted to over the longer term... the amount may be significant and is likely to increase over time”, but the only quantitative estimate is for agriculture where residual impacts are estimated at about a fifth of all impacts in 2030, so that adaptation is 80% effective for this sector (p13).

The adaptation inputs are policy variables in PAGE09. They result from policy decisions and so are represented as single choice values rather than probability distributions. These default assumptions in PAGE09 assume less adaptation than in PAGE2002, particularly in the economic sector, which was criticised for possibly being over-optimistic (Ackerman et al, 2009).

The costs of adaptation in any year are calculated by multiplying the amount of plateau and impact reduction adaptation bought by the unit costs of adaptation. The unit costs of economic and non-economic adaptation are uncertain inputs, and their default values are shown in table 2 for the EU. The table shows the minimum, mean and maximum points on the assumed triangular probability distribution, with the mean value also shown for information.

Table 2 Unit costs of adaptation in the default PAGE09 model for the EU economic and non-economic sectors

	mean	min	mode	max	
Sea level plateau	0.0233	0.01	0.02	0.04	%GDP per metre
Sea level impact	0.0012	0.0005	0.001	0.002	%GDP per %reduction per metre
Economic plateau	0.0117	0.005	0.01	0.02	%GDP per degC
Economic impact	0.0040	0.001	0.003	0.008	%GDP per %reduction per degC
Non-econ plateau	0.0233	0.01	0.02	0.04	%GDP per degC
Non-econ impact	0.0057	0.002	0.005	0.01	%GDP per %reduction per degC

In PAGE09 the adaptive costs are specified as a % of GDP per unit of adaptation bought. This is scale independent (like the impacts measure). Regional factors describing the costs in other world regions then become about factors like the length of the coastline, and not about the amount of economic activity in a region, much like regional factors for the impacts. Adaptive costs benefit from autonomous technical change in the same way as abatement costs.

Parry et al (2009) is again the main source for these numbers, with the sea level and non-economic costs calibrated to the sea-level and ecosystem costs in the report, and total costs calibrated to the report’s finding of \$100 – \$300 billion per year in 2030.

All inputs, including the policy values in table 1 and the unit costs in table 2, are fully under the control of the user, and new values can be input in a few seconds with the minimum of effort.

**Illustrative runs with different EU adaptation policies**

The PAGE09 model can be used to calculate full probability distributions of the change in cost, change in impact and net benefit of more or less stringent adaptation.

Two examples are given here. They both involve changes in adaptation policies, with emissions following the SRES A1B business as usual path with minimal abatement. The changes in adaptation policies are for the economic sector in the EU region alone; changes in other sectors, regions, or combinations of sectors and regions, can be modelled just as easily.

In the first example, the plateau input, which defines the temperature rise which we will eventually be able to tolerate with no impacts is increased by 50%, from a 1 degC rise in temperature to a 1.5 degC rise.

Fig. 4 shows the mean global mean temperature rise up to 2100 (in red), and the tolerable temperature rise from the default adaptation policy (blue line), and the revised policy (dotted blue line), all in degC above pre-industrial.

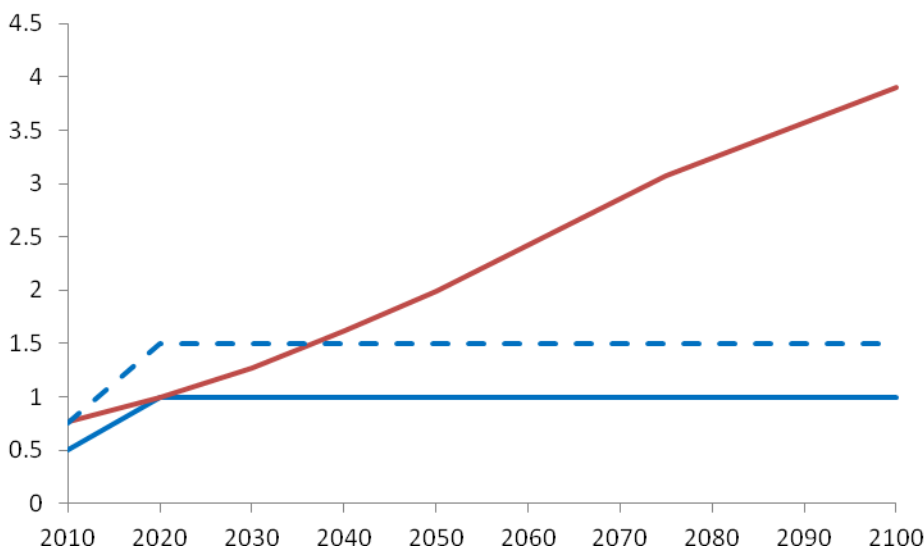


Fig. 4. Mean global mean temperature and tolerable temperature by date in the EU for the default adaptation policy and a revised policy with a higher plateau in the economic sector

The tolerable temperature rise in the EU from the default adaptation policy just matches the mean global mean temperature rise in 2020, but falls below it thereafter; the tolerable temperature rise in the revised policy is above the mean global mean temperature until about 2040.

The mean net present value (NPV) of global impacts with the default adaptation policy is \$nn trillion, with a mean net present value of global adaptation costs of \$mm trillion. For the EU, the corresponding figures are \$m trillion for impacts and \$n trillion for adaptation costs.

The revised EU adaptation policy decreases the mean NPV of impacts by \$1587 billion, while increasing the mean NPV of adaptation costs by \$56 billion, giving a strongly positive mean net benefit of the revised



adaptation policy of \$1531 billion. Impacts and adaptation costs in other regions are not affected. On balance this revision is very worthwhile.

Fig. 5 shows the full probability distribution of the net benefit. The monetary units of the model are \$million, so figure 5 shows the net benefit in \$trillion. The distribution is significantly skewed, with a small chance of much higher net benefits. There is a 5% chance that the net benefit is over about \$5 trillion.

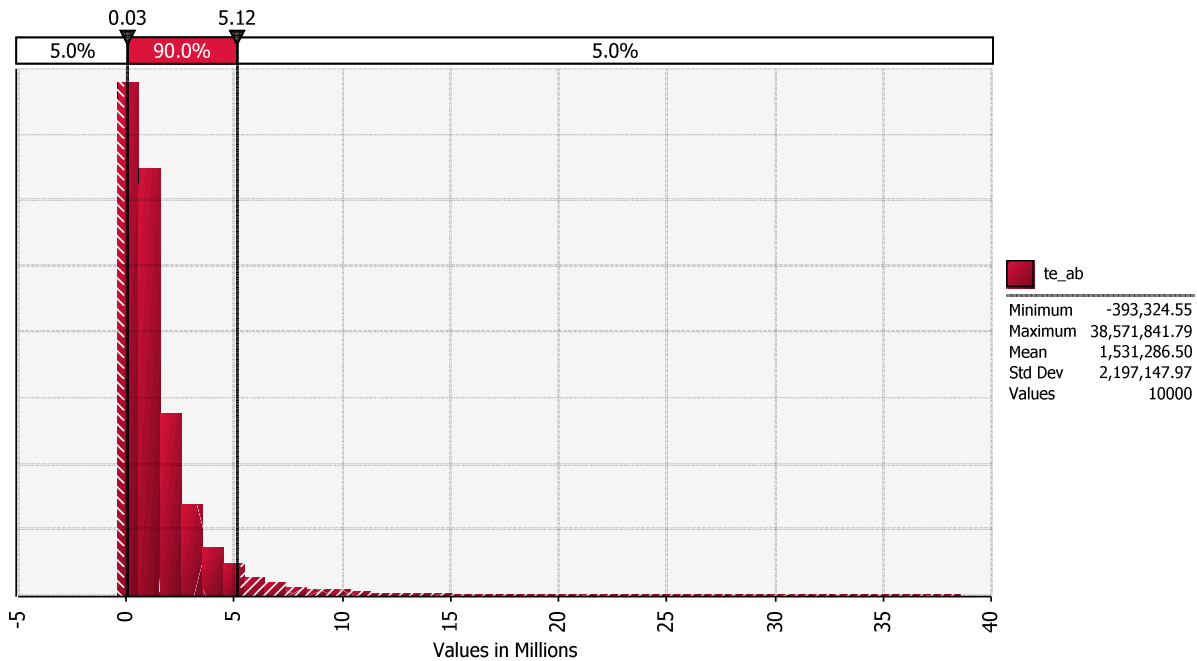


Fig 5. Probability distribution of the net benefit from an adaptation policy with a higher plateau in the economic sector in the EU.

As there are 10000 runs, the standard error of the mean value is about \$2 trillion divided by the square root of 10000, so about \$20 billion. There is a 95% chance that another 10000 runs will give a mean value within about plus or minus \$40 billion of the \$1531 billion found here.

In the second example, the Pstart parameter, which defines when the plateau adaptation commences, is delayed by 20 years, from 2000, to 2020. Fig. 6 shows the mean global mean temperature rise up to 2100 (in red), and the tolerable temperature rise from the default adaptation policy (light blue line), and the revised policy (dotted light blue line), all in degC above pre-industrial.

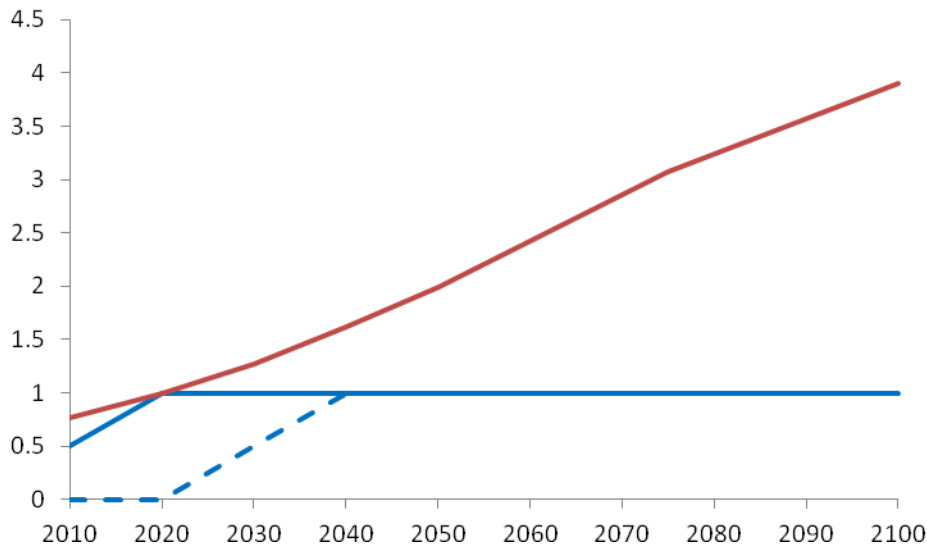


Fig. 6. Mean global mean temperature and tolerable temperature by date in the EU for the default adaptation policy and a revised policy with a later Pstart in the economic sector.

The tolerable temperature rise in the EU in the revised policy is over half a degree C below the mean global mean temperature in all years. It would be expected that this revised policy has greater impacts from climate change, but saves some costs, because of its later start.

This revised EU adaptation policy increases the mean NPV of impacts by \$47 billion, while decreasing the mean NPV of adaptation costs by \$26 billion, giving a negative mean net benefit of the revised adaptation policy of -\$21 billion. Impacts and adaptation costs in other regions are not affected. So on balance this revision is not worthwhile.

Fig. 7 shows the full probability distribution of the net benefit. The distribution is slightly negatively skewed, and there is about a 43% chance that the net benefit is positive.

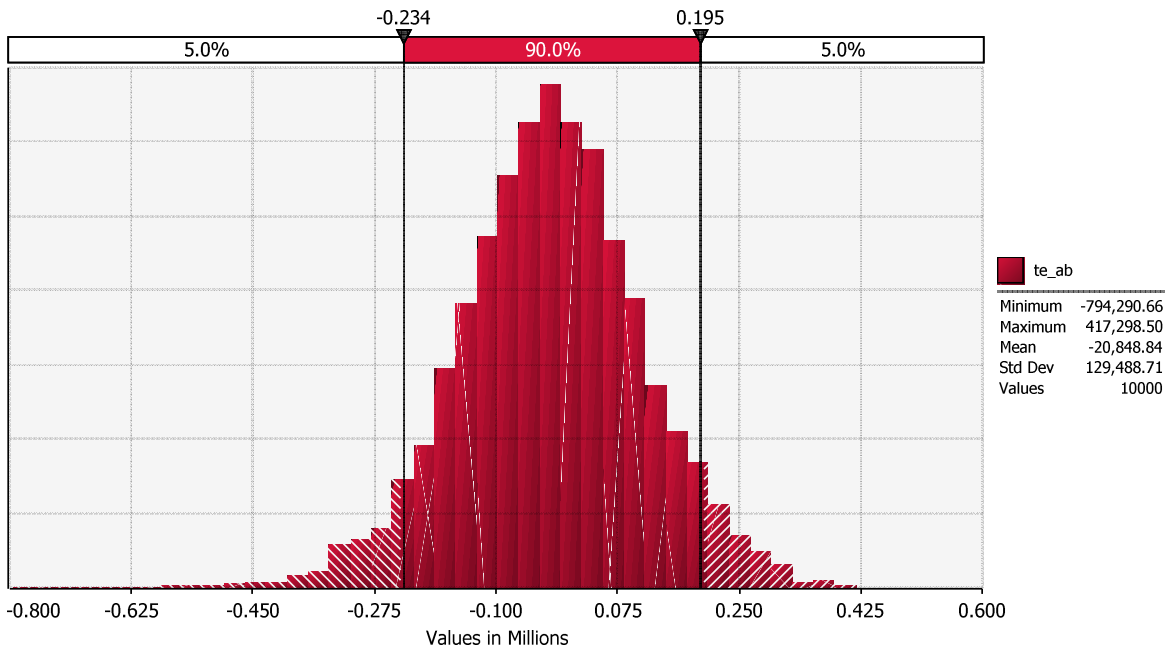


Fig. 7. Probability distribution of the net benefit from an adaptation policy with a later Pstart in the economic sector in the EU.

As there are 10000 runs, the standard error of the mean value is about \$130 billion divided by the square root of 10000, so about \$1.3 billion. There is a 95% chance that another 10000 runs will give a mean value within about plus or minus \$2.6 billion of the -\$21 billion found here.

One other feature of the PAGE09 model is that the model automatically gives information about which of the uncertain inputs to the model has the greatest effect of the results. Fig. 8 shows such a tornado diagram for the net benefit of the second revised adaptation policy.

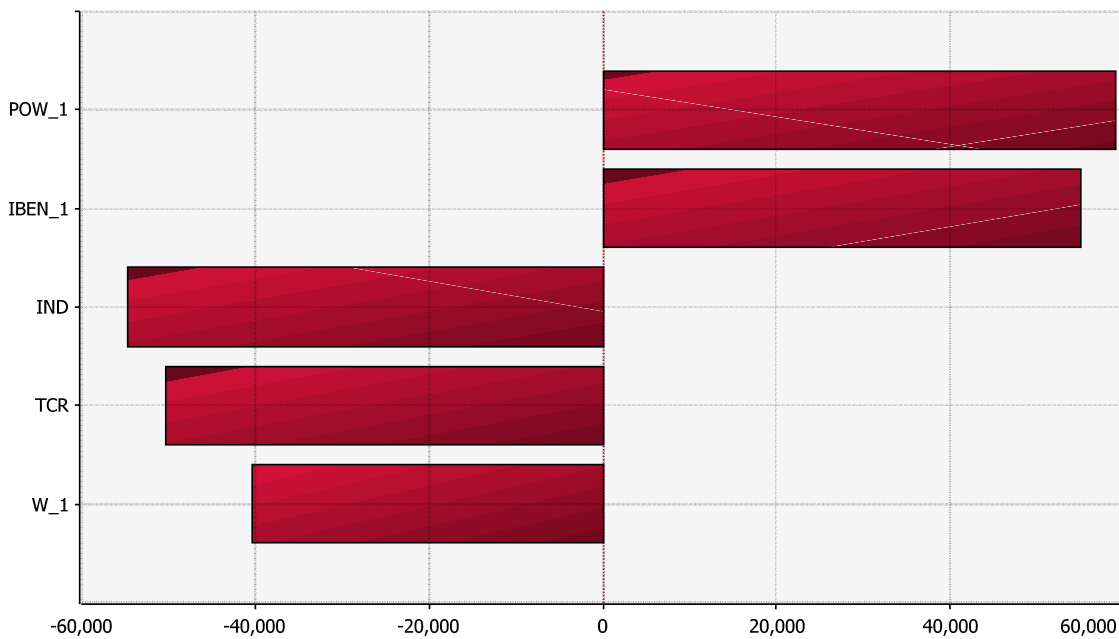


Fig. 8 Major influences on the net benefit from an adaptation policy with a later Pstart in the economic sector in the EU.

The length of the bar for each input shows how much the net benefit of the revised adaptation policy increases for a one standard deviation increase in the input.

The top bar is for the input POW\_1, which is the exponent of the power function linking economic impacts to regional temperature. The higher this input, the higher the net benefit of delaying adaptation; a one standard deviation increase in the input gives about a \$60 billion increase in the net benefit.

This might seem to be the wrong way round, but all the differences in impacts between the default and the revised adaptation policy occur before 2040, since the two policies are identical after that date, as shown in figure 6. Before 2040, the rise in mean temperature is well under the 2.5 to 3.5 degrees against which the impact function is calibrated, so a higher value for the exponent of the power function actually means a lower value for the impacts before 2040, and so delaying the adaptation has less harmful consequences.

The second most influential input is IBEN\_1, the initial benefit in the economic sector for small temperature rises. The higher this input, the higher the net benefit of delaying adaptation; a one standard deviation increase in the input gives about a \$55 billion increase in the net benefit. This is easier to understand; the higher the benefit for small temperature rises, the lower the harmful effects of delaying adaptation.

The next two inputs are scientific ones. The first is the indirect cooling effect from sulphates. The higher (i.e. less cooling) this is, the lower the net benefit from delaying adaptation. The second is the transient climate response. The higher this is, the lower the net benefit from delaying adaptation. Both influences are in the expected direction, as the higher the input values, the more the climate changes and so the higher the impacts.

The final input in figure 8 is W\_1, the economic impact at the calibration. If this is one standard deviation higher, the net benefit of delaying adaptation is about \$40 billion lower, once again because the higher the input, the greater the impacts will be.

The unit cost of economic plateau adaptation does not feature in the top five influences. In fact it is the ninth most important influence, with a one standard deviation higher value leading to about a \$7 billion greater net benefit from delaying the start of adaptation.

These results are only illustrative as they are predicated upon emissions continuing along their business as usual path from the IPCC SRES A1B scenario. In reality, more or less aggressive abatement policies will be pursued if climate change continues to be seen as a serious issue. Exactly similar calculations of the costs and benefits of different adaptation policies can be made with the PAGE09 model assuming whatever abatement policy is thought likely to occur.

***Which caveats from section (1) can be tackled by PAGE09?***

PAGE09 applied in our conceptual framework (see section 3) that looks at the risks associated with different combinations of adaptation and mitigation, can simulate the damages remaining for different levels of investment in adaptation. Hence, an emissions scenario including a particular level of mitigation effort can be used to drive calculations of impacts in PAGE, including or not including adaptation.

Table 3. List of caveats and the degree to which PAGE can overcome these, or could be adapted to overcome them.

CAVEAT/ISSUE COMMON FOR IAMs	IS THIS OVERCOME IN PAGE09?
Representation of climate change out of date or inconsistent with more complex models	This is not an issue in PAGE09, for which the representation of climate change is consistent with Met office mean and uncertainty results from medium scale climate models
Representation of climate change does not cover uncertainties	This is not an issue in PAGE where a probability distribution is used to represent climate sensitivity, corresponding to the latest scientific information. In the conceptual framework it is suggested to choose particular levels of climate change to examine, i.e. particular points in the pdf: this could be done in PAGE09 too
Representation of climate change does not cover catastrophic climate change	PAGE09 does include catastrophic climate change. Of course, the probability distribution is still scientifically uncertain so the issue cannot be completely resolved, but it can be made consistent with the current literature
Damages usually underestimated	The damage function in PAGE is neither linear nor quadratic (both these representations were criticised in section 1). Instead the damage function in each impact sector can take any polynomial form, and also includes a separate damage function for discontinuities.
Damage representation lags behind literature	Not an issue in PAGE, as long as the results from the AVOID programme continue to be incorporated into the model.
Discount rate	Uncertainty range for this used in PAGE09 allows user to understand how this affects the outcome, the key issue missing for some other IAMs
Equity weighting	Included in PAGE09 (but can be switched off if desired)
Sectoral coverage	Market and non-market impacts are represented, but there is no detailed representation of individual sectors. This could be included with 18 months work .
Limits to adaptation, organisational constraints apply	Especially with the limited sectoral breakdown, limits to adaptation need to be specified from other studies – this is consistent with the approach taken to climate sensitivity, impacts and abatement costs.
Current adaptation deficit not modelled	Estimates of impacts include adaptation deficits where they exist.

Local scale issues cannot be represented	Always a problem in global scale modelling approaches. PAGE09 divides the world into 8 regions. With 18 months effort, the number of regions could be increased, but probably not beyond 15.
Adaptation and mitigation are not perfect substitutes for each other	The PAGE09 model doesn't assume that they are. Neither adaptation nor abatement completely remove impacts. The model allows various combinations of adaptation and abatement to be investigated.
Assuming that adaptation will be optimal and optimally timed	PAGE09 includes lags to represent this
Adaptation agents have access to perfect information	PAGE09 does not assume perfect information.
Adaptation decisions driven by climate change when they are actually not	Adaptation decisions are choice variables in PAGE09; no assumptions are made about the reasons for the choices.
Adaptation will be uniform within regions	With 18 months effort, the number of regions could be increased, but probably not beyond 15.
Limits to adaptation	A major issue – identifying whether or not if the model 'chooses' to adapt, whether it's simulating a feasible process or not (refers to both physical, financial, organisational and social feasibility)
Maladaptation ignored	Can't really handle using this approach
Adaptation costs underestimated	PAGE uses probability distributions from the literature on adaptation costs. Six months effort could allow estimates of costs outside the EU to be aligned with the best available literature.
Adaptation costs only affect income, not capital stocks or productivity	If economic estimates of these costs exist they can be included into PAGE09 with six months effort.
Additional issue	Optimizing under uncertainty is a very difficult technical task. Eighteen months effort would allow the model to reach the state of the art in optimization.

Hope (reported in Parry et al, 2009) used the PAGE02 model to assess the aggregated global costs and benefits of adaptation, based on adaptation levels and assumptions from the Stern Review. This uses the regional costs of adaptation reported in UNFCCC (2007). Adaptation measures were found to be very worthwhile, with a mean benefit to cost ratio of about 60 in the A2 scenario and about 20 in a '450ppm' abatement scenario, and that adaptation reduces the mean net present value (NPV) of aggregate economic impacts over the next two centuries by around one third.

However, the adaptation component in PAGE02 (economic sector) was criticised for possibly being over-optimistic (Ackerman et al, 2009). This led to an update in the PAGE09 model, which assumes less adaptation. This has a significant effect in reducing the economic costs of climate change. The default adaptation assumptions in the PAGE09 model are in aggregate about half as effective as those assumed in the previous model. While the setting can be altered by the user, the default PAGE09 settings are that adaptation in the economic sector is assumed to largely reduce impacts to zero up to 1C of temperature rise from current, but above this it has declining effectiveness, only reducing impacts by 30%, and it is considered ineffective above 3 degC above pre-industrial. Adaptation is also considered less effective for the non-market sectors, recognizing the challenges for ecosystems, and only reduces impacts by 15% for the first 2 degC of temperature rise above pre-industrial levels. Similarly, adaptation is not effective against tipping elements. As highlighted above, these changes more accurately consider the trade-off between mitigation and adaptation, more accurately putting constraints on where adaptation is likely to be effective

In summary, whilst PAGE overcomes many of the caveats, there remain several aspects of uncertainty that cannot be captured (e.g., gaining an understanding of how sensitive the results are to an uncertain limit to adaptation or an uncertain adaptive capacity is useful, but cannot provide a certain answer to the degree to which it is possible to adapt to a particular impact).

Similarly, we may understand the sensitivity of the results to an unknown climate sensitivity or carbon cycle feedback parameter, but as we cannot be certain about the values, we cannot use this information to derive a tradeoff – any ‘optimal’ decision could turn out to be very wrong. PAGE allows such an optimisation process to take account of uncertainties, and whilst this is a great improvement, the outcome is still dependent on the uncertain shapes of the probability distributions which are provided to the model.

#### **2.1.6.2 CRED** Based on update v1.3 (Ackerman et al., 2012).

The recent update of CRED now provides ‘choices’ of damage functions, some of which incorporate up-to-date evidence on catastrophic climate change and losses to economic output (Ackerman *et al.*, 2012). Climate and Regional Economics of Development (CRED) is an integrated assessment model, with a central focus on the global distribution of climate damages and climate policy costs. It is designed to estimate both the best pace of investment in mitigation, and the best distribution of the cost of that investment to regions of the world, with the goal of informing global climate negotiations and to help break the stalemate between developed and developing countries. Version 1.3 of the CRED model was completed in June 2011.

CRED uses the DICE 20075 model’s equations for climate dynamics, based on a three-compartment model (atmosphere, shallow oceans, and deep oceans) with separate carbon concentrations and transition probabilities for movement of carbon between them. CRED has been re-calibrated so that its results align with the MAGICC model (The Model for the Assessment of Greenhouse-gas Induced Climate Change; see <http://www.cgd.ucar.edu/cas/wigley/magicc/>) for a range of scenarios, which involved modest but significant changes to the parameters used in DICE.

The inputs to the climate module are current global emissions and non-CO2 forcings, previous temperature, and previous concentrations of carbon dioxide in the three compartments. The outputs are current temperature and concentrations.

Four different ‘options’ of damage functions are included in CRED (Fig, 9), with two (c and d) having a bigger influence at higher temperatures. As with other IAM damage functions, damages are based on increases in mean temperature. However, CRED is noteworthy for its inclusion of damage functions that tend towards total loss of global output (99%) as a result of climate change at upper temperature ranges, in response to evidence from Weitzman (2010). Other damage function options within CRED (which are more typical of IAMs), in contrast, estimate that 50% of global output is not lost until temperature increases reach between 12°C and 18.8°C.

CRED uses its own vulnerability index to account for the distribution of damages across nine global regions. This index is based on the proportion of GDP in agriculture and tourism, the proportion of total population living below 5m (as a proxy measure of coastal exposure) and freshwater resources per person. It is therefore a crude index of vulnerability that does not account for the true nature of exposure, sensitivity or adaptive capacity. However, there are few options to improve the index without a clearer consensus in the literature on the actual components of vulnerability. The CRED vulnerability index assumes that vulnerability does not change over time.

Figure 2: Four damage function options

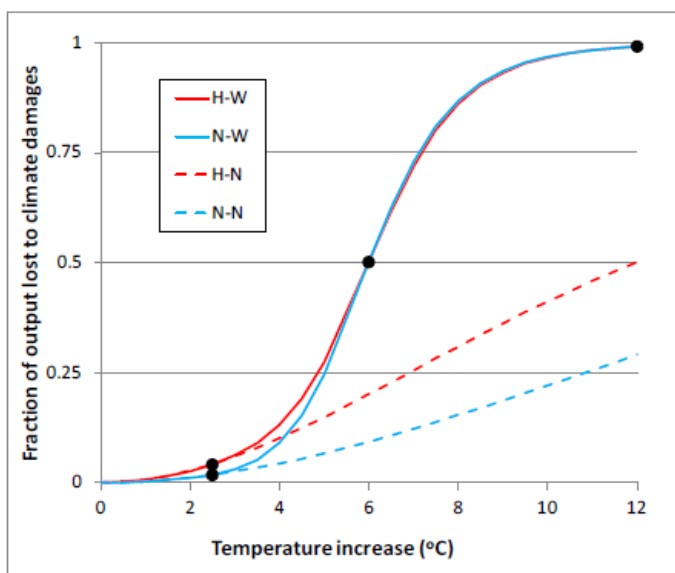


Fig. 9 Damage function options in CRED.

**Which caveats from section (1) can be tackled by CRED?**

Table 4. List of caveats and the degree to which PAGE can overcome these, or could be adapted to overcome them.

CAVEAT/ISSUE COMMON FOR IAMs	
Representation of climate change out of date or inconsistent with more complex models	CRED is based on the DICE 2007 model, but its representation of climate change has been updated (in 2011) to align with the MAGICC model ( <a href="http://www.cgd.ucar.edu/cas/wigley/magicc">http://www.cgd.ucar.edu/cas/wigley/magicc</a> ) for a range of scenarios. This involved



	modest but significant changes to the parameters used in DICE.
Representation of climate change does not cover uncertainties	A range of climate scenarios are covered but uncertainty is not explicitly dealt with.
Representation of climate change does not cover catastrophic climate change	The updated version of CRED (v1.3) does cover catastrophic climate change through a ‘choice’ of four different damage functions. CRED is noteworthy for its inclusion of damage functions that tend towards total loss of global output (99%) as a result of climate change at upper temperature ranges, in response to evidence from Weitzman (2010). Other damage function options within CRED (which are more typical of most IAMs), in contrast, estimate that 50% of global output is not lost until temperature increases reach between 12°C and 18.8°C.
Damages usually underestimated	Potentially, although damages are affected by a vulnerability index. CRED uses its own vulnerability index to account for the distribution of damages across nine global regions. This index is based on the proportion of GDP in agriculture and tourism, the proportion of total population living below 5m (as a proxy measure of coastal exposure) and freshwater resources per person. It is therefore a crude index of vulnerability that does not account for the true nature of exposure, sensitivity or adaptive capacity. However, there are few options to improve the index without a clearer consensus in the literature on the actual components of vulnerability. The CRED vulnerability index assumes that vulnerability does not change over time.
Damage representation lags behind literature	Recent update of CRED reflects developments in the literature.
Discount rate	Can be adjusted in different scenarios in CRED, including the effect of very low discount rates. Results are sensitive to discount rate and this is explored (e.g. Ackerman et al, 2011).
Equity weighting	The treatment of global equity is a key innovation of the CRED model, mostly through international investment flow requirements for mitigation across global

	regions, though no equity weighting for climate impacts or adaptation.
Sectoral coverage	Simplified to ‘land use sectors’ (agriculture and forestry) and ‘industry’ (all other sectors).
Limits to adaptation, organisational constraints apply	Not covered beyond the influence of the vulnerability index in moderating damages.
Current adaptation deficit not modelled	No – although vulnerability index may act as proxy for some regional differences in adaptation deficits.
Local scale issues cannot be represented	Some local detail is included (e.g. separate carbon price for each of the nine regions), but not spatial variation within regions.

### 2.1.6.3 The Millner & Dietz model (2011)

Millner & Dietz develop a numerical model based on the standard Ramsey-Cass-Koopmans growth model used in much climate change economics (e.g. Nordhaus, 2008). The model is designed with developing countries in mind.

In Millner & Dietz’s model the economy consists of two capital stocks: vulnerable capital, which is productive but susceptible to climate impacts; and adaptive capital, which is not inherently productive, but which reduces the impacts of climate change on output derived from vulnerable capital. Adaptive capital has no benefit when there is no climate change. An additional unit of adaptive capital is more effective at reducing damage from climate change when temperature change is large than when it is small. Gross output in the model is modified by a climate change damage function (based on a review of multiple IAMs by Aggrawala et al, 2010).

The model includes features that effectively disincentivise rapid adaptation (large investment flows into adaptive stock) in recognition that such adaptation will be largely publicly-funded and therefore subject to planning costs, policy delays, etc. and will therefore be inefficient. The model therefore attempts to recognize the sub-optimal reality of adaptation investments.

The time series for the model run in this paper is 500 years. Temperature trajectories are based on DICE. Millner & Dietz conduct extensive sensitivity analysis on the underlying assumptions about the economy, the effectiveness of adaptation and the magnitude of climate change.

**Which caveats from section (1) can be tackled by CRED?**

Table 5. List of caveats and the degree to which PAGE can overcome these, or could be adapted to

CAVEAT/ISSUE COMMON FOR IAMs	
Representation of climate change out of date or inconsistent with more complex models	Based on DICE
Representation of climate change does not cover uncertainties	Based on DICE
Representation of climate change does not	Based on DICE

cover catastrophic climate change	
Damages usually underestimated	Based on DICE
Damage representation lags behind literature	Very recent model developed in 2011, although based on previous literature.
Discount rate	Extensive sensitivity analysis tests for influence of discount rate.
Equity weighting	Not covered.
Sectoral coverage	No sectors (simple economy model based on two capital stocks: : vulnerable capital, which is productive but susceptible to climate impacts; and adaptive capital, which is not inherently productive, but which reduces the impacts of climate change on output derived from vulnerable capital. Adaptive capital has no benefit when there is no climate change. An additional unit of adaptive capital is more effective at reducing damage from climate change when temperature change is large than when it is small.)
Limits to adaptation, organisational constraints apply	Partially covered. The model includes features that effectively disincentivise rapid adaptation (large investment flows into adaptive stock) in recognition that such adaptation will be largely publicly-funded and therefore subject to planning costs, policy delays, etc. and will therefore be inefficient. The model therefore attempts to recognize the sub-optimal reality of adaptation investments.
Current adaptation deficit not modelled	Partially covered. Treatment of sub-optimal adaptation (see above) partially accounts for future adaptation deficits in rapidly changing climate.
Local scale issues cannot be represented	No.

## 2.2 Incorporating adaptation into physically based models of climate change impacts

In this section, we generally focus on global/regional scale models, but as DECC asked to consider also UK and local scale effects, we also include a section describing the UK Climate Change Risk assessment indicators, and also a local scale model.

The previous section has examined how adaptation is, or could be, incorporated into Integrated Assessment Models (IAMs). This section considers the incorporation of adaptation into impact assessment models, with a particular focus on models which seek to estimate impacts across the regional or global domain. Impact assessment models, as developed so far, are used to estimate the impacts that climate change would have

on a physical or socio-economic system, typically in the absence of explicit adaptation to climate change. As such, they can be seen as estimating the ‘demand’ for adaptation, in terms of the impacts that need to be avoided by adaptation.

Conceptually, it is possible to incorporate adaptation more explicitly into these models, as outlined in the following section. An important distinction is between assessments of the effect on impacts of specific adaptation options implemented perfectly (with perfect knowledge), and assessments of the potential ‘actual’ effect of adaptation on impacts, taking into account how adaptation decisions are made in the face of, amongst other key influences, uncertainty. This second type of assessment requires an ability to model the adaptation *process* in a specific sector.

## **2.2.1 The water sector**

### **2.2.1.1 Introduction: simulation of the water balance**

There are a number of global-scale assessments of the impacts of climate change for hydrological regimes and water resources, using a variety of hydrological models and a wide range of metrics of water resources stresses. There are rather fewer assessments of river flood risk at the global scale.

The WaterMIP intercomparison exercise (<http://www.eu-watch.org/watermip>) is currently comparing the performance of different global hydrological models, including Mac-PDM as used at the Walker Institute. This exercise focuses on measures of the water balance. First results were published in 2011 (Haddeland et al., 2011). Some of the global hydrological models (not Mac-PDM) include human interventions in their simulation of runoff, incorporating direct human abstractions for municipal, industrial and agricultural uses (and returns), and the effect of reservoirs on the downstream hydrological regime. In most cases, municipal and industrial abstractions are estimated off-line, based on population and economic development, and used as input to the global hydrological model. Some models also read in irrigation withdrawals data, but a number calculate irrigation water requirements within the hydrological model. The effect of reservoirs on hydrological regimes is incorporated by using a global spatial data base of reservoir storage capacity and generic operating rules (e.g. Hanasaki et al., 2010). To date, none of the global hydrological models which include the effect of human interventions on the water balance have considered the effects of adaptation to climate change on changes to the water balance.

In principle, however, it is possible to account for the effects of adaptation to climate change on the water balance by (i) adjusting abstractions (the ‘demand side’) and (ii) altering reservoir locations and operating rules (the ‘supply side’). A first assessment of the effects of adaptation in municipal and industrial demands would simply evaluate the effect of feasible adaptation options (such as use of water-saving technologies or demand management measures) on the demand for water. This is relatively straightforward, and there is a large literature on the potential effects of water-saving technologies and demand management on water use efficiency (per capita use or use per unit of production). However, in practice the effect of adaptation on demands will be very strongly determined by the uptake and implementation of measures – particularly as decisions are made by large numbers of individual decision-makers. An assessment of ‘potential’ effects may therefore rather overestimate actual effects of adaptation, and in this case it is important to incorporate an assessment of the implementation of measures to reduce demand. In practice the effect on the water balance of adaptation in municipal and industrial demands is likely to be most easily simulated simply by exploring sensitivities to different percentage changes in demands. The same applies where irrigation demands are input to the hydrological model, but where irrigation demands are calculated as part of the model there is greater scope for simulating the effects of adaptation. In this case, it is conceptually possible

to incorporate changes in crop variety and planting dates (see 2.2.3), as well as changes in irrigation water use efficiency.

It is more difficult to incorporate the effects of changes to reservoir characteristics (a ‘supply-side’ adaptation) on the downstream water balance. For existing reservoirs, global hydrological models use generic operating rules, and adaptation will of course be locally-determined. In some cases, for example, operating rules might need to be changed to cope with higher inflows during the filling season, whilst in others they may need to change to hold water for longer during the dry season. It will also not be feasible to model directly the location of new reservoirs (whether for climate change adaptation or indeed any other reason).

In summary, the effects of adaptation to climate change in the water sector on the water balance – across the global domain – are therefore best assessed through assumed changes in unit water use (per capita, or per unit of production). The effects of supply-side adaptations on the water balance cannot be simulated across the global domain.

### 2.2.1.2 Impacts on water resources stresses

The impacts of climate change on water resources in human or environmental terms (rather than the water balance) are assessed at either the catchment or the global scale using some metric of water resources stress or scarcity. At the catchment (or operational) scale this can be a measure of the difference between supply and demand in drought periods, or the frequency of supply restrictions. These are determined by local supply and demand conditions, including local infrastructure, operating rules and procedures. Adaptation measures too are highly locally-determined.

At the regional and global scale, water resources stresses are typically characterised by either the amount of runoff (and recharge) available per person, or the ratio of withdrawals to runoff. The available runoff is usually defined as the average annual runoff, but sometimes seasonal runoff or drought runoff (e.g. 10-year return period drought annual runoff) is used. The ‘available runoff’ is not the same as the amount of water physically available to users, either through their own abstraction efforts or through public water supply systems. This volume of ‘supply’ is determined by infrastructure and access rights, and not only is there no comprehensive data base containing this variable, it is not possible to model actual ‘supply’ over a large geographic area; the supply system is simply too complex and data are not available. Measures of water resources stress based on available runoff therefore represent *exposure* to water stress, rather than ‘actual’ experienced water stress. A high ‘stress index’ in one region may mean that communities periodically face real hardship due to a lack of water, but in another previous investment in water supply infrastructure may mean that the threat of actual hardship is low – but at a cost.

It is therefore difficult to incorporate adaptation into currently-used metrics of water resources stress applied at the regional and global scales. All published studies of the impact of climate change on water resources stresses at the global and regional scales therefore characterise *exposure* to impact. The measure of ‘water available’ used in these metrics does not correspond to actual local supply, and therefore the effects of adaptation options on supply cannot be incorporated. The effect of demand-side adaptation (see 2.1.1), however, could be incorporated in metrics comparing runoff with withdrawals.

An alternative approach is to estimate the *demand* for adaptation due to climate change, by estimating the reservoir storage required to provide a given yield with a given reliability. The change in storage required due to climate change can be seen as an indicator of the amount of adaptation that needs to occur (either provide additional storage, or do nothing where storage remains adequate). Kirshen et al. (2005) applied this approach in China to estimate the costs of adaptation to future water shortage in China, and Kirshen

(2007) applied a variant (with more generalised national-scale data) to estimate the global requirement for adaptation (and indicative costs) under one climate scenario. Fischer et al. (2007) used a similar approach to estimate the costs of maintaining future irrigation withdrawals. It is possible to apply this approach across the global domain using a global hydrological model and estimates of withdrawals, and assuming that these withdrawals are supplied in each model grid square with a given reliability by a simple reservoir whose capacity depends on the grid cell hydrological regime. Such a reservoir model has already been implemented at the Walker Institute within the QUEST-GSI project using Mac-PDM runoff, but has not yet been applied.

Table 6. Potential for simulating adaptation in the water sector

MODELLING APPROACH	Managing the demand for water	Managing the supply of water
Creating scenarios with different levels of adaptation	YES	NO
Attempting to project how much adaptation might be physically feasible	NO	NO
Attempting to project how much adaptation might be financially and socially feasible without any investment from outside a country	NO	NO
Calculating what is necessary to do to meet the projected demand for water in the future	YES	YES
Assessing effect of ‘perfect’ implementation of adaptation options on impacts	YES	YES
Assessing likely effect of actual adaptation on impacts	YES	YES

### 2.2.1.3 Impacts on river flood hazard

Whilst there have been a few assessments of potential changes in the frequency of flooding across the global domain, there have so far been very few studies of human implications of such changes. One metric is the number of people exposed to a ‘substantial’ change in the frequency of the current 20 or 50-year flood (e.g. Kleinen & Petschl-Held (2007) and the GSI AVOID flood impact metric). As implemented so far, this metric does not take flood protection into account, so is not a measure of the actual number of damaging events, and it does not account for adaptation. In principle it is possible to refine this metric by assuming a protection standard (which may vary geographically) and counting the number of times floods exceed this standard, rather than using a blanket 20 or 50-year flood frequency. Adaptation could be incorporated by changing the protection standard over time. Of course, if adaptation is perfect then there will be no change in the frequency of damaging events (but there will have been a cost in improving protection standards: these can perhaps be estimated using generic data on cost per unit of protection provided). In practice, adaptation will not be perfect (it may lag behind the changing climate), and this can be modelled too.

A more standard metric of flood hazard is average annual flood loss, estimated by combining a flood frequency curve with a relationship between flood magnitude and loss. Whilst this is frequently used in

flood management, very few studies have assessed how this may change with climate change. At the European scale, Feyen et al. (2009) combined simulated flood frequency curves with flood depth-damage functions to estimate current and future average annual flood loss. They assumed fixed standards of protection – which varied across Europe – and assumed no change in protection over time. A similar flood metric was produced across the global domain within the QUEST-GSI project, but using generic rather than site-specific damage functions. This metric also assumes a standard of protection, but this standard can change over time reflecting adaptation. As with the previous metric, adaptation may not be perfect.

In summary, it is conceptually feasible to estimate the effect of adaptation on metrics of river flood hazard, and also to calculate (using generic relationships) the relationship between costs of adaptation and the impacts avoided. However, the answers will depend significantly on the assumed timing of adaptation, level of foresight, and treatment of uncertainty.

Table 7. Potential for simulating adaptation to river flood hazard

MODELLING APPROACH	Managing exposure to flood	Providing protection against flooding
Creating scenarios with different levels of adaptation	YES	YES
Attempting to project how much adaptation might be physically feasible	NO	NO
Attempting to project how much adaptation might be financially and socially feasible without any investment from outside a country	NO	NO
Calculating what is necessary to do to meet the projected demand for protection in the future	YES	YES
Assessing effect of ‘perfect’ implementation of adaptation options on impacts	YES	YES
Assessing likely effect of actual adaptation on impacts	YES	YES

## 2.2.2 The agricultural sector

### 2.2.2.1 Introduction

Adaptation can take place at several stages in the crop production process, and the effects of many of these can be modelled.

#### 2.2.2.2 Impacts on suitability for cropping

One metric of the impact of climate change on agriculture is its effect on the suitability of land for cropping. This metric (using Ramankutty et al.’ (2002) index of crop suitability) has been applied in the

AVOID and QUEST-GSI projects. However, as it is a generic physical measure of suitability, based on soil characteristics, rainfall, evaporation and temperature, it cannot incorporate the effects of adaptation.

### **2.2.2.3 Impacts on crop productivity**

The impacts of climate change on crop productivity have sometimes been estimated from empirical relationships or experimental data, but the most robust estimates come from the use of process-based crop simulation models (such as the GLAM model used in QUEST-GSI and AVOID). The AgMIP intercomparison exercise (<http://www.agmip.org/>) is currently evaluating and comparing different crop simulation models.

GLAM is a typical crop simulation model and, for a given crop type, incorporates adaptation in three ways. The first is to adjust planting dates to optimise yield under changed climatic conditions. The second is to change crop variety, selecting the variety which produces the highest yield. As implemented in QUEST-GSI and AVOID, GLAM simulates three varieties for each crop and selects the best one under each climate. Different crop varieties are represented by different parameter values. The third adaptation option is to switch from rain-fed to irrigated production (or indeed vice versa). Other models incorporate fertiliser applications and other management practices.

PEGASUS (Deryng et al.2011) is one of the few current process-based crop simulation models designed especially for global scale analyses. Unlike local or regional crop simulation models, PEGASUS does not require site-specific calibration and therefore, can be run using a limited amount of input data. Driven by daily climate data of temperature, precipitation and cloud cover, PEGASUS is designed to evaluate the impact of climate change and climate variability and potential farming adaptation strategies on global crop yield.

Similarly to GLAM, PEGASUS includes adaptation options to climate change such as planting dates decision, crop variety selection and irrigation implementation. However, crop variety selection is slightly different from GLAM. In PEGASUS, crop variety selection is based on crop specific heat-unit requirement to reach maturity. Different crop varieties have different heat-unit requirement so that farmers select varieties with a lower heat-unit requirement in colder climate (and vice versa) to get the highest yield. In addition, PEGASUS can be used to assess optimum land-use allocation in term of land productivity and water use efficiency. Finally, PEGASUS includes the effect of fertiliser applications, which offers the adaptation option to increase the amount of fertiliser application to alleviate potential crop productivity losses triggered by climate change.

### **2.2.2.4 Impacts on crop production**

The effects of adaptation on the impacts of climate change on crop production, however, are rather more complicated. Future production of a crop will depend not only on future crop productivity and the effects of changing planting dates, variety or irrigation, but also on (i) the extent to which farmers implement these adaptations and (ii) the area cultivated under that crop.

The effect of farmer uptake can either be simulated based on farmer characteristics (difficult at the large scale due to limited data availability) or, more simply, approximated by an 'uptake factor'. The future area under a given crop will depend partly on changes in the suitability of land for that crop, and partly on changes in the economics of that crop type and its competitors. These may be locally determined, but are often controlled by global crop and commodities markets. Regional and global agricultural economic models are currently being evaluated under AgMIP (<http://www.agmip.org/>). These agricultural economics



models implicitly incorporate the effects of adaptation on crop productivity. Additional adaptation options that would need to be represented explicitly include government incentives and subsidies, and constraints (or inducements) to land cover change.

Table 8. Potential to simulate adaptation in the agricultural sector

MODELLING APPROACH	Managing the demand for food	Managing the supply of food
Creating scenarios with different levels of adaptation	We could explore scenarios for reduced meat consumption?	YES
Attempting to project how much adaptation might be physically feasible	NO	YES
Attempting to project how much adaptation might be financially and socially feasible without any investment from outside a country	NO	NO
Calculating what is necessary to do to meet the projected demand for food in the future	YES	YES
Assessing effect of ‘perfect’ implementation of adaptation options on impacts	YES	YES
Assessing likely effect of actual adaptation on impacts	YES	YES

### 2.2.3 The built environment sectors

#### 2.2.3.1 Introduction

The effects of climate change on the built environment include loss or damage during extreme events, and changes to building performance. Loss models are widely adopted by the insurance industry (known as catastrophe models or ‘cat models’). In principle these can incorporate the effects of adaptation through changes to the damage functions which relate damage to external forcing event. In practice, most cat models are proprietary, and none have so far been used in published climate change impacts assessments.

A key aspect of building performance is the energy requirements necessary to maintain comfort and efficiency within the building.

#### 2.2.3.2 Impacts on residential heating and cooling energy demands

Residential heating and cooling energy requirements are a function of external climate, preferences, household characteristics and technology. Isaac and van Vuuren’s (2009) model explicitly incorporates all of these, with preferences represented by a target internal building temperature. A simplified version of this model was used in the QUEST-GSI and AVOID projects (with less variability in technology between countries).

Adaptation can be incorporated in this model through (i) changing preferences (i.e. changing the target temperature) and (ii) changing technology assumptions. These technology assumptions include market

penetration and energy use per unit of heating or cooling. It is relatively straightforward to assess the sensitivity of impacts on residential heating and cooling demands to changing preferences and changing technologies.

Table 9. Potential to simulate adaptation in the infrastructure sector

MODELLING APPROACH	Meeting energy demands
Creating scenarios with different levels of adaptation	YES
Attempting to project how much adaptation might be physically feasible	NO
Attempting to project how much adaptation might be financially and socially feasible without any investment from outside a country	NO
Calculating what is necessary to do to meet the projected demands for energy in the future	YES
Assessing effect of 'perfect' implementation of adaptation options on impacts	YES
Assessing likely effect of actual adaptation on impacts	YES

#### 2.2.4 Biodiversity models

**Avoided impacts on biodiversity.** The Wallace Initiative is a multi-institution effort to model the potential impacts of climate change on a broad array of terrestrial species. Phase I looked at almost 50,000 species for seven climate models, a range of emission scenarios and a range of dispersal scenarios (an effort requiring 60,000 hours of CPU time). The primary aims of the Wallace Initiative were to bring together experts in climate change models, bioclimatic models, and bioinformatics to provide a single coherent set of results for policymakers and adaptation practitioners, and to identify those areas likely to be refugia under a range of climate change scenarios. Refugia are defined as those areas with a suitable climate for a species currently, and also under various climate change scenarios. These are areas in which modification of current management practices would likely be enough to conserve species under a changed climate in those areas. However, in the areas identified as becoming climatically unsuitable varying levels of adaptation would be required in order to minimize ecosystem transformation in those areas, with concomitant change in ecosystem services available to communities in the area. The Wallace Initiative data thus can be used to show amount of adaptation effort required depending on the number of species an area is projected to become climatically unsuitable for. By looking at various emission scenarios these data can show the amount of avoided damages, or the amount of adaptation effort not required by undertaking different levels of mitigation effort. The web portal for Phase I is available at <http://wallaceinitiative.org>.

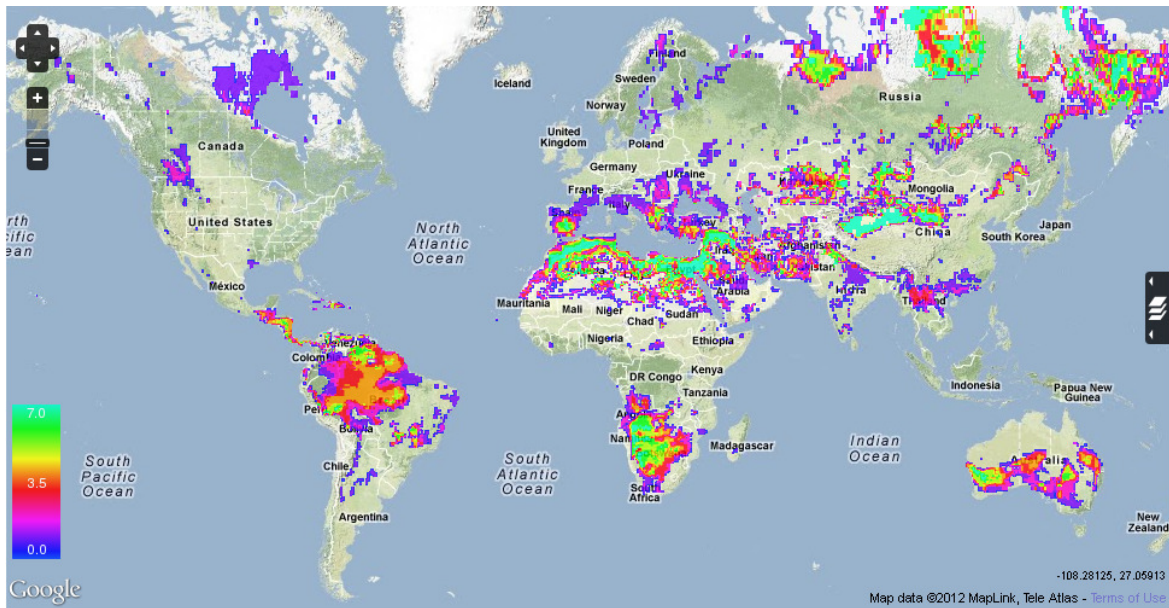


Fig. 10. Areas projected to become climatically unsuitable for 75% of the plants studied (approximately 30,000 total) under the A1B baseline AVOID scenario 2070-2099. Colours represent numbers of GCMs (out of 7) in agreement.

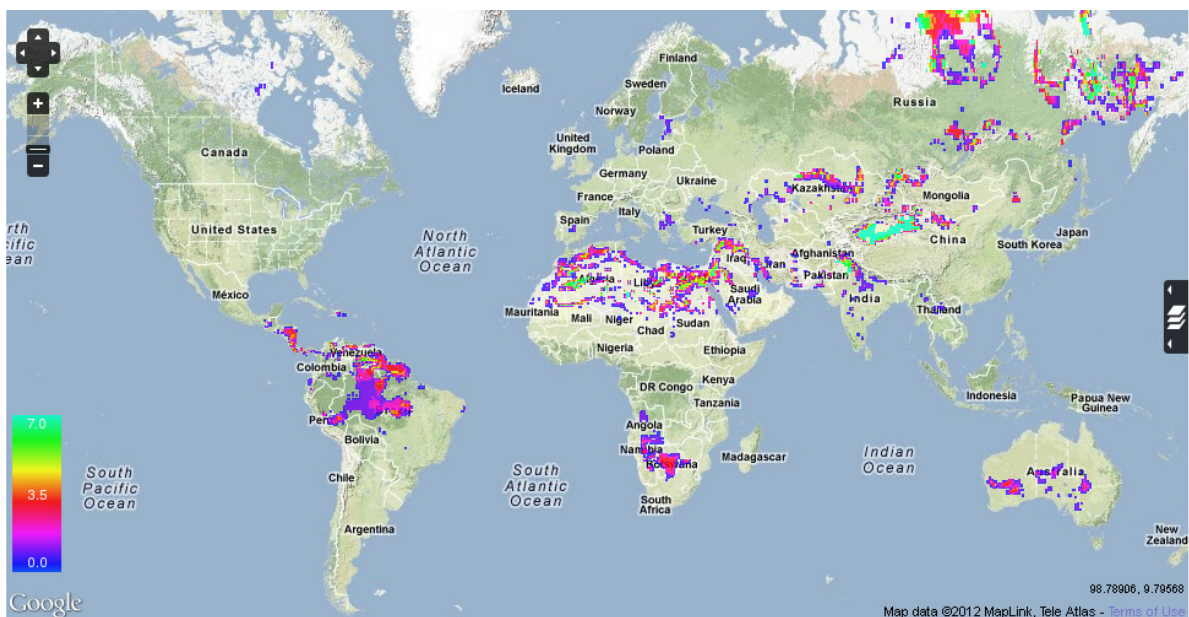


Fig. 11. Areas projected to become climatically unsuitable for 75% of the plants studied (approximately 30,000 total) under the AVOID 30r51 scenario 2070-2099. Colours represent numbers of GCMs (out of 7) in agreement.

Fig 10 shows an example of Wallace Initiative 1.0 output. One way of looking at this is as a measure of adaptation effort. Areas maintaining the majority of their plant species would be expected to require less climate change adaptation, that a modified conventional conservation approach would be adequate. This map includes the small amount of natural dispersal likely to occur in this time frame. Wallace 2.0 is now underway and will be looking at 18 climate models and the new RCP scenarios.

Fig. 11 shows an example of the reduced adaptation effort required with mitigation. In comparison with map in Fig. 10, far fewer areas have colour shading, and those areas with colour shading are both reduced

in areal extent and in the agreement between the GCMs as to potential species loss owing to climatic unsuitability. Thus a substantially reduced adaptation effort would be needed even under the 2030r51 mitigation scenario. Areas benefitting the most include Africa, the Amazon, and southern Australia.

Phase II of the Wallace Initiative is now underway. Phase II will use far more data, for more climate models (18 rather than 7 climate models), the RCP scenarios and more time periods (and will require more than 500,000 CPU hours). Phase II will also have a web portal but this portal will allow users to comment on data and mark suspect data to improve the models over time.

## 2.2.5 Coastal Models

This section considers the state-of-art in terms of assessing the potential to mitigate and/or adapt in coastal areas being impacted by sea-level rise. It first briefly considers key issues concerning sea-level rise, followed by a review of the impacts of sea-level rise and the role of mitigation and adaptation in responding to these impacts. Using this foundation of understanding, the available models are assessed and a research agenda to develop them to be better able to assess global trade-offs and the synergies between mitigation and adaptation are made.

### 2.2.5.1 Sea-Level Rise

There are several aspects of sea-level rise that are important to understand before proceeding to consider the ability to assess global trade-offs and synergies between mitigation and adaptation in coastal areas.

Impacts of sea-level rise are produced by *relative* sea-level rise, which represents the relative movement of the land to the sea. In other words, sea level may rise because the sea rises (due to climate change) or because the land sinks due to subsidence (due to natural processes and human influence, such as groundwater withdrawal). Hence coastal managers do not care about climate-induced sea-level rise per se – they are concerned about the local downscaled change which includes non-climate components. Deltaic areas in particular are prone to human-induced subsidence and the maximum *observed* subsidence due to groundwater withdrawal over the 20<sup>th</sup> Century in cities built on deltas or alluvial plains is as follows: Tokyo (5 m), Osaka (3 m), Tianjin (2 m), Shanghai (3 m), Bangkok (2 m) and Jakarta (4 m) (Nicholls, 2010; 2011). The World Bank (2010) recently concluded that subsidence is as big a threat to major Asian cities built on deltas as climate-induced sea-level rise. Hence, sea-level rise is more complex than often assumed and (a) separating climate and non-climate induced sea-level rise may be problematic, and (b) solving climate-induced sea-level rise still leaves major residual problems in many coastal areas. The following discussion will focus on the incremental implications of climate-induced sea-level rise.

When compared to other climate factors, we are fairly certain that global sea-level rise will continue beyond the 21st century irrespective of future greenhouse emissions (Nicholls and Lowe, 2004). This is because it takes centuries to millennia for the full ocean depth to adjust to a surface warming, resulting in ongoing thermal expansion as noted in the First IPCC Assessment (Warrick and Oerlemans., 1990) and discussed in the most recent IPCC Assessment as well (Meehl et al., 2007). This inevitable rise has been termed the ‘commitment to sea-level rise’. If global warming continues to occur and passes key but uncertain thresholds for the irreversible breakdown of the Greenland or West Antarctic ice sheets, the committed rise could be 13 to 15 metres, albeit over long time-scales (centuries or longer). The implications of this commitment are considered below, and are fundamental when considering this issue of global trade-offs between mitigation and adaptation.

### 2.2.5.2 Impacts of Sea-Level Rise

Relative sea-level rise causes more effects than simple submergence (the “bath-tub” effect): the five main physical effects are summarized in Table 10. Flooding/submergence, ecosystem change and erosion have received significantly more attention than salinisation and rising water tables. Along with rising sea level, there are changes to all the processes that operate around the coast. The immediate effect is submergence and increased flooding of coastal land, as well as saltwater intrusion into surface waters. Longer term effects also occur as the coast adjusts to the new environmental conditions, including wetland loss and change in response to higher water tables and increasing salinity, erosion of beaches and soft cliffs, and saltwater intrusion into groundwater. These lagged changes interact with the immediate effects of sea-level rise and generally exacerbate them. For instance, erosion of sedimentary features (e.g. salt marshes, mangroves, sand dunes and coral reefs) will tend to degrade or remove natural protection and hence increase the likelihood of coastal flooding over time.

Table 10. The main natural system effects of relative sea-level rise and example adaptation approaches in each case. Other interacting factors which could offset or exacerbate these impacts due to other climate change and non-climate factors effects are also shown. Some interacting factors (e.g., sediment supply) appear twice as they can be influenced both by climate and non-climate factors. Adaptation approaches are coded: P – Protection (hard or soft); A – Accommodation; R – Retreat. (from Nicholls, 2011).

NATURAL SYSTEM EFFECT		POSSIBLE INTERACTING FACTORS		POSSIBLE ADAPTATION APPROACHES
		CLIMATE	NON-CLIMATE	
1. Inundation/ flooding	a. Surge (flooding from the sea)	Wave/storm climate,  Erosion,  Sediment supply.	Sediment supply,  Flood management,  Erosion,  Land reclamation	Dikes/surge barriers/closure dams [P – hard],  Dune construction [P – soft],  Building codes/floodproof buildings [A],  Land use planning/hazard mapping/flood warnings [A/R].
	b. Backwater effect (flooding from rivers)	Run-off.	Catchment management and land use.	
2. Wetland loss (and change)		CO <sub>2</sub> fertilisation,  Sediment supply,  Migration space	Sediment supply,  Migration space,  Land reclamation (i.e., direct destruction).	Nourishment/sediment management [P – soft].  Land use planning [A/R],  Managed realignment/ forbid hard defences [R],

3. Erosion (of 'soft' morphology)		Sediment supply, Wave/storm climate.	Sediment supply.	Coast defences/seawalls/land claim [P – hard], Nourishment [P – soft], Building setbacks [R].
4. Saltwater Intrusion	a. Surface Waters	Run-off.	Catchment management (over-extraction), Land use.	Saltwater intrusion barriers [P], Change water abstraction [A/R].
	b. Ground-water	Rainfall.	Land use, Aquifer use (over-pumping).	Freshwater injection [A], Change water abstraction [A/R].
5. Impeded drainage/higher water tables		Rainfall, Run-off.	Land use, Aquifer use, Catchment management.	Drainage systems/polders [P – hard], Change land use [A], Land use planning/hazard delineation [A/R].

Changes in natural systems as a result of sea-level rise have many important direct socio-economic impacts on a range of sectors, with these impacts being overwhelmingly negative (Table 11). For instance, coastal flooding can damage coastal infrastructure, ports and industry, the built environment, and agricultural areas, and in the worst case lead to significant mortality as shown in recent events, such as Hurricane Katrina (USA) in 2005, Cyclone Nargis (Myanmar) in 2008, and Storm Xynthia (France) in 2010. Erosion can lead to loss of beachfront/cliff-top buildings and related infrastructure and have adverse consequences for sectors such as tourism and recreation. In addition to these direct impacts, there are potential indirect impacts such as adverse effects on human health: for example, the release of toxins from eroded landfills and waste sites, or mental health problems triggered by floods. These indirect impacts are much less studied, but will have economic consequences in terms of the damages caused (and/or the diversion of investment to fund the adaptation to avoid them). Thus, sea-level rise has the potential to trigger a cascade of direct and indirect human impacts.

Table 11. Summary of sea-level rise impacts on socio-economic sectors in coastal zones (from Nicholls, 2011). These impacts are overwhelmingly negative.

Coastal Socio-economic Sector	Sea-level rise natural system effect (Table 1)				
	Inundation/flooding	Wetland loss	Erosion	Saltwater intrusion	Impeded drainage
Freshwater Resources	<b>X</b>	x	-	<b>X</b>	<b>X</b>
Agriculture and forestry	<b>X</b>	x	-	<b>X</b>	<b>X</b>
Fisheries and Aquaculture	<b>X</b>	<b>X</b>	x	<b>X</b>	-
Health	<b>X</b>	<b>X</b>	-	<b>X</b>	x
Recreation and tourism	<b>X</b>	<b>X</b>	<b>X</b>	-	-
Biodiversity	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>

Settlements/ infrastructure	X	X	X	X	X
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X = strong; x = weak; - = negligible or not established.

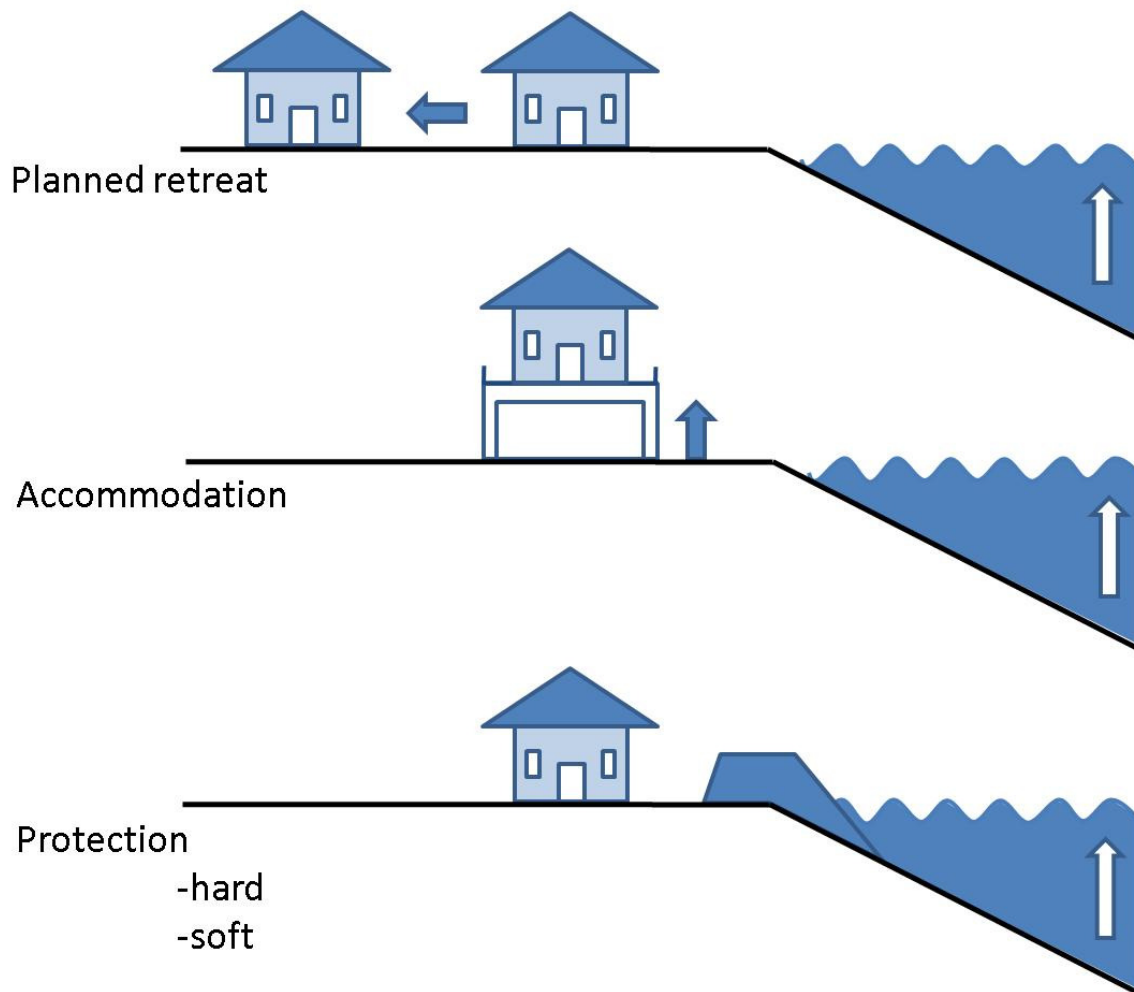
### 2.2.5.3 Responding to Sea-Level Rise

The two potential responses to sea-level rise are mitigation and adaptation. They operate at two very different scales with mitigation being by necessity a global scale activity, linked to climate policy, while adaptation is a local to national activity, linked to coastal management policy. Hence, our understanding and assessment of responses to sea-level rise also need to operate at multiple scales.

Mitigation can slow the rise in sea level and reduce its impacts, and given its strong inertia, mitigation has an important additional effect of stabilising the rate of sea-level rise (rather than stabilising sea level itself) (Nicholls and Lowe, 2004). But it is fundamental to recognise that climate-induced sea-level rise will continue even with the most stringent mitigation (Section 2.2.5.1). In essence, the commitment to sea-level rise leads to a commitment to adapt to sea-level rise (Nicholls et al., 2007a). Given that the rate of sea-level rise controls some impacts such as wetland loss or coral reef submergence, mitigation reduces these impacts. In the case of flooding, the absolute rise is of more concern, and many impacts may be delayed rather than avoided with mitigation due to the commitment to sea-level rise (but importantly this gives more time to adapt which is an important benefit, including lowering annual adaptation (and damage) costs).

Adaptation to sea-level rise involves responding to the rise in both mean and extreme water levels (i.e. mean sea-level rise leads to higher extreme water levels). Given the large and rapidly growing concentration of people and activity in the coastal zone, autonomous (or spontaneous) adaptation processes alone will not be able to cope with sea-level rise. Adaptation approaches can be classified in a variety of ways: one widely followed approach is the long-standing IPCC typology of planned adaptation strategies which is originally outlined by IPCC CZMS (1990) and elaborated by others such as Bijlsma et al (1996), Klein et al. (2001), and Linham and Nicholls (2010) (Fig. 12):

- - (Planned) Retreat – all natural system effects are allowed to occur and human impacts are minimised by pulling back from the coast via land use planning, development controls, etc.;
- - Accommodation – all natural system effects are allowed to occur and human impacts are minimised by adjusting human use of the coastal zone via flood resilience measures, warning systems, insurance, etc.;
- - Protection – natural system effects are controlled by soft or hard engineering (e.g., nourished beaches and dunes or seawalls), reducing human impacts in the zone that would be impacted without protection. (In the extreme this could involve building seaward – i.e. land claim (see Linham and Nicholls, 2010)).



Fig

12 Generic adaptation approaches for sea-level rise (after IPCC CZMS, 1990).

Note that sea-level rise does not happen in isolation and coasts are changing significantly due to non-climate-induced drivers such as changing sediment budgets. Potential interactions with sea-level rise are indicated in Table 1 and need to be considered when assessing sea-level rise impacts and responses. For instance, a coast with a positive sediment budget may not erode given sea-level rise and vice versa. Hence, coastal change ideally requires an integrated assessment approach to analyse the full range of interacting drivers, including the feedback of policy interventions (i.e. adaptation) (Klein and Nicholls, 1999). This must be considered when evaluating global trade-offs between mitigation and adaptation.

In conclusion, in coastal areas adaptation and mitigation are complimentary policies (Nicholls et al., 2007a). The fundamental goal of mitigation in the context of coastal areas is to reduce the risk of passing irreversible thresholds concerning the breakdown of the two major ice sheets (Greenland and Antarctica), and constrain the commitment to sea-level rise to a rate and ultimate rise which can be adapted to at a reasonable economic and social cost. Quantification of the most appropriate mixtures of mitigation and adaptation remains to be done.

#### 2.2.5.4 Sea-Level Rise Impact and Adaptation Models

This section reviews the available models to assess coastal impacts due to human-induced climate change that are relevant to an assessment of the global trade-offs and synergies between mitigation and adaptation. Hence only global models are considered. It also draws on the preceding Sections (2.2.5.1 to 2.2.5.3) in



terms of relevant aspects of sea-level rise, its impacts and adaptation and mitigation responses, against which to assess these models.

There are a wide range of global-scale “integrated assessment” models that consider the consequences of climate change across a range of sectors (e.g., Weyant, 1997). Hence many of these models consider coastal impacts as part of the portfolio of damages due to human-induced climate change. However, in general they are flawed when considering mitigation and coastal areas in that the models are highly aggregated (with essentially one factor or at most one equation describing coastal impacts) and based purely on global temperature change as the driver of impacts. As already noted, sea-level rise has a longer timescale than temperature rise (Section 2.3.1). Hence under mitigation, the response of temperature change is much faster than sea-level change. In general these models fail to capture this process and hence overestimate the benefits of mitigation for coastal areas in terms of avoided damages. It should be noted that there are exceptions, with the FUND model being considered below. The PAGE09 model explicitly considers the different timescales of temperature and sea-level change (Hope, 2011). However, the treatment of impacts in PAGE09 remains highly aggregate. Hence specification of the impacts or adaptation options defined in Section 2.2.5.3 remains abstract.

More spatially explicit models of sea-level rise impacts and adaptation have been developed. The first global assessment of adaptation costs was IPCC CZMS (1990), followed by Hoozemans et al (1993) that assessed some impact and adaptation costs. These were coastal flood risk, coastal wetland loss, rice production change (in East, South-East and South Asia only) and defence costs for developed coasts. This work was based on a national level database with calculations performed in approximately 200 nation states/territories with coastal areas and a single scenario of a 1-m global rise in sea level. These results were the basis of two different bodies of assessment work: (1) the DEFRA-funded “Fast Track” impact studies, and (2) the Fankhauser/FUND costing studies.

The “Fast Track” studies developed more flexible impact models from the Hoozemans et al (1993) approach to look at the global consequences of a range of climate-induced sea-level rise scenarios for coastal flooding (in terms of numbers of flooded people) and coastal wetland loss (e.g. Nicholls, 2004). The benefits of mitigation were explicitly considered with these models, including Arnell et al (2002) and Nicholls and Lowe (2004).

The Fankhauser/FUND studies focussed on the costs of land loss due to sea-level rise assuming protection based on benefit-cost decision approaches. Fankhauser (1995) used the global data from IPCC CZMS (1990) and found that protection would be a widespread response in developed coastal areas. Tol (2002a; 2002b) used the Fankhauser approach to develop the coastal module of the FUND model, including improving the underlying data using Hoozemans et al (1993) and Nicholls and Leatherman (1995). The model considers the costs of dryland loss, wetland loss and unit defence costs from Hoozemans et al (1993). Tol (2007) has used FUND to explicitly investigate the benefits of mitigation for coastal areas. Further developments of the Fankhauser approach have been undertaken using new and improved global datasets (e.g., Sugiyama et al., 2008).

The Dynamic Interactive Vulnerability Assessment (DIVA) model was developed in the EU-funded DINAS-COAST Project (Nicholls et al., 2007b; Vafeidis et al. 2008, Hinkel and Klein 2009). It draws on both the Fast Track and Fankhauser/FUND approaches and considers impact estimates such as people flooded and wetland loss as in the earlier fast track studies, as well as costs of impacts and adaptation strategies as in the Fankhauser/FUND studies. Importantly, DIVA includes a series of internal consistent adaptation options and impacts are a product of climate and socio-economic drivers and decisions about adaptation. The adaptation options are dike construction and upgrade for flood risk reduction, and beach nourishment for erosion. Hence, the adaptation options are rather stylised compared to the available options as

illustrated in Table 1. (The DIVA model also includes a new global database which resolves over 12,000 linear segments around the world’s coasts, making it two orders of magnitude more resolved than previous assessments).

Mitigation scenarios can be applied directly via the sea-level rise scenarios (e.g., Pardaens et al., 2011), while adaptation is applied with the model (e.g., Hinkel et al., 2010; Nicholls et al., 2010). Hence mitigation only, adaptation only and various combinations of the two policies can be evaluated.

### 2.2.5.5 Next Steps

Table 12 summarises the potential to simulate adaptation processes in the coastal zone in the DIVA model. It already provides some capacity to assess mitigation and adaptation trade-offs and this could be further developed with the existing software. If these were conducted across a range of sectors, attention would need to be made in terms of consistent assumptions about adaptation and there may be a need to develop a wider range of adaptation options and/or look at the adaptation rules. The DIVA model might also be developed in conjunction with a simpler integrated assessment model which is designed to appropriately capture the issue of different timescales that has been mentioned in the report.

Table 12. Ability to simulate adaptation processes in the coastal zone (covering coastal flood risk and sea level rise)

MODELLING APPROACH	Managing the demand for coastal protection (i.e. managed retreat etc)	Managing the supply of coastal protection (i.e. building sea walls)
Creating scenarios with different levels of adaptation	YES	YES
Attempting to project how much adaptation might be physically feasible	YES	YES
Attempting to project how much adaptation might be financially and socially feasible without any investment from outside a country	NO	NO
Calculating what is necessary to do to reduce exposure to coastal flood risk in the future	YES	YES

### 2.2.6 Indicators of impact and adaptation in the UK

The 2012 Climate Change Risk Assessment evaluates the risks posed by climate change to the UK across a range of impact indicators, as summarised in Figure 13. These indicators characterise the impact of climate change *in the absence of adaptation*.

A series of indicators relating to adaptation have been developed by the Adaptation Sub-Committee of the Committee on Climate Change (ASC, 2011). These distinguish between measures of *impact* (some of which are also represented in the CCRA list), *components of vulnerability*, and *action*. The components of vulnerability largely relate to measures of changes in exposure to loss (or opportunity), including development in flood-prone areas and changes in demand for water. The actions are a mix of extent of uptake of broad policy measures and specific actions. Table 13 shows the indicators of adaptation action used by the Adaptation Sub-Committee in its 2012 report (ASC, 2012), which focuses on flood risk and water scarcity. Each has a precise operational definition, but the indicators are heavily constrained by data availability.

Table 13: Indicators of adaptation action (ASC, 2012)

Indicator	Indicator definition
<b>Flood risk</b>	
Design of new development in areas at flood risk	Proportion of Environment Agency objections to planning applications on flood risk grounds that are over-ruled by local authority
Provision of flood defences	Number of households at reduced risk due to construction of new or enhanced defences
	Effective spend on flood risk management activities
Retrofitting property-level measures	Number of existing properties at flood risk retrofitting property-level measures
Management of surface water in built-up areas	Proportion of new development with sustainable drainage systems
Provision of early warning systems	Uptake of flood warnings by properties in the floodplain
<b>Water scarcity</b>	
Reducing demand	Percentage of properties with water meters
Increasing supply	Total leakage

**Figure ES1 A selection of potential risks (threats and opportunities) for the UK based on the Medium emissions scenario**

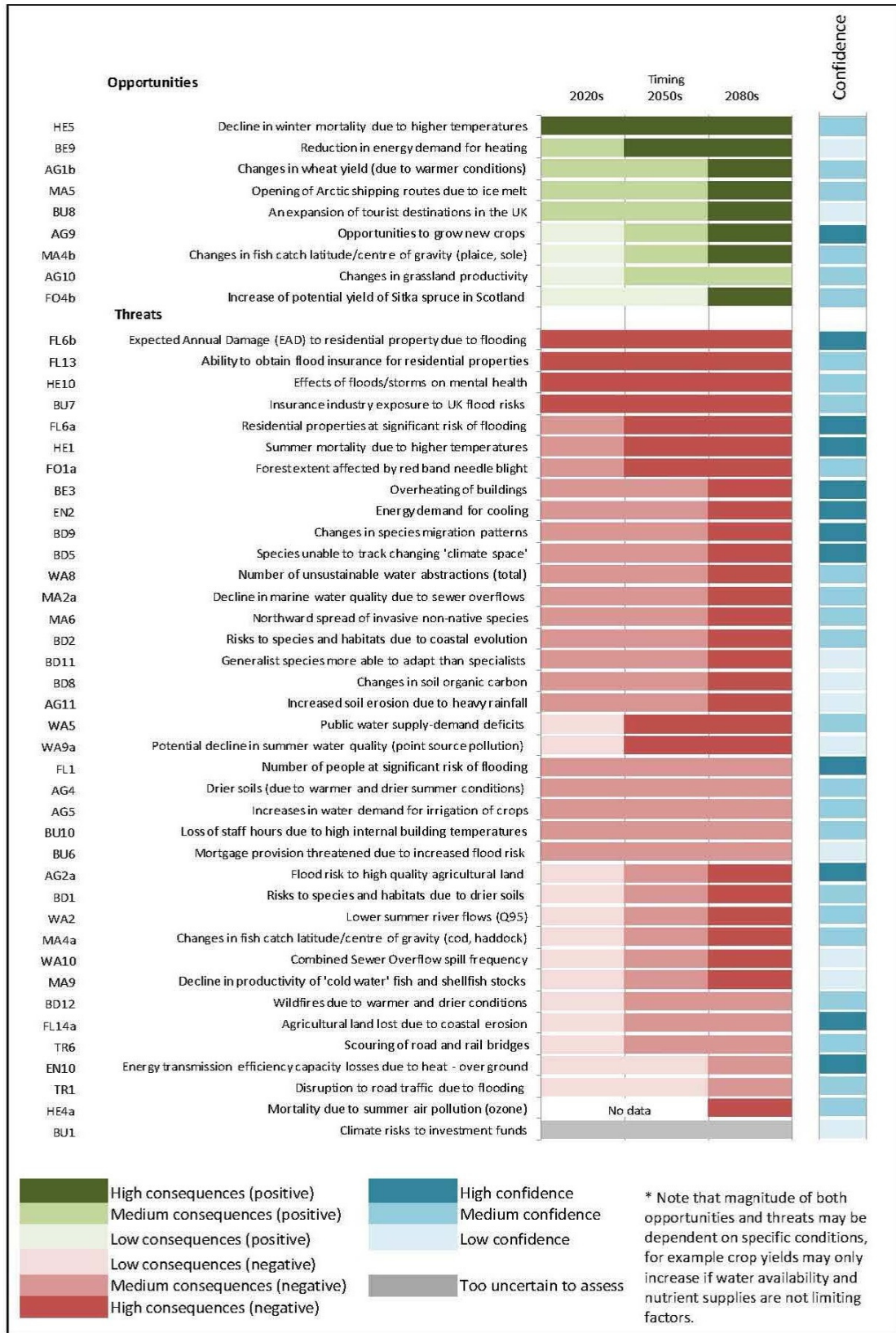


Fig. 13 Potential risks (threats and opportunities) for the UK, as defined in the 2012 Climate Change Risk Assessment

### **2.2.7 Local scale model: WEAP**

The Water Evaluation and Planning System (WEAP) model is a computer tool for integrated water resources planning that provides a comprehensive, flexible and user-friendly framework for policy analysis. WEAP's integrated approach to simulating water systems is useful for examining alternative water development and management strategies and can therefore be used to undertake *stylised scenario-based costing assessments of Integrated Water Resource Management adaptation*. The WEAP model has been applied at river basin scale in a range of countries worldwide to support decision makers by examining the effectiveness of various adaptation measures and strategies. It is able to provide a relatively robust simulation of local decision contexts and physical characteristics and therefore overcomes many of the problems with IAMs discussed above in this report. The WEAP model could be applied to a UK river basin to demonstrate the value of sectoral models in complementing IAMs to assess adaptation.

### 3. REALISING THE CONCEPTUAL FRAMEWORK

#### 3.1 A Conceptual Framework for Global Scale Assessments

The conceptual framework which we have designed creates a risk assessment framework for considering a potentially justifiable mix of adaptation and mitigation, as opposed to a mechanism for calculating a tradeoff

- (a) Produces sectoral and regional impacts for different levels of global climate change, taking into account various different potential levels of adaptation effort
- (b) Includes the combination of *different global climate outcomes* with different levels of *adaptation effort* in various sectors and regions. Note that the same climate outcome can arise from different combinations of climate sensitivity and mitigation effort.
- (c) Allows an uncertainty analysis of how estimates vary.
- (d) Quantifies the remaining (residual) impacts in each sector and region that results from these various combinations.
- (e) Assesses how these estimates vary for a range of possible future socioeconomic pathways

We now outline application of the framework to analyse consequences for climate change impacts in the 2080s for different combinations of mitigation and adaptation, taking into account the uncertainties in future climate and in our socioeconomic future. The process is detailed in below and shown schematically in Figure 14.

- Set a mitigation target that has even chances of constraining global climate change to 2 degrees above pre-industrial levels
- Examine the limits to adaptation in each sector and region, (with such limits placed in the models) whether or not they can address the impacts that are expected for 2 degrees of climate change. Apply different levels of adaptation and quantify the remaining impacts
- Imagine that the experienced climate change is then 4 degrees above pre-industrial, and scope the state of the world. Assess whether the limits to adaptation would allow coping to this level of impacts.
- This produces, for example, figures such as the example shown in Fig 15 for the different scenarios.
- This produces a scenario for ‘mitigate to 2, adapt to 4’: this can be repeated for many different scenarios, e.g. mitigate to 3, adapt to 5, etc, etc.
- Also repeat for different socioeconomic scenarios

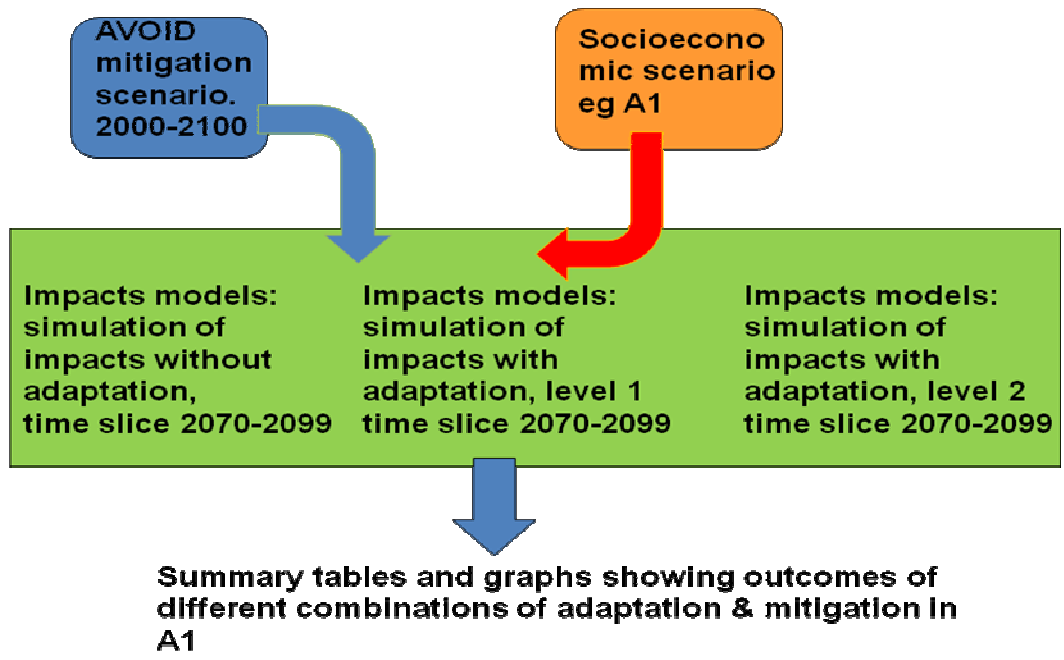


Fig. 14 Schematic of our conceptual framework applied to a combination of an SRES socioeconomic scenario and an AVOID mitigation scenario

**Hypothetical: Impacts in three sectors in Australia for three levels of adaptation (none, 1 and 2) (arbitrary units) In AVOID baseline and mitigation scenarios, A1B world.**

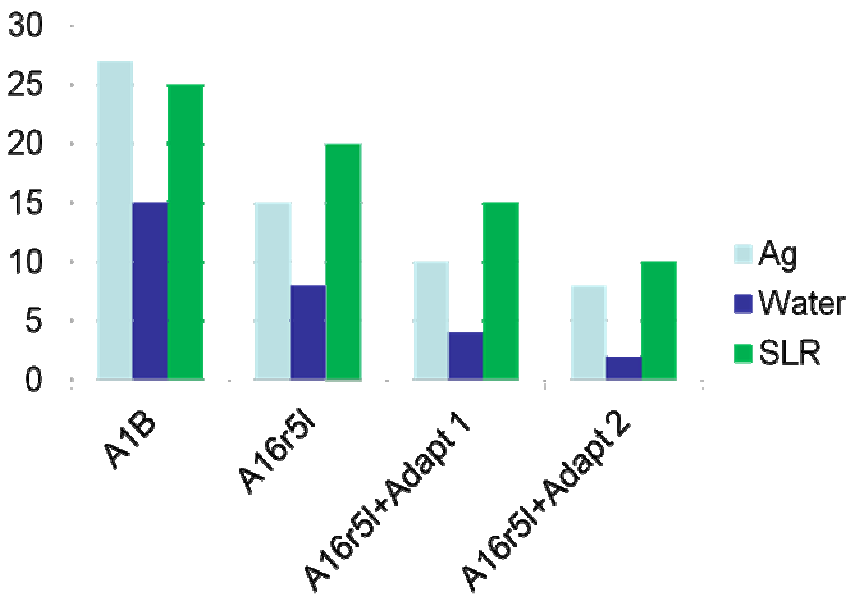


Fig 15. Hypothetical residual impacts plot comparing alternative combinations of mitigation and adaptation under the SRES socioeconomic scenario A1

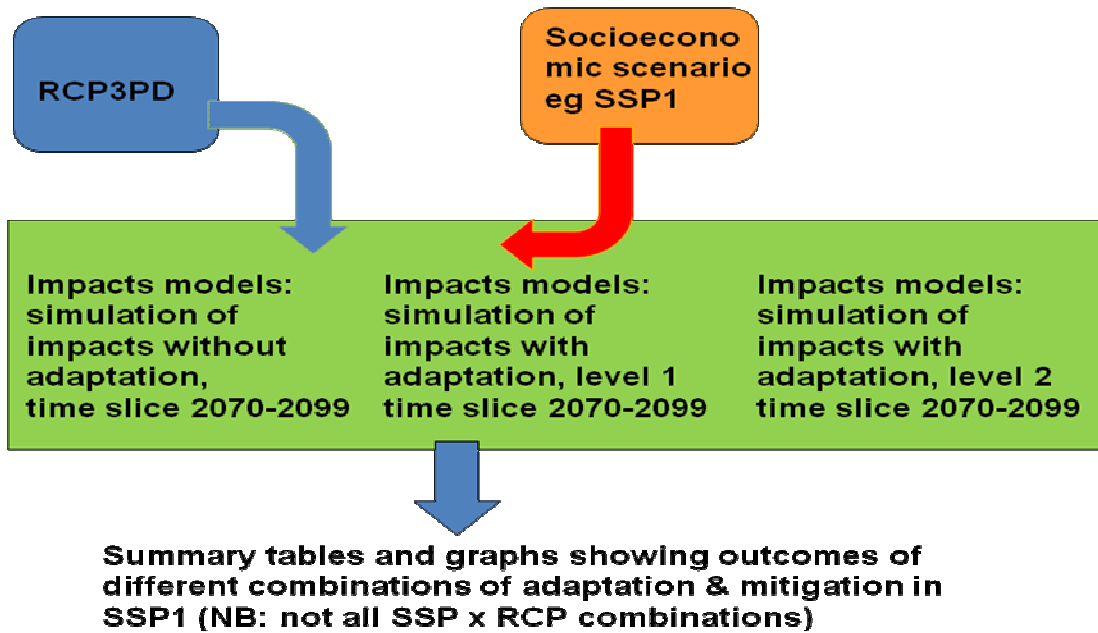


Fig. 16 Schematic of our conceptual framework applied to a combination of an SRES socioeconomic scenario and an AVOID mitigation scenario

**Hypothetical: Impacts in three sectors in Australia for three levels of adaptation (none, 1 and 2) (arbitrary units) In an SSP1 world.**

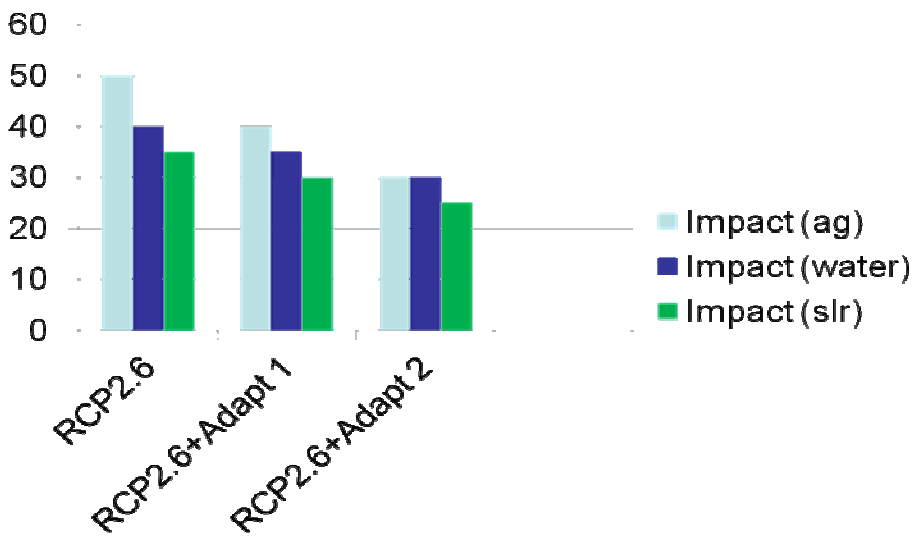


Fig 17. Hypothetical residual impacts plot comparing alternative combinations of mitigation and adaptation under a combination of representative concentration pathway RCP2.6 and socioeconomic pathway SSP1

*Climatic and socioeconomic scenarios:*

We propose that such work should draw upon the new representative concentration pathways (RCPs) since these will become standards in the literature in coming years, and use of these will facilitate comparison with impacts studies at other institutions. Further, that it should be based upon the new Shared



Socioeconomic Pathways (Fig 16) that are characterised by ease of adaptation versus ease of mitigation, which makes them particularly suitable for this kind of analysis. In the physically based models, it is feasible to combine pairs of RCP and SSP, whereas in PAGE any combination of socioeconomic pathway and emissions can be used.. This approach is recommended (Moss et al. 2010) for impacts analysis.

The new shared socioeconomic pathways are described in a report of group which met recently in Boulder (O'Neill et al. 2011). Matrices are presented therein which highlight how pairs of RCP and SSP may be usefully combined, and provides narrative storylines for the five SSPs. In the next 6 to 12 months the integrated assessment modelling community will derive quantitative versions of the five SSP which will quantify the global pathways as well as considering downscaling issues. They will also be producing scenarios based on the SSP which include the right amount of mitigation to deliver the climate in each RCP.

*Aspects of uncertainty that can be included if the models reviewed in (2) are used in the conceptual framework*

- Socioeconomic future (population, GDP, etc) (PAGE and physical impacts models)
- Emissions scenario, climate sensitivity, carbon cycle feedback (PAGE and physical impacts models)
- Downscaling: through sensitivity studies using different GCM patterns for downscaling; using CMIP5 outputs;
- Impacts modelling: by drawing upon for example, water models across WaterMIP
- Impacts modelling: by carrying out uncertainty analyses for model parameter uncertainty
- Adaptation modelling: using sensitivity analysis to scope range of uncertainty in adaptive capacity and limits to adaptation

We recommend attempting to estimate the costs of mitigating to 2 and adapting to 4, because this is a precautionary principle that caters for uncertainty in both the climate system and the socioeconomic system (i.e. the uncertainties in climate models and our knowledge of the potential of humans to adapt their systems to climate change). This strategy also gives the best chance to ecosystems which have little potential to adapt naturally, but allows humans the greatest amount of time to work on preserving vital ecosystem services under a changed climate.

### 3.2.1 **WAYS FORWARD**

#### 3.2.2 **DIVA work programme**

*A six month project with DIVA would*

Review the literature on implementation and costs for planned retreat, accommodation and protection and develop stylised descriptions that could be implemented within an improved DIVA model.

*An 18 month project with DIVA would also*

Implement the improved DIVA model

Conduct simulations of different combinations of adaptation (planned retreat, accommodation and protection) without mitigation to better understand adaptation choices.

Conduct simulations of different combinations of adaptation (from above) with mitigation to better understand adaptation/mitigation choices.

Have discussions with other IAMS about generalising results to cross-sectoral modelling

6 month project -- £50,000 for two post-docs and PI time

18 month project -- £150,000 for two post-docs an PI time

### **3.2.2 Water resources and river flood risk**

#### **3.2.2.1 Water resources**

It is not feasible to incorporate adaptation into global-scale water resources models within six months.

*An 18 month global-scale project would:*

develop and apply simple models characterising the uptake and rate of implementation of supply-side adaptation options (i.e. providing storage), incorporating cost functions. These models would be run with global hydrological models to characterise (a) the costs and residual impacts of ‘perfect’ adaptation (i.e. assuming future climate change is known) and (b) costs and residual impacts in the face of uncertainty (e.g. providing storage for the ‘worst case’ climate scenario at each point);

develop and apply simple models to characterise the uptake and effectiveness of demand-side measures, by sector (municipal, industrial and agricultural);

examine sensitivity of the simulated effect of adaptation to assumptions about implementation

#### **3.2.2.2 River flood risk**

*A six month project would*

represent the effects of adaptation to river flood risk in terms of standards of protection, and explore the sensitivity of flood risk (indicative average annual loss) to evolving standards of protection, assuming (a) perfect adaptation and (b) adaptation to the ‘worst case’ climate scenario.

*An 18 month project would*

develop regional functions characterising standards of protection, costs of protection and rates of implementation of flood defence, and repeat the above analysis;

develop simple models for the uptake of measures to reduce loss at the property-scale (‘demand-side’)

examine the sensitivity of the simulated costs and residual impacts to adaptation assumptions.

### **3.2.3 Agriculture sector**

*A six month project would*

develop and apply additional farm-level adaptation options for currently-modelled crop types, looking at effects of changes in cropping dates and varieties

*An 18 month project would*

focus on the food system as a whole, by combining a food trade model with crop production models, to assess the effects of farm-level adaptation and policy-level adaptations (e.g. relating to trade) on food prices.

### **3.2.4 Infrastructure sector**

*A six month project would*

represent adaptation to changing heating and cooling energy requirements by changing parameters of an energy consumption model (e.g. relating to energy use efficiency, heat tolerance and uptake of devices), and assessing sensitivity of the effects of adaptation to assumed changes.

### **3.2.5 PAGE09 work programmes**

The PAGE09 Model can be applied in our conceptual framework that looks at the risks associated with different combinations of adaptation and mitigation, to simulate the damages remaining for different levels of investment in adaptation. Hence, an emissions scenario including a particular level of mitigation effort can be used to drive calculations of impacts in PAGE, including or not including adaptation.

#### *A six month project with PAGE09 would*

- use the most recent impact assessments from AVOID to update the impact functions in each sector.
- include the most credible adaptation costs from the literature.

#### *An 18 month project with PAGE09 would also*

- use insights from the literature to specify appropriate world regions and impact sectors.
- perform extensive analysis of a range of adaptation and abatement options under uncertainty.
- specify adaptation and mitigation combinations at the right level of detail for optimization under uncertainty.
- perform some optimization analysis and critically evaluate the insights that come from this.

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