Aggregating, presenting and valuing climate change impacts: Appendices

: vivideconomics

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vivideconomics

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1 Current presentation of impacts

1.1 Current use of presentational devices

This appendix reviews the ways in which climate change impacts have been presented recently. A wide survey of the literature has been conducted and the forms of presentation are categorised by type. Types of presentation are assessed on their effectiveness in communicating impacts in context, across time, space, states of nature and human well-being in table 1. Section 1.2 provides a gallery of presentational devices currently used.

Throughout much of the climate change impacts literature only biophysical impacts are reported, such as changes in temperature, or, where impacts with a direct bearing on human well-being are presented, indicators tend to be of historical, related impacts, such as the cost of floods in general. As a result there is little presentation of the impacts on human well-being.

The literature falls into four categories: academic, review, advice to policy makers and public advocacy.

The academic literature does not make presentation a priority, rarely moving beyond tables and simple bar or line graphs. Reviews of the literature, such as the IPCC's assessment reports, use presentational devices to summarise and synthesise impact information from a range of sources. The 'burning embers', in figure 11, is a good illustration of this synthesis approach. The use of 'traffic light' forms of presentation, where an ordinal scale is communicated using colour, and temperature scales, where impacts are listed alongside the corresponding temperature, are frequently used in reviews.

Documents and tools for policy makers contain more advanced ways of presenting information. For example, the World Development Report and reports on adaptation present a high level of detail in an accessible manner. Bar charts, waterfall diagrams and maps are frequently employed. These diagrams, while requiring some effort to understand, are effective because they communicate at least two, if not three, of the four dimensions along which climate impacts can occur: time, space, states of nature and well-being.

There are examples of work from the UK Met Office or US federal bodies such as the

Environmental Protection Agency and the National Science and Technology Council which use innovative forms of presentation, employing computer animation to display the dynamic aspects of climate change. These agencies may deliver the most influential contribution when they combine representative, local case studies with key global information.

Table 1 Presentational devices can be assessed for their ability to present impacts in context, time, space, uncertainty and dimensions of human well-being

Type of presentational device	Ability to present impacts in: context	time	space	uncertain states of the world	multiple dimensions of human well-being	Examples
Line charts	— baselines may provide context	✓ ideal for presenting changes over time	✓ area under a line can be divided into wedge	✓ states of the world can be represented by different lines	— dimensions may be aggregated into an index	% GDP loss over time according to SRES scenarios (figure 1)
Bar charts	— baselines may provide context	— each bar may represent a time step	✓ each bar may represent a region	✓ error bars show extreme states of the world	— dimensions may be aggregated into an index	contribution of sector damage to total GDP loss across regions (figure 2)
Waterfall diagrams	✓ ideal for presenting a change from a baseline	— illustrates a snapshot in time	— can display impacts across regions	X ranges of impact cannot be displayed	X only one dimension of well-being may be explored	changes in income due to impacts (figure 4)

Note: table 1 continues on the next page

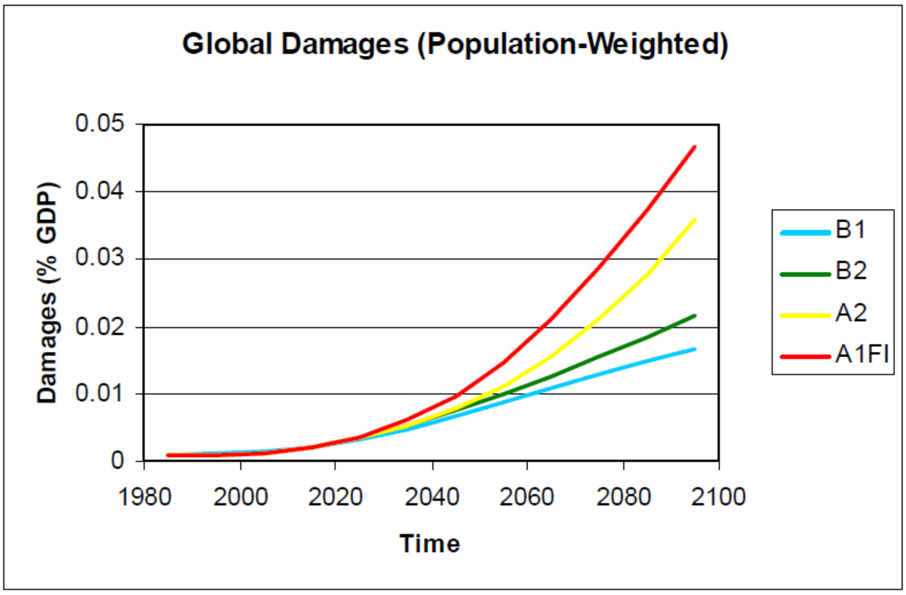
Type of presentational device	Ability to present impacts in: context	time	space	uncertain states of the world	multiple dimensions of human well-being	Examples
Maps	— can be provided by adjacent map	— can be provided by adjacent map or, 'location equivalence'	✓ ideal for presenting impacts over space	— different states of the world can be presented in an adjacent map	— multiple layers of information may be added	the Met Office 4 degree map (figure 9)
Traffic lights and temperature scales	X poor at providing context	—	— traffic lights can be presented for each region	X limited to 'better' or 'worse' description of states	✓ primarily used to present multi dimensional impacts but can lack precision	IPCC summary of sector impacts by temperature change (figure 12)
Local case studies	X specificity inhibits comparison	—	X specificity inhibits comparison	✓	✓	City flooding or local tipping points (figures 13 & 14)
Web-based, interactive, impact data	✓ baselines and ability to change data viewed provide context	✓ user selection of timescales aids communication	✓ user selection of regions aids communication	✓ probability distributions can be displayed in a variety of ways	— yet to be demonstrated, but high potential	UK Climate Projects (figure 15)

Source: Vivid Economics

1.2 Gallery of presentational devices

1.2.1 Line charts

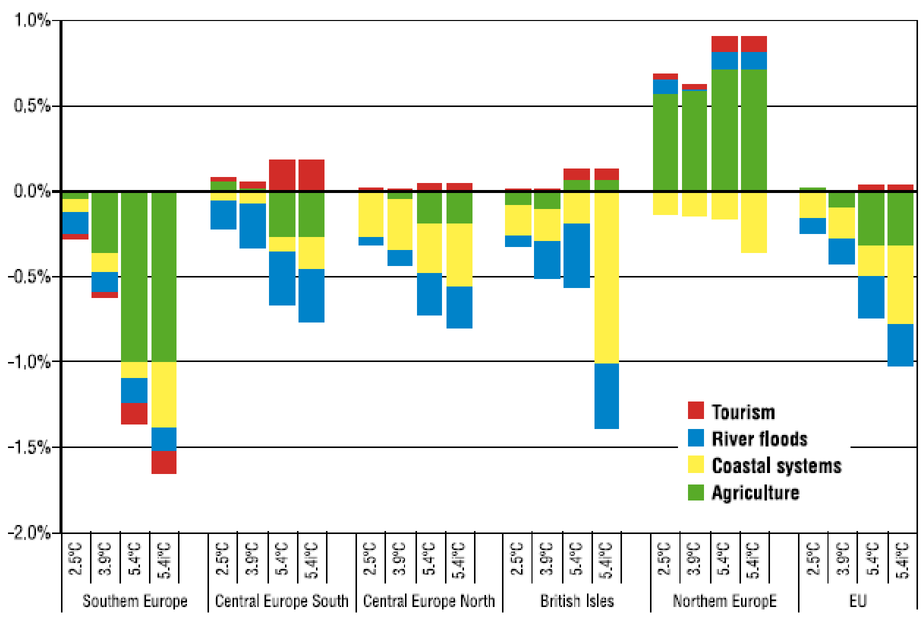
Figure 1 Line charts communicate the change in an indicator over time and across states of nature but they do not present the drivers of change



Source: Warren, R., C. Hope, et al. (2006)

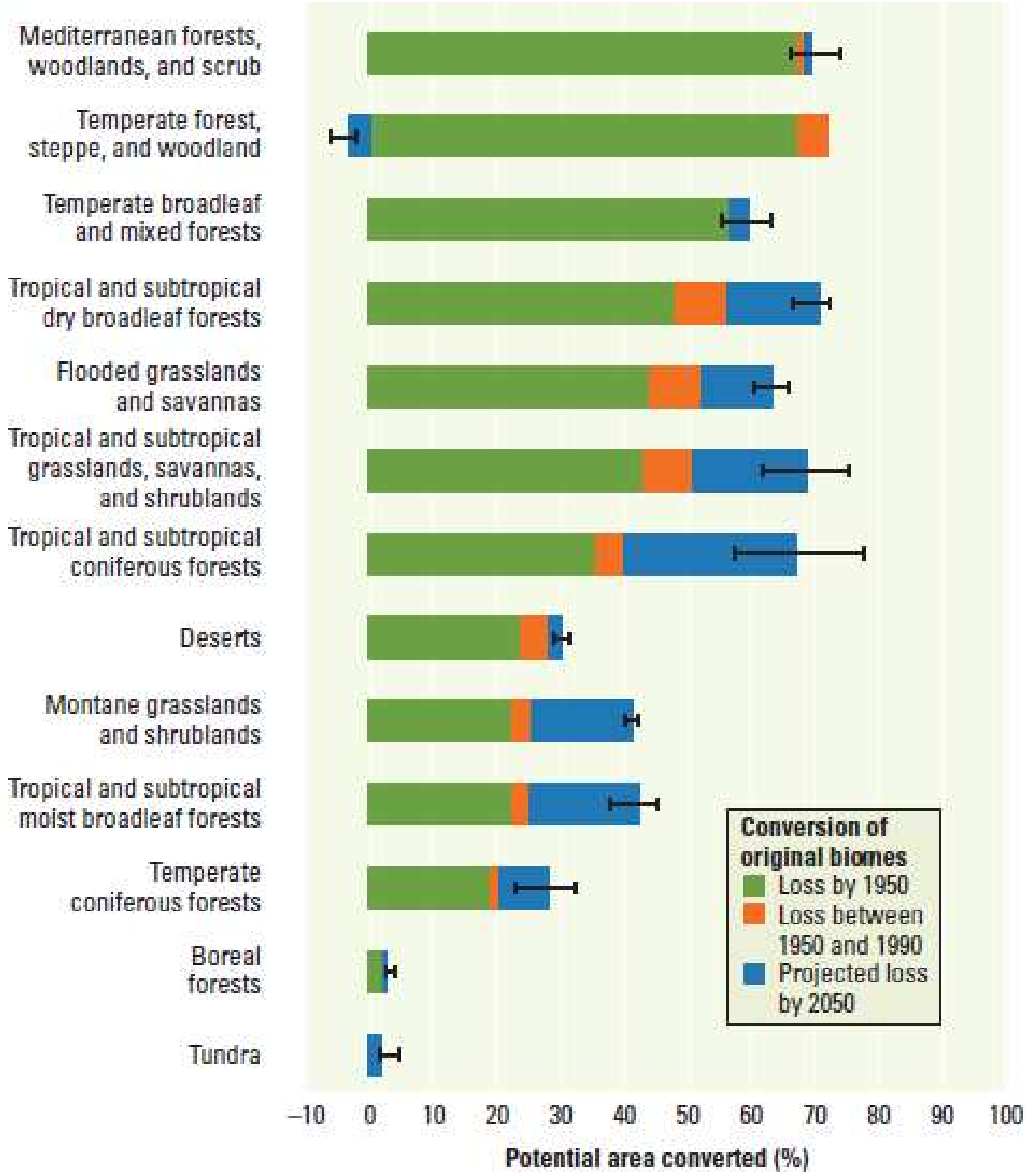
1.2.2 Bar charts

Figure 2 Bar charts can present information across dimensions of time and space and show the contribution to impacts of multiple drivers



Source: PESETA (2009)

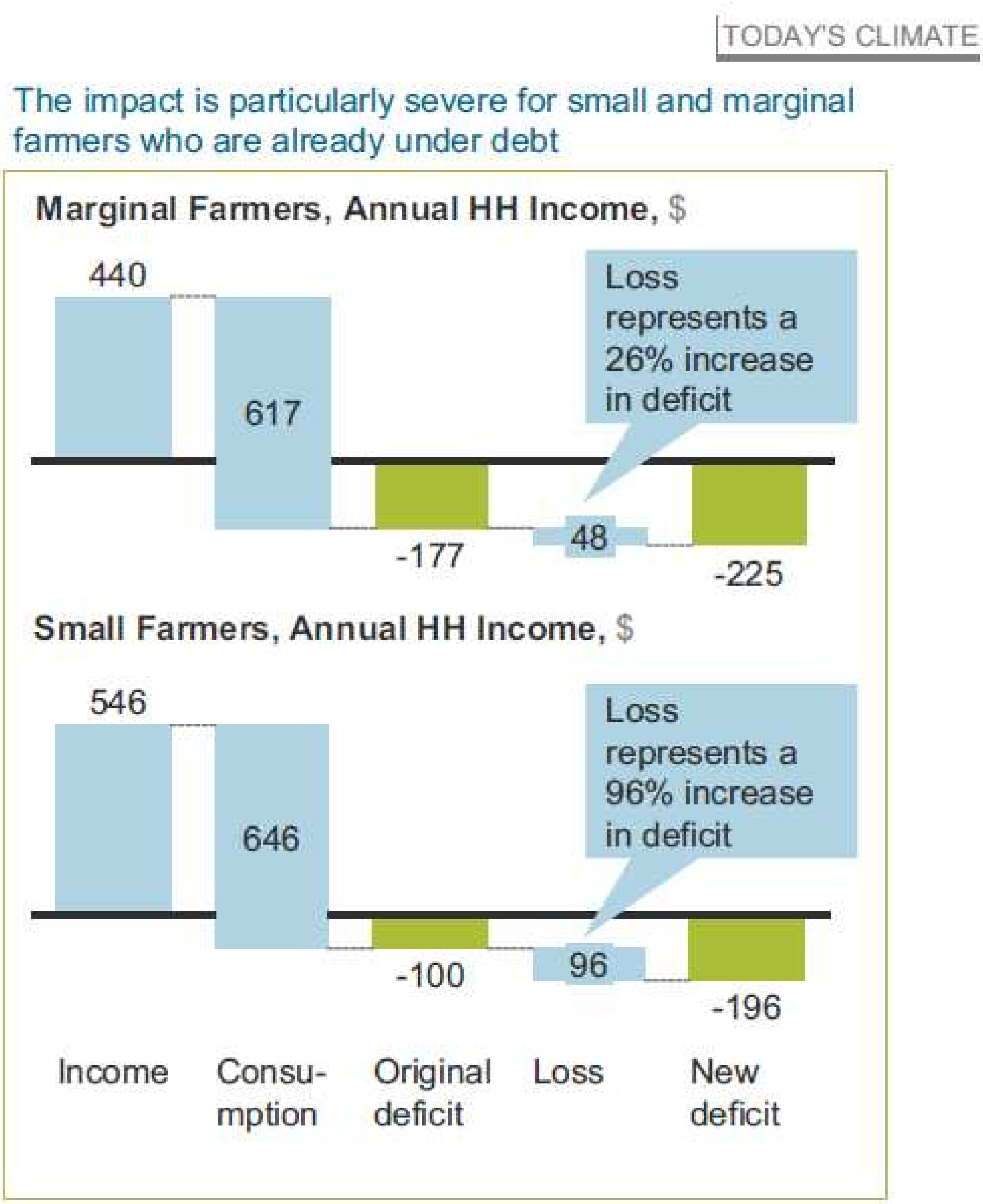
Figure 3 The use of error bars allows uncertainty to be communicated



Source: Millennium Ecosystem Assessment (2005)

1.2.3 Waterfall diagrams

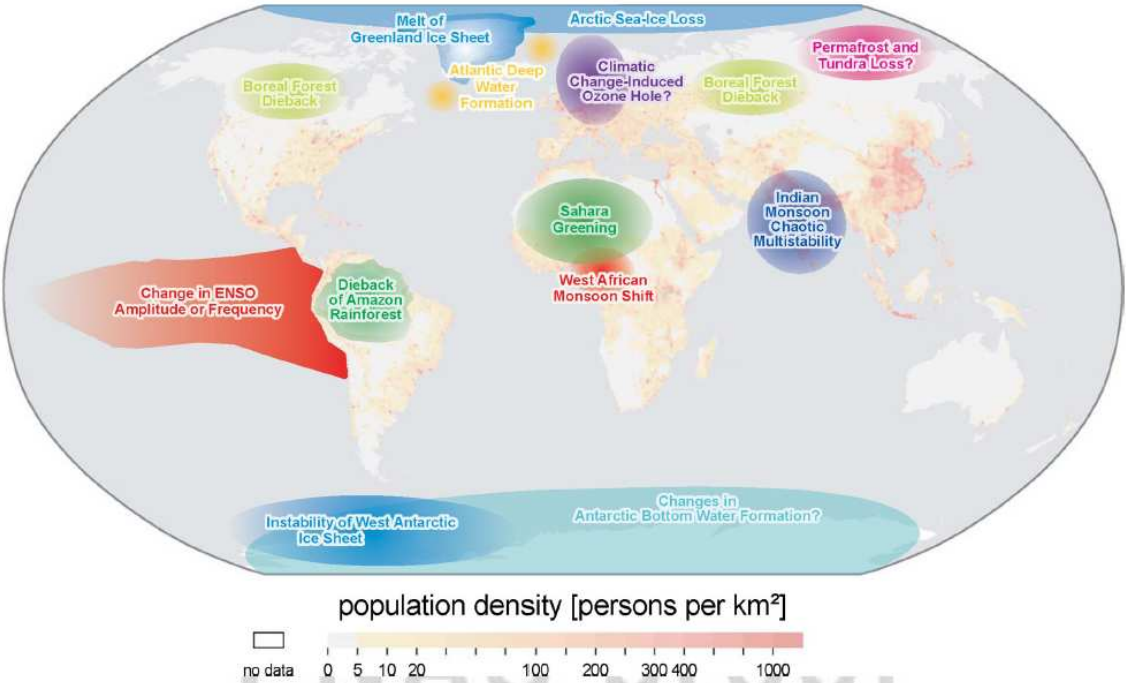
Figure 4 Waterfall diagrams show the change from a baseline and the relative importance of contributing factors



Source: Economics of Climate Adaptation (2009)

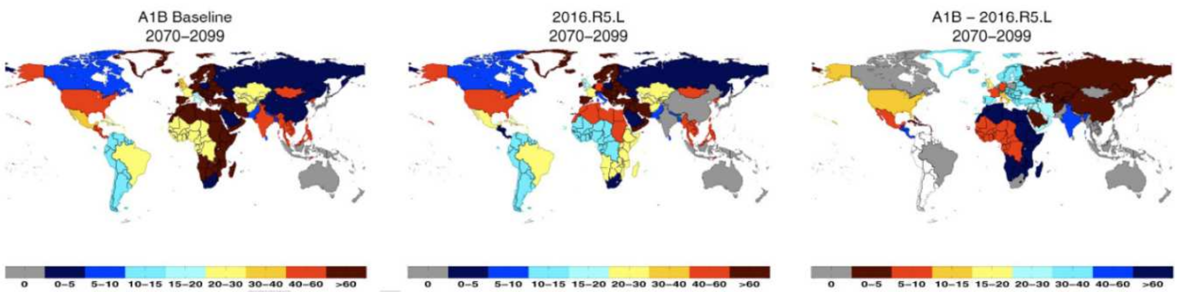
1.2.4 *Maps*

Figure 5 Maps can be used to show hotspots of climate change impact, such as vulnerability to discontinuities (non-linear effects)



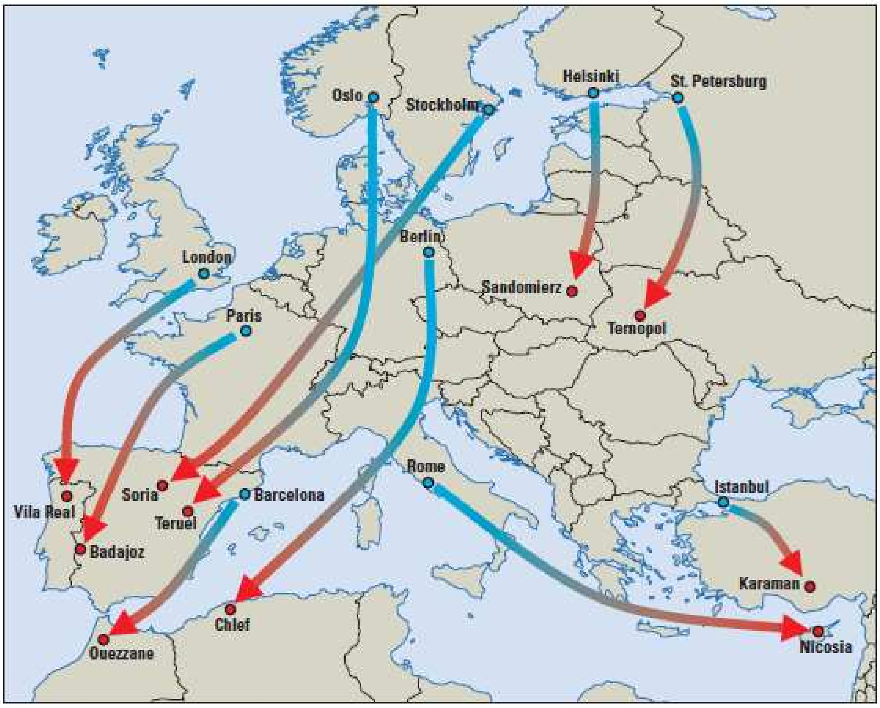
Source: Lenton et al. (2008)

Figure 6 Colour-coded maps allow an easy comparison across states of nature as these maps of millions of people at risk of increased water stress show



Source: AVOID (2010)

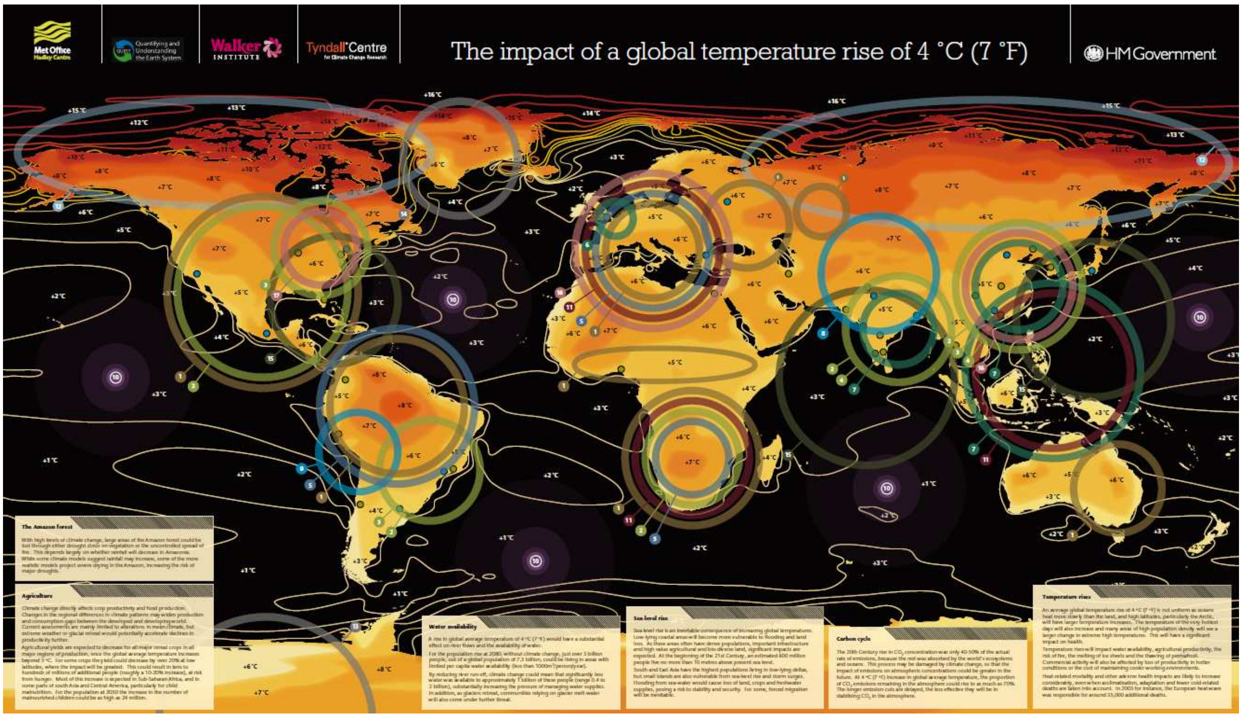
Figure 7 A map comparing the future climate of northern cities to the climate of southern cities today



Source: WDR team, reproduced from Kopf, Ha-Duong, and Hallegatte 2008.

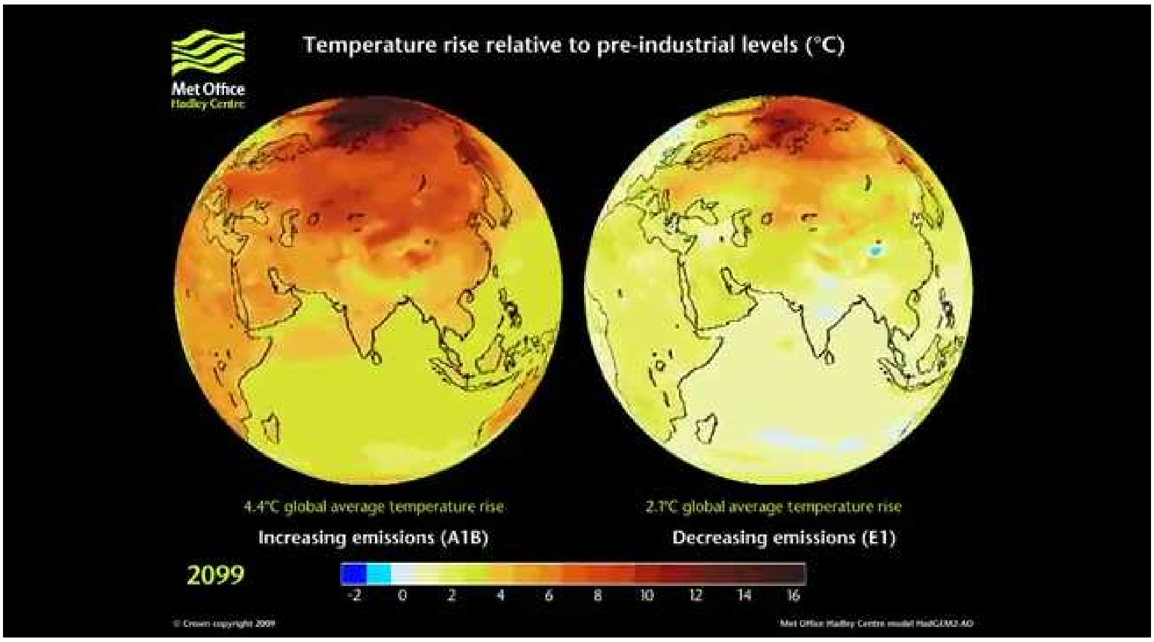
Source: World Development Report (2010)

Figure 8 The Met Office '4 degrees' map presents many layers of information



Source: Met Office (2009)

Figure 9 The use of technology allows the dynamic display of information



Source: Met Office (2009)

1.2.5 *Traffic lights and temperature scales*

Figure 10 Traffic light charts display ordinal rankings of impact, which conveys limited information

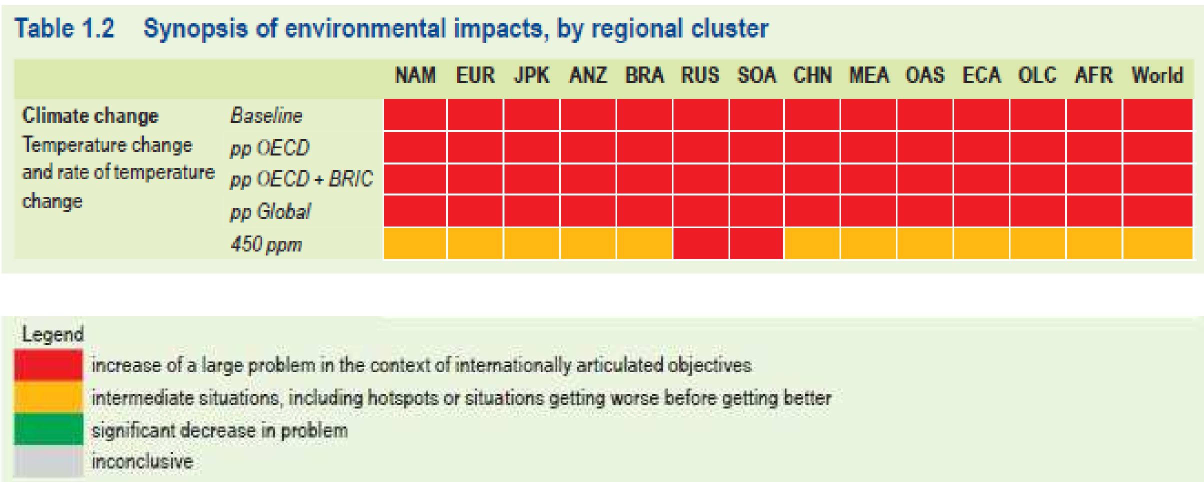


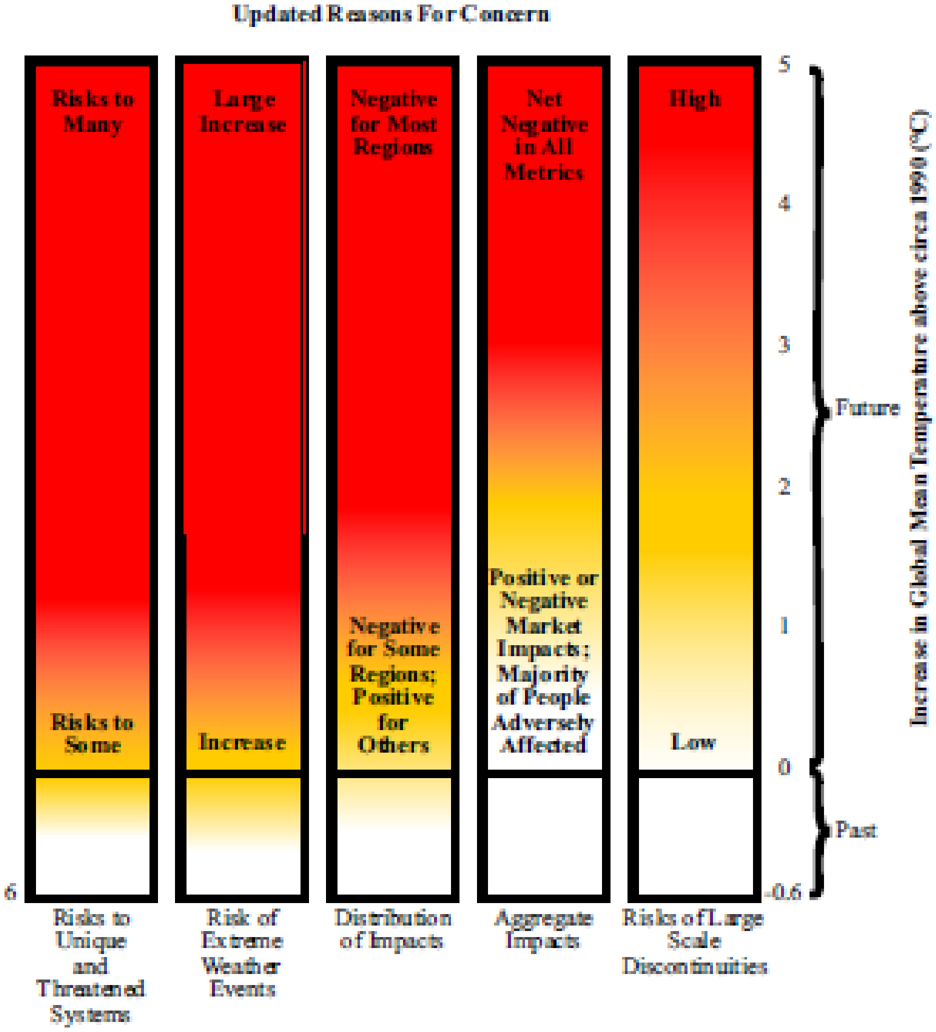
Table 1.2 Synopsis of environmental impacts, by regional cluster

		NAM	EUR	JPK	ANZ	BRA	RUS	SOA	CHN	MEA	OAS	ECA	OLC	AFR	World
Climate change Temperature change and rate of temperature change	*Baseline*														
	pp OECD														
	pp OECD + BRIC														
	pp Global														
	450 ppm														

Legend
- increase of a large problem in the context of internationally articulated objectives
- intermediate situations, including hotspots or situations getting worse before getting better
- significant decrease in problem
- inconclusive

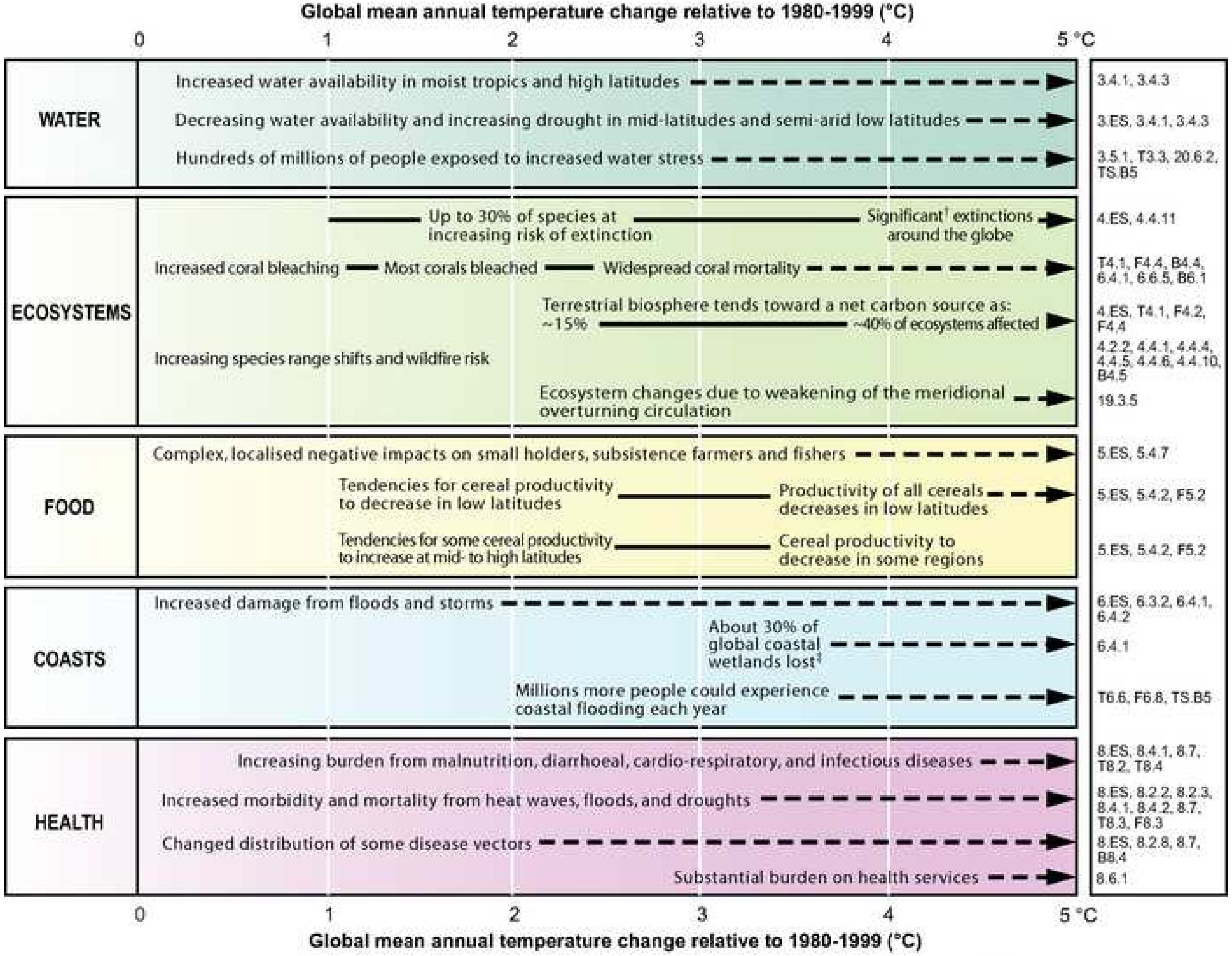
Source: OECD (2008)

Figure 11 The 'burning embers' chart synthesises impacts from a wide range of sectors and sources



Source: Smith et al. (2008)

Figure 12 The IPCC often makes use of temperature scale diagrams, which give structure to a wide variety of impact information

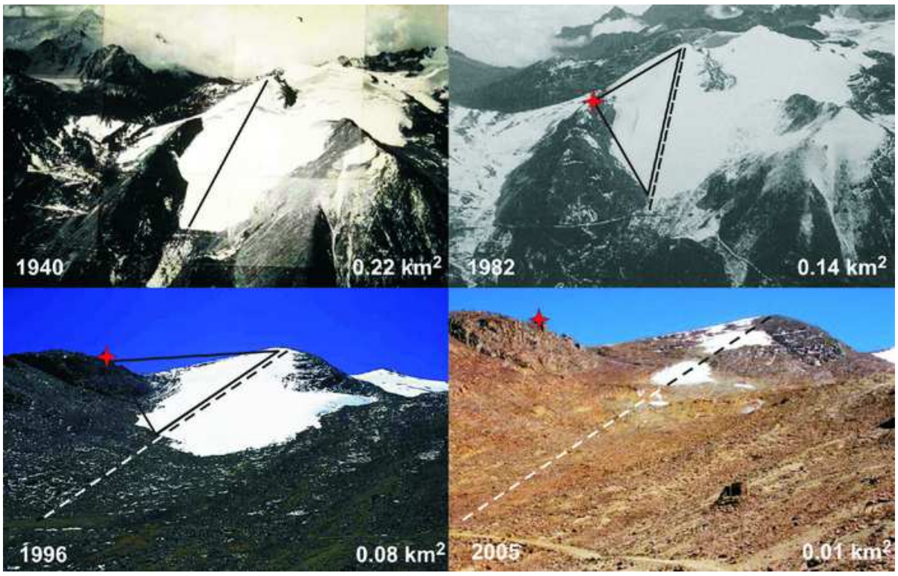


† Significant is defined here as more than 40%.
‡ Based on average rate of sea level rise of 4.2 mm/year from 2000 to 2080.

Source: IPCC (2007)

1.2.6 *Local case studies*

Figure 13 Local case studies can be very effective at communicating the impact of climate change



Source: IPCC (2007)

Figure 14 Case studies can focus on the worst case, which may mislead the audience

The light blue area above depicts today's FEMA 100-year flood zone for the city (the area of the city that is expected to be flooded once every 100 years). With rising sea levels, a 100-year flood at the end of this century (not mapped here) is projected to inundate a far larger area of New York City, especially under the higher emissions scenario.[91] Critical transportation infrastructure located in the Battery area of lower Manhattan could be flooded far more frequently unless protected. The increased likelihood of flooding is causing planners to look into building storm-surge barriers in New York Harbor to protect downtown New York City. [234,370,371]

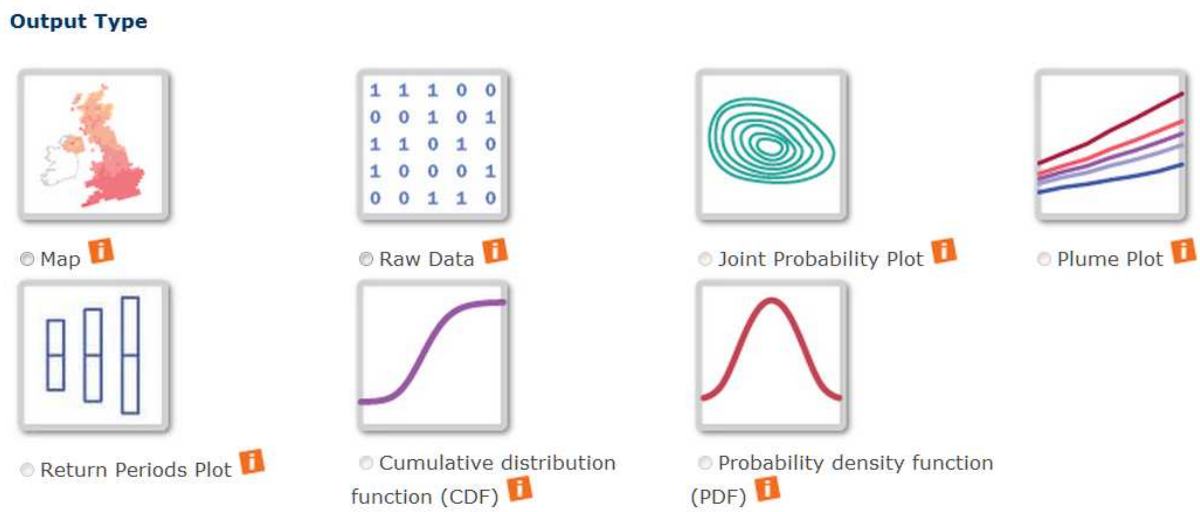
Source: US Global Change Research Program (2009)

1.2.7 *Web-based, interactive, impact data*

A small but increasing number of impact databases can be accessed via the web. The use of technology allows users to interact with the data by selecting time, space and uncertainty parameters. Examples include weADAPT and the RFF's Adaptation Atlas.

The UK Climate Projections is a Defra-funded project of special note as it presents an advanced web-based user interface accessing high-resolution data for 47 biophysical indicators including land and sea temperature, precipitation, sea level rise, cloud cover, humidity, wave flux, salinity and sea heat dynamics. Data is available by time period and aggregated from 25 km grid squares to regional grouping. Uncertainty is captured through the presentation of results at various deciles of climate change. Users can define the time period and level of aggregation desired for each indicator and represent uncertainty in a number of ways. The metrics presented are all biophysical and often technical, so they have no direct relation to human well-being. However, the format of the database could be a template for the presentation of future, more relevant, indicators of climate change impact.

Figure 15 The UK Climate Projections project is exploring innovative ways to handle and present data on uncertain climate change impacts



Source: UKCP09 (2009)

2 Insurance industry valuation of natural catastrophes

The insurance industry has a history of studying the impact of natural catastrophes. The impact of natural catastrophes is of interest when assessing the impact of climate change. As a result it is informative to understand the ways in which the insurance industry measures the impact of natural catastrophes.

Insurers of natural catastrophes consider the nature of a hazard, the vulnerability of assets to the hazard, the geographic location of assets and their level of insurance. Only insurable assets are valued. (Swiss Re., 2006)

Insurers promise to cover the impacts of a hazard if it occurs in return for a premium that is paid irrespective of whether the hazard occurs. They use two key indicators: the **expected loss** within a period, such as one year, and the **extreme event loss**, which is the maximum loss possible. In the process of calculating these, they estimate other intermediate indicators, which are also of interest. This section explains that process and the intermediate indicators that are generated.

Insurers use four modules for their estimation. First, the hazard module estimates the frequency, location and intensity of the hazard. Second, the vulnerability module brings together the intensity of the hazard and the mean damage ratio, to produce a curve similar to a dose-response function. In contrast, the IPCC uses a wider definition of vulnerability, which spans susceptibility to and ability to cope with the adverse effects of climate change. The mean damage ratio is the percentage of value lost by insured objects due to the hazard. Third, the value distribution module assesses how the value of assets at risk is distributed spatially. The replacement cost of the asset at market prices is used, regardless of the sum insured. Finally, the insurance conditions module estimates the proportion of the loss that is insured, taking into account insurance penetration, the ratio of insurance premiums to GDP, deductibles and excesses. The four modules link together to determine the expected annual loss, which is used to set premiums, and the extreme event loss, which is used to calculate the insurer’s maximum liability that in turn determines the level of capital or reinsurance an insurer needs in order to remain solvent in the worst case.

Insurance policies can only be offered if all four of the modules can be well-characterised and if the extreme event loss does not exceed the insurer's ability to bear it.

The indicators are only concerned with insured value, which is a subset of total economic value.

3 The capabilities framework

This appendix supports section 3.7 of the main report by proving further discussion of the capabilities framework.

3.1 Sen's capabilities framework

Sen looks much wider than consumption or utility measures of development. He describes development as the provision of a set of freedoms. These freedoms are:

- personal choice, to be one's own agent and to exert control over authority through a democratic mechanism;
- sufficient income, to secure food, education and health care, although not income for its own sake;
- employment, bringing the self esteem of work;
- access to health care; and
- equality of opportunity.

He does not espouse a global benchmark, and his framework sits somewhat uncomfortably as a global index. One reason is that it is intended to account for differences in need, encompassing differences brought about by:

- personal diversity;
- environmental diversity;
- variations in social climate; and
- differences in relational perspectives, such as relative poverty and social access.

These are difficult to incorporate into a global index.

The lack of freedoms is described as deprivation. A deprivation can relate to a shortfall of any of the freedoms. Sen concludes that social provision can avoid deprivation in most cases. The same appears to be true for climate impacts: social provision can avoid deprivations resulting from the impact.

3.2 Link to UN millennium development goals

The UN has drawn up a list of development goals which play a central role in defining the outcomes which it pursues across its programmes of work. These goals are grouped under five headings, set out below. They adopt a similar structure and coverage to the capabilities framework. As a result, by adopting the capabilities framework to measure climate change impacts, the effects of climate on the UN's programmes of work will be shown:

- live a long and healthy life by reducing child mortality, improving maternal health and combating HIV/AIDS, malaria and other diseases;
- be educated by achieving universal primary education;
- have a decent standard of living by eradicating extreme poverty and hunger and ensuring environmental sustainability;
- enjoy political and civil freedoms and promote gender equality by empowering women;
- develop a global partnership for development.

4 Background information on sources of sectoral impact estimates

4.1 Introduction

This section presents some background information on the sources of estimates presented in section 5 of the main report. The selection of work presented here has been chosen by the authors to support the discussion in the main report, within the resources available to this study.

The sectors considered are health, biodiversity, coastal flooding, and agriculture.

4.2 Health sector

The impact of climate change on health is presented in section 5.2 of the main report. This section of the appendix explains how the impact of climate change on Disability Adjusted Life Years (DALYs) lost is calculated by the World Health Organisation, whose data was used in section 5.2 of the main report.

The estimation of health impacts of disease has been led by the World Health Organisation's Global Burden of Disease (GBD) project (WHO, 2008) and the Comparative Quantification of Health Risks project (WHO, 2004). The GBD provides a database of current health impacts, describing impacts not only on mortality but also on morbidity through the use of DALYs lost, which were introduced in section 2.2 of the main report and illustrated here in figure 16. Indeed, it was the GBD project that developed the concept of a DALY and ascertained weights that describe the departure from perfect health caused by a particular disease.

Figure 16 An illustrative calculation of DALYs from two health impacts

DALYs equal the sum of Years of Life Lost (YLLs) and Years Lost due to Disability (YLDs).

YLLs equal the number of deaths in an age, sex cohort x the discounted and weighted global standard expected life years remaining of that age, sex cohort.

For example, if 10,000 20 year old males died from road traffic accidents, then, given that their discounted and weighted expected life years remaining are 35 years each, YLLs would be 10,000 x 35 = 350,000 YLLs.

YLDs equal the number of incident cases of a disease x the diseases' disability weight x the discounted and weighted duration of the disease in years until remission or death.

For example, if in a population of 1 million 40 year old females, 1 per cent contracted blindness due to glaucoma, then, given that blindness does not go into remission prior to death, 10,000 females would suffer a disability weighted at 0.600 for their remaining 23¾ years of discounted and weighted expected life years remaining, so YLDs would be 10,000 x 0.600 x 23.75 = 142,500 YLDs.

DALYs over these two examples would be 350,000 + 142,500 = 492,500 DALYs

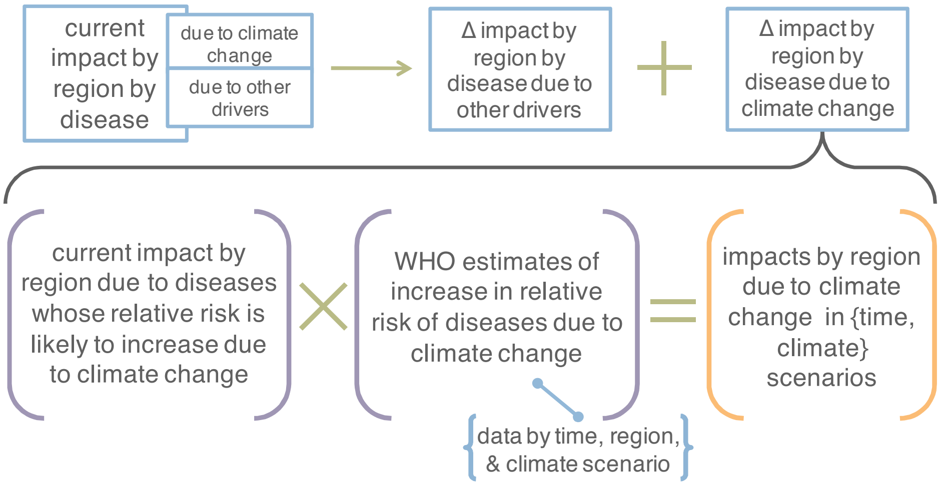
Source: Vivid Economics

The Comparative Quantification of Health Risks project provides an index of how the relative risk of a disease evolves over time in response to twenty-six drivers, including climate change. The index is based at 1.000 for the present level of burden, with the future burden being the product of the index and the current burden. So an index of 1.055 would describe a 5.5% increase on today's health impact.

The relative risk index is a regression co-efficient between observed temperature change and health impact. Some diseases, in particular Dengue, have proved very hard to model reliably. So while Dengue is thought to be a disease whose impact is likely to increase with climate change it is often absent from health impact analysis.

Two notable studies have used the WHO work on the global burden of disease and comparative quantification of health risks. These are Ebi (2008) and Campbell-Lendrum et al (2005). In section 5.2 of the main report a similar method to those found in these papers is used to calculate the scale of climate change impacts on health and present them as suggested in section 4.2 of the main report.

Figure 17 WHO data allows the impact of climate change on the burden of disease to be considered in the context of other diseases



Source: Vivid Economics

4.3 Biodiversity

The impacts of climate change on biodiversity are presented in section 5.5 of the main report. This section of the appendix provides a brief overview of the literature that informed the impacts in that section; the impacts are Mean Species Abundance (MSA) loss and the risk of extinction due to climate change.

Methods exist to model the global impact of MSA reduction, while the risk of extinction can be assessed on a regional basis. For the estimation of MSA loss due to climate change, the GLOBIO3 model leads the field (Alkemade et al. 2009). It has been used for biodiversity impact assessments by the Convention on Biological Diversity, The Economics of Ecosystems & Biodiversity and the OECD Environmental Outlook. It has its strengths and weaknesses, and further discussion among experts would be worthwhile before deciding how to make use of this and alternative approaches.

GLOBIO3 embodies a set of equations describing the biodiversity impact of changes in environmental drivers, such as agriculture, habitat fragmentation and climate change. The relationship between climate change and environmental drivers is estimated by regression analysis of biome or species shift in response to changes in temperature in the IMAGE or

EUROMOVE models. Where IMAGE and EUROMOVE estimates overlap the lower estimate is used.

The risk of extinction lacks a widely accepted global impact model. Furthermore, few studies have considered the impact of climate change at any greater level of resolution than the local level. Two studies that provide a global overview stand out; these were influential in the conclusions of IPCC AR4. Thomas et al. (2004) estimate that by 2050, with warming of 1.8°C – 2.0°C, between 15% and 37% of species in a set of representative regions would be at risk of extinction. Malcolm et al. (2005) estimate that, under a 550 ppm stabilisation scenario, between 1% and 43% of species in biodiversity hotspots face extinction.

These models rely on climate envelope modelling, where the current population of a species is considered to be a function of the area of its habitat, and the area of its habitat is, all else being equal, a function of temperature. As temperature changes habitat changes and thus the 'envelope' that supports a species changes. If the envelope fails to meet certain criteria, such as being extensive enough to support a breeding population, the species is considered at risk of extinction. Climate envelope modelling has proven controversial because climate envelopes are difficult to characterise. Furthermore, if species can migrate to new areas then a species may not be at risk of extinction even if its old envelope is no longer viable. Indeed much of the uncertainty in the estimates of Thomas et al. (2004) and Malcolm et al. (2005) is driven by assumptions regarding migration.

4.4 Coastal flooding sector

The impacts of climate change on coastal flooding are presented in section 5.6 of the main report. This section of the appendix discusses the DIVA tool, which was used in the AVOID program to estimate the impacts presented in section 5.6 of the main report.

The Dynamic Interactive Vulnerability Analysis (DIVA) tool was developed in 2006 to evaluate the global impacts of coastal flooding due to climate change and remains the state-of-the-art global model for estimating the impacts of coastal flooding.

Prior to DIVA, evaluation of the global impacts of sea level rise was based on the work of Hoozemans et al. (1993), where 192 polygons represented the world's coastal countries; this work underpins many influential coastal impact assessments, such as Tol's 2007 work for IPCC AR4. DIVA improves on Hoozemans et al., containing a database of 12,148 coastline segments with each segment associated with topographical, socio-economic, ecosystem and flood defence data; the granularity of the data allows DIVA to evaluate regional impacts.

Since DIVA's introduction, it has become the model of choice for global assessments of sea-level rise, and it has been used in the AVOID and UNFCCC programs. However, more detailed regional studies are often conducted.

In addition to a coastal topology, DIVA uses climate and socio-economic scenarios. Scenarios of sea-level rise and changes in surge levels are used as inputs to DIVA; these inputs are region specific where possible, and may be taken from a variety of sources, including MAGICC. The socio-economic scenarios are based on SRES scenarios and there is no exogenous migration toward or away from the coast. The valuations are sensitive to socio-economic scenario assumptions. Adaptation options, which may be either protection or retreat, are modelled. Adaptation through beach nourishment to counter erosion occurs if it passes a cost-benefit analysis against the monetised outputs of DIVA. The main adaptation measures are adopted wherever the risk of flooding exceeds an acceptable level of risk, using a cost-effectiveness analysis. Due to the high value of coastline in almost all areas, adaptation is often found to be cost-effective, so the dominant cost of coastal flooding is money spent on protection.

DIVA's principal strength lies in its ability to model impacts (in physical and economic terms) and adaptation costs and benefits. The cost of protection is taken from engineering estimates and varies by technology selected, which may be either sea dykes or beach nourishment. Methods of monetisation and indicators expand on the 1992 IPCC Coastal Zone Management Subgroup common methodology: land loss costs and flood costs are multiples of coastal GDP, but the methodologies for the cost of wetland lost and saltwater intrusion are not described by the author.

4.5 Agriculture

The impacts of climate change on agriculture are presented in section 5.7 of the main report. This section of the appendix provides a brief description of the main types of models used to estimate these impacts. The interested reader is encouraged to pursue the references in the agriculture section of the bibliography.

The impact of climate change on agriculture has been estimated using crop models, Ricardian techniques and, more recently, Dynamic Global Vegetation Models (DVGMs). No single method overcomes all the challenges of modelling agriculture in a changing climate. In particular issues of CO_2 fertilisation and adaptation generate significant uncertainty in estimates. Furthermore, crop models and Ricardian models are local models, which can have limited global usefulness. The difficulty in aligning models spatially has meant that the attempts to estimate global agricultural output or yield change across a range of scenarios have met with varying degrees of success.

Crop models describe functional relationships between drivers and yields, such as temperature and precipitation. Estimates of change in the drivers of yield are taken from General Circulation Models or regional climate data forced by emissions scenarios and applied to these production-functions, so the change in yield due to climate change is estimated. Crop models allow for different types and degrees of adaptation. Changes in yields can be transformed into changes in output (changes in net revenue in dollars) using food trade models. Overall, there is a wide range of models drawing from a number of data sources, using different assumptions and producing different outputs.

Ricardian models focus on how net revenue is correlated to characteristics. The assumption is that farmers will choose the type of production that maximises their profits, subject to the constraints of climate, prices, water availability, soil characteristics and wages. Changes in these constraints affect profits. Climate change affects these constraints, such as number of growing days, and the change in output (change in net revenue in dollars) is estimated. Adaptation is implicit as the constraints change. Ricardian models can underestimate the impact of climate change if the constraints are positively correlated (i.e. climate and water availability).

Recently, Dynamic Global Vegetation Models (DVGMs) have been adapted to include agriculture. DVGMs specify 'crop functional types' and make the response of a crop to climate change become part of an ecosystem wide response. An important application of a DGVM to the impact of climate change on agriculture is the work of Muller et al (2010) for the World Bank, World Development Report 2010.

5 Background information on IAMs estimates

This appendix provides a detailed overview of key Integrated Assessment Models (IAMs) as they are an important source of monetised, aggregated, climate change impacts data.

5.1 Introduction to global economic IAMs

We use the term IAM (integrated assessment model) to mean those models which integrate climate science and economics and adopt a global scale, for the purpose of exploring the sensitivity of global aggregate economic impacts to key parameters and emissions scenarios.

IAMs are worthy of review because they are the only method currently used to produce global monetised estimates of climate change damages, and have had influence in policy decisions. They incorporate the results of sectoral studies, for example estimates of the costs of coastal protection, so sectoral models and global IAMs are not substitutes. They either adopt sectoral-study relationships directly, or build their own functional relationships from evidence contained in sectoral studies. IAMs estimate the monetary costs and benefits of mitigating and adapting to climate change, and some also find the optimal policy, where the total net present cost of climate change, mitigation and adaptation is minimised. However, each IAM makes its own simplifications of the problem. For example, adaptation is implicit in DICE. At the same time, economic growth is exogenous to FUND and PAGE.

Some of the large uncertainties in estimating the economic impact of climate change are not addressed by sectoral studies. For example, sectoral studies do not address issues of aggregation such as discounting nor do they usually model issues such as the crossing of tipping points. It is an advantage of IAMs that they can explore sensitivities to these assumptions.

Within the IAM literature three of the main models currently in use are DICE/RICE, FUND and PAGE. These are used here as examples. RICE is a regionally disaggregated version of DICE. The release of both DICE-2009 and PAGE-2009 are imminent, however they are still (at the time of writing in summer 2010) in a testing phase and are not described here.

There are five major modules in the IAMs, and each is described:

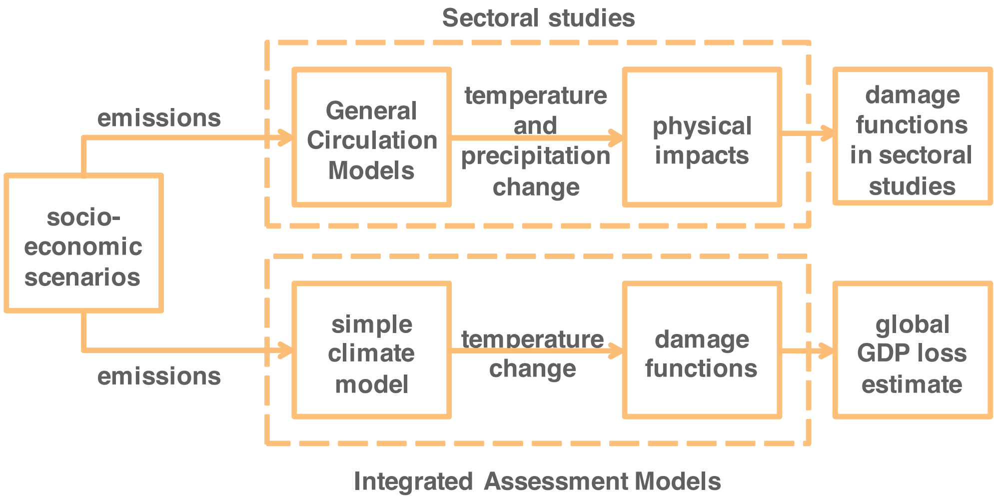
— model structure and socio-economic scenarios;
— climate response, covering climate sensitivity, transient temperature response, carbon cycle feedbacks;
— impacts, comprising damage functions, functional forms used, level of sectoral and regional aggregation, treatment of market, non-market, extreme and catastrophic events and sources of parameters;
— treatment of adaptation; and
— valuation, including discounting, equity-weighting and risk aversion.

The models take a number of parameter values as exogenous. Either a single best estimate is used or a range of parameter values over a probability distribution is used. DICE and FUND were originally designed as deterministic models, which only use single best estimates, although they have subsequently been run with ranges of values. PAGE was designed as a stochastic model and uses a range of values over a probability distribution.

These exogenous values are drawn from the literature. Many of the climate response values were originally calculated using more sophisticated GCMs while the parameter values of damage functions are drawn from a small pool of studies.

There is significant overlap between sectoral studies and IAMs in terms of the modelling process and the source of parameters, as illustrated in figure 18.

Figure 18 Sectoral studies, general circulation models and the DICE model are closely related



Source: Vivid Economics

5.2 Socio-economic scenarios

AVOID is similar to FUND and PAGE in using SRES scenarios to provide socio-economic, and thus emissions, projections whereas DICE models economic growth endogenously. In DICE, emissions are a function of economic activity and vary with economic growth. The modelled economy is calibrated to 2005 and emissions projections in the base case run of DICE lie between the SRES A2 and B2 scenarios (Nordhaus, 2008). The Special Report on Emissions Scenarios (IPCC, 2000), known as SRES, sets out a widely used set of socio-economic scenarios together with emissions projections.

FUND specifies 5 scenarios: SRES A1B, A2, B1 and B2 and a separate, FUND-specific scenario. Socio-economic variables other than emissions, such as technological improvement, affect the damage functions of some sectors. PAGE makes use of two scenarios in most of its past published studies: SRES A2 and B2, but can be run for any scenario. For comparison, the AVOID scenarios are A1B and a suite of scenarios more stringent than A1B. AVOID's more stringent scenarios are characterised by the date at which emissions peak (2016 or 2030), the rate of emissions reduction (2 per cent to 5 per cent a year) and the final level of emissions (high or low).

5.3 Climate response

Climate sensitivity is the long-run temperature increase expected from a doubling of CO_2-e concentrations. A climate sensitivity of 3°C means that, in equilibrium, a doubling of CO_2-e concentrations from pre-industrial levels (550 ppm) will lead to a 3°C temperature increase. It may take hundreds of years for the model to reach equilibrium. This time period is determined by the transient temperature response.

The IPCC (2007) give a best estimate for climate sensitivity of 3°C and a likely range of 2–4.5°C, the lower bound is considered more certain than the upper bound. Climate sensitivity is determined by models such as Atmosphere-Ocean General Circulation Models (GCMs); IAMs use these GCM outputs as inputs. FUND and the previous version of PAGE use a best estimate that is lower than the IPCC recommendation but have a maximum climate sensitivity that is just greater. The current version of PAGE has been brought into line with the IPCC AR4 report.

Table 2 Climate sensitivity estimates used by three IAMs

FUND	DICE	PAGE
uses a gamma distribution with a best estimate of 2.5°C, a mean of 2.85°C and standard deviation of 1°C	uses a single value of 3°C	uses a triangular distribution with a best estimate of 2.5°C, a mean of 3°C, a min of 1.5°C and a max of 5°C

Source: Vivid Economics

IAMs model the transient climate response in a simple but representative way. DICE and PAGE are found to be in the middle of the range of GCMs' transient climate response while FUND is slower than the consensus (Van Vuuren, 2009).

Changes in the climate may affect the rate at which carbon sinks remove CO_2-e from the atmosphere. Carbon sinks are reservoirs of carbon other than the atmosphere, such as forests or the oceans; carbon in these reservoirs does not increase temperature.

If the effectiveness of carbon sinks decreases as a result of climate change at certain concentrations of CO_2e then the rate of mitigation increases in such scenarios to compensate if warming is to be constrained to certain levels. While the behaviour of carbon sinks under increasing temperatures, known as a feedback effect, is an important climate response it remains an area of significant uncertainty.

Table 3 Transient climate assumptions used by three IAMs

<table>
<tr><th></th><th>FUND</th><th>DICE</th><th>PAGE</th></tr>
<tr><td>Method of representation</td><td>‘half-life’ approach</td><td rowspan="2">simple representation of heat uptake by the ocean, which determines years to equilibrium</td><td>‘half-life’ approach</td></tr>
<tr><td>Length of ‘half life’ period</td><td>most likely: 50 years, min: 25, max: 100</td><td>most likely: 50 years, min: 25, max: 75</td></tr>
<tr><td>Inter-model comparison (van Vuuren 2009)</td><td>temperature increase is slowest and smallest</td><td>most rapid initial rate of temperature increase</td><td>rate of increase is low early on but increase in the rate of increase declines more slowly, so temperature increase overtakes DICE at ~75 years</td></tr>
<tr><td>Modelled sectors affected?</td><td>agriculture and ecosystems</td><td>no sector impacts dependent on rate of temperature increase</td><td>no sector impacts dependent on rate of temperature increase</td></tr>
</table>

Source: Vivid Economics

In IAMs, carbon reservoirs are key to the calculation of atmospheric concentration. Simple representations are calibrated to the results of more complex GCMs. Different methods of representation are used among the FUND, DICE and PAGE IAMs. Van Vuuren (2009) finds that in baseline emissions scenarios the carbon cycle behaviour of the three IAMs is consistent with each other and other GCM models. However, in a range of other emissions scenarios the feedback effect included in PAGE leads to divergent concentrations of CO_2-e. In all cases the representation of carbon sinks is simplistic, however FUND and PAGE incorporate feedbacks while DICE does not.

Table 4 Carbon feedback assumptions used by three IAMs

	FUND	DICE	PAGE
Representation of carbon reservoirs (for CO_2)	five generic reservoirs that capture constant but different shares of emissions	three reservoirs: the deep ocean, the biosphere and the atmosphere that capture constant but different shares of emissions	no sinks represented, instead a fraction of emissions is removed upon emission
Rate of CO_2 removal from reservoir	each reservoir has a different exponential rate of removal	constant rates of exchange between reservoirs	emissions remaining are removed at an approximately exponential rate
Carbon-cycle feedbacks under increasing temperature	a 'terrestrial biosphere feedback' that increases as a function of temperature works against the removal of CO_2 from reservoirs	no change to the carbon cycle as temperatures increase	a 'natural emissions' term that increases as a function of temperature works against the fraction of emissions removed

Source: Vivid Economics

5.4 Introduction to damage functions

Damage functions transform changes in temperature due to emissions into changes in consumption-equivalent welfare. To convey the relative magnitude of these changes, they are expressed as a percentage of GDP, although it is important to realise that damage estimates do not just include losses in economic output (i.e. GDP), they also include the monetary value of non-market impacts. Damage functions are key to the policy relevance of IAMs. Physical impacts are monetized, which enables aggregation across sectors and regions and provides a simple metric for presentation.

Damage functions have two key components: the rate at which damage changes as temperature changes and the value of damages at a particular temperature, to which the function can be calibrated. The characteristic of damage functions is that the rate at which damages change is often non-linear (and for damage functions aggregated over sectors it is in practice always non-linear). This implies a view that the initial degrees of warming are not as damaging as further degrees of warming. The rate of damage increase relies in part on expert judgement and in part on calibration to studied impacts.

Damage functions can be specified for any configuration of regions and sectors. The FUND model is fairly disaggregated on the one hand while DICE and PAGE are highly aggregated on the other.

IAMs tend to lag state-of-the-art sectoral monetised damage estimates, yet the ability of IAMs to structure the rate of marginal damage is valuable. The sources of damage valuations at benchmark temperatures tend to be over a decade old for the IAMs under consideration; such a vintage suggests that damage estimates are outdated given the increase in knowledge of physical impacts in the last ten years.

There are other specific causes for concern regarding monetisation. For example, the extinction of species, a permanent loss, is treated as a transient decrease in consumption. Only FUND considers the impact of extreme events, such as tropical storms, that can have high impacts, yet its representation is simplistic.

There are two important issues for which sectoral studies have yet to provide a basis for any form of valuation. One issue is the interaction of impacts between sectors, for example increases in water stress and agricultural productivity, although computable general equilibrium models, such as ICES, are being developed and might address these. The second issue is climate change induced socially contingent events, such as wars.

5.5 Degrees of valuation and aggregation in damage functions

The regional coverage of the three IAMs is listed in table 5, showing overlap where possible.

Table 5 The spatial coverage of IAMs which tends to be aggregated into broad, supra-national, regions

FUND	DICE (aggregated to a single global damage function)	PAGE
Western Europe	EU	EU
USA	USA	USA
Canada	Other high-income countries	other OECD nations
Middle East	Middle East	Africa & the Middle East
China plus	China	China & Centrally Planned Asia
South Asia	India	India and South East Asia
South America	Latin America	Latin America
Central & Eastern Europe	Eastern Europe & non-Russian FSU	FSU & Eastern Europe
FSU	Russia	
Japan & South Korea	Japan	
Sub-Saharan Africa	Sub-Saharan Africa	
North Africa	Other Asia	
Australia & New Zealand		
Southeast Asia		
Small Island States		
Central America		

Source: Vivid Economics

The IAMs monetize impacts in all sectors. Sector damages are split into three categories: market impacts, where damages can be estimated directly as a loss of GDP, non-market impacts, where damages are often estimated via an assessment of willingness to pay, and catastrophic impacts, where damages are stylized to represent as yet unknown high consequence events. Their treatment in the IAMs and in AVOID, for comparison, is summarised in table 6.

Table 6 Comparison of the treatment of market, non-market and catastrophic impacts in AVOID and three IAMs

	AVOID	FUND	DICE	PAGE
Market impacts	coastal flood; fluvial flood; crop productivity; water stress; heating and cooling requirements	agriculture; forestry; energy consumption; sea level rise	single damage function for all three categories, which is calibrated to the following sectors: agriculture; sea level rise; other market sectors	single damage function for market impacts calibrated to damage estimates of IPCC TAR (2001)
Non-market impacts	aquatic ecosystems; biodiversity health; heat related deaths	ecosystems; health: diarrhoea, vector-borne diseases, cardiovascular & respiratory mortality; tropical storms	single damage function calibrated to: health; non-market amenity impacts; human settlement and ecosystems (see above)	single damage function for non-market impacts calibrated to damage estimates of IPCC TAR (2001)
Catastrophic impacts (low probability, high impact events)	the probability of breaching a suite of thresholds is described	no explicit modelling of catastrophic impacts	single damage function calibrated to the willingness to pay to avoid catastrophic damage, estimated via expert judgement	single damage function for catastrophic impacts with the likelihood of a catastrophe increasing with temperature

Source: Vivid Economics

The contribution of each sector to overall damage is not consistent between IAMs. For example, energy and water dominate the FUND estimate. Settlements, which is the cost of adapting the physical capital stock to climatic change, forms the majority of damages in DICE and non-market impacts provide most of the impact in PAGE. Also of note is the variation in the contribution of health, coastal and agricultural sectors. At 2.5°C of warming above 1990 levels, FUND estimates that the health impacts of climate change increase global GDP by 0.3 per cent while DICE estimates damage in the health sector to reduce global GDP by 0.1 per cent. Coastal impacts are also low in FUND compared to DICE, at 0.01 per cent damage versus 0.32 per cent damage, perhaps because FUND builds in more adaptation. The situation is similar for agriculture, where the effect of CO_2 fertilisation included in FUND provides a slight addition to global GDP of 0.01 per cent; in the absence of CO_2 fertilisation however, DICE estimates a 0.13 per cent decrease in global GDP. Section 5.8 of the main report provides further illustration of the differences.

The damage functions are now described in detail for each IAM in turn, starting with FUND, followed by DICE, and finally, PAGE.

5.5.1 *Damage functions in FUND*

FUND is the most disaggregated IAM with damage functions for 9 sectors, which provide damage estimates for 16 regions. The disaggregated sector damage functions are a key feature of FUND. The functional forms and parameter values are determined through a mixture of statistical work, estimates from the literature and expert judgement.

Agriculture is the most studied sector. FUND takes results from a range of sectoral studies and adjusts them to account for CO_2 fertilisation and some adaptation. The CO_2 fertilization in agriculture might be overstated. A quadratic damage function is estimated by regression of impacts against temperature.

FUND relies on a single forestry sector study. The study is a linked ecosystem and partial equilibrium timber trade model, used to test temperature scenarios from 1.6 to 3.1°C warming. It estimates productivity changes, changes in prices and the effects on patterns of trade.

Changes in energy use are derived from estimates of energy used for heating and cooling in nine regions, scaled to one degree warming. It is extrapolated to other regions using an income elasticity of 0.8, and is assumed to be linear in temperature. Its value is reported as 5 to 10 times larger than impacts on agriculture.

Like forestry, FUND draws on a single study for the water sector. This generates an impact value of 1 per cent of GDP by 2200. Tol makes what he describes as an 'ad hoc' assumption that the damages are linear in temperature.

The estimates for non-market goods are not as valid. Ecosystem losses are assumed to be related to the number of habitats lost, without a clear definition of when a habitat is lost. The unit value of a loss is based on two studies, of an unconventional type, and there appears to be no link between scale of impact and willingness to pay.

The approach to flooding is more valid. Tol takes the size of the population living in the 1 in 1,000 year flood plain and multiplies it by the chance of inundation. He uses a GDP/km^2

economic index and population density in the coastal zone and applies a value of assets per km^2 from an OECD study.

The approach to health is different again. For cardiovascular and thermal stress, Tol examines only long term average effects, to avoid counting harvesting effects. Using a regression, he derives a relationship between mortality and temperature based on 17 observations. The regression has poor explanatory power. It is interpolated and extrapolated to obtain estimates for countries outside the sample set. Tol assumes that the relationship is linear in the temperature of the warmest and coldest months, and applies the relationship to the population over 65, which itself is estimated using an income elasticity.

For vector-borne diseases, FUND draws upon three studies, examining temperature changes of 1.2, and 2.8 to 5.2°C. A linear temperature relationship was found for land becoming suitable for malaria, and this is assumed to apply also to dengue fever and schistosomiasis. Vulnerability to disease is assumed to be linearly related to per capita income, falling to zero above $3,100/capita. This assumption can be compared to the World Health Organisation's assumption that vulnerability to malaria only falls to zero when per capita income is above $6,000/capita.

Food and water-related health impacts are not estimated. Crucially, the value of a statistical life is set at 200 times per capita income, which is high in comparison to other studies. For example the EU PESETA project uses a central value of statistical life of 1.1 million euros, which, given an EU GDP/capita of 26 thousand euros, is 42 times per capita income.

In the FUND model, the sum of damages for all sectors, aggregated globally, falls for the initial degrees of warming, then rises with temperature. The impacts vary with socio-economic conditions, for instance, water resources become more vulnerable with population growth and agriculture becomes less vulnerable with economic growth.

Agriculture and ecosystem impacts are affected by both the rate of temperature increase and the level of temperature increase, while all other sectors are just affected by the level of temperature increase. Energy cooling requirements dominate the damage function as demand for air conditioning grows with increasing temperatures and economic growth.

5.5.2 *Damage functions in DICE*

DICE uses a single global damage function that is calibrated, prior to modelling runs, to damages in sectors at a regional level.

A quadratic damage function is used, which is calibrated to damage estimates at 2.5°C, with the curvature of the function producing more rapidly rising damages at higher temperatures. The benchmark values to which this function is calibrated are calculated from 7 sectors across 12 regions.

Damages for all sectors except catastrophic impacts are calculated using a future impact index, which expresses the willingness to pay to avoid an impact according to per capita income in the period and the income elasticity of the impact; this implies that damages increase with income. The value of impacts is drawn from the literature and monetized via the future impact index.

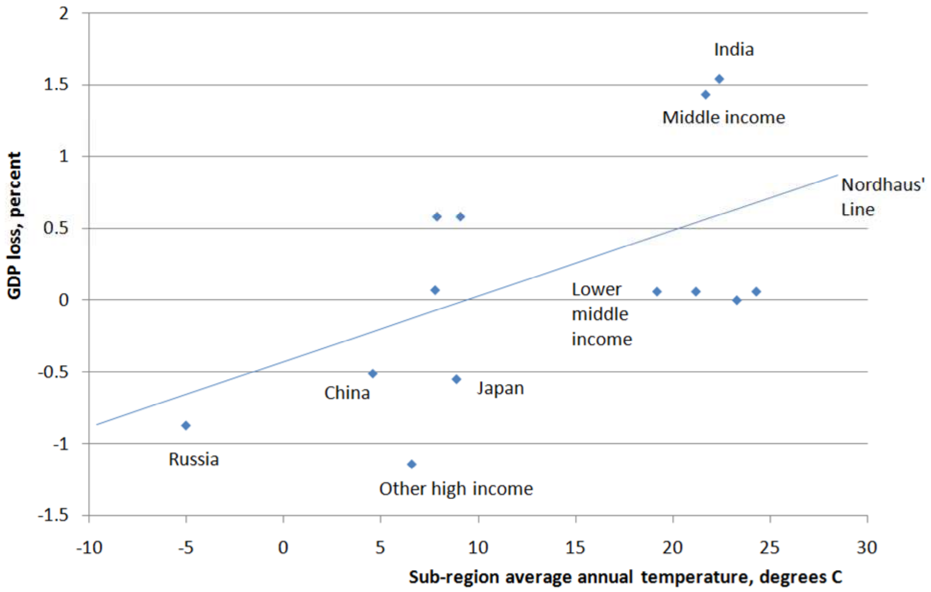
For agriculture, the quadratic damage function is the integral of a linear regression line from limited data. The line is fitted on only 13 data points and at least five of these data points are based on Nordhaus' own assumptions, whilst the other estimates are mostly based on Darwin (1995). The temperatures are averaged over large areas, for example Russia, and lower middle income countries. Our estimate of the R^2 is 0.35, which is a poor fit and gives low confidence that the relationship is linear. Nordhaus integrates this linear function to give a quadratic damage function, adjusted so that the GDP losses in figure 19 are predicted when the temperature increase is 2.5°C.

The coastal damage estimate is based on a US study and is transferred to other regions, scaling for income, and varies with temperature to the power of 1.5.

For health, years of life lost from tropical diseases such as malaria and dengue, as well as pollution, are based on Murray and Lopez's study. Nordhaus assumes that a year of life lost is worth two years of per capita regional income and expresses the total as a percentage of regional GDP. He estimates a semi-logarithmic regression function, T_i ^0.2243, between health damage and regional temperature.

Uniquely, Nordhaus includes a leisure value. He assumes a quadratic relationship between time spent engaged in outdoor leisure and temperature, peaking at 20°C. This is calibrated to US survey data, the unit value of outdoor leisure time is assumed equal to the wage rate and there is no consideration of the value of substitutes. This benefit substantially offsets some of the costs of climate change in other sectors.

Figure 19 Nordhaus fits a straight line for marginal damage sensitivity in agriculture



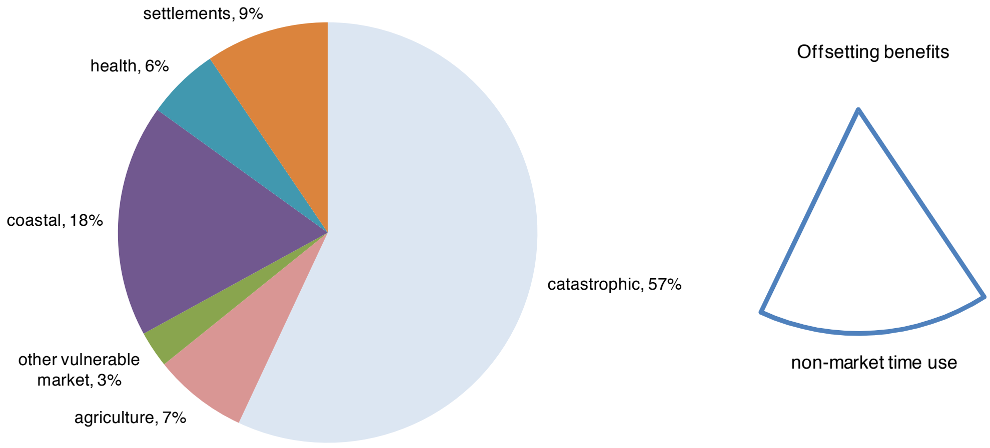
Source: Nordhaus & Boyer (2000)

Catastrophic impacts are valued on the basis of a 1996 survey of 24 expert opinions. Nordhaus takes the survey results, doubles the probabilities from the survey, applies the 2.5°C figure to 3.0°C, and increases the global percentage of GDP lost by 20 per cent. The result is that the probability of a catastrophe rises from 1.2 per cent at 2.5°C to 6.8 per cent at 6°C and the expected global loss is 30 per cent of GDP. The value of catastrophic impacts increases in importance as temperature rises, representing over half of all damages at 6°C of warming. The next largest impact is coastal flooding, at around 18 per cent of the total.

The growth rate is endogenous in DICE, a unique feature, which means that damage in a given year will affect growth in future years through depressed investment. However, the effect is not large compared with instantaneous damages.

As a final step, Nordhaus sums regional impacts across all sectors at 2.5 and 6°C of warming. He fits a quadratic function for each region which goes through three points: the origin, and the damage estimates at 2.5 and 6°C. He then sums the regional functions, to obtain two global quadratic functions weighted by 1990 population and 2100 forecast output.

Figure 20 At 2.5°C, catastrophic risk dominates the DICE damage estimates, and coastal flooding and non-market time are influential



Source: Nordhaus (2008) and Vivid Economics calculations

Note: percentages are the share of total damage attributed to each sector

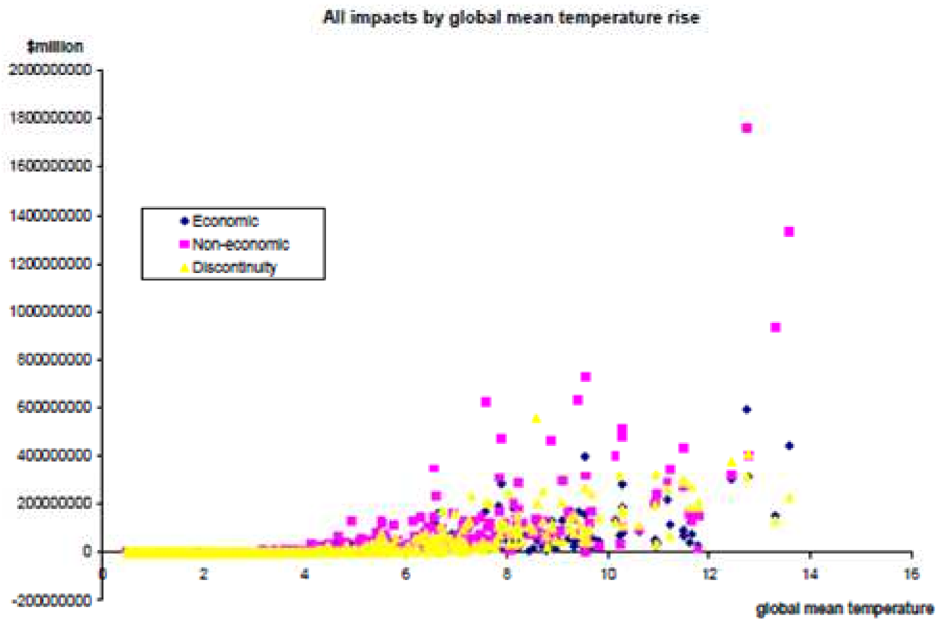
5.5.3 Damage functions in PAGE

PAGE has damage functions for market impacts, non-market impacts and catastrophes, which can be calibrated to the latest research. A single damage function is estimated for each of market and non-market impacts. These two functions are estimated on the results of other IAM studies, making PAGE in this sense a meta-model. Market, non-market and catastrophic impacts all make an important contribution to the total impact figure, as shown in figure 22.

The sector weights which allow aggregation of economic and non-economic impacts are stochastic variables. Both the economic and non-economic weights span zero, thus for some rolls of the dice the impacts are assumed to be zero. Regional multipliers are held constant and the regional multipliers for the US, China and other OECD regions also span zero. The weights are held constant through all emission scenarios so that a region which benefits initially may continue to benefit.

Adaptation in PAGE is a deterministic, exogenous input. It reduces the impacts of climate change in two ways. First, each region and impact sector (i.e. economic or non-economic impacts) is associated with a tolerable rate and level of temperature change, before impacts occur. For economic impacts in developed regions, the tolerable rate of temperature change, known as the tolerable 'slope', is set by default to 1°C per decade, up to a tolerable 'plateau' of 2°C. Thus warming in excess of 2°C produces climate impacts, regardless of the rate of temperature change, while warming below 2°C can result in climate impacts if it is faster than 1°C per decade. For economic impacts in developing regions, the tolerable slope and plateau are set to zero, so any amount of warming produces impacts. This is also true for non-economic impacts in all regions.

Figure 21 PAGE 2002 generates similar magnitudes of market, non-market and catastrophic impacts



Source: Warren et al, 2006

The second mechanism of adaptation is to reduce climate impacts above the tolerable slope and plateau, at a cost. This is free for the modeller to set. In its default mode, PAGE assumes that 90% of economic impacts are avoided through costly adaptation in the developed world, while in the developing world the figure is 50%. Twenty five per cent of non-economic impacts are assumed to be reduced by adaptation in all regions. The costs of adaptation are generally low.

5.6 Adaptation

Adaptation decreases the cost of damage from a given physical impact. Adaptation has at least three features that make an accurate characterisation difficult to model. Firstly, it is a local response to minimise local damages, therefore regional aggregation masks the distribution of adaptation needs, costs and benefits. Second, some adaptation will be autonomous and the nature, extent, cost and benefit of this is very hard to estimate. Third, adaptation policy decision making is difficult, as it requires the valuation of multi-dimensional damages.

The three IAMs do not describe adaptation strategies, but assume that economically worthwhile adaptation occurs. Furthermore, since they use assumptions about the cost of adaptation which are sometimes optimistic in assuming low costs, they may predict more adaptation than would actually occur.

Table 7 The treatment of adaptation in AVOID and three IAMs

AVOID	FUND	DICE	PAGE
adaptation is incorporated in the various impacts models used, but to varying extents	adaptation is implicitly expressed as lower damage estimates in some of the sources of damage values the variation of impacts with socio-economic changes also represents adaptation	adaptation is implicitly expressed as lower damage estimates in some of the sources of damage values	adaptation is explicitly modelled for market impacts, as an increase in the tolerable temperature before impacts occur for both market and non-market impacts, a percentage reduction in damage experienced

Source: Vivid Economics

6 Further information on the handling of uncertainty

6.1 Weitzman's Dismal Theorem

This section of the appendix supports section 6.3 of the main report, 'Climate policy as insurance', by providing more information on the influential work of Martin Weitzman, which concerns the role of uncertainty in climate change policy decision making.

Weitzman finds a *reductio ad absurdum*, which he brands the Dismal Theorem, whereby a series of assumptions and model choices leads to the conclusion that willingness to pay to avoid a climate catastrophe is infinite. Weitzman uses a standard approach to decision-making with probabilities, called Bayes Theorem. With Bayes Theorem, one starts with a prior probability distribution on the parameter in question and updates that distribution with observations, thus refining estimates as knowledge accumulates. However, in the context of climate damages, Weitzman (2009) shows that if the priors are fairly uninformed and there exists a finite set of observations of the system, the updated posterior distribution of damages can have a fat tail (a high probability of high consequence outcomes) and willingness to pay for climate mitigation today can become infinite. He calls this the Dismal Theorem, because quantitative cost-benefit analysis becomes impossible. It follows from the finding of infinite willingness to pay that the rate of pure time preference is irrelevant.

The Dismal Theorem provokes much comment, because it appears to contradict intuition and experience. Society faces a number of risks to existence, such as near-Earth asteroids, and individuals face a myriad more, such as the risk of being killed while crossing the road. People do not take infinite pains to avoid running these risks, either at the individual or societal level, but the Dismal Theorem says that society should, which may indicate that Weitzman's characterisation of damage is incorrect (Nordhaus, 2009). In particular, it has been shown to depend on the assumption of a particular (iso-elastic) utility function, where marginal utility goes to infinity as consumption goes to zero (i.e. extinction).

6.2 Risk-averse decision making when probabilities are known

This appendix provides a description of the standard expected utility problem of a risk-averse decision maker when probabilities are known to support section 6.4 of the main report.

The structure of an expected utility problem is as follows. Firstly, define the probabilities and the values of possible states of the world. A project may have one of many outcomes, for our purposes it has two, and the full range of possible outcomes is known, with each outcome occurring in separate states of the world. x_1 is the value of one state of the world and x_2 is the value of a second state of the world. For example, x_1 may be a state of the world without catastrophe and x_2 may be a state of the world with a catastrophe. p_1 is the probability of x_1 occurring and p_2 is the probability of x_2 occurring. This information can give us the expected value of the project, which is:

$$E(\widetilde{x}) = p_1 x_1 + p_2 x_2$$

Second, define a utility function to describe risk preferences. If society is risk averse then it is sensitive to changes in the variables even if the expected value remains constant. In particular it assigns a greater weight to lower levels of consumption. This sensitivity is described by a utility function, which is just a function over values. It is a decreasing function if it is to describe risk averse preferences, for example the utility function could take the square root of the value:

$$U(x) = \sqrt{x}$$

The more risk averse a decision maker is, and the riskier the gamble, the greater the difference between the certainty equivalent value and the expected value. The certainty equivalent is the utility of the outcome if the outcome could be guaranteed at the expected value rather than face the equivalent set of risky outcomes. The difference between the utility of the expected value and the expected utility of outcomes is the risk premium. This is the amount that society is willing to pay to avoid the gamble.

6.3 The Ellesberg paradox and aversion to unknown probabilities

This section of the appendix supports section 6.5 of the main report, 'Approaches where probabilities are unknown' by discussing the Ellsberg paradox, which describes evidence that decision-makers may have an aversion making decisions where they do not know the probabilities of outcomes.

As Ellsberg (1961) famously identified, people make different choices in the presence of ambiguity than they do in the presence of standard risk. He described a paradox which is repeated here. One of two versions of the paradox begins with an urn containing 30 red balls, and 60 black and yellow balls in unknown proportion. The decision maker is presented with two choices between gambles. First, bet on (A) red or (B) black. Second, bet on (C) red and yellow or (D) black and yellow. In all four gambles, the prizes are the same. To satisfy the axioms of expected utility, the decision maker bets on A if and only if she believes that drawing a red ball is more likely than drawing a black ball. This also implies the choice of C over D. But in fact most people choose A and D, which are the gambles with known probabilities, and thus they appear to prefer gambles with known probabilities over those with unknown probabilities. This has come to be known as 'ambiguity aversion'.

The significance of this finding is debated. Some consider ambiguity aversion to be irrational. Rationality is defined as the axioms underpinning expected-utility analysis. These scholars recommend the continued use of expected-utility analysis, albeit with probabilities assigned to outcomes that are interpreted more vaguely as beliefs, rather than estimates. On the other hand, in contrast to some other paradoxes, the experimental subject often sticks to her choice in this case, even when it is pointed out to her that she has violated (one of) the axioms of expected utility (Slovic and Tversky 1974). And so a case can be made that the behaviour people exhibit, ambiguity aversion, can be legitimately employed in policy making (Gilboa, Postlewaite and Schmeidler 2009).

7 Brief survey of the treatment of uncertainty in policy statements

7.1 Introduction

This appendix examines the treatment of uncertainty in the policy conclusions of recent influential documents. Three examples were selected: Lord Nicholas Stern in his review published in 2007, the European Union in 2008, and the UK's Climate Change Committee in 2008.

7.2 The Stern Review

The Stern Review is important primarily because of the influence it had in advocating mitigation action. It based its argument on a broad assessment of the costs and benefits of action to tackle climate change, in particular impacts on GDP estimated by the PAGE model. This was supplemented by evidence from sectoral studies. The Stern Review was cited by both the European Council and the European Commission when they each made the case for action at European level in 2005 and 2007.

The Stern Review uses the following metrics to describe the impacts of climate change:

— millions at risk from coastal flooding and hunger;
— percentage change in agricultural production;
— deaths from malaria, malnutrition, diarrhoeal diseases;
— loss in GDP, loss in GDP/capita.

Lord Stern concluded that 'costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever ... the estimates of damage could rise to 20% of GDP or more'. This figure is expressed as a balanced-growth-equivalent estimate.

Uncertainty is discussed in the Stern Review in relation to several issues. It appears in the selection of a discount rate, where extinction risk and the economic growth rate are both uncertain. It appears as an impediment to adaptation because of an uncertain threat of climate change. In particular, it appears as an argument for a more demanding emissions target, because of the magnitude of worse-case scenarios, driven by:

— impacts which become rapidly more adverse at higher temperatures; and
— the magnification of pecuniary impacts on wellbeing in the worst cases, due to lower levels of income.

Not only is society risk averse, Lord Stern argues, but it is also averse to ambiguity, or not knowing the probability distribution of outcomes, and this ambiguity aversion is embodied in the precautionary principle.

In conclusion, Lord Stern uses expected-utility analysis to show that the costs of inaction exceed the costs of action. He then argues qualitatively for more demanding action, for the two linked reasons of asymmetric uncertainty in the worst case scenarios and ambiguity aversion.

7.3 European Union

The rationale for mitigation action stated by the European Commission in support of the Union's strategic policy, published in 2008 and known as '20 20 2020', was the 'enormous costs of failure to act'. It cites Lord Stern's estimate of 5–20 per cent of global GDP, which it describes as 'crippling for the world economy'. It concluded that costs of mitigation of around 0.5 per cent of total global GDP over the period 2013–2030 would be an appropriate 'insurance premium' which 'would significantly reduce the risk of irreversible damages resulting from climate change'. The European Council's decision document reflects the Commission's argument.

The European Commission had previously made an assessment of the case for action, in 2007. It drew from the IPCC's third assessment report, and supported its argument with figures from the PAGE model and Parry's millions at risk estimates, in other words, a very similar approach to the Stern Review.

There is little to separate the European Union and Stern Review in terms of their arguments. Like the Stern Review, the European Union places emphasis on the avoidance of worst case outcomes in addition to its main conclusion on expected values.

7.4 The UK Climate Change Committee

The Climate Change Committee recommends a policy objective which is to limit 'the central expectation of temperature rise to 2°C, or as close as possible'. In addition, it proposes that action is taken 'to reduce the risk of extremely dangerous climate change to very low levels (e.g. less than 1%)'. The Committee assesses that this threshold would be passed if temperatures rose to 4°C or more above pre-industrial levels during the course of this century.

The Committee's formulation is different to the European Union's and Stern Review's, because it proposes two constraints or targets, one nested within the other. Although not explicit, what it appears to be saying is that it would be optimal to achieve the lower target, and if the lower target were not met, failure to achieve the higher target would result in a high risk of a large regret. In this case, the regret-management or insurance strategy is to take action to keep the likelihood of a 4°C rise very small, while the strategy based on expected value requires tougher action. In the Committee's formulation, the high consequence outcomes do not encourage more demanding action than the expected value estimates, except in the case where the expected value argument is rejected, where they provide the back-stop position.

8 The feasibility of estimating key metrics

This appendix provides some supporting material to section 7 in the main report. A series of flow charts are presented for four key impact sectors: ecosystems, food and water availability, flooding and storms and health impacts. The purpose of these flow charts is to describe the information pathway that needs to exist to populate indicators in each sector. Understanding the necessary information required allows for an assessment of the feasibility of measuring indicators in these sectors. A view on the indicators that can and cannot be monetised is also presented.

We also communicate what information is already available (by emboldening the outline of the step) and provide an assessment of which steps it might be possible for a research program to generate information on. However no comment on difficulty is made and some steps might be possible but difficult.

— the possibility of further development is denoted by ✓ for possible, x for impossible, and ? for uncertain prospects

The indicators that are produced can be identified by a dotted outline. Indicators are shaded according to whether they can be monetised and via what method.

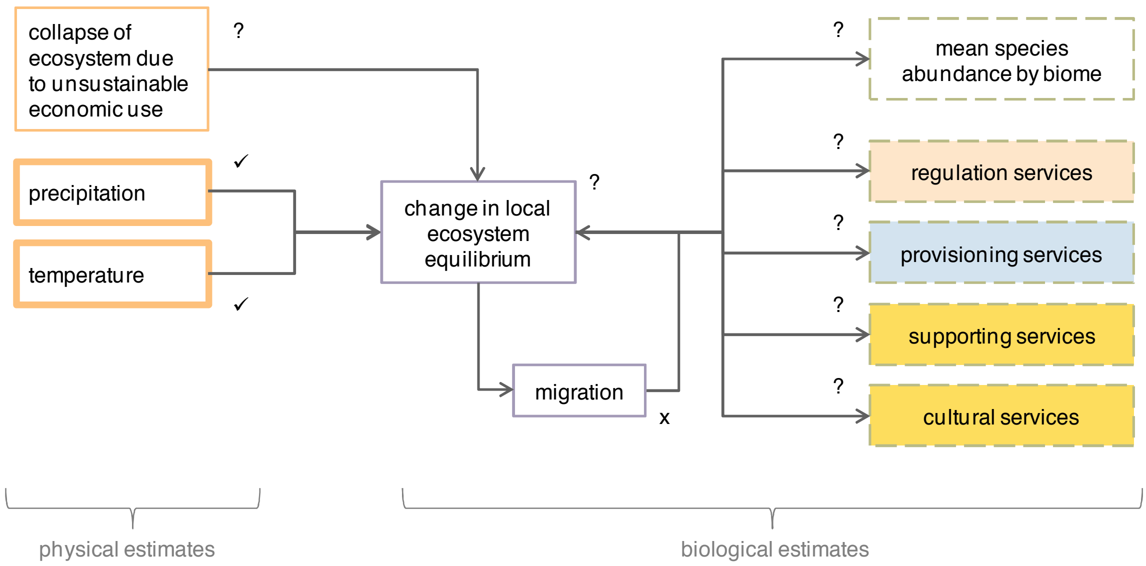
— indicators that can be monetised using market prices are shaded blue;
— indicators that can be monetised using values indirectly calculated from market prices, via methods such as hedonic pricing, are shaded red;
— indicators that can be monetised using hypothetical valuations, such as contingent valuation exercises, are shaded orange;
— indicators that cannot be monetized are not shaded (i.e. left blank).

Table 8 A number of indicators of impact could be relevant to each sector

Sector	Indicator
ecosystems	changes to ecosystem services changes to biodiversity
food and water availability	access to water malnutrition access to education, utility services and owned assets change in household budget
flooding and storms	cost of adaptation loss of owned assets access to education and utility services mortality cost of damages frequency and severity of events
health impacts due to disease vectors and extreme events	cost of health services life expectancy morbidity malnutrition infant mortality

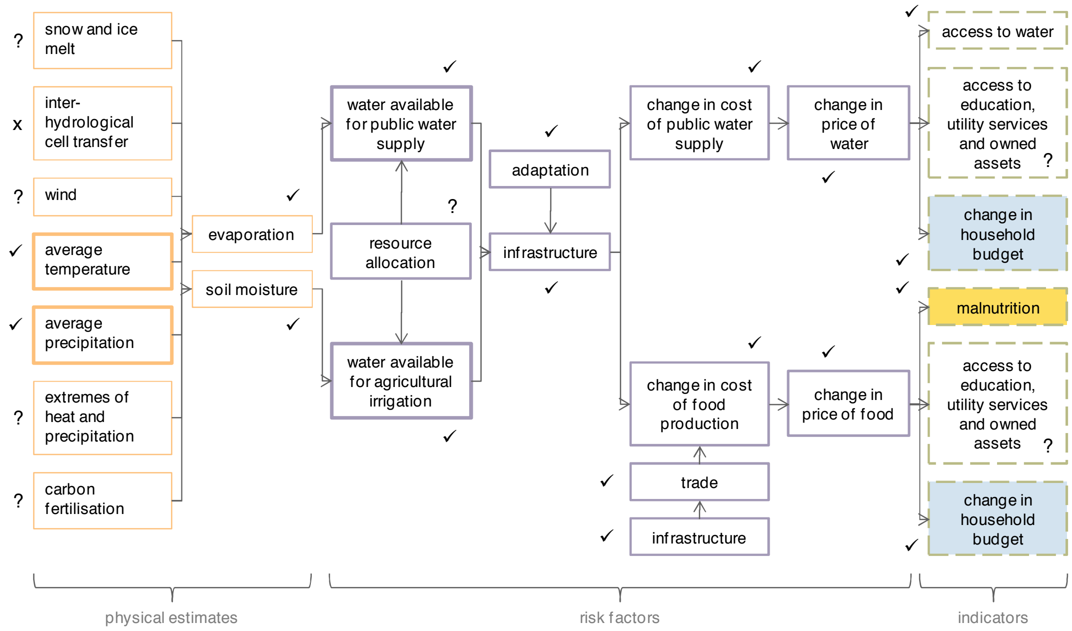
Source: Vivid Economics

Figure 22 The derivation of ecosystem indicators



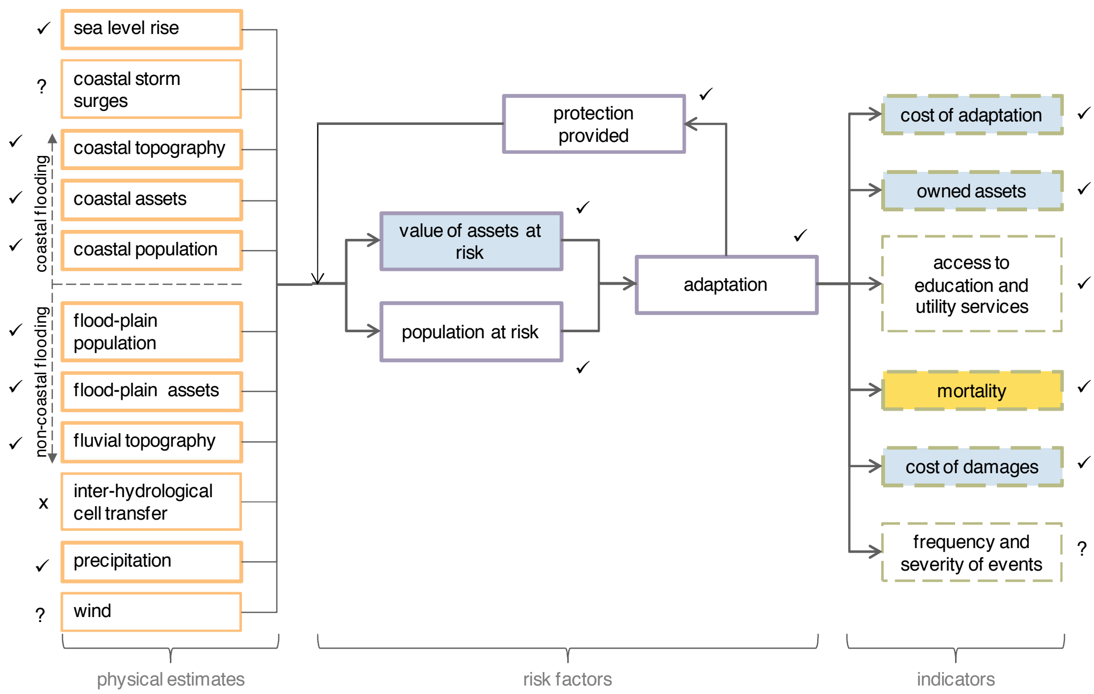
Source: Vivid Economics

Figure 23 The derivation of indicators affected by food and water availability



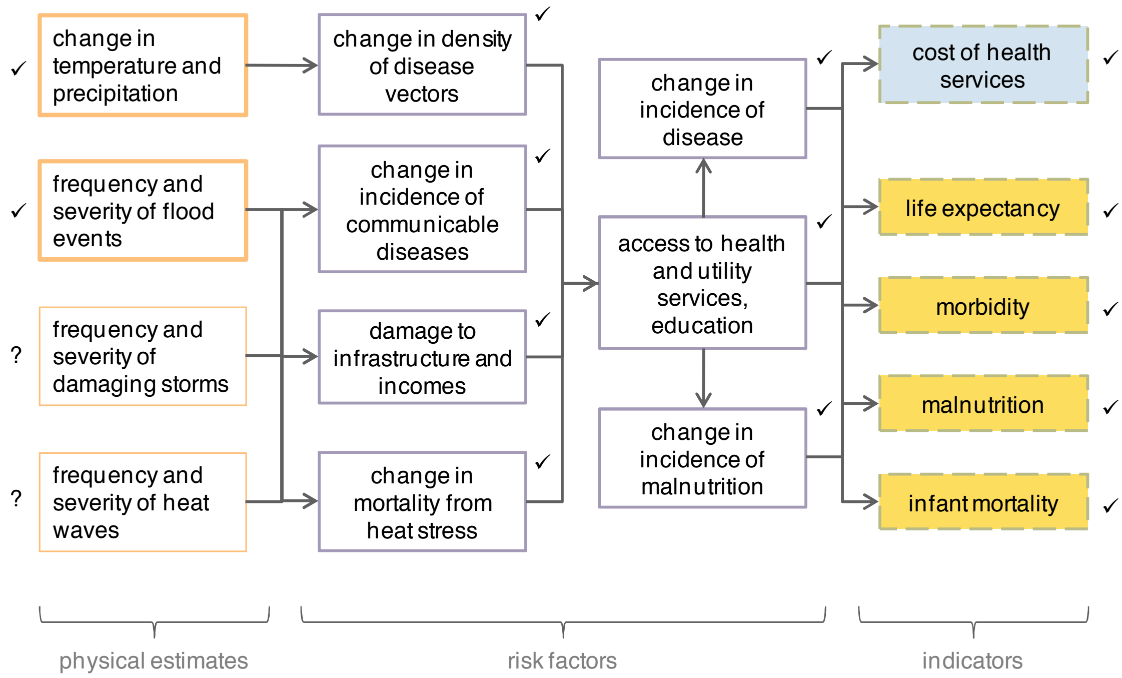
Source: Vivid Economics

Figure 24 The derivation of indicators affected by flooding and storms



Source: Vivid Economics

Figure 25 The derivation of health indicators affected by disease vectors, storms, flooding and heat waves



Source: Vivid Economics

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