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Social Cost of Carbon: A Closer Look at Uncertainty

Final project report

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Social Cost of Carbon: A Closer Look at Uncertainty

Uncertainty is inherent in estimates of the social cost of carbon (SCC). The UK Department for Environment, Food and Rural Affairs (Defra) initiated this research to evaluate the sources of uncertainties, plausible ranges of estimates of the SCC and areas for further research and assessment.

The analytical framework for the project is a risk assessment that brings together elements of uncertainty in climate change and its impacts with uncertainties in economic valuation; both are related to the context of decision making.

This review of uncertainty in estimates of the social cost of carbon is summarised in key messages:

Understanding of the social cost of carbon:

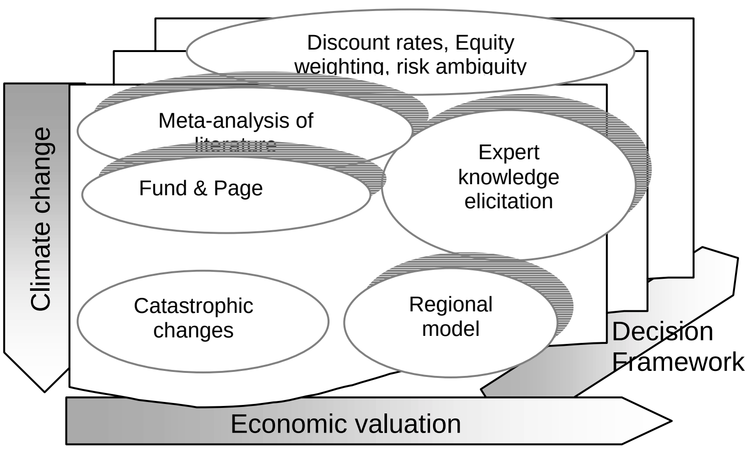
- Our understanding of future climatic risks, spanning trends and surprises in the climate system, exposure to impacts, and adaptive capacity, is improving, but knowledge of the costs of climate change impacts is still poor.
- The lack of adequate sectoral studies and understanding of local to regional interactions precludes establishing a central estimate of the social cost of carbon with any confidence.
- The balance of benefits and damages in the social cost of carbon shifts markedly over time, with net damages increasing in later time periods. Estimates of the SCC are particularly sensitive to the choice of discount rates and the temporal profile of net damages
- Vulnerability and adaptation to climate change impacts are dynamic processes responding to climatic signals, multiple stresses, and interactions among actors. Large scale impacts, such as migration, can be triggered by relatively modest climate changes in vulnerable regions.

Uncertainty and risk:

- Climate uncertainties and the climate sensitivity are key factors in larger estimates of the social cost of carbon.
- Uncertainties in coverage, sectoral assessments and regional processes are likely to be significant, but are difficult to judge without further model development and inter-model comparison.
- Decision variables such as the discount rate and equity weighting also are extremely important.

The range of estimates of the social cost of carbon:

- Estimates of the social cost of carbon span at least three orders of magnitude, from 0 to over 1000 £/tC, reflecting uncertainties in climate and impacts, coverage of sectors and extremes, and choices of decision variables.
- A lower benchmark of 35 £/tC is reasonable for a global decision context committed to reducing the threat of dangerous climate change and includes a modest level of aversion to extreme risks, relatively low discount rates and equity weighting.
- An upper benchmark of the SCC for global policy contexts is more difficult to deduce from the present state-of-the-art, but the risk of higher values for the social cost of carbon is significant.



Uncertainty in the social cost of carbon: lines of evidence.
Significant improvement in estimates of the SCC will require well validated assessments at the regional scale of the dynamic processes of vulnerability and adaptation. Partnerships among researchers and stakeholders in developing countries are essential.

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Social Cost of Carbon: A Closer Look at Uncertainty

1 Introduction

The social cost of carbon (SCC) is the estimate of the cost of climate change damages—the net effects of impacts on economies and societies of long term trends in climate conditions, including extreme events, related to anthropogenic emission of greenhouse gases.[1] Such estimates have been compiled in order to aid consideration of greenhouse gas emission policies and to prioritise adaptation strategies according to their potential effectiveness.

The UK Department for Environment, Food and Rural Affairs (Defra) initiated a project to evaluate the range of uncertainties in estimates of the SCC; this report records the results of the project.

The scope of the assessment is described below and the methodology, based on a risk assessment framework, is introduced in Chapter 2. The key messages are grouped according to:

- Understanding the SCC—the scientific basis for a risk assessment
- Uncertainties and risks—the interpretation of current estimates of the SCC
- The range of estimates—our conclusion regarding a robust range of estimates for national and global policy on GHG mitigation
- Further research and next steps—pathways for further research

The conclusions reflect on the project and its importance in national and international climate policy. Appendices provide more technical material on each component of the project.

The project team brought together a diverse group of experts and analysts:

Thomas E Downing, Stockholm Environment Institute, Oxford Office (Team Leader), Geographer working on climate change impacts, vulnerability and adaptation, developed an early social cost of carbon model (Open Framework) as part of the EC ExternE assessment

David Anthoff, MSc Environmental Change Institute, University of Oxford, analysed equity weighting in FUND in his MSc, work extensively on converting FUND to Delphi and analysing uncertainty

Ruth Butterfield, Agricultural Meteorology, Stockholm Environment Institute, Oxford, reviewed regional syndromes of socially contingent effects of climate change

Megan Ceronsky, MSc, Environmental Change Institute, University of Oxford, analysed large scale anomalies in FUND

Michael Grubb, Economist, Imperial College, contributed to literature review and evaluation of the SCC in decision making

Jiehan Guo, MSc Environmental Change Institute, University of Oxford, analysis of discounting schemes

Cameron Hepburn, Economist, University of Oxford, coordinated four MSc theses and contributed to analysis of uncertainty in the SCC

Chris Hope, Policy Analyst, University of Cambridge, author of PAGE, assisted in design of the expert elicitation and reviewed results from the project

Alistair Hunt, Economist, Metroeconomica, Bath, review of research programmes on the social cost of carbon and economic valuation of health

Ada Li, MSc Environmental Change Institute, University of Oxford, investigation of risk and ambiguity aversion

Anil Markandya, Economist, Metroeconomica, Bath, review of social cost of carbon estimates

[1] The definition of the SCC is elaborated further in chapter 2.

Scott Moss, Economist, Centre for Policy Modelling, Manchester Metropolitan University, developed model of regional syndrome of climate vulnerability in Sahel

Anthony Nyong, Geographer, Jos University, Nigeria, contributed to design and data inputs in regional assessment of migration and climate change in the Sahel

Richard Tol, Economist, University of Hamburg, author of FUND, assisted MSc theses and new analyses of FUND

Paul Watkiss, Environmental Policy group, AEA Technology Environment, reviewed literature on SCC and use of estimates in decision making

Scope of the assessment

Defra commissioned two projects in 2004. A report by the team led by Paul Watkiss of AEA Technology and Environment addresses the use of estimates of the social cost of carbon in decision making (Watkiss et al. 2005). It draws upon the estimates of the SCC reported in the following chapters, relating them to different decision frameworks and contexts in which the SCC might be or should be considered.

The terms of reference of the 'scoping uncertainty' project focus on a review of the literature and nature of uncertainty in estimates of the SCC (Table 1). The overarching aim was to consider whether a consensus exists on the SCC, rather than produce an entirely new assessment. However, the project also produced new estimates of the SCC, most notably through upgrading the *FUND* model to allow full testing of parameter uncertainties and the analyses carried out in four MSc theses.

Table 1. Objectives and achievements of the scoping uncertainty project

Objectives	Project achievements
Scoping and research design phase	
To explore ways of improving the coverage of SCC estimates, including new sectors, dynamic processes of adaptation and low probability catastrophic events	Annotated bibliography and review of SCC literature; Locate existing studies and model results in the risk matrix to evaluate coverage; Review existing estimates from FUND and PAGE
To identify ongoing research programmes and approaches for improving estimates of the SCC	Inventory research programmes; Document pathways for further development of SCC estimates (see also the project progress report at the completion of the scoping phase)
Modelling and assessment phase	
To explore the feasibility of empirical improvements in the coverage of SCC estimate	Updated FUND with new work on health, tourism, catastrophic events (collapse of the thermohaline circulation, high climate sensitivities, large methane releases); Reported new work from FUND on extreme events; Prototype multi-agent model on Sahel
To incorporate the time varying discount rate recommended by the Green Book	Incorporated a range of discounting methods in FUND (MSc thesis) (also available in PAGE)
To explore how SCC estimates might vary over time based on the above modeling work	Reviewed FUND results for regions and sectors (see Annex); Data base of FUND results
To carry out a probabilistic sensitivity analysis on key model parameters	Implemented full sensitivity testing with upgraded FUND*;* Sensitivity analysis in PAGE; Knowledge elicitation using formal methods (see Annex); Exploration of non-linear responses using a multi-agent model framework for the Sahel
To recommend a range of possible values for the SCC based on the above analysis	Synthesis of estimates from FUND and PAGE, the expert knowledge elicitation, and the exploratory multi-agent modelling

Uncertainty is inherent in estimating the social cost of carbon. Experts disagree regarding the appropriateness of cost benefit aggregations, the nature of quantifiable damages and the range of resulting estimates of the SCC. The relevance of the decision context is noted in Ekins (1995), Grubb (2003) and Pearce (2003), among many other commentaries on climate policy. The two extreme views are (i) that the SCC should be part of a cost-benefit analysis with assumptions consistent across current public policy and (ii) that climate policy is an issue of social justice and sustainability that precludes calculation of a robust SCC estimate (and obviates the need to do so). The 'economic' argument follows a weak sustainability paradigm where net welfare is the measure of potential damages, discounted to a net present value, with 'winners' and 'losers' aggregated at a global level. The 'social justice' view is essentially a strong sustainability approach that cautions against trade-offs between winners and losers in different impacts sectors, regions or societies.

A salient difference between the extremes is their view of decision making. An optimising, cost-benefit analysis gathers the available information, recognising uncertainties, and makes a decision to set policies for the foreseeable future. A more cautious approach suggests that policies in areas of deep uncertainty such as climate change should be incremental—act based on the present understanding of risks, learn about the consequences of those actions, then act again (Figure 1). An incremental, iterative approach updates the expected SCC at each decision node. However, a low estimate of the SCC might lead to mitigation targets that result in higher impacts, and subsequent decisions will need to account for much higher estimates of the SCC. Or, setting targets for large GHG reductions now, based on a 'business as usual' estimate of considerable climate impacts, would stimulate technological innovations that would reduce the cost of achieving effective climate stabilisation in the future (see Grubb et al. 2002). This sense of estimates of the SCC as part of a decision-outcome feedback loop over the course of a century timescale may preclude calculating robust estimates of the SCC at any single time step.

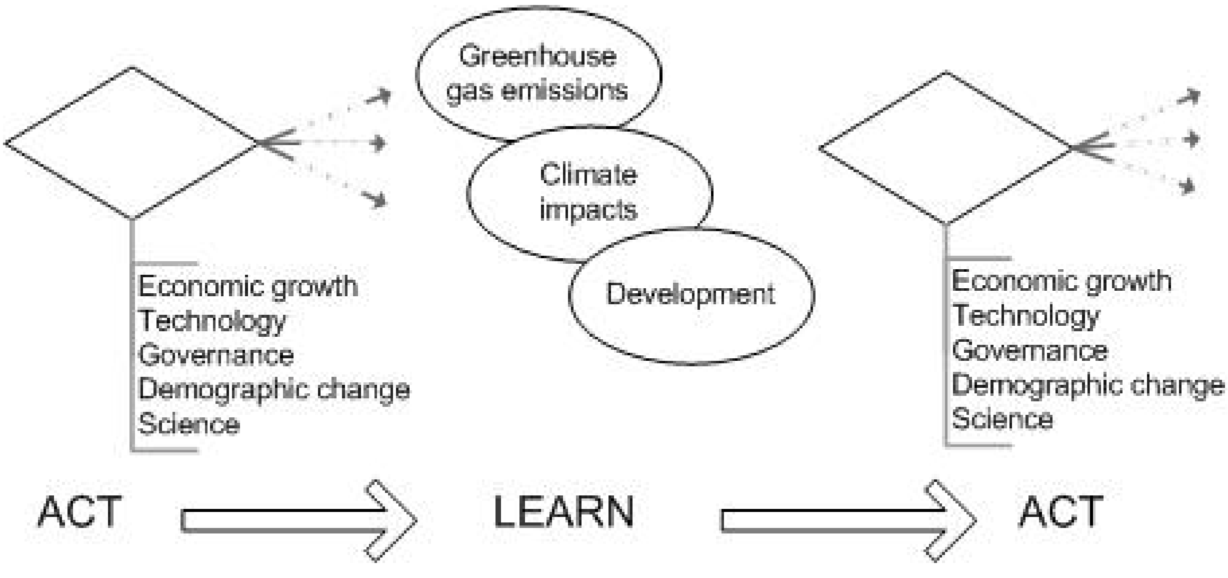

Figure 1. An iterative framework for setting climate policy
Decision nodes are represented by diamonds, with contextual considerations related to economic growth, technology, governance, demographic change and scientific information. The consequences of the decision are represented by outcomes (ovals) affecting greenhouse gas emissions, climate impacts and development status. Source: After R. Richels, personal communication.

Acknowledgements

Funding for this work was from Defra. Some of the work reported here was carried out for the European Commission Methodex project, an extension of the ExternE projects that produced early estimates of the social cost of carbon associated with various fossil fuel power station emissions. Draft results from the Defra project were reviewed at a workshop in September 2004 (see www.socialcostofcarbon.aeat.com) and draft reports were reviewed by experts commissioned by Defra. The project steering committee also provided helpful advice and comments. The authors are grateful for the many insightful comments from these reviewers. We acknowledge that many of the comments are inadequately addressed in the final report. Indeed, the wider debate regarding the SCC is reflected in the disagreement of the reviewers with elements of this report. The authors remain solely responsible for any oversights or errors in the report.

2 A methodology based on risk assessment

This chapter describes the risk assessment framework that the project developed and applied. The first section explains the risk matrix of uncertainty in climate forcing and economic valuation of impacts. Issues related to defining the social cost of carbon and uncertainty are described in the second and third sections, including treatment of measures of the distribution of results and central tendency in a data set. A note on units and conversion factors is included.

The methodology can be represented graphically as evaluating three sources of uncertainty, related to climate change, valuation of impacts and parameters in the decision framework (Figure 2). Uncertainty in climate forecasts are well documented, and the potential for catastrophic effects appears to be increasing as scientists learn more about the climate system (see the conclusion of the Exeter workshop on stabilising climate change; see Tirpak et al. 2005, www.stabilisation2005.com,). Economic valuation becomes increasingly speculative as the impacts move beyond market commodities to non-market sectors, including effects on societies and economies. Decision frameworks bound any policy assessment, implying different considerations for equity among present populations and for future generations. For instance, a global decision maker might adopt a strong sustainability framework based on social justice, while a local authority planner may have a more constrained view based in strategic environmental assessment and best practice in land use planning.

The time profiles of climate change, its impacts and decision making are important. This report does not focus on the temporal dimensions other than through the parameters of a decision framework (most commonly the choice of a discount rate). The policy analysis report (Watkiss et al. 2005) looks at time profiles of SCC values.

No single method, model or tool adequately captures all of these uncertainties. The complexity of coupled socio-ecological system (climate change is driven in part by its impacts over time) and the range of decision frameworks that might be employed in using the SCC imply that estimates of the SCC will remain diverse and contentious. That is, there is little consensus regarding the central value that should be adopted and relatively little confidence in the reliability of the evidence available upon which SCC estimates can be made. In the language of decision sciences, the uncertainty is in the realm of speculative estimates, often reflecting competing explanations.

Multiple lines of evidence are reviewed and employed in reaching our conclusions regarding estimates of the SCC. The majority of the literature and models focus on trends in climate change (e.g., in regional temperature) and market and non-market economic impacts. Such models as FUND and PAGE also handle choices in the decision framework, such as discount rates and equity weighting—the subject of four MSc theses in this project. Greater economic and climatic uncertainties are covered through three exploratory methods: (i) a formal elicitation of expert knowledge, (ii) an MSc thesis on catastrophic changes, and (iii) a prototype model of a region where current trends in climate change could have widespread social and economic consequences, in this case the Sahel region of West Africa.

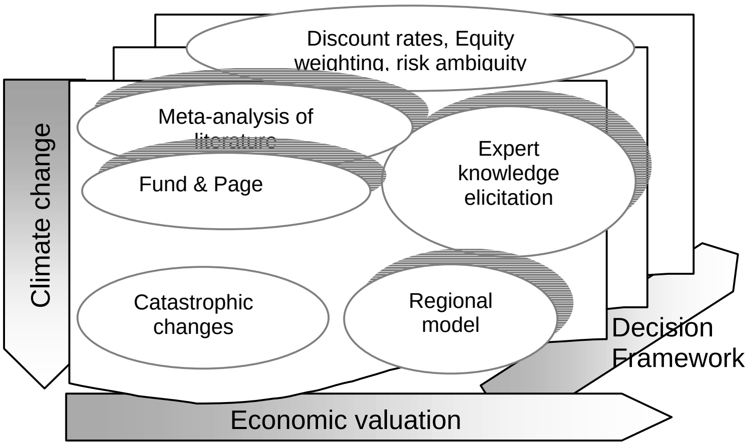

Figure 2: Schematic mapping of multiple lines of evidence in understanding uncertainty in the social cost of carbon
The arrows on the three axes imply increasing uncertainty, although not necessarily larger estimates of the SCC.

Interpreting the SCC in a risk matrix

Framing of estimates of the SCC is organised as a matrix of confidence in projections of future climate change and understanding of economic valuation (Figure 3). The climate axis ranges from projections of global and regional temperature, to bounded scenarios of changes in precipitation and risk of storms, to systemic, large scale changes such as collapse of the West Antarctic Ice Sheet, shift in ocean circulations, or reversal of the biosphere carbon sink.

The corresponding economic axis begins with market sectors, with uncertainty expanding to the valuation of non-market sectors such as coral reefs, and socially contingent feedbacks, such as conflict over water, that exacerbate sectoral impacts or present non-marginal impacts at the local to regional level. Note that socially contingent effects are a class of non-market impacts, where B might be considered micro-economic effects and C includes macro-economic effects.

The gradient across the matrix, from top-left to bottom-right suggests an increase in uncertainty. The larger scale climate changes are still speculative and often described as surprises outside the realm of current global model predictions. The relative lack of studies of non-market and socially contingent effects increases uncertainty in estimates of the SCC.

The gradient also reflects different timings of impacts—systemic changes in the global climate are posited on a century time scale (e.g., collapse of the West Antarctic Ice Sheet); collapse of regional societies and economies is not forecast in the next few decades (if at all). Some of the largest uncertainties—such as release of methane hydrates—are events that are not fixed to a particular time frame. On the other hand, impacts on market-based resources related to projections of temperature and sea level rise may follow a relatively smooth profile over the next few decades (time profiles from FUND are shown Chapter 3.

At present, the most commonly held assertion is that the net non-market and socially contingent costs will be adverse (rather than benefits). However, there is insufficient evidence to suggest that the gradient from upper-left to lower-right is necessarily a substantial increase in the total social cost of carbon.

The axes and cells are described in qualitative terms below.

We use this framework to gauge progress in understanding the social cost of carbon in this report. Note, that the matrix is not intended to be a sampling frame or to weight independent estimates. That is, we do not attempt to derive probabilistic estimates of the SCC for each cell in the matrix and to produce a final estimate based on the aggregation of such values.

Uncertainty in valuation

Uncertainty in Climate Change		A. Market	B. Non-market	C. Socially contingent
	1. Projection			
	2. Bounded risks			
	3. System change and surprise			

Figure 3. A risk assessment framework
This is a simpler version of Figure 2, without the overlays related to decision choices.

The typical situations with each cell may help to illustrate both the range of issues inherent in estimating the SCC as well as the role of the risk matrix.

For the column of impacts related to markets (A):

- A1: Global and regional temperatures are projected to increase with relatively high confidence. To the extent that warmer conditions would expand the area suitable for agriculture, leading to climate impacts (in this case benefits) that are readily valued through market exchanges (such as the price of major commodities, value of agricultural land, net profit to producers or net benefit to consumers). Sea level rise is the other major climatic element with high confidence, leading to impacts on coastal communities, loss of dryland and wetland, forced migration, and the costs of coastal protection.
- A2: Most climate elements are uncertain at the regional level, but current climate models project changes within a reasonable range. Such bounded risks include increases or decreases in precipitation, intensity and tracks of storms, and the frequency and magnitude of other climatic extreme events (e.g., floods, droughts, lightning). The market impacts, for example of drought on agriculture, can be estimated in principle although it is difficult to differentiate between the effect of climate change and other stresses and responses that shape economic outcomes. Current scenarios of climate change may underestimate drought risks, leading to a possible bias toward short-term benefits of climate change for agriculture.
- A3: System change and surprises are plausible climate outcomes that are not readily evaluated in a probabilistic framework, such as a weakening of the thermohaline circulation, changes to the phases of the major ocean-atmosphere modes (such as ENSO), the more extreme scenarios of collapse of the West Antarctic Ice Sheet, large releases of methane hydrates or reversals of the terrestrial carbon uptake. While the market effects can be described, the impacts over large areas and time scales are not linear and therefore difficult to value in a micro-economic framework. For example, what would be the (net) value of displacement of all of the major world coastal cities due to a 3-5m sea level rise? (for example, see the results of the Atlantis project, Lonsdale et al., 2005, Nicholls et al. 2005, Tol et al. 2005).

Effects on non-market sectors (B) are more difficult to value in that there are little empirical data on how people in different countries and economic classes value amenities, species, landscapes and other qualities of livelihoods. Contingent valuation based on willingness to pay or willingness to accept principles give some guidance, but such values are often contentious and may not scale up from local issues to the widespread effects of climate change. Examples of the sectors and issues in this column are:

- B1: Warmer temperatures and higher humidity—both projected to increase with some confidence—will alter the amenity value of climates. In northern Europe, for instance, longer and warmer summers will encourage more people to enjoy the outdoors and visit local tourist destinations. On the other hand, a greater incidence of heat waves in southern Europe may be problematic and losses in boreal and mountain ecosystems and winter tourism are likely.
- B2: The bounded risks of changes in major cyclones, for instance, would affect coastal ecosystems and agricultural land subject to increasing frequency and severity of coastal flooding and salt water inundation. The value of species lost in local environments is difficult to estimate.
- B3: Catastrophic effects that lead to global losses of species are even more difficult to value, not least because the impacts of climate change on global ecosystems and species biodiversity is not well understood.

The socially contingent column (C) captures the secondary effects and multiple stresses of climate change across a range of sectors. For instance, it is possible that reasonably small changes in climate change could lead to significant impacts through multipliers (such as the effect of water shortages on agriculture), high vulnerabilities (such as migration triggered by increased cyclone frequencies) and behavioural responses to the risk (such as disinvestment from commercial agriculture in some regions due to a perceived increase in drought risks). Such socially contingent effects are a sub-set of non-market impacts. The mechanisms of such responses may not be readily captured in either micro-economic valuations or macro-economic models. The range of potential values is likely to be influenced by the decision framework—for instance whether potential liability for regional damages is a motivation for a precautionary approach. Examples include:

- C1: Projected changes in mean temperatures and sea level rise, at least over the next few decades, are unlikely, on their own, to trigger significant socially contingent effects. The exception may be snow melt and glacial lake outburst floods, significant in some regions.
- C2: Changes in water cycles, along with drought and flood risks, are potential drivers of regional migration, loss of an agricultural economy and crises for mega cities without reliable water supplies. The extent of the world where such effects are most likely has not been rigorously evaluated, but the Sahel and coastal deltas such as Bangladesh are frequently mentioned. Regions of existing and exacerbated water scarcity could be subject to conflict.
- C3: The displacement of entire cities due to extreme sea level rise is a good example of a socially contingent effect with high uncertainty—in both the risks of climate change and in the means to value such impacts. A case study of the potential impacts of and adaptation to a 5 meter sea level rise illustrates the issues (see Lonsdale et al., 2005, Nichols et al. 2005, and Tol et al. 2005).

The risk matrix is a guide to understanding uncertainties in the social cost of carbon (taken up in the next chapter). The risk matrix does not show explicitly three additional factors affecting uncertainty. Two are mentioned above: (i) the role of decision frameworks and choice and (ii) the time profile of climate change and its impacts.

The third factor (iii) concerns the method for aggregating estimates of the SCC in each cell to an overall value. It is not immediately apparent that decision makers would simply add up net values for each cell in the matrix. They may wish to account for those who suffer losses differently from those who gain. Such a concern might arise from awareness of political responsibilities, assessment of the risk of disruption associated with losses, or recognition of the non-substitutability of some environmental systems and cultural inheritance. Or, they may chose to weight some values differently than others—for instance market values might not be equity weighted while a high equity weight might be applied to the socially contingent values.

The risk matrix is a frame of reference, but does not imply specific values for the SCC for the less certain impacts and valuations (that is, for row 3 and columns B and C). Further studies and estimates of all of the cells are required to judge the extent to which sampling across all of the cells is required to produce a robust estimate of the SCC. However, the Intergovernmental Panel on Climate Change (IPCC) suggests that the larger impacts will become more likely as global temperatures rise particularly beyond the middle range of 2-3 °C (see IPCC 2001a, and the Summary for Policymakers, www.ipcc.ch/pub/spm22-01.pdf). The cascade of impacts across sectors and regions becomes an increasing concern if global warming exceeds 5 °C or so. However, this conclusion is in the nature of expert judgement, since there are few detailed studies presently available in the literature.

Defining the social cost of carbon

The term, social cost of carbon (SCC), generally refers to the marginal cost of climate change impacts. The SCC is usually estimated as the net present value of the impact over the next 100 years (or longer) of one additional ton of carbon emitted to the atmosphere today. This should not be confused with the total impact of climate change or the average impact (the total divided by the total emissions of carbon). The SCC is expressed as the economic value (in US$, € or GB£) per ton of carbon (tC). In this assessment, the baseline is the year 2000 for the emissions as well as for the net present value. In some literature, but not in this report, marginal damages are related to 1 ton of carbon dioxide. 1t C = 3.664t CO_2. So, a value of £100/tC would be equivalent to £ 27/t CO_2.

The sensitivity of the SCC to the timing of the additional emission of 1tC can be evaluated in models such as FUND. Emission of the additional carbon in 2020 would occur against a reference scenario of larger impacts (assuming the climate system has not stabilised by that time) and generally results in a larger value of the SCC at that time. The temporal profile of SCC estimates is taken up in the report on policy implications (Watkiss et al. 2005).

Uncertainty and measures of the distribution of estimates

Estimates of the SCC are often distributions of results from a wide range of assumptions and plausible values for uncertain parameters. This raises the question of which measures to use to portray the range of results as well as the central tendency.

For example, there are a considerable number of extreme values in the full suite of results from FUND. Some are likely to be anomalies in the model and are considered outliers—these have been filtered from the results presented here. Extreme values that remain are possibly conditions in which the impacts of an additional ton of carbon on regional climates affect the projected economy. The marginal SCC refers to the effect of 1 additional (marginal) ton of carbon released to the atmosphere. The implied assumption is that the marginal greenhouse gas emission leads to impacts that are only slightly different from a reference scenario of greenhouse gas emissions. However, if the climate change crosses a threshold of sensitivity, the impacts may be quite large, indicating a non-linear response. In effect, the FUND model results may be drawn from more than one population—those scenarios that conform to the model's expectation of marginal impacts and those scenarios that indicate non-linear changes in regional economies.

In such situations, it is not possible to a priori define the best measure of the central tendency of the data set. Table 2 shows three approaches to measuring the central tendency. If the data conforms to a normal distribution (or a homogeneous population with few real outliers), the average and standard deviations are unbiased estimates. However, the arithmetic mean is sensitive to outliers that may not be representative of the underlying probability distribution.

Measures based on a cumulative probability function include the quartiles and median. The distribution of the data is captured in the median and quartiles: The minimum, maximum, and three quartiles (lower 25%, median or 50% and upper 25%) are derived from the ordered data set. The median is the value for which 50% of the data are larger. The median is less sensitive to outliers, but is biased towards low values when the probability distribution has a long, high-value tail.

An alternative to the arithmetic average is to trim the data to remove some outliers and then calculate a trimmed mean. Trimming more outliers, from a data set with large positive anomalies, reduces the trimmed average. Thus, a trimmed mean with 20% of the outliers removed (10% from each tail) is lower than a trimmed mean with 10% of the outliers removed.

In this report, we use several measures of the central tendency. For example, where the data sets are available we report a trimmed mean with 10% or 1% of the values removed (5% or 0.5% from each tail): this is represented as $SCC(T)_{10}$ or $SCC(T)_1$. The range of plausible estimates of the SCC is designated SCC_{min} to $SCC_{max.}$ These values are not referenced to a specific use or decision framework. We also suggest a value for the SCC for setting global targets for mitigation: the range of plausible values is labelled as SCC^g_{low} to SCC^g_{high}.

We also report other measures where they are commonly cited in the literature or model results. The FUND annex shows the results for the various measures of central tendency.

Table 2. Measures of central tendency

Normal distribution

Absolute minimum	-2 Standard deviations	-1 Standard deviation	Average	+1 Standard deviation	+ 2 Standard deviations	Absolute Maximum

Quartiles

Q0 Absolute minimum	Q1 Lower 25% of values	Q2 Median, 50% of values	Q3 Upper 25% of values	Q4 Absolute maximum

Trimmed mean

Tmean(20) < Tmean(10) < Tmean(5) < Tmean(1)

SCC

SCC_{min}	SCC^{g}_{low}	$SCC(T)_{10}$	SCC^{g}_{high}	SCC_{max}

These measures are derived from model results (or collections of studies in the case of the meta-analysis). Of course, the normal distribution does not contain an absolute minimum or maximum.

A note on units and conversion factors

This assessment necessarily involves technical detail on units and conversion factors.

The FUND model uses USD1995 as the benchmark, while PAGE reports damages in USD2000. Where possible, we have inflated the FUND results to USD2000 by using the average U.K. Retail Price Index over the period from 1995 to 2000, an increase of 22.5%.

We have converted both PAGE and FUND results from USD2000 to GBP2000 ($1.42 = £1.00) and Euro2000 ($1 = €1.01) using purchasing power parity exchange rates from 2000. Thus, the conversion from FUND USD1995 to GBP2000 is a multiplier of 0.863.

Results from the literature are cited in the units and time periods reported. For example, the meta-analysis reported below reflects the range of base years used in each study. To provide a consistent analysis, the modelling and olicy studies assumed the estimates in the literature used USD1995. These estimates are updated to GDP2000 using the multiplier of 0.863. For example, an estimate of the SCC of USD1995 100/tC = USD2000 122.5/tC = GBP2000 86.3/tC.

3 Understanding the social cost of carbon

Our understanding of the social cost of carbon depends on a cascade of steps, each with inherent uncertainties:

(i) Reference socio-economic scenarios (baseline) →

(ii) Climate change projection/scenario →

(iii) Local to regional impact modelling →

(iv) Projected baseline and impacts over time →

(v) Valuation of local to regional impacts including adaptation →

(v) Aggregation to global values

Uncertainties and choices in the evaluation influence the final social cost of carbon. For instance, notable sources of uncertainties are:

- A reference baseline of high economic growth is often assumed to lead to less vulnerability to climatic risks, at least in the loss of life, as wealthier societies can afford a wider range of adaptation strategies.
- Climate change projections of temperature are commonly included, but quantified impacts of changes in multi-year drought are not.
- Impacts at the scale of livelihood are not easily scaled up in a regional model based on GDP per capita or the share of agriculture in the economic accounts.
- Adaptation over time attenuates impacts in many sectors (for instance as farmers adjust to new climatic conditions); while behavioural responses to climate outlooks could accelerate effective adaptation or induce maladaptation and higher costs that may not be warranted.
- Relatively small climate impacts may cross a threshold of vulnerability that leads to positive feedbacks and non-linear effects (e.g., the socially contingent column in the risk matrix).
- The choice of valuation methods, for instance willingness to pay or willingness to avoid damages, is at least as important as the reference scenario.
- Equity weighting seeks to compensate for the different value of marginal impacts to poor people compared to rich people; but it does not account for rights or differential vulnerability *per se*.
- A precautionary approach seeks to avoid damages without offsetting consideration of benefits.
- Discounting procedures and the time profile of rising GHG emissions and climate impacts are well documented factors (see Watkiss 2005 for time profiles and Guo 2004 for comparison of discounting schemes).

Our assessment adopts a conventional view of the SCC as a representation of future impacts that are given in the assumptions of a certain reference scenario. Of course, the reality is that present estimates of the SCC might (or should, depending on one's view of economic policy) influence our efforts to stabilise greenhouse gas concentrations (and reduce emissions). If we underestimate the future risks of adverse impacts, and do not stabilise the climate system, we increase the likelihood that future impacts will be much greater than we currently estimate. This recursive nature of setting targets based on a cost-benefit analysis is central to the concerns addressed in the companion assessment led by Paul Watkiss (2005).

This chapter illustrates such concerns from the lines of evidence developed in the project. Our key messages are contained in the section headings. Note that we focus on the nature of the uncertainties behind the range of SCC estimates; as such we use several measures of central tendency and cumulative probabilities.

3.1 Our understanding of future climatic risks, spanning trends and surprises in the climate system, exposure to impacts, and adaptive capacity, is improving, but knowledge of the cost of climate change impacts is still poor.

The project did not seek to revise the chain of assessment underlying global estimates of climate change damages (essentially the steps (i) to (v) above. We began the project with a review of the published literature, related to the risk matrix presented in Chapter 2. We also elicited estimates of the social cost of carbon from experts, using a prescribed set of scenarios. Results from these two lines of evidence support this key message.

Richard Tol reviewed existing estimates of the social cost of carbon (Tol 2004), which includes a fairly complete list of references to original studies (see the annex).[2] Five substantive conclusions emerge from the review of the literature.

First, the Defra seminar in 2003, including Tol's meta analysis, the Defra background paper (Pittini et al. 2003, 2004) and Pearce's review (2003), were reasonably complete in terms of the published literature, but not in terms of the full coverage of potential impacts. However, we have not uncovered a substantial body of new estimates. This reflects the relatively restricted character of the field—it is unlikely that a major project or result would escape our collective notice—and the relative lack of new work in this area.

Second, the coverage of existing studies is almost exclusively in the upper left quadrant of our risk matrix (see Table 3). Most of the studies, and relatively greater confidence, is in the market-projected climate change cell. For instance, FUND is benchmarked to changes in temperature (and sea level rise), with only an indirect connection to changes in precipitation (included in the middle row).

Third, the range of uncertainties mentioned in the literature includes the familiar concerns. Most studies include some regional and sectoral breakdown and discounting over time. Other sources of uncertainty, such as equity weighting, cross-sectoral interactions, and a full range of future economic scenarios are mentioned in some studies. (See the following boxes for detail on discounting and equity weighting.)

Fourth, few of the published studies provide sufficient detail (of either the model or results) to decompose the uncertainties and their relative importance. Thus, a formal meta-analysis of all of the sources of uncertainty in the prevailing literature is not possible (without getting additional information and model results from each study).

Fifth, some uncertainties have been ignored. Regional impact assessments (such as the plethora of country studies) are not captured in the global estimates—which are based on global integrated assessment models at a coarse spatial and socio-economic scale. Valuation issues such as aggregating social preference functions, risk aversion and socially contingent factors have not been explored in the published quantitative estimates.

The conclusions in Table 3 also apply to FUND and PAGE. In a strict sense, both models only use global projections of mean temperatures (the first row) although the regional impacts are based on studies that include some estimates of the bounded risks (the second row). Both FUND and PAGE include market and non-market sectors, although neither would claim that the sectoral coverage is complete. Neither provides robust results of system changes and socially contingent effects, although both have explored these areas to some extent (see the Annex for FUND results undertaken by this project).

[2] An Endnote library of references and abstracts on the social cost of carbon has been prepared as well.

Table 3. Locating the literature in a risk assessment framework

		Uncertainty in valuation		
		A. Market	**B. Non-market**	**C. Socially contingent**
Uncertainty in Climate Change	**1. Projection**	Over 95% of the studies are in this category; with a bias toward market costs.		Plausible effects have been posed but not adequately valued nor included in the marginal SCC
	2. Bounded risks	Some models have explicit scenarios but most are tied to benchmark 2xCO2 scenarios and do not cover local changes in weather.		
	3. System change and surprise	A few exploratory studies*, but not sufficient to provide robust estimates of the marginal SCC		No credible studies

* Nordhaus and Boyer (2000), Ceronsky (2005)

A range of experts were asked to provide estimates of the SCC for some 30 prescribed scenarios of climate change, coverage of impacts sectors, and decision choices (such as discount rate). The experts included well-known advocates for a high SCC as well as for low SCC values. Each expert was asked to rate their confidence in each response. This question was not benchmarked in any way—the interviewer did not prompt the respondent to anchor the range or the mid-point. (This could be done, for instance to mention the scores given by the research team, or to suggest a scale relative to the average of the experts.) The confidence ratings are subjective. The experts received the results with an opportunity to comment on the conclusions—but this was not an iterative exercise nor was it designed to achieve a consensus among the experts.

Of the nearly 450 scenario-responses, fully 70% had a confidence rating of very low or low. None of the scenarios were judged a confidence of very high and only 3% had a high confidence.

The respondents were grouped into three categories (4 to 5 in each group) based on their overall view of the SCC (Figure 4). For those respondents who held low or high values for the SCC, their confidence was very low for at least some scenarios. Only those who held low values had high confidence in at least one estimate (generally one of the scenarios based on low climate change and only market sectors). None of the respondents in the medium to high group had more than a medium level of confidence in their estimates.

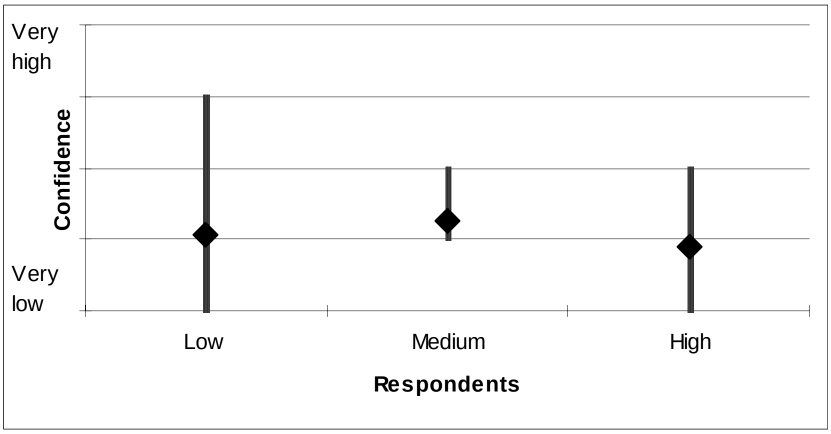

Figure 4. Expert confidence in estimates of the social cost of carbon for three groups of experts based on their overall expectation of the SCC

Confidence was judged on a 5-point scale, from very low to very high. The central values are the average for all scenarios and respondents in the group, bracketed by the minimum and maximum confidence rating. Note that the confidence ratings are given by each respondent for each scenario.

3.2 The lack of adequate sectoral studies and understanding of local to regional interactions precludes establishing a central estimate of the social cost of carbon with any confidence.

In a field where the parameters that drive the range of estimates are well understood, a probabilistic assessment can be constructed that produces a central estimate. Examination of the cumulative probability distributions for different reference scenarios and compared for different models then would give a sense of whether the central estimate is robust (i.e., estimates of the central value fall within an acceptable range).

A robust estimate of the central value for the SCC is not possible at present. Our primary reason for this conclusion, noted in the previous section, is that the full range of risks and exposures has not been included in present models. Therefore, sensitivity testing of model parameters is not necessarily based on the full range of the drivers of uncertainty.

This section explores some of the evidence and reasoning behind this conclusion. We begin by presenting three probability distributions—from the analysis of results published in the literature, from the revised FUND model, and from the more reduced-form depiction of impacts from PAGE. We then examine some of the output from FUND to illustrate issues related to sectoral and regional scale. In the following section we look at temporal and dynamic uncertainties.

As noted above, Tol (2004) reviewed published estimates of the SCC. The 103 estimates from 28 published studies are used to calculate the distribution of the SCC. These published studies concentrate on market sectors and global or regional projections of temperature. While many include some non-market sectors few included regional precipitation or extreme events in a rigorous fashion.

Tol filtered the estimates using four schemes:[3]

1. The simple average of all of the 103 estimates results in a mean value of the marginal damages of $114/tC (£80/tC), with a standard deviation of $249/tC (£175/tC) (and a median of $17/tC (£12/tC)).
2. For studies that report more than one estimate, the authors generally provide a weight (or probability range) for the various estimates. This weighting increases the mean to $158/tC with a standard deviation of $392/tC (or £111/tC and £276/tC) (and a median of $20/tC (£14/tC)). This is partly due to some authors assigning very low weights to low estimates (for instance, those proposed by Nordhaus, 1994).
3. Tol calculated his own weights for each study based on six criteria: whether they had been peer reviewed, were independent impact assessments, had included dynamic climate change scenarios rather than equilibrium responses, used economic reference scenarios, calculated the marginal damage costs, and the year of publication. This weighting scheme results in a mean estimate of $105/tC, still with a high standard of deviation, of $305/tC (£74/tC and £215/tC).
4. If only the peer reviewed studies are included, with Tol's weights applied, the estimates are much lower, with a mean of $61/tC and standard deviation of $102/tC (£43/tC and £72/tC) (and a median of $17/tC (£12/tC)).

The results are shown in Figure 5 as cumulative density functions for three of the weighting schemes (#2 – 4 above). The published, but not peer reviewed literature, accounts for a substantial degree of the uncertainty at the high end of estimates. For instance, the 90 percentile marginal damage cost is $245/tC (£173/tC) in the peer reviewed literature, increasing to $350/tC (£246/tC) if all literature is included (but with Tol's weighting for the quality of the assessment (#3 above).

In summary, the distribution of results from the meta-analysis of the literature is shown in Table 4.

[3] The estimates cited in the literature are taken to be US$1995. In the following text, these are inflated to US$2000 using the average UK Retail Price Index, an increase of 22.5%. The inflated results in US$2000 are converted to GBP2000 based on $1.42 = £1.00 (as for the FUND and PAGE model results).

Table 4. Distribution of the SCC from a meta-analysis of the literature, GBP2000/tC

	All literature		Peer reviewed literature
	No weights	**Weighted by study authors**	**Weighted by R Tol**
5%	-9	-10	-8
Mean	80	111	43
95%	300	550	210

Based on Tol (2004).

Discounting

Social time preference is the value society attaches to present consumption. The Social Rate of Time Preference (SRTP) is used to discount future benefits and costs. The Green Book recommends that the SRTP be used as the standard real discount rate.

The rate at which individuals discount future consumption, on the assumption of an unchanging level of consumption per capita over time, is called the Pure Rate of Time Preference (PRTP). The Green Book suggests a PRTP of around 1.5 per cent a year for the near future. If per capita consumption is expected to grow over time, future consumption will be plentiful relative to the present and thus have lower marginal utility. This effect is represented by the product of the annual growth in per capita consumption (g) and the elasticity of marginal utility of consumption (μ). The Green Book indicates the annual rate of g is 2 per cent per year, and the elasticity of the marginal utility of consumption (μ) is around 1. SRTP is the sum of these two components:

$$SRTP = PRTP + \mu * g$$

With a pure time preference rate of 1.5%, and values of 2% of g and 1 for μ, the resulting discount rate is 3.5%. Note that the Green Book allows other declining discount rates to be used in more cautious risk assessments.

Source: *Green Book, HM Treasury*

Tol emphasises the discount rate (see box) and aggregation across countries (equity weighting according to per capita income) as the two most significant factors explaining the range of results. However, it is likely that these are only two of the most salient differences recorded in the studies, and further uncertainties may be important.

The shape of the curves shows the difficulty in defining a robust central estimate. The mean values in the four filters applied to the data are in the range of £35 to £91/tC. The probability distribution is right-skewed, with a steep increase up to about $25/tC and a long tail of much higher values. Values in the region of £5-10/tC, as suggested by Pearce (2003), are in the region of high uncertainty in the S-shape of the curve. A small change in the value results in a large change in probability. For example, moving from $0 to $25/tC is a jump from 10% to 50% probability in these plots. Beyond about $20/tC the three curves start to diverge. Thus, the probabilities of higher estimates are strongly influenced by the assumptions made in applying different filters to the literature.

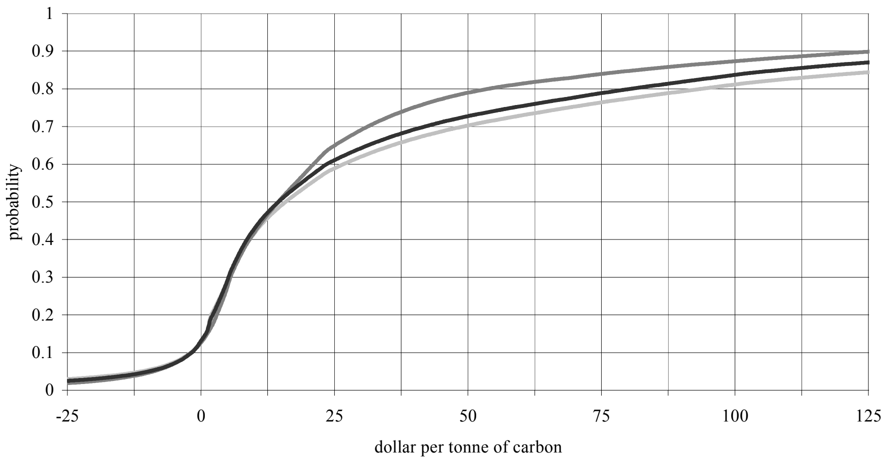

Figure 5. The composite cumulative density function of the marginal social cost of carbon.
The curves represent weights assigned by the study authors (top, grey), Tol's quality weights (middle, black), and Tol's quality weights including only peer-reviewed studies (bottom, light grey). The values shown are for US$1995 (from the original studies). Source: Tol (2004).

FUND also produces probability distributions. The current model (November 2004) tests the full uncertainty with parameters set to values that are sampled from distributions for each parameter. (A reference mode using 'best guess' estimates for the parameters is also possible. This mode is not used in this report although results are presented in the Annex. Two of the main drivers of the SCC estimates are the choice of discounting scheme and equity weighting (see boxes for more detail).

Figure 6 shows probability distributions for the full set of parameters, for several discounting schemes. The 0% Pure Rate of Time Preference (PRTP) without equity weighting is unrealistic, but provides a standard basis of comparison of impacts. The UK Treasury Green Book discounting scheme starts with a discount rate of 3.5% for the first 30 years, then 3% for 45 years, and then a declining rate to 1%.[4] FUND produces a range of estimates that includes a substantial proportion of net benefits (i.e., estimates less than 0). But it also has a strong skew toward higher numbers, well beyond £150/tC. The distribution of FUND results for the lower discounting schemes (Green Book and PRTP=1%) suggests the upper and lower quartiles are in the range of £-10/tC and £100/tC after rounding off. Trimmed means for two discounting schemes are (£/tC):

	Trimmed mean (10%)	Trimmed mean (1%)
Green Book, with EW	38	57
PRTP=0%, no EW	98	157

[4] The Green Book discounting scheme results in estimates close to the 1% PRTP scenario, rather than the 3% PRTP scenario. This is because the Green Book rates are consumption discount rates, which already include the growth component. The PRTP scenarios have this added on. Thus the 3% PRTP scenario represents considerably higher discounting than Green Book discounting.

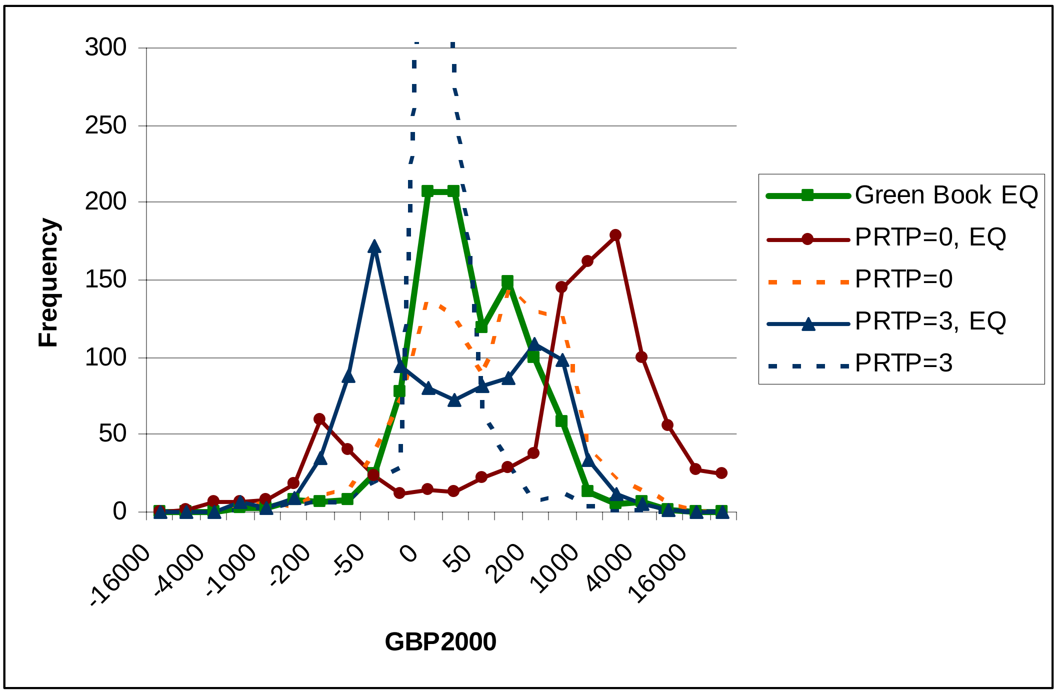

Figure 6. Probability distributions from FUND
The heavy green line is the Green Book with equity weighting. Other runs are for PRTP=0% and 3%, with equity weighting (solid lines) and without equity weighting (dashed lines). The uncertainty is for the full set of parameters, but with some of the extreme values (positive and negative) eliminated as implausible.
Values are in GBP2000, converted from the FUND USD1995 by multiplying by 0.863. The PRTP values are discounted by the growth rate in addition to the Pure Rate of Time Preference. Note that the x-axis scale is not linear in order to highlight the range of values in the tails of the distributions. See the Annex for further details and results.

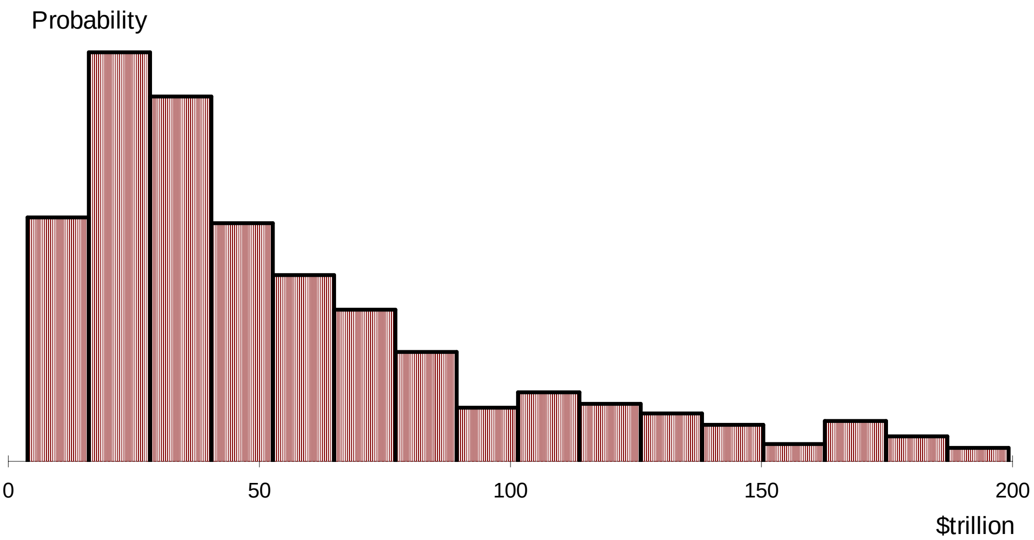

Figure 7. Distribution of the total climate damages ($2000) for the A2 reference scenario from the PAGE model
The A2 scenario is from the IPCC Special Report on Emission Scenarios. It has a high projected population with mixed regional economies reliant on fossil fuels. Carbon emissions are quite high, 28.9 GtC/yr in 2100. See Nakicenovic and Swart, 2000, www.grida.no/climate/ipcc/emission.

Equity Weighting

With a utilitarian social welfare function, each person's utility counts equally. It is generally accepted that each additional unit of consumption provides diminishing marginal utility. That is, giving £1 to a rich person produces less utility (*welfare* or *happiness* may substitute as rough equivalents) than giving £1 to a poor person.

The impacts/damages routines in PAGE are much simpler than FUND. Damages are disaggregated into 8 world regions but only two sectors (market and non-market). It assumes all impacts will be adverse, scaled to a 2xCO2 benchmark for damages (as in FUND. A strength of PAGE is the relative ease of altering assumptions and the rapid calculation of probability distributions. The baseline scenario for the project (including the policy report) is the IPCC SRES A2 reference scenario of GHG emissions, purchasing power parity exchange rates, the Green Book SRTP, and an equity weight of 1 (using PAGE2002 V1.4e green book).

Under the A2 scenario, the mean impacts of climate change are GBP 51 trillion ($73 trillion) for a time horizon of 2200 and discounted to a net present value. The PAGE model uses a range of parameters, including for discount rate and equity weighting. The range of results is shown in Figure 7. A small number of runs that gave impacts above $200 trillion are not shown on the graph, but are included in the mean impacts of $73 trillion.

The resulting distribution of the SCC (£/tC) for emissions in 2000 is:

5%	mean	95%
9	46	130

This assessment draws upon four formal lines of evidence for the estimate of the social cost of carbon—the published literature, new results from the FUND and PAGE models, and the elicitation of estimates from experts. The latter was not designed to produce a probabilistic range of estimates; the values are reported here only for comparison.

Surprisingly, the four lines of evidence show some consistency in the central estimates. Means range from £40 to £60/tC for the peer reviewed literature (converted to GBP2000) and in the PAGE and FUND model results undertaken for this assessment. The corresponding median estimates are on the order of £10 to £40/tC.[5]

The range of estimates is still quite wide, from £-50/tC to well over £200/tC. The 5% and 95% range in FUND is the widest span, and the models and experts have a wider range than the means and medians reported in the analysis of the literature (as expected) (see Figure 8).

The PAGE results are all positive, but with less indication of the very large costs from FUND. This is not surprising, since PAGE is benchmarked to this literature and is not an independent valuation of the sectoral and regional impacts. The PAGE mean estimate is £47/tC).

Similarly, the knowledge elicitation reveals a range of estimates with the median very similar to the literature, FUND and PAGE. However, the elicitation from the experts was not designed to reach consensus around a central value, nor was it intended to set bounds to the range of plausible estimates (see the Annex for more details).

[5] The median has a 50% probability of being exceeded and is less than the mean due to the right-skewed distribution of the SCC estimates.

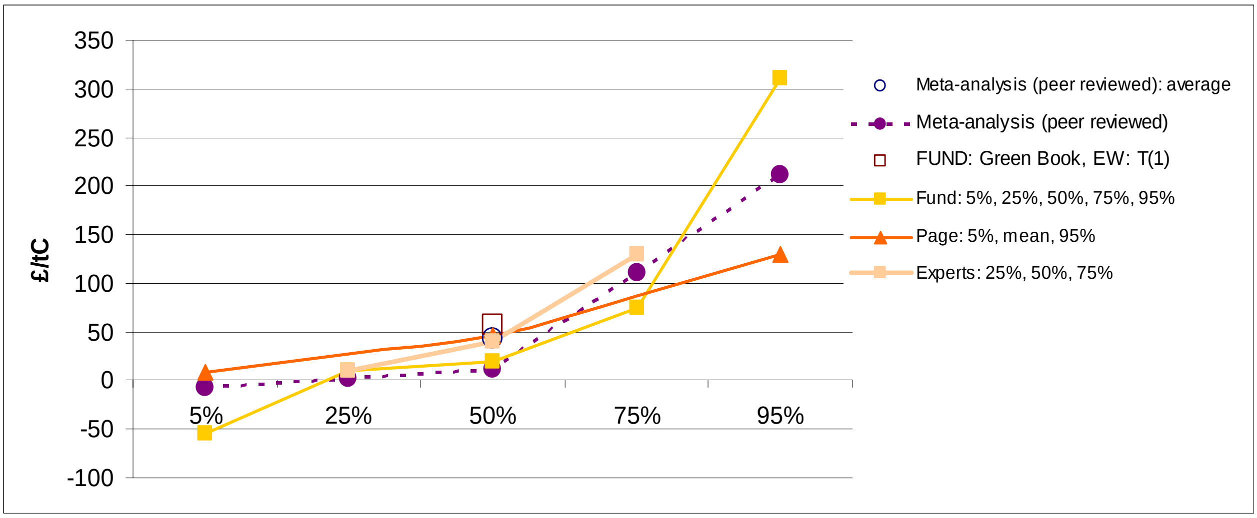

Figure 8. Comparison of distributions of estimates of the SCC
The markers indicate data points from four sources. The meta-analysis of the literature, using only the peer reviewed literature and Tol's weights, shows values from £-8/tC (5%) to £211/tC, with an average of £43/tC. The average from FUND (with 1% of the outliers trimmed) for the Green Book discounting and equity weighting is £57/tC, with a range from £-54/tC (5%) to £310/tC (95%).

What do we know about the decomposition of the estimates to the sectoral and regional level? To address this question, we rely primarily on the results from FUND since neither the literature, PAGE, nor the knowledge elicitation provide sufficient disaggregation to analyse our confidence in the SCC estimates. It is precisely because FUND attempts to build up consistent global estimates from regional and sectoral analyses that an examination of the robustness of those components is possible.

Five concerns are apparent in the analysis of the disaggregated results: (i) regional and sectoral balance of impacts, (ii) regional validation, (iii) independence of the sectoral damages, (iv) aggregating damages and distribution of winners and losers, and (v) other constraints on impacts.

(i) Figure 9 and Figure 10 present the regional and sectoral breakdown of results from FUND. For the regional breakdown, the richer regions (such as Japan/Korea, USA, China and Western Europe) account for a large fraction of the costs, compared to the smaller economies of the small island states or Eastern Europe for example. In this example, Japan/Korea, China and Western Europe account for 30% of the total benefits and costs of climate change, for the case of no discounting and no equity weighting. With equity weighting and the Green Book discounting, Africa has the highest impacts.

Similarly, the sectoral disaggregation from FUND is shown in Figure 10. The dominance of the results by agriculture and energy costs for space heating and cooling is notable. For the Green Book scheme with equity weighting, these three sectors account for some 75% of the total costs estimated in FUND (i.e., adding benefits to costs).

(ii) FUND applies the same sectoral damage functions, with different parameters, to each region and the results are not validated by high resolution national or regional assessments. In fact, few such assessments exist, so this remains an enduring challenge (see the conclusion regarding further work, section 6.2). An informal discussion of the FUND results with an impacts specialist from China (Lin Erda, personal communication, 2004) suggested that there would be considerable differences of opinion regarding the underlying impact models, in addition to the well-known debates over economic valuation. Where the model estimates are dominated by a few regions, the case for regional validation would be even stronger. Ideally, validation should be done at the regional and sectoral level, and over time, to ensure a robust analysis.

(iii) The sectoral impacts are considered in isolation, with the assumption that climate change drives the sectoral impacts independently of other effects.[6] Yet, the multiple stresses of climate change may lead to an acceleration of the impacts. Conversely, adaptive capacity might be built up across sectors resulting in reduced damages (or increased benefits). A classic example of the former is the case where water shortages will prevent irrigated agriculture from reaping its full benefits. This appears to be a significant constraint in China—the ability to take advantage of longer growing season and increased radiation would depend on an irrigation infrastructure and water resources that are not likely to be available in the near future.

(iv) The distribution of the SCC values within a region may differ significantly from the regional total. This is the well known issue of spatial resolution. Regions with net costs near 0 (in these results), including the Middle East, small island states, and Canada, are likely to have significant impacts in some sectors. Some justification can be made for treating a country or integrated regional economy as one ‘exposure unit’, to the extent that trade-offs between winners and losers within an economy can be addressed by specific policies. Even so, the balance of effects between one sector and another may be difficult to accommodate. For example, reduced heating costs will benefit northern Europe while increased cost of air conditioning and cooling will be significant in southern Europe. And, reduced heating costs might not compensate for loss of land and species due to sea level rise. The sectors where damages are significant (i.e., not the damages net of benefits) may be a primary concern for decision makers.

(v) Sectoral damages are often related to first-order impact variables without other social or economic constraints. It is by no means clear that the early benefits of climate to agricultural potential (as noted for China) will be realised in the face of the enduring agricultural surpluses, constraints on trade, and costly producer price supports.

A conclusion from this analysis is that regional-sectoral estimates of the SCC are not well validated, and those produced from global models should not be taken as reliable regional or sectoral estimates. This does not necessarily lead to the conclusion that existing global estimates of the SCC are unrealistic. The model results presented here are based on multiple runs (1000 in the case of FUND) using a range of input parameters. To some extent, the uncertainty at the region-sector level should be reduced in aggregating to the global level—a specific region-sector may have a low estimate in one run and a high estimate in another run. This reinforces the need to understand the sources of uncertainty in the SCC and to evaluate the estimates in an explicit risk framework. The regional-sectoral validation remains a high priority if better estimates of the SCC are to be developed and used.

[6] Note that the coastal zone sectors are related through a simple model of the least cost of coastal protection or retreat (the value of abandoning dryland and wetland).

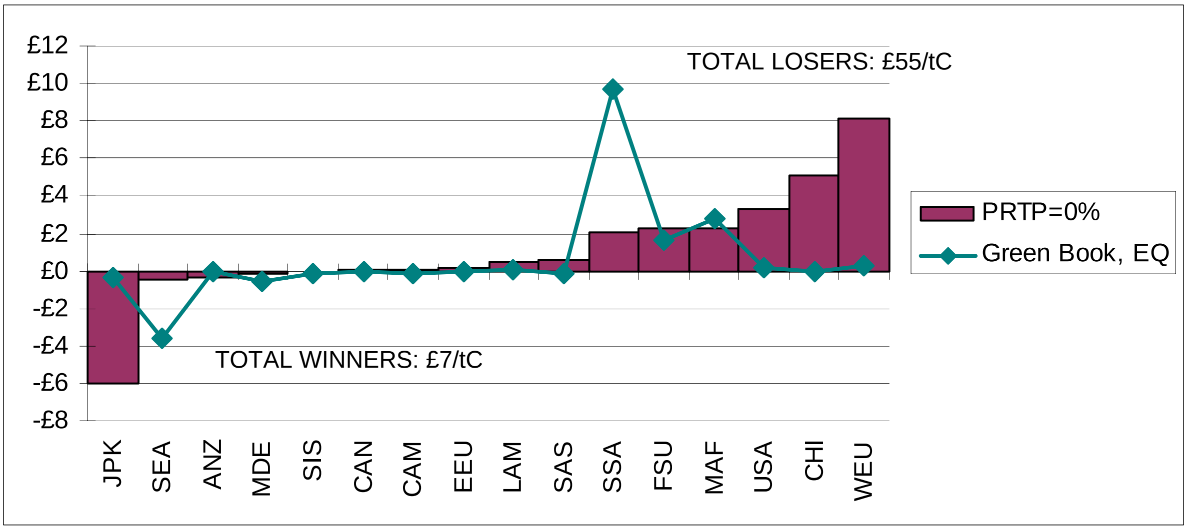

Figure 9. Regional disaggregation of median estimates of the SCC in FUND
The bars show the total damages with a Pure Rate of Time Preference = 0%), sorted from those that benefit from climate change (with a total benefit of £7/tC) to those that suffer the greatest losses (total losses are £55/tC). The regional values for the Green Book discounting scheme with equity weighting is shown for comparison—with some notable differences in the distribution of winners and losers. Note that the regional breakdown of FUND results is not intended to imply estimates of the SCC at the regional level. The uncertainty in the regional values (not shown) is likely to be greater than the global uncertainty (already considerable).

Key		
	JPK = Japan and Korea	LAM = Latin America
	SEA = Southeast Asia	SAS = South Asia
	ANZ = Australia and New Zealand	SSA = Sub-Saharan Africa
	MDE = Middle East	FSU = Former Soviet Union
	SIS = Small island states	MAF = North Africa
	CAN = Canada	USA = United States of America
	CAM = Central America	CHI = China
	EEU = Eastern Europe	WEU = Western Europe

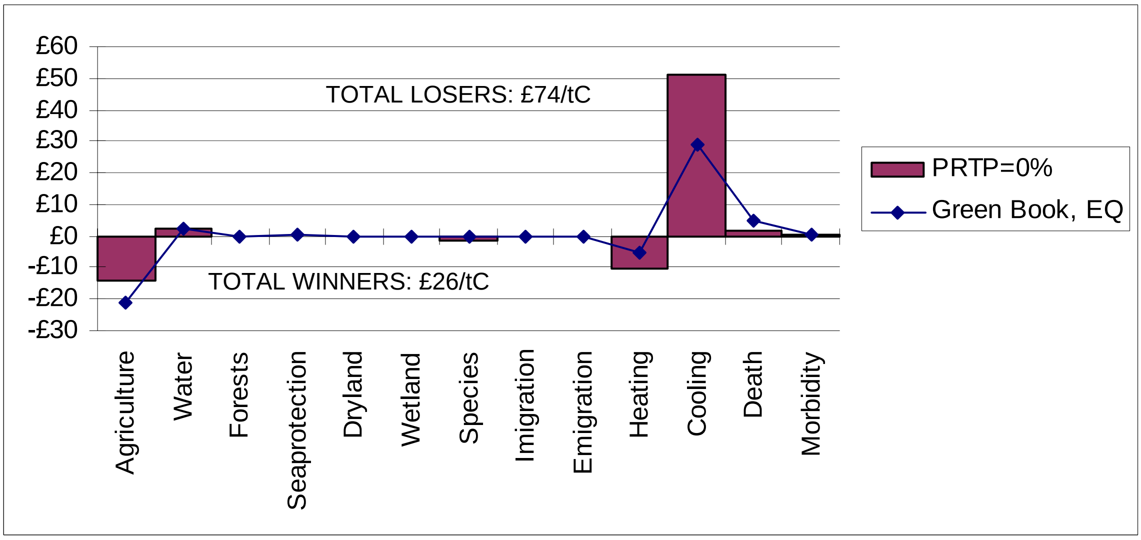

Figure 10. Sectoral disaggregation of median estimates of the SCC in FUND
The bars show the total damages with a Pure Rate of Time Preference = 0%), grouped according to impacts on the rural economy, coastal zone, energy costs, and health. The total of the sectors that benefit (for PRTP=0%) is £26/tC, compared to total losses of £74/tC. The sectoral values for the Green Book discounting scheme with equity weighting is shown for comparison—with a similar ranking of sectors. Note that the sectoral breakdown is not intended to imply estimates of the SCC for single sectors.

3.3 The balance of benefits and damages in the social cost of carbon shifts markedly over time, with net damages increasing in later time periods. Estimates of the SCC are particularly sensitive to the choice of discount rates and the temporal profile of net damages.

Clearly there are some benefits to climate change. Agriculture can benefit from higher carbon dioxide concentrations and longer growing seasons. Rainfall may increase in some regions, sufficient to balance or exceed increased evapotranspiration due to warmer temperatures. Reduced costs of heating are likely to be widespread.

In FUND, net benefits are apparent for the first few decades of the 21st Century. This can be seen in (Figure 11) which represents the time profile of annual damages in different regions.[7] In these results, FUND shows net benefits for China in both scenarios. Regional benefits for other regions differ largely due to the equity weighting. What is less clear, is the extent of the benefits (noted in section 3.2 for agriculture and China) and the length of time for which benefits might exceed damages. If the benefits are large and last for say 30-40 years, then higher discount rates will tend to tilt the balance in favour of net benefits in calculating the SCC as a net present value. Conversely, with smaller net benefits for a shorter period of time, lower discount rates will tend to favour the longer term exposure to increasing net damages. Thus, temporal uncertainty interacts with the discount scheme (at least in FUND). The issue does not arise in PAGE, which assumes the SCC is a net damage from the baseline time period.

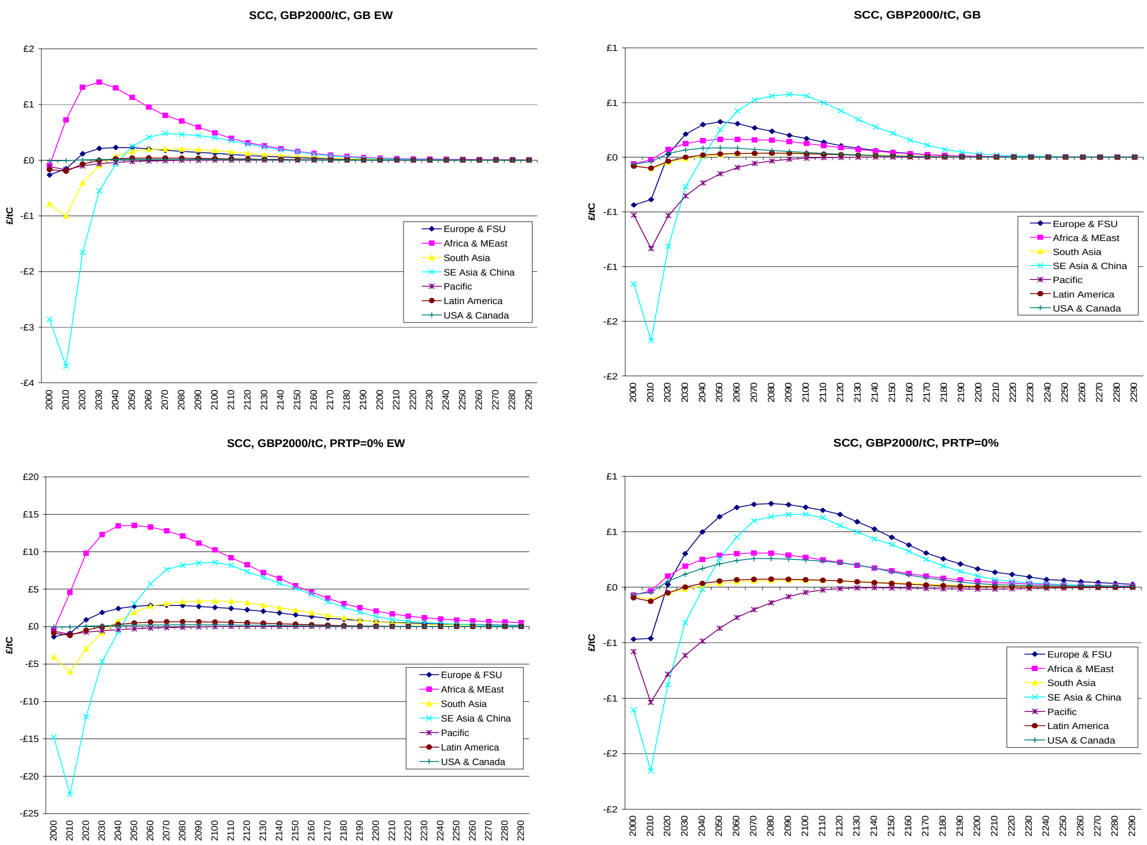

Figure 11. Temporal profiles for regional estimates of the SCC in FUND
Results are for the Green Book (top) and PRTP=0% (bottom) discounting schemes, with equity weighting (left) and without equity weighting (right). Note the units are GBP2000/tC. Convergence to zero in the long term is because of discounting rather than reduction of absolute valuations (which may increase over time).

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[7] It is these annual damages that are discounted to a net present value

The corresponding temporal profiles for groups of sectors are shown in Figure 12. As already noted, agriculture and heating have early benefits, in both discounting schemes. The same observations regarding balancing benefits and damages over time apply.

In this assessment, we have not explored the sensitivity of our outcomes to very different temporal profiles. It would be possible, for instance, to weight losers more than winners, following a concern of policy makers to prevent dangerous climate change rather than to optimise the balance of mitigation and impacts.

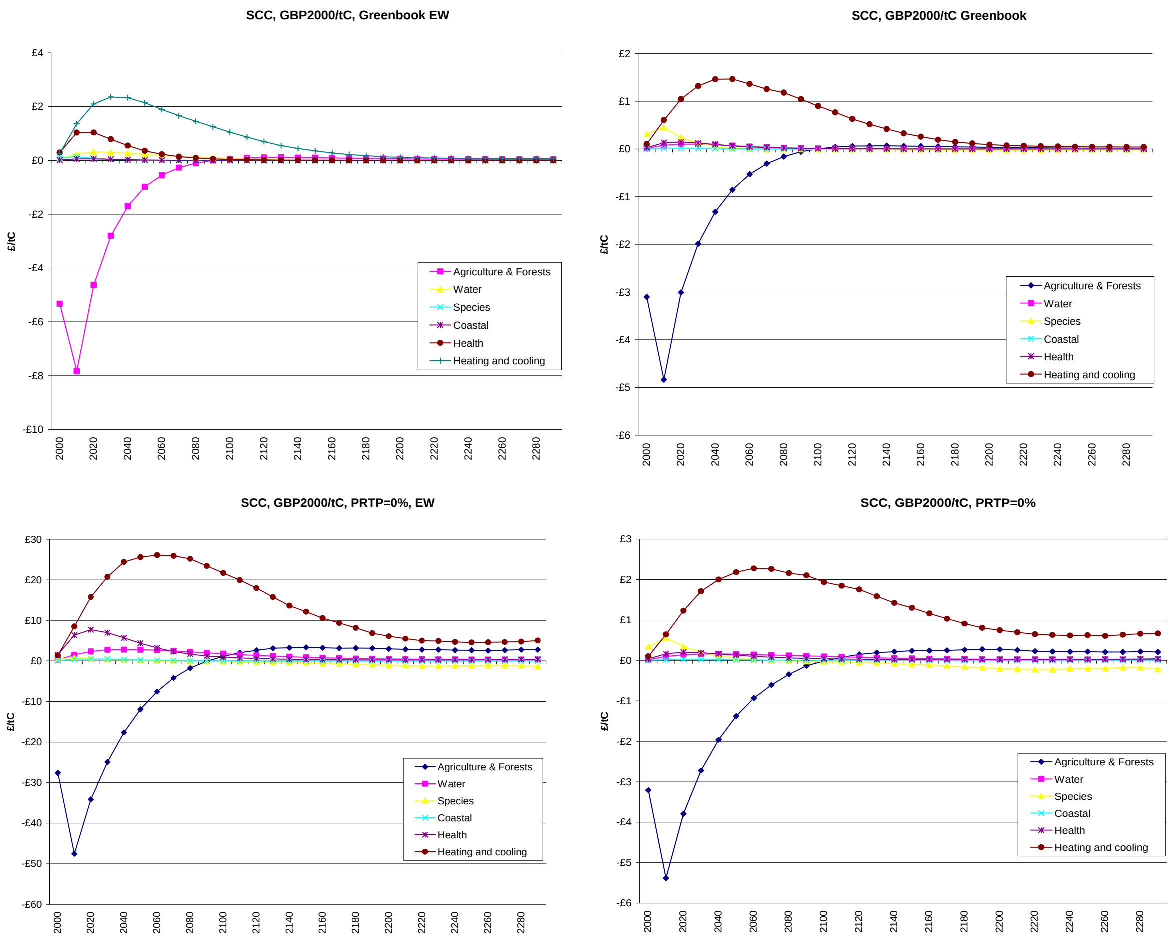

Figure 12. Temporal profiles for sectoral estimates of the SCC in FUND
Results are for the Green Book (top) and PRTP=0% (bottom) discounting schemes, with equity weighting (left) and without equity weighting (right). Note the units are GBP2000/tC. Convergence to zero in the long term is because of discounting rather than reduction of absolute valuations (which may increase over time).

3.4 Vulnerability and adaptation to climate change impacts are dynamic processes responding to climatic signals, multiple stresses, and interactions among actors. Large scale impacts, such as migration, can be triggered by relatively modest climate changes in vulnerable regions.

The usual estimates of the SCC are based on average conditions (e.g., increments of warmer temperatures) in generalised damage functions with few feedbacks over time, between regions or among actors. However, assessments of the impacts of climatic variations, and the ability to adapt to them, are based on increasingly sophisticated, dynamic models of decision making, multiple stresses, and socio-institutional conditions. For example, syndromes of poverty and environmental degradation have been developed and tested with scenarios of different climatic risks. At present, it is not possible to scale up such local to regional models of dynamic responses to global estimates of the social cost of carbon.[8]

This assessment of the SCC included an exploratory evaluation of the kinds of vulnerability hot spots that might lead to large scale impacts of climate change. We noted three conditions would immediately qualify as hot spots:

- Coastal deltas where dense populations are subject to increased coastal erosion, recurrent storm surges and cyclone risk. Migration out of the high hazard area is constrained by the lack of space, social and cultural factors and poverty. Bangladesh is the archetypical example, but mega-cities in coastal zones could also become increasingly hazardous.
- Semi-arid regions at the boundary of agricultural and pastoral production systems where climatic episodes, primarily of drought, already create stresses and may tip the system into an increasingly instable state. Migration is constrained by ethnic conflicts, as well as economic constraints. The Sahel is an archetypical example, and indeed has been subject to decreasing rainfall since the 1960s.
- Small island states where sea level rise, and possibly increased cyclone risks, threaten the physical resources, literally inundating an entire country. Migration is the only feasible solution, often to a foreign country (Nicholls et al. 2005).

A key question for global estimates of the SCC is the extent of area and number of people subject to such conditions. A related concern is how to value such non-linear impacts and the multipliers associated with migration, loss of an economic sector and socio-political stress and conflict. These are the sorts of socially contingent impacts that are represented by the right hand column of our risk matrix, and specifically the cells C-1 and C-2.

This assessment did not attempt to quantify these risks in terms of £/tC or to compile an inventory of indicators of impacts (a related EC project is beginning to do some of this). Rather, we identified the issue in general terms, focussed on a representative example (migration in the Sahel in West Africa) and developed a pilot model of the potential impacts of climate change. These results are presented in some detail as an annex to this report.

To the extent that vulnerability and adaptation are dynamic processes, with significant changes over time, they should both be understood in estimates of the long-run impacts of climate change. The literature on vulnerability and adaptation science (e.g., Downing 2003) is rapidly growing, recognising the many climate and non-climate factors that influence the levels of risks that threaten specific social, economic and environmental conditions. The approach to adaptation that prevails in the SCC literature, in contrast, is quite limited. Adaptation is generally seen as a reduction in potential impacts related to a few macro-level variables, such as GDP per capita. Or, the case for adaptation is made based on an equilibrium comparison of climate sensitivity in other regions,

[8] The lack of regional validation of global estimates of the SCC has two implications: (i) regional breakdowns from global models should not be taken as accurate assessments of regional damages (see section 3.2) and (ii) regional experts and climate policy negotiators are less likely to have confidence in global SCC estimates.

assuming the adaptation capacity is easily translated to new conditions and other places. In reality, adaptation is a process that will have its own costs, including the costs of failed investments and maladaptation.

4 Uncertainty and risk

Different integrated assessment models generate different estimates partly because they adopt different assumptions about (uncertain) future states of nature (such as global warming), society (e.g., population growth) and economies (e.g. GDP), and of the sensitivity of impact sectors to both the exogenous driving forces and climate change. However, estimates of the SCC are arguably driven even more by different assumptions about preferences (e.g., ethical choices and decision frameworks) and future policy responses (the role of the decision framework and time in Figure 1).

It should be clear that uncertainty regarding the climate system, impacts and their valuation is only one driver of the estimates of the social cost of carbon. Three categories of drivers are commonly noted:

1. ***Exogenous uncertainty.*** Over a time horizon of two centuries, the underlying rate of innovation and economic growth are uncertain and generally taken as exogenous to the estimate of the SCC. However, a climate policy model integrating the SCC and greenhouse gas mitigation should include economic growth and technology as endogenous properties. Equally, much of the underlying climate science has to account for exogenous uncertainty, for instance in future solar radiation and volcanic eruptions.
2. ***Policy uncertainty.*** Different assumptions about public and private responses to climate change generate different estimates of the marginal social cost of carbon.
3. ***Ethical judgments.*** Ethical judgements about equity, time weighting and our aversion to risk (and ambiguity in risks) have a significant impact upon the marginal social cost of carbon.

In the following lists, uncertainties are classified:

* topic of an MSc thesis completed for the project
^ included in the scenarios used in the expert knowledge elicitation

The Clarkson and Deyes (2002) paper identifies four main 'economic valuation uncertainties':

1. The range of sectors included: market and non-market (^)
2. Assumptions about how valuations of climate impacts will change over time
3. Assumptions about equity weighting (*,^)
4. Assumptions about discounting (*,^)

These are certainly important. The background paper for the Defra International Seminar on the Social Cost of Carbon (Pittini and Rahman 2003, 2004) adds a further three drivers of variability:

5. The valuation of low-probability catastrophic effects (*)
6. The valuation of 'socially contingent' effects (^)
7. Differences between valuation based upon willingness to pay and willingness to accept loss

In addition to these seven items, two further items which have so far escaped much attention by policy makers are also important:

8. The degree to which preference heterogeneity is accounted for (*). Replacing the standard (but incorrect) assumption of identical preferences with the assumption that people have different (heterogeneous) preferences can produce surprising results. For instance, Gollier and Zeckhauser (2003) show that if people use constant heterogeneous discount rates, their aggregate behaviour will reveal a declining discount rate.[9] Hence allowing for heterogeneity in time preference means that more weight is placed on the future, generating a higher estimate of the social cost of carbon. Similar results may obtain for heterogeneous preferences on risk or equity weighting.

[9] The logic is that as time advances, more weight is placed upon the preferences of people with lower discount rates.

9. Assumptions about risk and ambiguity aversion (*). As dealing with climate change represents an exercise in risk management, our risk preferences are critically important. Moreover, because distributions over outcomes are generally not properly defined — they are 'ambiguous', in that the probability distribution itself is uncertain — our preferences over ambiguity aversion are also critical. Integrated assessment models that do not take risk and ambiguity aversion into account are implicitly assuming risk and ambiguity neutrality. The existence of the insurance industry clearly suggests that this is an erroneous assumption.

Of these nine items, the sensitivity of estimates of the social cost of carbon to the five starred items (*) were evaluated in four MSc theses (supervised by Cameron Hepburn, see Anthoff 2004, Ceronsky 2004, Guo 2004, and Li 2004). These five items — equity weighting, discounting, catastrophic impacts, preference heterogeneity and risk and ambiguity aversion — were selected because they are large drivers of variability. We do not examine growth and development scenarios, speed and effectiveness of adaptation, or innovations in CO_2 abatement technology. Abstracts of the four theses on these topics are found in the annex.

The project also conducted a knowledge elicitation of 14 experts. The methodology posed scenarios of key drivers of uncertainty and variations in the SCC and asked the experts to provide an estimate of the SCC as well as their confidence in the estimate. In addition to the economic factors noted by a carot (^) above, the scenarios included the range of projected temperature and sea level rise, whether precipitation and storm risks were included, whether adaptation was included, and a choice of local, world average or EU decision perspective (primarily relating the values assigned to impacts such as loss of species and human life). Further details are included in an annex to this report.

This chapter discusses the results grouped according to three key messages.

4.1 Climate uncertainties and the climate sensitivity are key factors in larger estimates of the SCC.

Clear drivers of the SCC are the assumptions regarding climate change itself. If climate change is expected to be in the lower range of the IPCC, less than 2°C by 2100, then lower estimates of the SCC are expected. On the other hand, if climate change is in the upper range, above 5°C by 2100, then it is difficult to escape a higher estimate of the SCC.[10]

For instance, in Figure 13 expert responses to the scenarios of relatively low climate change (less than 2°C, labels beginning with L) averaged less than £10/tC. In contrast, scenarios of higher climate change (over 5°C, labels beginning with X) were in excess of £50/tC, and often above £100/tC.

Ceronsky (2004) tested FUND for different climate sensitivities—the equilibrium warming expected with a $2xCO_2$ scenario. The current 'best guess' is 2.5°C, with a range in the IPCC extending to 4.5°C. The SCC is 5-6 times higher at 4.5° than at 2.5° (Table 5, Figure 14). And, if the climate sensitivity is more extreme, the SCC increases by a further factor of 3 to 7 (comparing 9.3° to 4.5°).

[10] Estimates of higher temperature changes have emerged recently, see the results of the Exeter conference and Stainforth et al. (2005).

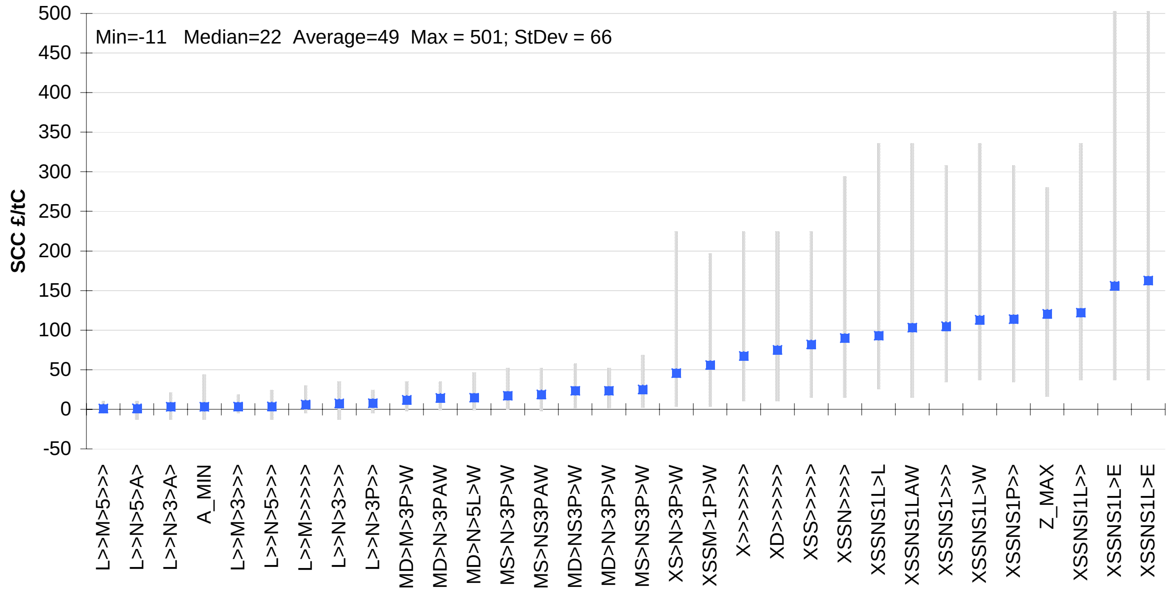

Figure 13. Expert responses to scenarios of the drivers of the SCC, £/tC

The range is the minimum, average and maximum for 14 experts. The scenarios are coded on the 9 characters of labels:

> Temperature and sea level rise: **L**ow, **M**edium, high (**X**)
> **D**rought and regional declines in precipitation or increased **S**torms
> Climate **S**ystem surprise
> **M**arket or market and **N**on-market sectors
> **S**ocially contingent impacts included, along with market and non-market sectors
> Discount rate: **1**%, Green Book (**3**) or **5**% (Pure Rate of Time Preference)
> **P**er capita income equity weighting or weight **L**osers greater than winners
> **A**daptation included
> **L**ocal, **W**orld average or **E**uropean decision perspective
> \> indicates no information on this factor is included in the scenario

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Table 5. Sensitivity of FUND estimates for different climate sensitivities

	2.5˚C	4.5˚C	7.7˚C	9.3˚C
PRTP=0%	57	321	1446	2321
Green Book	18	**100**	268	357
PRTP=1%	11	88	357	571
PRTP=3%	-2	17	73	116

Notes: The values produced by FUND (in the July04 version) were converted to GBP2000 and then indexed to the 4.5°C Green Book value (=100, in bold). Thus, the value for 2.5°C and PRTP=0% is about half (57%) of the 4.5°C Green Book value. Conversely, the 9.3°C , PRTP=3% value is 16% (index = 116) higher than the Green Book 4.5°C value. The July04 version of FUND was subsequently updated, however the relative range of results should be similar. Source: Ceronsky (2004).

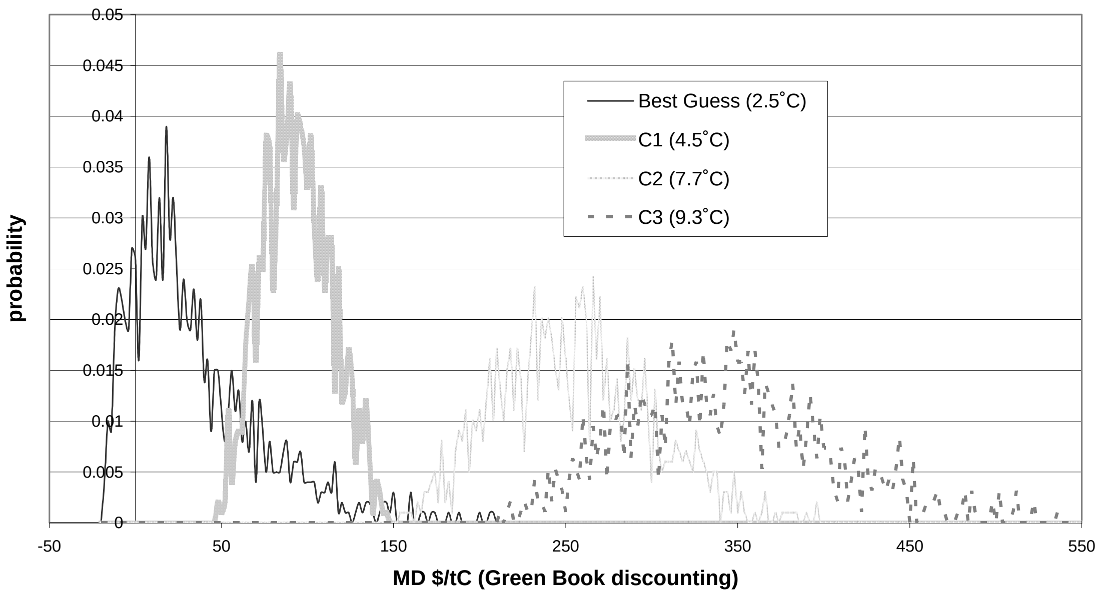

Figure 14. Distribution of the SCC in FUND with four climate sensitivities
Results are for Green Book discounting. Note that these runs of FUND are for the July2004 version; more recent results are presented elsewhere in this report. Extreme results from FUND have been dropped in these probability distributions. Source: Ceronsky (2004).

This high degree of sensitivity to the underlying climate projection, might be reflected in policies that seek to limit the extent of economic exposure to the higher range of damages. Further, the sensitivity of estimates of the SCC to climate projections reveals a methodological issue of some importance. The usual method of calculating the (marginal) SCC is to project a reference scenario (comprising at least economic growth and climate change), add a pulse of carbon at the start of the run and calculate the difference between the reference run and the scenario of added climate change resulting from the marginal increase in a greenhouse gas. In reality, the climate-impacts-policy system is more recursive. A cogent argument runs as follows:

> A low estimate of the social cost of carbon, if used to set policy now, will lead to low targets for stabilisation of carbon in the atmosphere. This is likely to lead to rapid climate change, unless our understanding of the climate system is fundamentally wrong. So, over time the SCC is likely to increase, partly due to the delay between releasing carbon into the atmosphere and experiencing the impacts. Conversely, a high estimate of the SCC now, would lead to high targets and lower climate changes, which hopefully would have lower costs in the future.

Thus, in reality the SCC cannot be estimated without considering the feedbacks between policy, emissions and impacts. We know of no model that makes this policy feedback explicit, although some (including FUND) have a weak link between experienced impacts and economic growth, which also affects GHG emissions.

4.2 Uncertainties in coverage, sectoral assessments and regional processes are likely to be significant, but are difficult to judge without further model development and inter-model comparison.

Chapter 3 documented issues in the regional and sectoral coverage of existing estimates of the SCC, with the conclusion that a lack of regional/sectoral validation hampers confidence that the full range of potential impacts have been reflected in current global estimates. The lack of independent estimates and adequate data sets for validation preclude definitive statements about the range of uncertainty that might be expected in each cell of our risk matrix. A priori, there is little evidence to indicate that each new sector or better regional representation will lead to higher or lower global estimates. Indeed, there is a sense that many of the key drivers of uncertainty are known and further refinement might lead to compensating effects, at least at the global level.

We propose below to pursue a systematic bounding exercise where experts attempt to define the range of potential impacts for each cell of the risk matrix (see section 6.1 below). As a starting point, we would expect that further research on the market-projections quadrant (the upper-left cells) are unlikely to lead to large effects on global estimates. On the other hand, decision values and frameworks are certain to dominate the socially contingent-system change quadrant (the lower-right cells) and it may not be possible to bound these estimates in a useful way. In between, uncertainties might be several orders of magnitude but should be amenable to further refinement.

4.3 Decision variables such as the discount rate and equity weighting also are extremely important.

A recurrent thread in the literature on the SCC is the importance of the discount rate and equity weighting. This is confirmed in our assessment, with new investigations led by Cameron Hepburn (Anthoff 2004, Guo 2004, Li 2004; see the Annex for a synopsis of these theses).

In FUND, as an example of the general effects, the higher discount rate of 1% PRTP produces estimates that are on the order of $1/5^{th}$ of the SCC calculated with a PRTP of 0%. The Green Book scheme produces similar or somewhat lower estimates as a PRTP of 1% in FUND.

Equity weighting also has a potentially significant effect as well. With a PRTP of 0%, equity weighting could increase the SCC by a factor of 5 to 15, depending on the way equity weights are calculated. Even with higher levels of discounting, the increase might be a factor or 3 to 12. As noted above, the results are sensitive to the shape of temporal profile and may be somewhat different in other models.

Complex discounting schemes have been proposed and were tested in FUND. Their effect appears to be sensitive to compounding factors such as economic growth rates. The Annex introduces this literature.

5 The range of estimates

Despite uncertainties in the SCC, it is possible to draw some conclusions from the current estimates. Although the range is quite large, there seems to be a reasonable consensus regarding a lower bound.

5.1 Estimates of the social cost of carbon span at least three orders of magnitude, from 0 to over 1000 £/tC, reflecting uncertainties in climate and impacts, coverage of sectors and extremes, and choices of decision variables.

The minimum expectation of the SCC is £0/tC, or even a net benefit on the order of £5-10/tC. The lower range of climate scenarios produced estimates of this order from the experts (Figure 13). At the same time, the upper range of climate scenarios produced estimates as high as £500/tC. The distribution of results from FUND are from £0 to over £1000/tC for a PRTP=0% and from £-100 to over £500/tC for the Green Book discounting scheme (Figure 6). Similarly, the PAGE damage estimates range from £0 to over £400 /tC.

Of course, the extreme tails of these estimates depend as much on decision values (such as discounting and equity weighting) as on the climate forcing and uncertainty in the underlying impact models. However, even reducing the range by half, say from £10/tC to £500/tC, still produces a wide range of estimates.[11] The high valuations cannot simply be dismissed as outliers.

5.2 A lower benchmark of 35 £/tC is reasonable for a global decision context committed to reducing the threat of dangerous climate change and includes a modest level of aversion to extreme risks, relatively low discount rates and equity weighting.

The Defra paper (Clarkson and Deyes, 2002) recommended £35/tC as the lower estimate for policy evaluation. Pearce (2003) reviewed this estimate, concluding that a central value was in the region of £10-20 /tC. Since the Defra paper, we have updated FUND and PAGE to produce new estimates, evaluated the expert judgments and explored the role of the drivers of uncertainty more thoroughly in a risk framework. The 2003 and 2004 Defra workshops reviewed progress in understanding the uncertainties in estimates of the SCC, but was not designed to reach a new consensus.

Clearly, there continues to be enormous debate regarding the range of estimates of the SCC, whether a central value makes sense and whether a minimum threshold for policy evaluation could be supported from the current estimates. This debate is likely to continue for some years; certainly the absence of new models and regional/sectoral studies leaves the validity of global estimates in some doubt.

We have not attempted to define a plausible, robust minimum value for all contexts. That would require substantial new work on the difficult uncertainties (for instance, the non-market and socially contingent effects that might arise from increases in climatic hazards).

Rather, we have evaluated whether the lower benchmark in the Defra paper is credible. Note that this estimate is specifically related to a global decision context that has already agreed to the UNFCCC commitment to prevent dangerous climate change. The global context also implies at least a modest aversion to large scale risks, a long term view that is often associated with relatively low discount rates, and concern for global welfare that implies at least a modest level of equity weighting.

We observe that £35/tC (using GBP2000 values) is a reasonable lower benchmark for the SCC in this context. To be clear, we refer to this benchmark as: $SCC^{g}_{low.}$ It is our judgment (not a model estimate per se) of the lower benchmark (not statistically defined) that reflects a global context (g).

[11] The full range might be expressed as £-10^2 /tC to £10^3 /tC, or even £10^4 /tC for some of the outliers in FUND. This would be a range of five to six orders of magnitude.

This conclusion draws upon two lines of evidence. First, the model results show that this benchmark has a significant likelihood of being exceeded. In FUND, with the Green Book discounting scheme and equity weighting, there is about a 40% chance that the SCC exceeds £35/tC (Table 6). Table 7 shows several measures of the central tendency in FUND results—the Green Book trimmed mean estimate with equity weighting is £38/tC. Similarly, the median value from PAGE is £46/tC.

Second, a number of scenarios judged by the experts give rise to values near or above £35/tC. The respondents were grouped according to their overall perception—tending to low estimates of the SCC, medium estimates, or high estimates. Among those with generally low estimates, values exceeding £35/tC were given, but only for high climate scenarios and usually with other decision factors such as European values (Table 8). In the middle group, values around £35/tC occurred for all climate scenarios, and were quite common for middle to high scenarios. As expected, those with higher scores regularly produced estimates greater than £35/tC.

Table 6. Summary of the probability that the SCC exceeds a given threshold in FUND

	Green Book, EW	PRTP=0%	PRTP=0%, EW	PRTP=3%
£35/tC	40%	52%	78%	8%
£50/tC	33%	47%	77%	5%
£140/tC	12%	27%	73%	2%

EW = Equity weighting.

Table 7. Summary of FUND results, GBP2000 /tC reference, averages and standard deviation

	Reference		Average		Standard deviation		Trimmean(10%)		IQMean	
	EW	No EW	EW	No EW	EW	No EW	EW	No EW	EW	No EW
Green Book	£20	£19	£63	£24	£314	£165	£38	£20	£23	£11
PRTP=0%	£728	£56	£815	£171	£1,375	£671	£785	£98	£601	£54
PRTP=1%	£174	£11	£429	£43	£1,221	£240	£294	£24	£182	£10
PRTP=3%	-£1	-£2	£40	-£1	£434	£165	£30	£0	£5	£5

EW = Equity weighting based on per capita income; No EW = no equity weighting
Median is the 50% value. Reference is the single run with the 'best guess' of FUND parameters. Average is the arithmetic average (or median). The trimmean discards the first and last 5% of the values. The IQMean is the average of the values between the lower and upper quartiles. Results are shown for four discounting schemes.

Table 8. Selected estimates of the SCC from experts for a range of scenarios, £/tC

	Climate					
	Low		Medium		High	
Respondent	SCC range		SCC range		SCC range	
L1	1	8	8	17	11	66
L2	-3	7	6	29	12	111
L3	-2	1	4	21	19	190
M1	8	33	17	50	17	78
X1	8	22	33	83	56	145
X2	0	22	0	36	11	167

5.3 An upper benchmark of the SCC for global policy contexts is more difficult to deduce from the present state-of-the-art, but the risk of higher values for the social cost of carbon is significant.

We did not reach a consensus for an upper benchmark for the SCC, SCC^{g}_{high} in our notation. The above tables suggest that, under pessimistic scenarios of climate change, it is not implausible to consider estimates of the illustrative value proposed by Clarkson and Deyes (2002) of £140 /tC or even higher (see also Pittini and Rahman, 2003, 2004). For instance, the analysis of the literature showed approximately a 10% probability of the SCC exceeding £100/tC for all of the literature and no weights and a 5% change that the SCC exceeded £210/tC using the peer reviewed literature and Tol's weights).

Examination of the risk matrix would suggest that a decision maker with some aversion to large-scale, high-consequence risks would extend the SCC estimates to at least some socially contingent effects, with some preference to reduce the risk of system changes and large scale consequences. While these are not quantified, they are likely to be additional to the central estimates often cited for the SCC based on market sectors, some non-market sectors and scenarios of climate change based on temperature (with less clear links to changes in precipitation). The addition of equity weighting or European values, perhaps related to concerns for a liability regime, would push the estimate of the SCC still higher.

The experiments forcing FUND with releases of methane hydrates, high climate sensitivities and a reduction in the thermohaline circulation show that large numbers are possible, but difficult to verify (Ceronsky 2004, see Annex).

The deep uncertainty in the underlying accounts of the SCC precludes assigning a confidence interval to the upper benchmark.

6 Further research and next steps

In this chapter we offer insights for further research on the social cost of carbon.

6.1 Substantive improvement in estimates of the social cost of carbon requires well validated assessments at the regional scale that value the dynamic processes of vulnerability and adaptation.

A comprehensive plan for improving estimates of the social cost of carbon has not been formulated, although there are regular meetings on integrated assessment and the benefits of climate mitigation. The IPCC fourth assessment report includes a chapter in working group II on the integration of adaptation and mitigation, and possibly this will lead to a greater sense of how the various uncertainties might be addressed in the future.

We propose four broad pathways of development. The first is the continued development of global integrated models, such as FUND. The second is to complement the global assessments with detailed sectoral studies and regional integrations. The third pathway is to explore the dynamics of socially contingent processes including adaptation. The fourth development is to systematically address the uncertainties through meta analyses and expert knowledge elicitation. These development strategies are described in more detail here.

Perhaps ten significant developments are ongoing or contemplated in the integrated assessment community. These developments can be charted in our risk matrix (Figure 15). Reducing uncertainty in the geophysical drivers of climate change include (i) improving the scale of assessment and understanding aggregation and disaggregation issues at the regional-sectoral scale, (ii) linking damage functions to probabilistic scenarios of climate change; (iii) understanding cross-sectoral and multi-stressor effects and (iv) refining estimates of potentially catastrophic impacts. Reducing uncertainty in economic valuation includes: (1) adding new sectors to the damage functions; (2) broadening the range of economic techniques (such as the premium attached to risk aversion); (3) including additional metrics that policy makers may wish to take into account; (4) bounding exercises to provide a first-order estimate of the range of potential damages (see section 6.1 below); (5) understanding the dynamic aspects of vulnerability and adaptive capacity and their relationship to damages over time; and (6) exploring the effects of alternative value systems, particularly in the loss of non-market resources and non-marginal, socially contingent effects. Of course, these developments are contingent upon improvements in climate and impacts science, which we note below.

Improving estimates related to the larger uncertainties—the lower and right-hand cells—requires several improvements, and these may be the more difficult developments, constrained by the lack of data, the choice of analytical tools and the framing of climate policy decisions.

Uncertainty in Climate Change	Uncertainty in valuation →	A. Market	B. Non-market	C. Socially contingent
	1. Projection	1, 2 i	1, 2, 4, 5, 6 i	1, 2, 4, 5, 6 i
	2. Bounded risks	1, 2 i, ii, iii	1, 3, 4, 5, 6 ii, iii	3, 4, 5, 6 ii, iii
	3. System change and surprise	2 ii, iii, iv	3, 4, 5, 6 ii, iii, iv	3, 5, 6 ii, iii, iv

Figure 15. Planned developments in integrated assessment models

I – ix relate primarily to uncertainty in climate change; 1 – 6 relate primarily to economic valuation.

Valuations of the social cost of carbon are benchmarked on global sectoral impacts studies. Usually this involves an analyst collecting the literature and deciphering an equation that fits the results to the model inputs available (usually regional temperature change and economic conditions). Further development of such global impacts models is essential. However, they are unlikely to provide the critical development path for reducing uncertainty in the social cost of carbon. Rarely do the global models include robust valuation methods. Their scale is too coarse to pick up the local conditions of vulnerability. Processes of adaptation are usually ignored, which means a neglect of the socially contingent damages. Increasingly, such efforts are adopting the SRES (Nakicenovic and Swart, 2000) as the only framing for vulnerability, thus ignoring scenarios of greater future baseline vulnerability (since all countries have significantly higher GDP per capita in the SRES).

The higher priority is to conduct robust regional studies that can focus on multiple stresses and socially contingent effects. By regional we mean studies from the level of a district to country and perhaps larger, depending on the availability of information, participation of experts and stakeholders, and socio-economic integration.

For global/sectoral and regional/multi-stressor studies a range of metrics is desirable (bio-geographical, human impact, economic values). A full understanding of climate change (not just temperature and a couple of scenarios) are essential, including existing trends and large ensemble or probabilistic forecasts with climate change. By convention, the studies should have a reference time period of 2100, but a focus on the next 50 years is desirable (which has a larger effect on discounted values) and a sense of the long term commitment beyond 2100 is helpful. The scale should match the scale of exposure of the actors, rather than be defined in purely Cartesian terms.

The OECD Working Party on Global and Structural Policies has developed a work plan for a second phase of research on the benefits of climate policies (OECD 2004). This follows from a set of background and contributed papers that review the state-of-the-art (available on their web site, in the process of publication; see http://www.oecd.org/document/).

Many potential impacts of climate change have yet to be included into the models used for estimating the marginal damage costs of carbon dioxide. These include recreation, tourism, amenity, urban infrastructure, many diseases, river floods, and storms. The reason for exclusion is that too little is known about these impacts to come up with a credible, global and regionally specific estimates of impacts. (In some cases, this knowledge is now emerging, and the reason for exclusion is the time-lag between primary impact study and comprehensive economic impact assessment.)

Even if too little is known about the impact for inclusion in marginal damage cost estimates, knowledge may suffice for a “bounding exercise”. In a bounding exercise, one makes rough calculations of the minimum and maximum damages, and compares these to the estimated damages to arrive at a rough estimate of the error introduced. Minimum damage estimates are as necessary as maximum damage estimates, because some impacts may be beneficial.

As a simple illustration of a bounding exercise, consider the following. Dorland *et al.* (1999) report that a 6% increase in the average wind speed, not inconceivable in Northwest Europe in 2050, would increase average wind storm damage by 300 to 500%. In the Netherlands, the hundred-year storm (Daria in 1990) did damage of about 0.5% of GDP. The average damage is then about 0.01% of GDP, accounting for other than the one-in-a-100-year storm. If we multiply this with a factor 5, then the damage done by climate change is 0.05% of GDP. If we assume that the Netherlands is representative for temperate countries, then we find that excluding extra tropical storms from the impact analysis leads to a small underestimate of total damages; if we use a total damage impact of 1%, then the error is 5%. In fact, the Netherlands is not representative, because it is on the coast and densely populated; real damages are smaller, and the underestimate due to excluding storm damages is therefore also likely to be smaller than 5%.

This is only an illustration of how a ‘thought experiment’ could be used to test a range of input assumptions and their potential effect on economic valuations of the impacts of climate change.

Bounding exercises should be a standard part of regional and sectoral studies, conducted by the experts involved in the assessment. This at least provides a simple approach that complements full economic valuations and can be readily scaled up to the global level to underpin the global estimates of the social cost of carbon.

6.2 Revisiting the SCC, and using avoided damages in global negotiations to set policy targets, will require substantial research in partnership with scientists and policy makers in developing countries.

Expanding research on the social cost of carbon will require international collaboration, not least to validate regional and sectoral results at a higher resolution than captured by global models. Previous estimates of the SCC have met with great scepticism by many scientists; further refinement of models in Europe (or other developed countries) is unlikely to gain acceptance for policy making without the hard work of validating estimates at the regional and sectoral level with specialists and stakeholders in each region.

7 Conclusion

This report has reviewed the current range of estimates of the social cost of carbon against a risk matrix of the uncertainty in climate change and confidence in economic valuation. Table 9 repeats the key messages from the preceding chapters.

Drawing upon these messages, five conclusions are salient. First, the risk matrix is a useful reference framework to ensure that estimates of the SCC are complete. The categories correspond to common typologies in climate science and economic valuation. The cells in the 3x3 matrix help organise and explain current methodologies and estimates. However, it is not clear whether the matrix could or should be used as a sampling frame for producing a new central estimate (and this has not been achieved in this report).

Second, the overwhelming concentration of estimates is in the first two cells—benchmarked to global projections of temperature increases (with the corollary of sea level rise) and market and non-market sectors. Most of the integrated assessment models, such as FUND and PAGE, are located in this cell. Therefore the range of estimates currently offered as the state-of-the-art is incomplete. However, it is not clear the extent to which this sampling bias necessarily leads to a systematic under-estimate of the SCC.

Third, there is strong evidence, based on peer reviewed literature, expert judgement and results from two global models, that the SCC is likely to exceed a policy-relevant benchmark of £35/tC. The underlying uncertainties preclude a consensus among researchers about a 'best guess' or 'upper bound'.

Fourth, planned developments will expand the 'frontier' of methods and estimates to include more sectors (particularly non-market sectors), incorporate additional aspects of climate change (bounded risks) and sensitivity to some economic assumptions (such as discount rates and risk aversion). Over the next five years or so, a greater pool of knowledge on the first 2x2 cells in the risk matrix should be apparent.

Fifth, addressing the greater uncertainties of systemic climate change and socially contingent impacts (as well as realistic adaptation) will not be developed quickly. A much wider range of methods is necessary, and bridging local and global scales is imperative. Based on the complete risk matrix, a full understanding of the social costs of carbon is unlikely in the next 10 years. Indeed, it is not clear that this scale of effort is in place at present.

Integration of estimates of the SCC into stakeholder decision frameworks offers opportunities to interpret the boundaries of the SCC according to the values of different stakeholders and decision contexts. However, further research on the utility of approaches is required. The methodological implications of a hierarchy of estimates, corresponding to the scale of decision making, and similarly the use of multiple indicators of concern, should be identified at an early stage.

Some ideas of a research strategy have begun to emerge. A dual track approach is warranted: with a balance between furthering the robustness of economic estimates in the left half of the risk matrix and exploration of complementary methods for understanding the socially significant risks of the lower right half of the matrix. Underpinning both is a consistent approach to expert elicitation and grounding of estimates in regional assessments of dynamic vulnerabilities and adaptive capacity.

Table 9. Key messages

Our understanding of future climatic risks, spanning trends and surprises in the climate system, exposure to impacts, and adaptive capacity, is improving, but knowledge of the cost of climate change impacts is still poor.
The lack of adequate sectoral studies and understanding of local to regional interactions precludes establishing a central estimate of the social cost of carbon with any confidence.
The balance of benefits and damages in the social cost of carbon shifts markedly over time, with net damages increasing in later time periods. Estimates of the SCC are particularly sensitive to the choice of discount rates and the temporal profile of net damages.
Vulnerability and adaptation to climate change impacts are dynamic processes responding to climatic signals, multiple stresses, and interactions among actors. Large scale impacts, such as migration, can be triggered by relatively modest climate changes in vulnerable regions.
Climate uncertainties and the climate sensitivity are key factors in larger estimates of the SCC.
Uncertainties in coverage, sectoral assessments and regional processes are likely to be significant, but are difficult to judge without further model development and inter-model comparison.
Decision variables such as the discount rate and equity weighting also are extremely important.
Estimates of the social cost of carbon span at least three orders of magnitude, from 0 to over 1000 £/tC, reflecting uncertainties in climate and impacts, coverage of sectors and extremes, and choices of decision variables.
A lower benchmark of 35 £/tC is reasonable for a global decision context committed to reducing the threat of dangerous climate change and includes a modest level of aversion to extreme risks, relatively low discount rates and equity weighting.
An upper benchmark of the SCC for global policy contexts is more difficult to deduce from the present state-of-the-art, but the risk of higher values for the social cost of carbon is significant.
Substantive improvement in estimates of the social cost of carbon require well validated assessments at the regional scale that value the dynamic processes of vulnerability and adaptation.
Revisiting the SCC, and using avoided damages in global negotiations to set policy targets, will require substantial research in partnership with scientists and policy makers in developing countries.

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Annexes

1. Description of integrated assessment models FUND and PAGE
2. Sensitivity of the SCC to extreme events, equity weighting, discounting, and risk and ambiguity aversion
3. Understanding uncertainty through expert knowledge
4. Regional studies of dynamic and multiple stresses

Social Cost of Carbon: A Closer Look at Uncertainty

Annex: Description of integrated assessment models FUND and PAGE

FUND

The FUND model

This annex describes the FUND model (based on Tol and Dowlatabadi 2001), the enhancements undertaken recently and for this project, and an overview of the results (providing further details to the summary in the main report.

The FUND model is specified with different geographic resolutions for socioeconomic and physical aspects. The socio-economic components are aggregated into major world-regions, nine originally, subsequently expanded to 16 regions (see table below). FUND simulations run from 1950 to 2200, in annual time steps. The IMAGE database of population, income, energy-use and emissions (Batjes and Goldewijk, 1994) is the basis for the calibration of the model to the period 1950–1990. FUND's base scenarios of demographic and economic change are derived from the EMF Standardised Scenario. In addition, a library of alternative scenarios is available, permitting examination of alternative scenarios specified by the IPCC (Leggett et al., 1992). The sectors covered are shown in the table below.

The atmospheric physics and climate change simulations of FUND are simulated globally. Emissions of carbon dioxide are tied to economic activity and policy. Emissions of other key greenhouse gases are assumed to follow exogenous scenarios. The atmospheric concentration of carbon dioxide is calculated from emissions using a five-box model originally developed by Maier-Reimer and Hasselmann (1987) and parameterized by Hammitt et al. (1992). Thus, 13% of total emissions remains forever in the atmosphere, while 10% on average is removed in two years. Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine et al. (1990). The global mean temperature *T* is governed by a geometric build-up to its equilibrium (determined by radiative forcing *RF*), with an equilibration time-constant of 50 years. In the base case, equilibrium global mean temperature rises by 2.5.C for a doubling of carbon dioxide equivalents. The equilibration time-constant is calibrated to the best guess temperature for the IS92a scenario of Kattenberg et al. (1996). Thus, the global temperature conforms to:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t \quad \textbf{(1)}$$

Like many models, FUND constantly evolves, as new analyses are undertaken and new data and studies are incorporated. The original ExternE estimates were based on FUND, version 1.6 (Eyre et al., 1999); the later ExternE studies used version 2.0 (Tol and Downing, 2000); the GreenSense project used version 2.4 (Tol and Heinzow, 2003). At the moment, version 2.8 is the latest.

Version 2.0 is radically different from version 1.6. Version 1.6 is based on the older climate change impact studies, which emphasized the negative impacts of climate change and paid little attention to adaptation. Version 2.0 is based on newer climate change impacts, also including potentially positive impacts and reflecting adaptation a bit better. Furthermore, the impacts module of version 2.0 is based on global impact studies, minimising the extrapolation uncertainties. Also, version 2.0 has a dynamic representation of vulnerability, so that some sectors grow more vulnerable over time (e.g., heat stress with aging) while others grow less vulnerable (e.g., infectious diseases with economic growth).

The differences between version 2.4 and version 2.0 are minor. Particularly, human morbidity was added for the mortalities already included (cardiovascular, respiratory, malaria, dengue fever, schistosomiasis). Furthermore, the scarcity value of biodiversity was added. The effects on marginal damage costs estimates of these changes are small.

Version 2.8 has more changes. First, 16 instead of 9 regions are modelled, separating North Africa from Sub-Saharan Africa and adding Small Island States as a separate region. Second, CO_2 fertilisation is now separated from climate change in agriculture and forestry. Third, the relationship between development and infectious diseases was changed from a linear to a more realistic exponential relationship, so that these diseases expand further into the future and further into temperate zone. Fourth, diarrhoea was added. Fifth, the horizon of the model is now 2300. The effect on marginal damages costs of these changes, particularly the inclusion of diarrhoea, is substantial.

Version 2.8 is now running in Delphi, allowing full sensitivity testing of the model and making updates somewhat easier. It includes five alternative scenarios (FUND, and SRES A1, A2, B1 and B2). The Weitzman and Green Book and Gollier accounting methods for discounting have been implemented. New routines have been added for equity weighting and analyses of risk and ambiguity aversion and extreme impacts have been undertaken. Added flexibility allows exporting of results to an Excel pivot table by region, sector and time horizon.

The planned developments in FUND depend on resources and demands from users. A global vulnerability assessment for sea level rise from 1m to 10m is underway (as part of the EC Atlantis and DynaCoast projects). Further analysis of regional-sectoral results and comparison with higher resolution assessments would be desirable. A decomposition of the results, using multi-variate statistics to examine the relative influence of each variable on the results would assist in validating the model results.

Results from the current FUND model

The FUND model can be run in several modes. Here we present:

- The reference result based on the central estimate for each parameter and only one simulation of the model. This is often called the ‘best guess’ run, which is accurate only in that the values of the parameters are the values most commonly associated as the best guess by experts (e.g., a climate sensitivity of 2.5 ° C). However, the non-linearities in the model are such that a single run with such parameters need not equate to the ‘best guess’ estimate of the SCC.
- Results from a Monte Carlo sampling of the plausible range of values for all of the parameters. This results in 1000 simulations. Some of these runs produce quite large (and small, i.e. negative) values. Where these extreme values appear to be singularities they have been removed from the results. That is, if a value is for example $100,000 /tC and the next nearest value is $50,000 /tC we assume that the extreme value is due to some combination of parameters that is implausible or at least unlikely. Note that this filtering does not remove values that are still quite large—several times the upper value of the range proposed by Defra (£140/tC) and thus the filtering does not have direct consequences for our conclusions. For the full range of results we present the results in several ways. Most useful is the quartiles (minimum, lower 25%, median or 50%, upper 25% and maximum) as these convey a sense of the distribution of the results. We also show the average and standard deviation, although these are greatly influenced by the extreme values (even after filtering).

Annex Table 1, Annex Table 2 and Annex Table 3 present the statistics from the FUND model runs (see the box below for a note on measures of central tendency). The first table shows the quartiles for the four discounting schemes, with and without equity weighting. The extremes are a minimum of £8000 /tC with PRTP=0% (that is, discounting only by the growth rate) and equity weighting and a maximum of £10,000 with the same discounting and equity weighting. The lower quartile is negative for most of the discount/weighting schemes. Conversely, the upper quartile is quite large for most of the schemes with equity weighting (over £100/tC). There is considerable variation for the median (the 50% values) and upper quartile across the schemes—from about £0/tC to £500/tC for the Green Book and PRTP 1% and 3% schemes. This suggests that the distribution of results is quite sensitive to several policy choices.

The second table confirms this conclusion, with standard deviations that are several times the average, and averages that are several times the median or reference estimates. The third table shows the effects of trimming the tails of the distributions.

Also apparent are the strong effects of equity weighting and discounting. However, these effects are not uniform across the distributions. For example, equity weighting is an order of magnitude effect for the median (e.g., PRTP=0% £500/tC to £50/tC), but makes little different for the minimums and maximums. Similarly, there is a very large difference between PRTP=0% vs PRTP=3% (e.g., 5 orders of magnitude for the median with equity weighting) but relatively little different for the extremes. Thus, it may not be possible to calculate a range of the SCC and simply adjust is by factors concerning discounting, equity weighting and similar decision parameters.

The distribution of FUND results can be presented as probability distributions (Annex Figure 1). As expected, with PRTP=0% and equity weighting the SCC reaches the highest levels. The PRTP=3% and Green book schemes result in relatively lower values.

Time series for the sectoral results from FUND are shown in Annex Figure 2. Several of the sectors reported by FUND have been aggregated in these charts:

- Agriculture and forests: both show early benefits from climate change (the spike of negative values for the first few decades).
- Water and species are shown separately, with fairly modest impacts.
- Coastal impacts include loss of dryland or wetland, immigration and emigration forced by rising sea levels, and the cost of coastal protection where it is cost-effective; these impacts are quite small in FUND.
- Health is the combination of morbidity (due to various diseases) and mortality, with significant impacts in early decades.
- Heating and cooling is the net impact of increased or reduced requirements for indoor heating and cooling, with a strong impact that dominates the total SCC.

Time series for regional results from FUND are shown in Annex Figure 3. The 16 regions included in FUND have been aggregated to illustrate the regional time profiles:

- Europe, including the Former Soviet Union, have small gains in the early decades but substantial losses in all of the schemes, although these are relatively less significant with equity weighting.
- Africa and the Middle East suffer adverse impacts in all schemes, and these dominate the losses in FUND with equity weighting.
- South Asia, shown on its own, has considerable benefits with equity weighting (assuming the weights apply equally to benefits as well as losses) but relatively minor losses without equity weighting.
- Southeast Asia and China consistently show large benefits from climate change in the early decades, but switching to significant losses toward the middle of the Century.

- The Pacific covers Australia & New Zealand, Japan & Korea and the Small Island States. Without equity weighting this regions shows early benefits, but relatively minor losses when equity weighting is included.
- Latin America (Central America and South America) follow the pattern of small benefits in early decades, but with relatively minor impacts.
- The combined USA and Canada follow the pattern of small benefits in early decades, with somewhat larger impacts than in Latin America in subsequent years without equity weighting.

The main report provides further discussion of the FUND results and their interpretation.

Measures of central tendency

Defining a central value in a data set with a large number of outliers is difficult. The usual measure, the arithmetic mean or average, is a measure of the central tendency of the data. That is, it is a prediction of the expected central value. However, the data may not be drawn from a single population and the average is sensitive to the tails of the distribution. For the full suite of FUND results, there are a considerable number of extreme values. Some are likely to be anomalies in the model and are outliers—these have been filtered from the results presented here. However, extreme values remain that are possibly conditions in which the impacts of climate change are no longer marginal to the projected economy. That is, the impacts have affected economic growth and resulted in large scale changes to regional economies. In such situations, it is not possible to a priori define the best measure of the central tendency of the data set.

The distribution of the data is captured in the median and quartiles: The minimum, maximum, and three quartiles (lower 25%, median or 50% and upper 25%) are derived from the ordered data set. The median is the value for which 50% of the data are larger.

The conventional measure of the arithmetic average or mean, the sum of all of the values divided by the number of values, appears to be overly biased by the extreme values, as marked by the large standard deviations.

Two measures of the central tendency of the middle range of values are used. The trimmed mean is the arithmetic average for values in the middle of the distribution, in our case discarding the first and last 5% of the values. The interquartile mean is similar, the average of values between the lower and upper quartiles.

For formulas on these measures, see: http://www.xycoon.com/index.htm.

Annex Table 1. Summary of FUND results, GBP2000 /tC quartiles

	Minimum		Lower 25%		Median		Upper 25%		Maximum	
	EW	No EW	EW	No EW	EW	No EW	EW	No EW	EW	No EW
Green Book	-£2,182	-£2,199	-£10	-£11	£19	£9	£74	£47	£4,155	£2,072
PRTP=0%	-£8,172	-£3,256	£55	-£7	£547	£46	£1,365	£160	£4,996	£7,745
PRTP=1%	-£5,848	-£2,310	-£33	-£11	£158	£7	£520	£46	£10,845	£3,345
PRTP=3%	-£3,490	-£2,328	-£65	-£10	£1	-£3	£109	£7	£4,062	£2,383

Annex Table 2. Summary of FUND results, GBP2000 /tC reference, averages and standard deviation

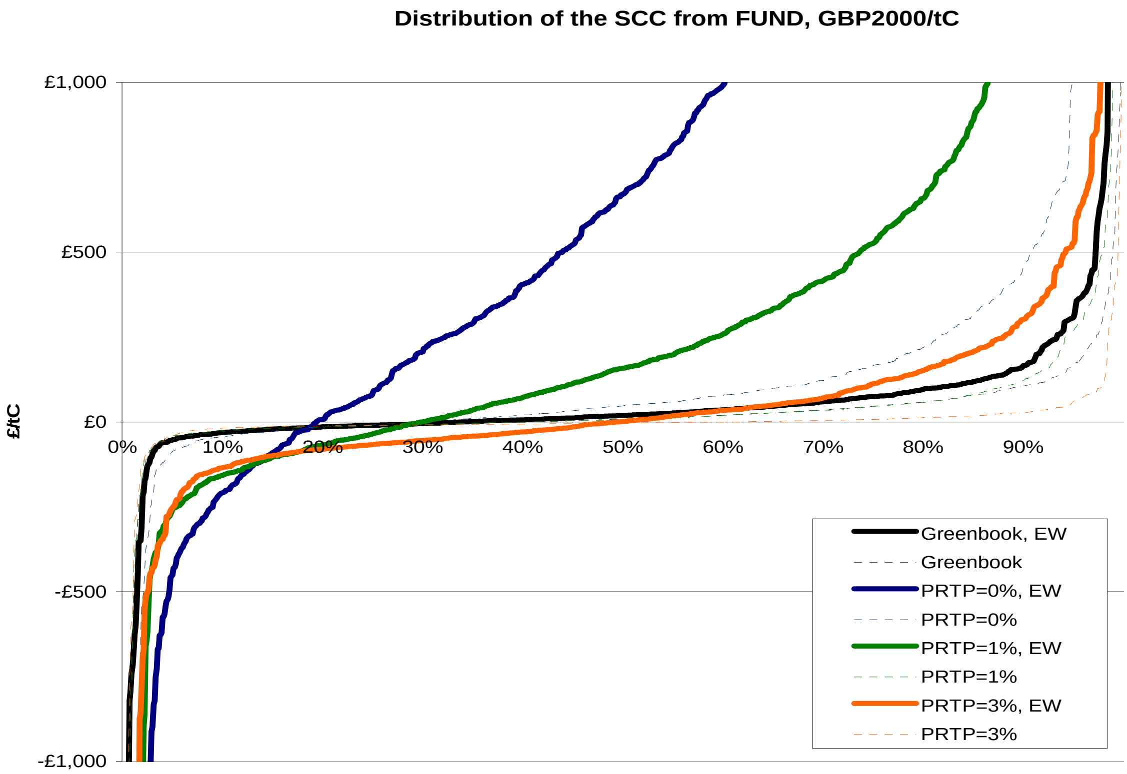
	Reference		Average		Standard deviation	
	EW	No EW	EW	No EW	EW	No EW
Green Book	£20	£19	£63	£24	£314	£165
PRTP=0%	£728	£56	£815	£171	£1,375	£671
PRTP=1%	£174	£11	£429	£43	£1,221	£240
PRTP=3%	-£1	-£2	£40	-£1	£434	£165

Table notes: EW = Equity weighting based on per capita income; No EW = no equity weighting
Median is the 50% value. Reference is the single run with 'best guess' of FUND parameters. Average is the arithmetic average (or median).

Annex Table 3. Summary of FUND results, GBP2000 /tC reference, trimmed and inter-quartile means

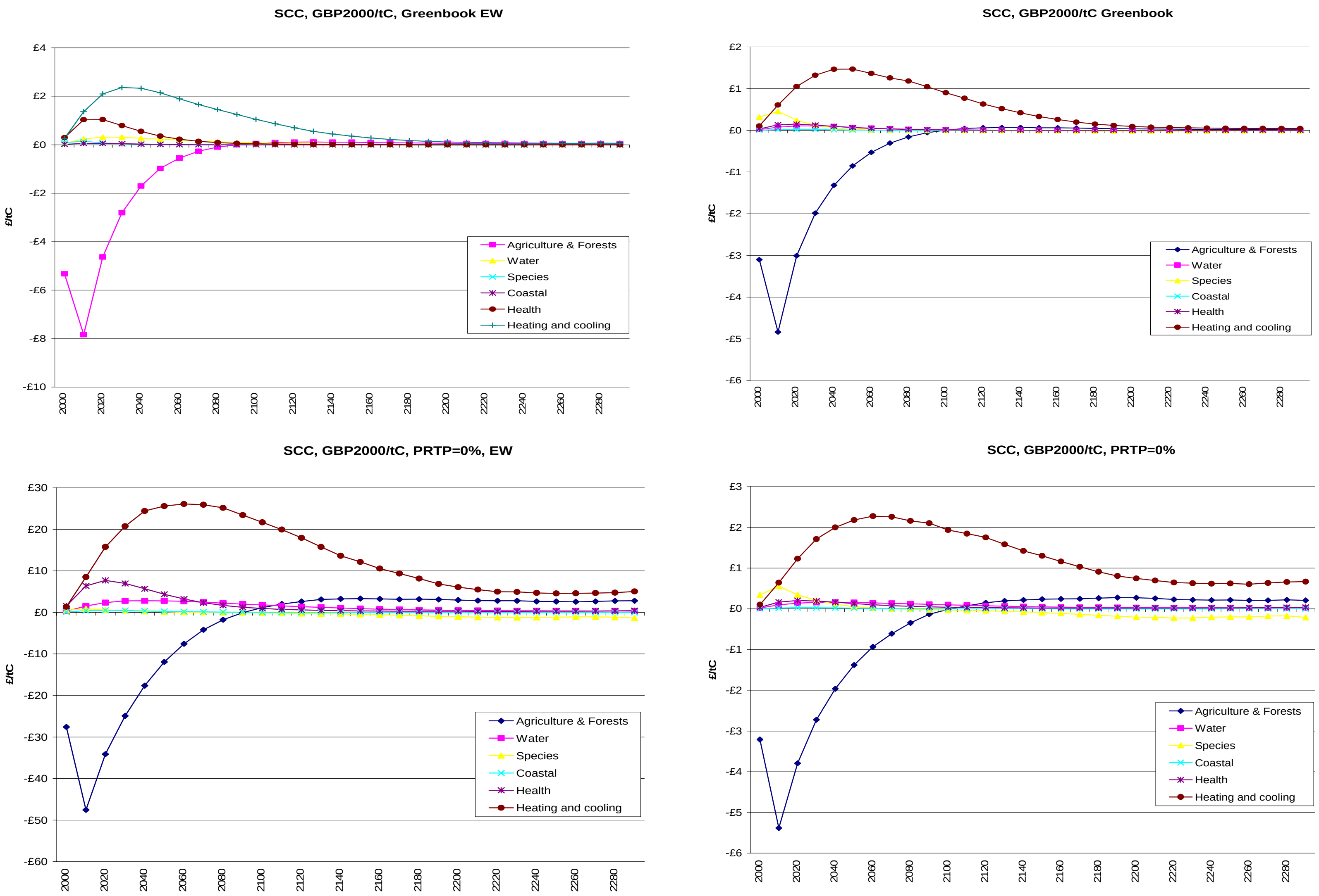
	Reference		Trimmean(10%)		Trimmean(20%)		IQMean	
	EW	No EW	EW	No EW	EW	No EW	EW	No EW
Green Book	£20	£19	£38	£20	£31	£17	£23	£11
PRTP=0%	£728	£56	£785	£98	£713	£79	£601	£54
PRTP=1%	£174	£11	£294	£24	£244	£17	£182	£10
PRTP=3%	-£1	-£2	£30	£0	£20	-£1	£5	£5

Table notes: EW = Equity weighting based on per capita income; No EW = no equity weighting
Median is the 50% value. Reference is the single run with 'best guess' of FUND parameters. Average is the arithmetic average (or median). The trimmean discards the first and last 5% of the values. The IQMean is the average of the values between the lower and upper quartiles for each discounting-equity weighting scheme.

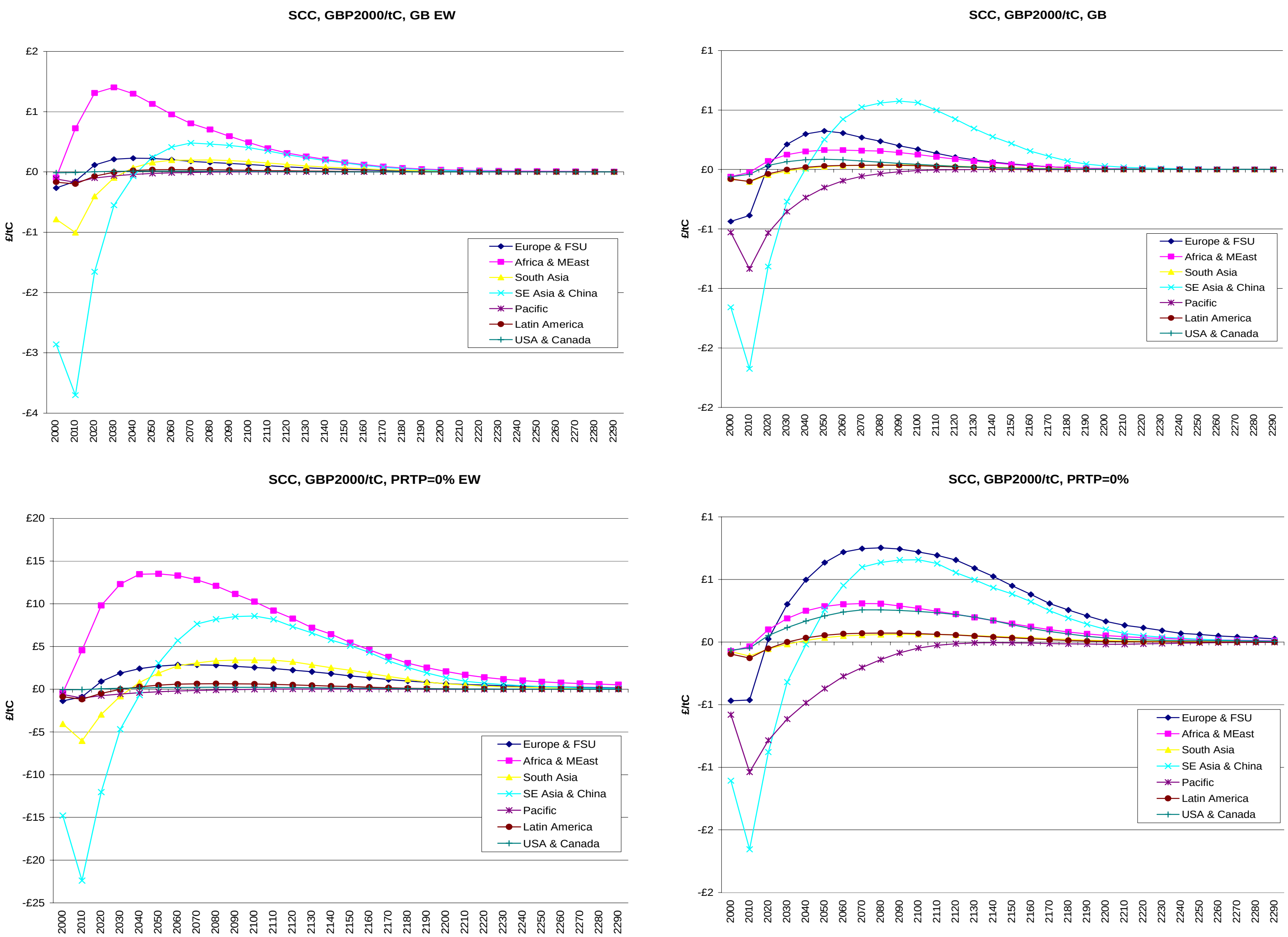


Annex Figure 1. Distribution of results from FUND, GBP2000/tC

The four discounting schemes, with and without equity weighting, are shown for the suite of simulations. 1000 simulations were run for each combination; the extreme values have been removed from the data set shown here. For graphical presentation, values less than £-1000/tC or greater than £1000/tC are not shown. Note that the x-axis is converted to the cumulative probability for the entire data set (before the extreme values have been removed) and this produces a slight difference compared to the calculated parameters (e.g., the upper quartile).



Annex Figure 2. Sectoral time profiles of the SCC from FUND for two discounting schemes, with and without equity weighting



Annex Figure 3. Regional time profiles of the SCC from FUND for two discounting schemes, with and without equity weighting

Annex Table 4. FUND sectors

Sector	Description
Agriculture	Impacts are positive or negative depending upon whether regional T is moving closer or further away from the climate optimum (influenced by plant physiology and farmer behaviour) with adaptation explicitly modelled
Cooling	Energy costs due to cooling—i.e. air conditioning
Death	People can die prematurely due to temperature stress (cardiovascular and respiratory disorders related to heat and cold stress) or due to vector-borne diseases (malaria, dengue fever, schistosomiasis, diarrhoea); VSL (value of a statistical life) set to be 200 times the annual per capita income in the region
Dryland	Losses of dryland due to sea level rise without defences; value assumed to be proportional to GDP per square km
Emigration	Losses experienced by individuals displaced by sea level rise; set to three times per capita income
Forests	Damages and benefits incurred by the forestry sector due to rising temperatures
Heating	Energy heating costs incurred or saved by T variation
Immigration	Costs of settling immigrants displaced by sea level rise; immigrants are assumed to assimilate after a short time and to no longer 'cost' the host government; costs set to 40% of per capita income in the host country
Morbidity	Damages due to individuals with ill health from heat related stress (cardiovascular or respiratory disease) or vector-borne diseases (malaria, dengue fever, schistosomiasis, diarrhoea)
Sea rise protection	Response costs incurred in building sea rise defences; the decision to protect wetlands and dryland from sea level rise is made annually; increasing amounts are protected as the economy grows
Species	Impacts on species (unmanaged ecosystems) are modelled as a simple power function and are assumed to be negative with increasing temperatures; value is determined relative to per capita income on a 'warm glow' basis (i.e. that actual amounts lost are irrelevant, but the fact that something is lost is relevant—thus this is a measure of the non-use value of biodiversity to individuals and not an attempt to value any loss of ecosystem services)
Water	Impacts on water resources (with changing availability and demand) are modelled as a simple power function and are assumed to be negative with increasing temperatures
Wetlands	Losses of wetlands due to sea level rise where no defences built; value assumed to have a logistic relationship to per capita income

Annex Table 5. Regions in FUND

Acronym	Name	Countries
ANZ	Australia and New Zealand	Australia, New Zealand
CAM	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
CAN	Canada	Canada
CEE	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, FRY Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia
CHI	China plus	China, Hong Kong, North Korea, Macau, Mongolia
FSU	Former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
JPK	Japan and South Korea	Japan, South Korea
MDE	Middle East	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, West Bank and Gaza, Yemen
NAF	North Africa	Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara
SAM	South America	Argentina, Bolivia, Brazil, Chile, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
SEA	Southeast Asia	Brunei, Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan, Thailand, Vietnam
SIS	Small Island States	Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, Comoros, Cuba, Dominica, Dominican Republic, Fiji, French Polynesia, Grenada, Guadeloupe, Haiti, Jamaica, Kiribati, Maldives, Marshall Islands, Martinique, Mauritius, Micronesia, Nauru, Netherlands Antilles, New Caledonia, Palau, Puerto Rico, Reunion, Samoa, Sao Tome and Principe, Seychelles, Solomon Islands, St Kitts and Nevis, St Lucia, St Vincent and Grenadines, Tonga, Trinidad and Tobago, Tuvalu, Vanuatu, Virgin Islands
SSA	Sub-Sarahan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo-Brazzaville, Congo-Kinshasa, Cote d'Ivoire, Djibouti, Equatorial guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
USA	USA	United States of America
WEU	Western Europe	Andorra, Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom

The PAGE2002 model

PAGE2002 is an updated version of the PAGE95 integrated assessment model (Plambeck, Hope and Anderson, 1997, Plambeck and Hope, 1995 and Plambeck and Hope, 1996). The main structural changes in PAGE2002 are the introduction of a third greenhouse gas and the incorporation of possible future large-scale discontinuities into the impact calculations of the model (IPCC, 2001a, p5). Default parameter values have also been updated to reflect changes since the IPCC Second Assessment Report in 1995.

PAGE2002 contains equations that model:

- Emissions of the primary greenhouse gases, CO2 and methane, and a third gas, SF6 in this investigation. PAGE2002 models other greenhouse gases such as N_2O and (H)CFCs as a time-varying addition to background radiative forcing.
- The greenhouse effect. Anthropogenic emissions of greenhouse gases exceed the rate of removal by chemical and biological processes and accumulate in the atmosphere. The greenhouse gases trap heat in the atmosphere so that less of the incoming solar radiation is re-radiated to space. This increases radiative forcing, the net flux of energy to Earth. The Earth's temperature rises slowly as excess heat is transferred from the atmosphere to land and ocean.
- Cooling from sulphate aerosols. Sulphate aerosols result from fossil fuel combustion and are commonly known as the cause of acid rain. They also backscatter incoming solar radiation and interfere with cloud formation, producing a direct and indirect reduction in radiative forcing. This counteracts the greenhouse effect.
- Regional temperature effects. Unlike greenhouse gases which remain in the atmosphere for decades and are globally mixed, sulphate aerosols have a very short atmospheric lifetime (about 6 days) and so tend to remain in the source region. Therefore sulphate aerosol cooling is a regional phenomenon. For the eight world regions in PAGE2002 (EU, Eastern Europe and FSU, USA, India, Africa, Latin America, China and OECD), temperature rise is computed from the difference between global warming and regional sulphate aerosol cooling. Sulphate cooling is greatest in the more industrialised regions, and tends to decrease over time due to sulphur controls to prevent acid rain and negative health effects.
- Nonlinearity and transience in the damage caused by global warming. Climatic change impacts in each analysis year are a polynomial function of the regional temperature increase in that year above a time-varying tolerable level of temperature change, $(T\text{-}T_{tol})^n$, where n is an uncertain input parameter. If the temperature rises beyond another threshold, there is a chance that a large-scale climate discontinuity will occur with very serious effects; the more the temperature rises beyond the threshold, the larger the chance of the discontinuity occurring. The parameters to allow for large scale discontinuities are taken from the IPCC. The tolerable level of global warming before a discontinuity could occur is 5°C (with a minimum and maximum of 2 to 8°). The probability of a discontinuity is 10.33$ (range of 1% to 20%). The loss if a discontinuity occurs in the EU is 11.66% of GDP (range of 5% to 20%.
- Regional economic growth. Impacts are evaluated in terms of an annual percentage loss of GDP in each region, for a maximum of two sectors- in this application defined as economic impacts and non-economic (environmental and social) impacts.
- Adaptation to climate change. Investment in adaptive measures (e.g. the building of sea walls; development of drought resistant crops) can increase the tolerable level of temperature change (T_{tol}) before economic losses occur and also reduce the intensity of both noneconomic and economic impacts.

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, as shown below, and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing 31 key inputs to the marginal impact calculations by probability distributions.

The full set of equations and default parameter values in PAGE2002 are given in Hope, 2004. Most parameter values are taken directly from the IPCC Third Assessment Report (IPCC, 2001b).

There is an on-going process of improvements to PAGE including:

- The incorporation of better information about all the uncertain parameters in the model, particularly climate sensitivities, discount rates, economic and non-economic impacts, and costs of abatement.
- The ability to optimise emission cutbacks across regions to minimise the costs of meeting a given abatement target, and to minimise the sum of impacts and abatement costs.
- Reporting of the full suite of SRES scenarios and calculation of the optimal level of emissions (balancing impacts, adaptation and mitigation). The model would then be used to superimpose a unit drop in emissions and calculate the social cost of carbon at the optimum.

Social Cost of Carbon: A Closer Look at Uncertainty

Annex: Sensitivity of the SCC to extreme events, equity weighting, discounting, and risk and ambiguity aversion

MSc Theses by David Anthoff, Megan Ceronsky, Jiehan Guo and Ada Li, supervised by Cameron Hepburn, University of Oxford

The four theses investigated the sensitivity of estimates of the social cost of carbon to: (1) extreme events, (2) equity weighting, (3) discounting and (4) risk and ambiguity aversion. The research on extreme events explored the sensitivity of estimates to different scientific forecasts, while research in the other three areas largely analysed the sensitivity to different parameters encapsulating ethical or value judgements. These parameters — such as the choice of equity weights, the utility discount rate, the coefficient of risk aversion, and the coefficient of ambiguity aversion — do not have a "correct" value, although aggregate market data can provide some indication of values employed by individuals. In the final analysis, however, they must be chosen by the government, representing citizens at large.

This annex presents a synopsis of the results, followed by the abstracts of the theses. Further articles are in preparation and the theses can be found on Cameron Hepburn's personal web page: www.economics.ox.ac.uk/members/cameron.hepburn/.

Note that the MSc students spent considerable effort with Richard Tol in revising Fund. The results presented here are from the version of July 2004. Fund reports values in USD1995, using 2000 as the baseline for discounting. These values have been converted to GBP using a conversion factor of USD 1.6 = GBP 1. The main report of the assessment uses a slightly higher conversion (1.7) that includes an update from USD1995 to USD2000. The main report also includes results from a later version of Fund, with runs conducted in November 2004. The main thread of the MSc conclusions are likely to be similar in the new runs.

Overview of results

The overarching conclusion from these theses is that estimates of the social cost of carbon are very sensitive to both the scientific forecasts employed and the corresponding ethical inputs. However, behind this overall conclusion are some interesting specific results — the social cost of carbon is far more sensitive to some parameters than others.

The thesis on extreme events (see abstract below) examined the effect of (1) high climate sensitivity; (2) thermohaline circulation (THC) shutdown; and (3) marine methane destabilisation. The primary conclusion is that the social cost of carbon is extremely sensitive to the climate sensitivity parameter, and far less sensitive to marine methane destabilisation or THC shutdown. Assuming a risk-neutrality and discounting according to the HM Treasury (2003) Green Book, the mean estimate from FUND for four different climate sensitivities are as shown in table below. Corresponding probability density functions are shown in the following figure.

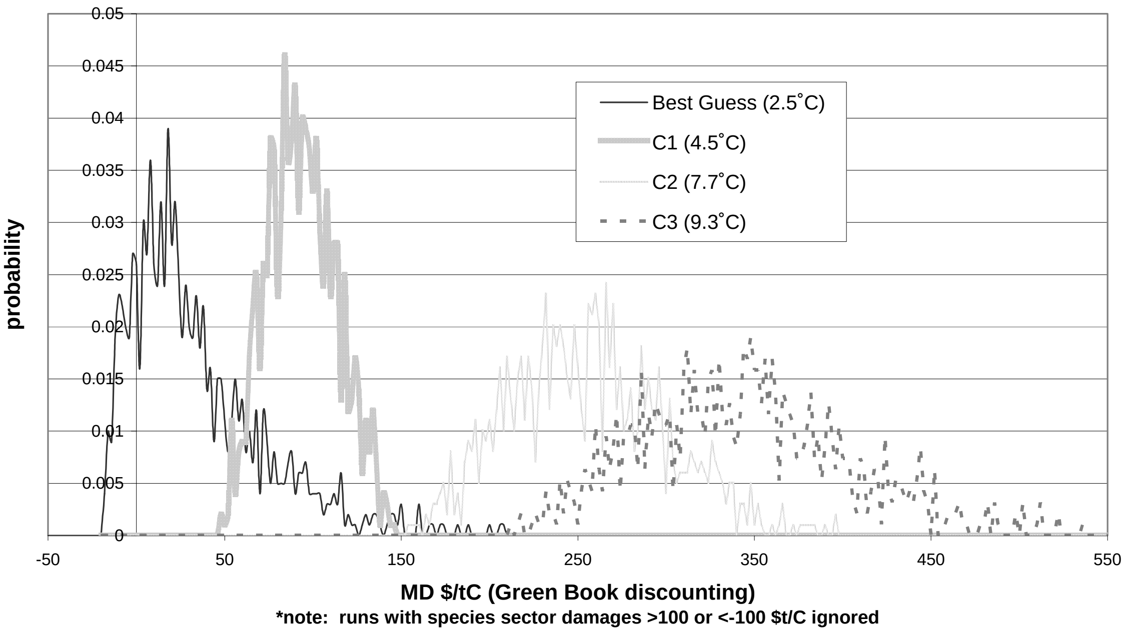
Annex Table 6. Results for different climate sensitivities with Green Book discounting

Climate Sensitivity	Social Cost of Carbon (mean estimate)
2.5°C (base case)	£11/tC (1995$ 18/tC)
4.5°C	£63/tC (1995$ 100/tC)
7.7°C	£170/tC (1995$ 270/tC)
9.3°C	£230/tC (1995$ 360/tC)

For reference, note that 4.5°C is at the upper end of the IPCC (2001) range. Furthermore, although a sensitivity of 9.3°C is extremely high, even this value is within ranges found in the peer-reviewed literature. However, the high climate sensitivities are well outside the FUND model's calibration domain, so the estimates in the table above are inevitably inaccurate, although whether they are over- or under-estimates is not clear.

Analysis on the THC indicated that a shutdown would have very little impact on the social cost of carbon. This is perhaps because a shutdown would have a cooling effect in an otherwise warming world. If accurate, this result suggests that the focus on this impact of climate change is unwarranted. Nevertheless questions remain about the validity of this result given that some of the possible impacts from a THC shutdown are not modelled by FUND.

Analysis from marine methane destabilisation indicated that a very significant extra methane release of 8670 Mt/yr would increase the SCC from £11/tC to £19/tC. Although this result is not derived from an explicit model of a runaway methane release, note that 8670 Mt/yr is an extremely high annual release rate, at the upper end of possible fluxes suggested in the literature.



Annex Figure 4. Results for different climate sensitivities with Green Book discounting

The thesis on equity weighting shows that whether we take into account the fact that a pound is worth more to the rich than to the poor has a significant impact on the social cost of carbon. The impacts of climate change will occur all over the world in regions that are both very rich and very poor. Given that some of the worst impacts may be in poor countries, it is perhaps not surprising that the social cost of carbon is sensitive to equity weighting. The table below presents the results, where the degree of equity weighting is expressed by reference to the parameter μ, which is the elasticity of marginal utility. A higher μ implies a higher aversion to inequality.

Annex Table 7. Results for different equity weighting with PRTP = 1%

Equity Weighting	Social Cost of Carbon
None (μ= 0)	£9/tC (1995$ 11/tC)
μ= 1, calibrated to world income	£26/tC (1995$ 41/tC)
μ= 1, calibrated to EU income	£120/tC (1995$ 200/tC)
μ= 1, calibrated to African income	£2/tC (1995$ 3/tC)

This thesis also serves as a reminder of the importance of the calibration process. The table shows the clear difference between calibration to world average incomes and calibration to European incomes. Frequently, the literature has employed world average income values for comparison with mitigation costs in Europe. However, only values calibrated at EU incomes are useful for policy making in Europe — like must be compared with like.

The thesis on discounting applied recent theoretical advances in discounting which have focussed upon the implications of uncertain and heterogeneous discount rates. Five different declining discount rate schemes were implemented in FUND to determine the impact on the social cost of carbon. Four are reported below. In addition to Green Book discounting, the approach proposed by Weitzman (2001) was examined, showing that his recommended scheme significantly increases the social cost of carbon. This is because Weitzman's proposed schedule of discount rates declines more rapidly, and to a lower level, than the Green Book schedule. The third row of the table shows, as a baseline, results for the social cost of carbon with a constant 1% utility discount rates (PRTP), where the corresponding consumption discount rate results from a particular forecast of future consumption growth. Row 4 examines the effect of assuming that this consumption growth rate is uncertain, as discussed by Gollier (2002). Accounting for this uncertainty can double the social cost of carbon. Finally, the thesis contains an extensive analysis of different discount rates in over 100 countries in order to analyse the impact of heterogeneity. However, because this analysis necessarily employs available market interest rate data, results are not comparable with results for social discount rates as reported in the following table.

Annex Table 8. Results for different discounting schemes

Discounting	**Social Cost of Carbon**
Green Book discounting	£11/tC (1995$ 18/tC)
Weitzman gamma discounting	£55/tC (1995$ 88/tC)
1% PRTP with growth forecast	£9/tC (1995$ 11/tC)
1% PRTP with uncertain growth	£9-18/tC (1995$ 15-29/tC)

Finally, a somewhat surprising result emerged from the thesis on risk and ambiguity aversion. One might have expected, and certainly it was our hypothesis, that given the uncertainty inherent in climate change impacts, the certainty-equivalent social cost of carbon would be particularly sensitive to risk and ambiguity aversion coefficients. Relative to results in the areas discussed above, however, this was not observed. Combined risk and ambiguity premiums were around 40%. Thus, *relative to the other factors outlined above*, the social cost of carbon is relatively insensitive to the coefficient of risk and ambiguity aversion.

There was some concern about whether the theoretical foundations for this research were secure — the theory on ambiguity aversion, in particular, is still in its infancy. Nevertheless, the resulting premiums, while relatively high, correspond approximately to premiums observed in the insurance industry. The conclusion from this thesis is that while risk and ambiguity do indeed matter, other factors matter even more.

Extreme events (Megan Ceronsky)

Climate change impacts research tends to focus on 'best guess' scenarios, producing damage estimates which ignore the potential for non-linear climate responses and very high damages. Such low-probability, high-risk events, however, are critically important for the policy which climate change impacts modelling aims to inform. This paper explores potential non-linear climate responses to anthropogenic greenhouse gas forcing and uses the FUND integrated assessment model to investigate the impact of three types of non-linear responses on estimates of marginal damage per ton carbon emitted. The results show that non-linear climate responses could be highly costly—20 times higher than the best guess damage estimates under the UK government's declining discount rate scheme and 40 times higher than the best guess under a low constant discount rate. This is evidence that marginal damage estimates based on "best guess" models cannot provide optimal emissions pathways and that the potential for "catastrophic" impacts should be taken into account by policy-makers. Further, the focus on thermohaline circulation changes in the catastrophic impacts literature seems unwarranted, as other potential non-linear climate responses such as high climate sensitivity (discussed here) and hydrologic changes (not yet modelled) could prove extremely costly.

Equity Weighting (David Anthoff)

Equity weighting enables fair comparison of monetary damages that accrue to regions with very different income levels. This is especially appropriate in the context of climate change where damages are likely to affect people with very diverse levels of wealth. This thesis makes both theoretical and practical contributions to the literature on climate change economics.

The theoretical foundation of equity weighting is advanced in two areas. Firstly, this thesis develops a new conceptual analysis of equity weighting that demonstrates the relationship between equity weighting and discounting. This new model also shows clearly that the way equity weighted results have been presented in the literature is open to misinterpretation and suggest a way of presenting equity weighted marginal damage figures that does not suffer from this problem. Secondly, the model for equity weighting is significantly enhanced when it is applied to aggregated damage figures for whole regions. An aggregation coefficient is derived that corrects errors that are introduced when regionally average data sets and scenarios are used.

All theoretical ideas have then been implemented in two leading impact assessment models (FUND and RICE) in order to test the magnitude of change these theoretical advances cause to the social cost of carbon figures. A significant amount of work was spent on improving FUND, not only in the area of equity weighting, but also in making in- and outputs more user friendly and implementing many other improvements to the model.

Results from modelling suggest that the effect equity weighting has on the social cost of carbon figures has been underestimated significantly in the literature. New, corrected, results are presented. At the same time, it is outlined why, in policy decision making, equity weighted numbers must be used differently than unweighted damage figures.

Discounting (Jiehan Guo)

This dissertation carries out a sophisticated sensitivity study on the impacts of declining discount rates on the social cost of carbon (SCC), an important number in the economic appraisal of climate change policies. Five declining discounting schemes are successfully implemented in the FUND 2.8 model. Combined with different assumptions of the pure rate of time preference, these five DDR schemes produce 10 estimates of the SCC number. Among them, the Gollier heterogeneous discounting scheme is, to the best of our knowledge, implemented for the first time in the literature. Without equity weighting, the percentages increase of SCC values ranges from 10% to 4100% and the value of SCC ranges from -£1.4/tC to £128/tC. Although this uncertainty range is large, most discounting schemes and combinations don't push up the number to the high level suggested by UK DEFRA (2002). The novel implementation of the Gollier heterogeneous discounting even suggests the possibility of negative SCC, although it also has to do with the damage profile in FUND. One of the major policy implications is that at the higher end of the values of SCC found here (although not all of them), many climate change related policies — such as the Kyoto Protocol — have no trouble passing a cost-benefit analysis.

Risk and Ambiguity Aversion (Ada Li)

The magnitude and probabilities of global warming consequences involve both risk and ambiguity. Consequences of global warming are risky because climate change may generate a variety of damage possibilities with different probabilities attached to them. Impacts of global warming are also ambiguous because the probabilities of the occurrences of events are imprecise. With risk and ambiguity surrounding a universal challenge of global warming, this thesis aims to give a realistic account of risk and ambiguity aversion in the estimation of the social cost of carbon (SCC) to reflect the level of risk and ambiguity society is willing to take based on our current knowledge.

This thesis studied the effect of risk and ambiguity aversion under different climate sensitivity, marine methane hydrate destabilisation and emission scenarios. It is found that in taking uncertainties of climate sensitivity into account, a risk premium of 0.8-23% of the expected SCC needs to be added to the social cost of carbon. Considering uncertainties in marine methane hydrate destabilisation, the SCC should increase by a risk premium of 0.1-6.4%. The uncertainties in emission scenarios also give a similar range of risk premium of 0.5-6.4%. When climate sensitivity, marine methane hydrate destabilisation and emission scenarios are taken into consideration altogether, it is shown that risk premium ranges from 1.4% to 22% and ambiguity premium varies between 2% and 34% of the SCC given our ranges of relative risk aversion and absolute ambiguity aversion.

Social Cost of Carbon: A Closer Look at Uncertainty

Annex: Understanding uncertainty through expert knowledge

Background and rationale

Our central framework is a risk assessment recognising two key dimensions of uncertainty--climate change science and economic valuation—along with choices of the decision framework. The geophysical and economic sciences are the subject of sophisticated and arcane methods, but neither is likely to be able to predict the social cost of carbon over the time and space scales of concern. In such a setting of deep uncertainty, risk assessment and (subjective) expert judgments are essential.

Formal techniques of expert judgment should be applied consistently and updated regularly. In the domain of climate change, solicitation of expert judgment has been largely ad hoc consultations (such as the repetitive filters of the IPCC) or based on Delphi protocols (for example in the ExternE and IEA GHG R&D study of the full fuel cycle).

While a risk assessment approach is powerful, there are readily apparent constraints in eliciting expert judgments (Annex Figure 5). For projections of climate change it is reasonably easy to envision a chain of impacts over a range of conditions, and these can be broadly quantified for market sectors. Extending the analysis to non-market sectors introduces more controversial valuation concepts (for example, willingness to pay (WTP) versus willingness to accept (WTA)). For more realistic climatic scenarios, the balance of the direction and magnitude of change introduces many plausible chains of impacts, which few experts will have significant experience of and possible sufficient mental capacity to process as a judgment. Even more fundamental problems of our personal experience, visions of the future, and value systems are apparent as the risks are extended to systemic climate change and socially contingent impacts.

Our approach has been to conduct a knowledge elicitation based on a wide range of experts and using formal techniques. A description of the general approach is found in the methodological briefing note on knowledge elicitation tools posted in the document hotel on www.VulnerabilityNet.org.

		Uncertainty in valuation		
		A. Market	**B. Non-market**	**C. Socially contingent**
Uncertainty in Climate Change	**1. Projection**	Consistent climate baseline Familiar impact categories, relatively large literature Some valuation techniques controversial		Context of elicitation and boundary of non-marginal changes No agreed economic indicators of impacts
	2. Bounded risks	Divergence in sign of climate change increases divergence in potential impacts		
	3. System change and surprise	Beyond present analogies or historical experience		

Annex Figure 5. Challenges in expert judgment

Drivers of uncertainty and elicitation protocol

The project team compiled a review of the literature that documented the major drivers of uncertainty in estimates of the social cost of carbon. From the long list, the team chose 9 factors that are salient and amenable to expert judgement. Choices of values for each of the 9 factors were compiled (Annex Table 9). This domain of factors and choices is the population from which scenarios of the context of the SCC were drawn.

The project team tested a pilot protocol, and refined the choices and factors based on principles of expert judgement and the practicality of interviewing experts.[12] The 8 factors were collected in an Excel spreadsheet. Although this was intended to be suitable for self-interviews, all of the experts were interviewed by Tom Downing, either in person or over the telephone.

The panel of experts to be interviewed was drawn from the wider list of experts compiled as an informal contact group by the project and Defra. The criteria for selection of experts to interview was their familiarity with the literature and range of estimates of the social cost of carbon. The core group to interview were those who had published original work in this field. Others who had reviewed the range of estimates and demonstrated some competence in the field were included. We were careful to include a range of those who had supported relatively large or small values. Fourteen experts were interviewed:

William Cline	Alan Ingham
Tom Downing	David Maddison
Sam Fankhauser	Anil Markandya
Michael Grubb	David Pearce
Cameron Hepburn	Joel Smith
Chris Hope	Richard Tol
Alistair Hunt	Paul Watkiss

Two were unable to respond to the protocol. Robert Mendelsohn uses a different metric for the SCC and this could not be readily converted to the marginal values used in the protocol. Paul Ekins was not willing to assign numeric values to the social cost of carbon, preferring to support a policy approach based on deliberative justice instead. In both cases, extensive notes were taken as the interviewer worked through the relevant comparisons. These have helped to interpret the results but are not part of the formal data. Two other experts, Dieter Helm and Clive Spash, were unavailable due to other commitments.

After analysis of the 14 experts included in the results, it appeared that the responses covered a wide range of opinions and further responses were unlikely to alter the main results. However, the protocol is quite simple to administer and additional interviews can be readily arranged.

Note that the method is not designed to provide a consensus about the range of estimates or a central value. There was no intention to consider the choice of experts as a random sample. Nor was there the opportunity to convene the panel to review the protocol or go through a process of agreeing on a consensus. Rather, the method focuses on the drivers of uncertainty and their relative importance across a range of experts.

The interview protocol involved several steps:

- The spreadsheet with the drivers of uncertainty was sent to the expert ahead of time or displayed on the day. There was no attempt to provide a baseline briefing regarding the social cost of carbon or the range of existing estimates in the literature. This was primarily to avoid anchoring the expert judgement—any material that the project team prepared would be a judgement regarding the uncertainties. At this exploratory stage, we felt it better to let the experts work through their own knowledge. Although the display form was provided, it was not used interactively.
- The first two questions where: What is your maximum estimate of the social cost of carbon? Followed by the minimum estimate. These were intended to anchor the range of estimates from each expert. In practice, all experts subsequently increased their maximum estimate, in response to some of the scenarios presented later.

[12] The experience of Chris Hope is particularly relevant here. Although not part of the original bid, he joined the team and helped to think through the methods and compare results.

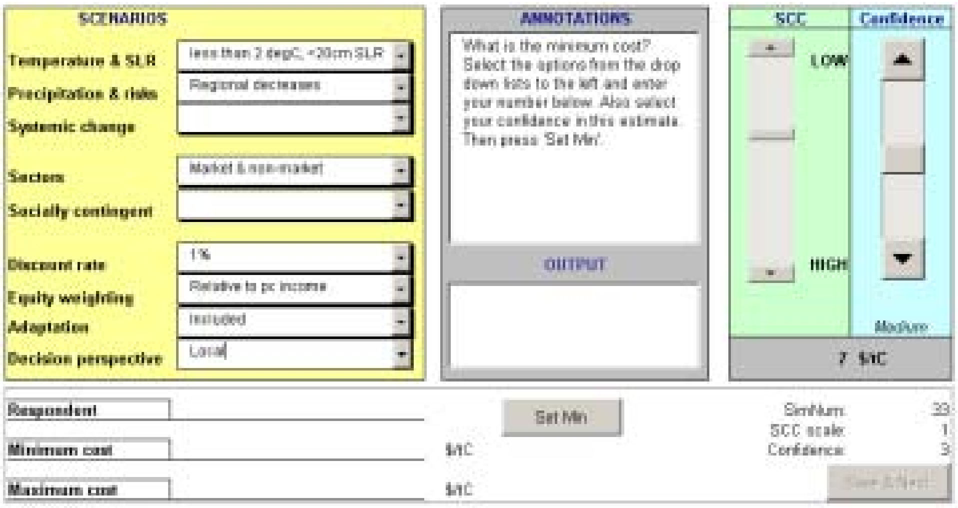
- The expert was then asked to provide an estimate of the SCC (in $/tC) for about 30 scenarios of combinations of the drivers of uncertainty. All of the experts were given the same scenarios, with an opportunity to add scenarios of their own (few took this on however). The scenarios started with drivers likely to yield high estimates, followed by those likely to yield low estimates. The final set concerned drivers of a middle range of estimates. Scenarios tended to be incremental—starting with a set of factors, then adding an additional factor (e.g, equity weighting) or changing the choice (e.g., of discount rate). Box shows an example of a scenario.
- The interviewer left the definition of the drivers to the expert and only interpreted the scenario when requested to do so. In all cases, the minimum of information was provided, relying on the experts' knowledge instead. This did not appear to be a problem. Qualitative interpretations of each response were noted, although these were not overly common.
- Along with an estimate of the SCC, the expert was asked their confidence in the estimate, on a 5-point scale from very low to very high. In practice, this was quite tedious and the interviewer only updated the estimate of confidence when the scenarios shifted from one type to another. For instance, when providing a high estimate the respondent might suggest that he has very low confidence in estimates under such scenarios. When the scenarios shifted to the low estimate (perhaps dealing only with market sectors) then the interviewer asked if his confidence changed.
- At the end of the interview, the respondent was given a quick debriefing. The Excel spreadsheet produced a graph of the results and the range of estimates was discussed. This was not a formal review of the responses, but did provide an opportunity for the expert to comment on the exercise. All of the respondents accepted the protocol and the validity of a structured elicitation. However, they all expressed disquiet over their ability to make consistent judgements between some of the combinations of drivers.

Box 1. Sample of a scenario of the drivers of the social cost of carbon

What would you estimate to be the SCC (in $/tC) for a scenario where:

1. Climate change is over 5 deg C by 2100 and over 70 cm SLR?
2. With additional information that large scale declines in precipitation occur in some regions?
3. What if both market and non-market sectors are included?
4. And what if the socially contingent effects are included?
5. What if the discount rate is 3% declining after 2030 (the Green Book)
6. With per capita income weighting of the impacts and a local decision perspective?

What is your confidence in these estimates?



Annex Figure 6. Interface for the knowledge elicitation

Annex Table 9. Categories and options for elicitation of uncertainty in estimates of the social cost of carbon

Environmental			Economic			Decision choices		
Temperature & SLR	Precipitation & storm risks	Systemic change	Sectors	Socially contingent	Discount rate	Equity weighting	Adaptation	Decision perspective
Less than 2 °C; less than 20 cm SLR	*	*	*	*	*	*	*	*
+ 2-4 °C; 30-50 cm SLR	large regions with rainfall decreases	Included	Market	Included	1%	Relative to pc income	Included	Local
Over 5 °C; over 70 cm SLR	large regions with increases in storm risks		Market & non-market		3%, declining after 2050	Weight losers greater than winners		World average
					5%			EU

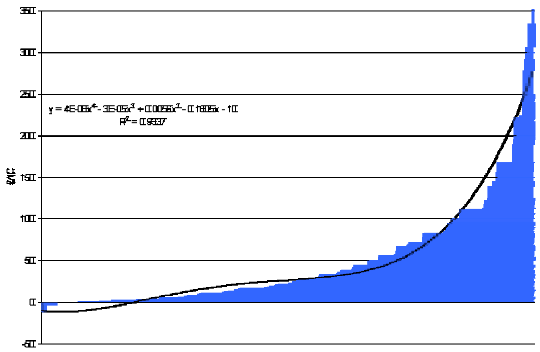
* No additional information is the first option for each category other than temperature.

Results

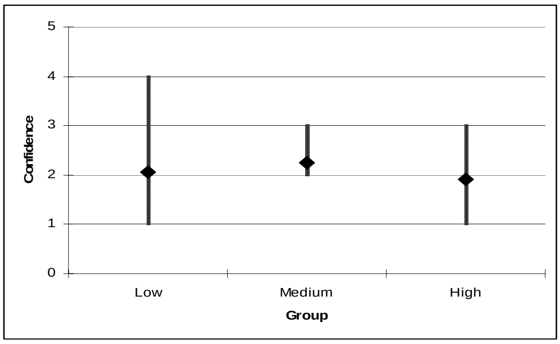
The responses ranged from small net benefits (£-11/tC) to quite large estimates of net adverse impacts (max = £500/tC) (Annex Figure **7**). However, of the nearly 450 scenario-responses, fully 70% had a confidence rating of very low or low. None of the scenarios were judged a confidence of very high and only 3% had a high confidence.

The respondents were grouped according to their overall tendency to give low, medium or high values—this was done by eye to show the range of experts. The distribution of confidence among the respondents does not indicate significant bias (Annex Figure 8). For those respondents who held low or high values for the SCC, their confidence was very low (1) for at least some scenarios. Only those who held low values had high confidence (4) in at least one estimate (generally one of the scenarios based on low climate change and market sectors).

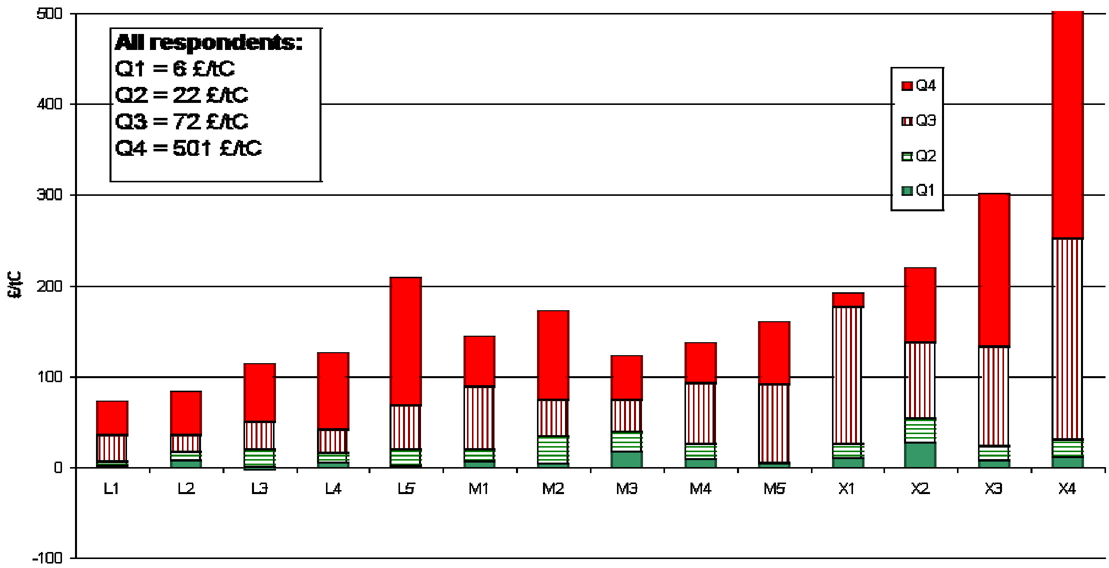
The responses for each expert are shown in Annex Figure 9. The minimum estimate was £0/tC for most of the experts, or slightly negative (not shown in the figure). The median estimates (Q2) range from £10/tC to £95/tC, with an average across all of the experts of £22/tC. Note that this figure is intended to show the range of results rather than to indicate that there is agreement around any particular estimate.



Annex Figure 7. Range of estimates of the SCC from 14 experts
The conversion from $/tC to £ is 1.6.

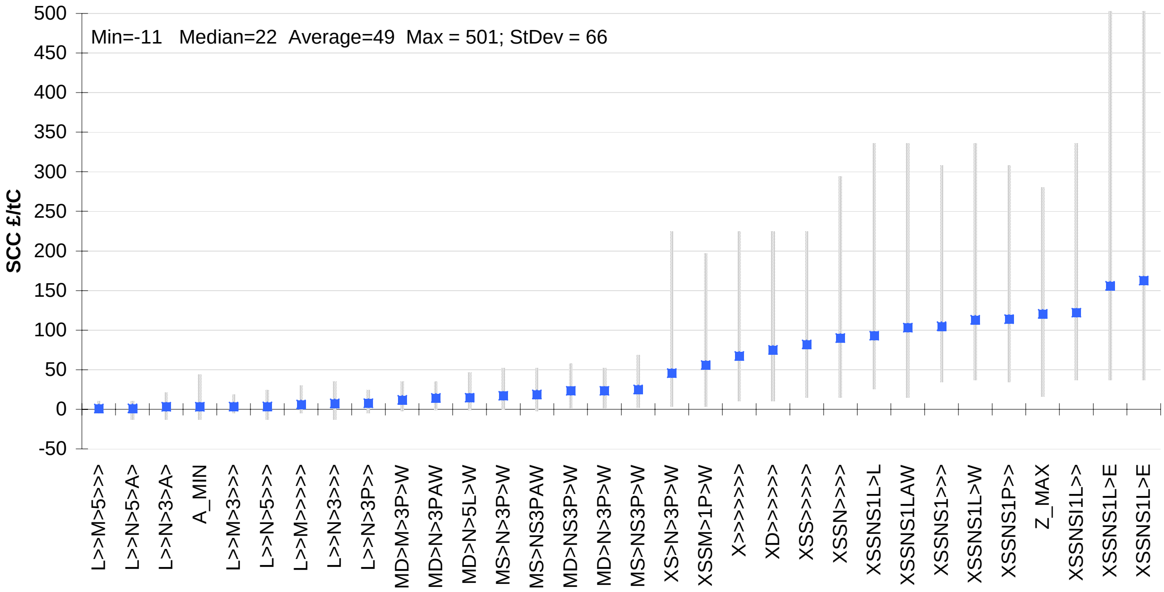


Annex Figure 8. Expert confidence in estimates of the SCC for three groups of experts based on their overall expectation of the SCC
The central values are the average for all scenarios and respondents in the group, bracketed by the minimum and maximum confidence rating.



Annex Figure 9. Estimates of the SCC for each of 14 respondents
The values shown are the lower quartile (Q1=25% of the scenarios are less than this value), median (Q2=50% value), upper quartile (Q3=25% of the scenarios are greater than this value) and maximum (Q4). Conversion from $/tC to £/tC is 1.6.

The responses grouped by scenario are shown in Annex Figure 10. Responses to the scenarios of relatively low climate change (less than 2°C, labels beginning with L) averaged less than £10/tC. In contrast, scenarios of higher climate change (over 5°C, labels beginning with X) were in excess of £50/tC, and often above £100/tC.



Annex Figure 10. Expert responses to scenarios of the drivers of the SCC, £/tC

The range is the minimum, average and maximum for 14 experts. The scenarios are coded on the 9 characters of labels:

Temperature and sea level rise: **L**ow, **M**edium, high (**X**)
Drought and regional declines in precipitation or increased **S**torms
Climate **S**ystem surprise
Market or market and **N**on-market sectors
Socially contingent impacts included
Discount rate: **1**%, Green Book (**3**) or **5**% (pure rate of time preference)
Per capita income equity weighting or weight **L**osers greater than winners
Adaptation included
Local, **W**orld average or **E**uropean decision perspective
> indicates no information on this factor is included in the scenario

Some of the scenarios were constructed to show the incremental effect of different factors. For the high scenarios of climate change (temperature greater than 5 °C):

- Adding equity weighting had an average effect of +£8 /tC (7%)
- Changing from local to world average values increased estimates by £20 /tC (22%)
- Changing from local to EU values increased estimates by £63 /tC (60%)

For scenarios of medium climate change (2-4 °):

- Including adaptation reduced estimates by £6 /tC (-25%)
- Including nonmarket sectors (compared to just market sectors) increased estimates by £12 /tC (98%)

Similarly, for low climate change:

- Including nonmarket sectors added £4 /tC (118%)
- Increasing discount rate from 3% to 5% reduced estimates by £2 /tC (-60%)

The main purpose of the expert elicitation was to produce a rich data base of scenarios and estimates of the SCC and then test to see what rules would differentiate between relatively low or relatively high responses. The responses were first coded into groups: low (below £35/tC), medium and high (above £140/tC). These thresholds were chosen as the end points in the range proposed by Defra (Pittini and Rahman, 2003). (In fact, a number of analyses were conducted, with similar results.)

Then the data were put through a rule-extraction algorithm. While several such algorithms have been put forward, we used a simple approach coded in an Excel spreadsheet (CTree.xls by Angshuman Saha, see www.geocities.com/adotsaha/CTree/CtreeinExcel.html). The CTree spreadsheet implements a basic C4.5 algorithm (one of the standard classification tree models, by Ross Quinlan, see www.cse.unsw.edu.au/~quinlan/).

In a variety of analyses—with different classes and sub-groups of experts—the rules extracted from the responses were broadly similar. Most of the analyses were able to classify the responses with an error rate of around 10-30%, indicating a reasonable ability to calculate individual responses based on up to 5 of the driving factors of uncertainty.

The temperature scenarios are almost always the first level node, that is the most important determinant of whether the response is high or low (Annex Figure 11). This is partly the design of the elicitation, with each scenario associated with a specific climate scenario. Other factors intervened, particularly in determining whether the middle range of climate scenarios resulted in low or high estimates. For the low respondents, the intervening factors tended to be whether or not socially contingent effects were included and the choice of decision perspective (local, world average or EU). For the high group, more factors were influential, including non-market sectors and adaptation as well as the discount rate and decision perspective.

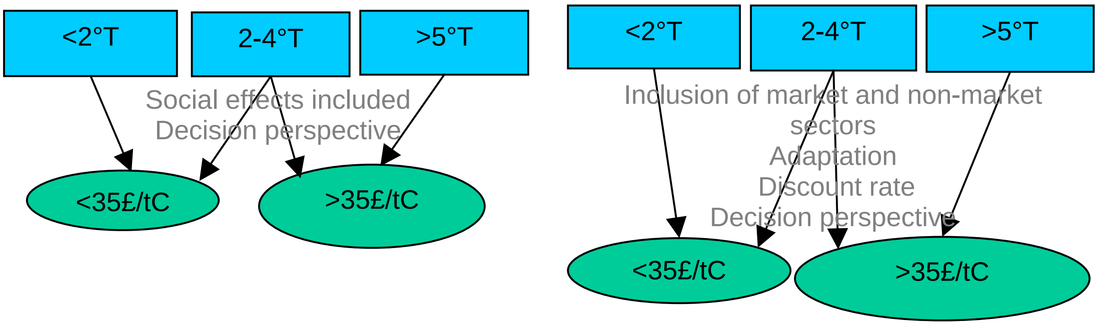
One conclusion from the expert elicitation is that there are several scenarios where estimates of the SCC are greater than £35/tC. While there is considerable uncertainty and disagreement among the experts as to what might be termed a central value, all three groups of experts—low, medium and high—reported responses above this threshold. For the medium and high group, over half of the scenarios were above £35/tC (Annex Table 10; for a sample of individual responses see Annex Table 11). This supports the notion that estimates above £35/tC are plausible, certainly if climate change is in the upper range of projections and probably depending on the bounding of the estimate (e.g., inclusion of more extreme risks) and choice of decision frameworks (particularly regarding world-wide effects and the discount rate).

Annex Table 10. Percentage of responses greater than £35/tC for three groups of experts

Group	>£35 /tC
Low	32%
Medium	53%
High	53%
All	*43%*

Annex Table 11. Selected estimates of the SCC from experts for a range of scenarios, £/tC

	Climate scenario					
	Low		Medium		High	
Respondent	SCC range		SCC range		SCC range	
L1	1	8	8	17	11	66
L2	-3	7	6	29	12	111
L3	-2	1	4	21	19	190
M1	8	33	17	50	17	78
X1	8	22	33	83	56	145
X2	0	22	0	36	11	167



Annex Figure 11. Schematic representation of classification trees from scenarios of SCC estimates by 14 experts grouped according to low responses (left) and high responses (right)

Conclusion

All of the respondents thought the minimum SCC might be near 0 or even a small net benefit. This reflects the common view that low or moderate climate change has net benefits for perhaps a few decades.

All respondents recognised the importance of equity and values in making choices about the various factors to be applied. That is, the choice of discounting scheme, the degree of risk aversion to extreme scenarios, and the validity of equity weighting are essentially decision choices that should be guided by policy objectives.

Uncertainty is much larger for the higher estimates (for example, over £35 /tC). This confirms our observation of the literature—the upper left quadrants of the risk matrix (projected climate change and market impacts) has received more attention and greater consensus compared to the non-market and socially contingent exposure to extreme events and large scale system changes. No single factor dominates the uncertainty for larger estimates—several combinations of factors could lead to the SCC being over £140 /tC.

Acknowledgements

The 14 experts provided their time and expertise without remuneration. This annex is the first full draft of the results and has been sent for review by the expert respondents, as well as other reviewers of the project. Their comments are appreciated and have been considered, both in this annex and the final report.

Social Cost of Carbon: A Closer Look at Uncertainty

Annex: Regional studies of dynamic and multiple stresses

Introduction

This annex explores studies that have looked at multiple stresses and socially contingent effects of climate change. Such impacts refer to social concerns such as migration, hunger, and conflict that depend heavily on underlying social, economic and political conditions. The risk matrix developed in the project differentiates between market and related impacts assessed against projected changes in temperature (the majority of studies) and the larger uncertainties associated with non-linear responses of vulnerable societies, particularly to changes in climatic hazards. In the risk matrix, these responses are labeled socially contingent effects.

A number of regions are candidates for significant socially contingent effects, or potentially widespread non-linear impacts of climate change. Three common 'hot spots' are:

- Small island states subject to sea level rise and storm surges could be inundated and disappear. While the total land area affected is small, a number of countries are potentially at-risk and have formed a vocal regime in climate negotiations.
- Delta cities are also exposed to sea level rise, with the added stresses of saline intrusion to groundwater, coastal erosion, and the potential impacts on water, food systems, urban infrastructure and health. Mega-cities such as Lagos and Shanghai are well-known examples. Again, the area affected is relatively small, but the high population concentrations and economic infrastructure at-risk give high priority to understanding their vulnerabilities.
- International river basins in semi-arid regions or where glacier sources are disappearing could accelerate conflicts over valuable resources. A current concern is the glacial melting in the Himalayas and the effects on rivers draining the central Asian republics (such as the Amu Darya). The notion of water wars has been debated for decades (or longer); with some of the higher projections of climate change impacts the instability of international hydro-social regimes cannot be dismissed.

As an example of the socially contingent category of climate impacts, we focused on the Sahel. We began with a small workshop to construct an influence diagram of how climate change might lead to regional impacts and migration (led by Tony Nyong, University of Jos, Nigeria). We then worked to review existing studies and build a prototype multi-agent model of the Sahel (led by Scott Moss and his colleagues at the Centre for Policy Modeling, Manchester Metropolitan University).

In this annex, we:

- Describe the Sahel region of Africa and its vulnerability to climate change
- Present several influence diagrams and thought experiments of potentially non-linear, widespread impacts of climate change
- Conclude with reflections on the implications of regional, socially contingent impacts for global estimates of the social cost of carbon

Climate changes in the Sahel region

The West African Sahel is the arid and semi-arid belt across northern Africa between the Sahara desert and the humid forests on the southern coast of West Africa. The natural vegetation changes from grassy savannah in the north to wooded savannah in the south, annual precipitation ranges from 200mm up to 1000 mm and the growing season length from 75 up to 150 days.

An analysis of climate change scenario impacts has been conducted specifically for Africa by Hulme *et al,* (2001). Future annual warming across Africa ranges from 0.2°C per decade (low scenario) to more than 0.5°C per decade (high scenario). This warming is greatest over the interior of semi-arid margins of the Sahara and central southern Africa. The inter-model range (an indicator of the extent of agreement between different GCMs) is smallest over north Africa and the equator and greatest over the interior of southern Africa.

Future changes in mean seasonal rainfall in Africa are less well defined. Under the lowest warming scenario, few areas experience changes in DJF or JJA that exceed two standard deviations of natural variability by 2050. The exceptions are parts of equatorial east Africa, where rainfall increases by 5-20% in DJF and decreases by 5-10% in JJA.

Under the two intermediate warming scenarios, significant decreases (10-20%) in rainfall during March to November, which includes the critical grain-filling period, are apparent in north Africa in almost all models by 2050, as are 5-15% decreases in growing-season (November to May) rainfall in southern Africa in most models.

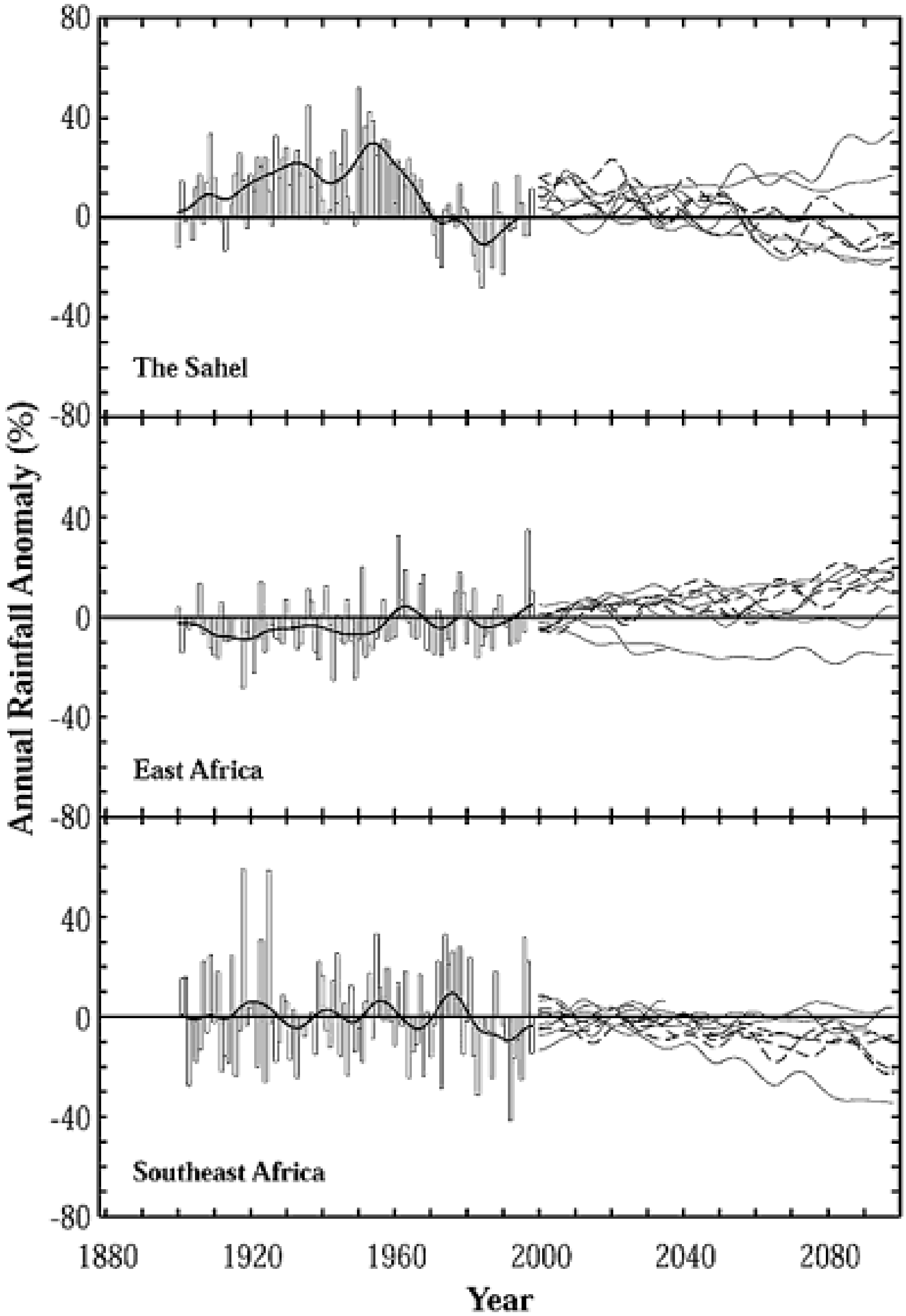
Under the most rapid global warming scenario, increasing areas of Africa experience changes in summer or winter rainfall that significantly exceeded natural variability. Large areas of equatorial Africa experience increases in DJF rainfall of 50-100% over parts of eastern Africa, with decreases in JJA over parts of the Horn of Africa. However, there are some JJA rainfall increases for the Sahel region.

Hulme *et al.* (2001) also analyzed future rainfall changes for three African regions, the Sahel, east Africa, and southeast Africa, to illustrate the extent of intermodel differences for these regions and to put future modeled changes in the context of past observed changes (Annex Figure 12). Although model results vary, there is a general consensus for wetting in East Africa, drying in southeast Africa, and a poorly specified outcome for the Sahel.

In the 1970s and 1980s the region experienced repeated, devastating droughts, most notably in 1972-73 and in 1982-84. The mean rainfall in the Sahel dropped 37 percent in the period from 1968 to 1997 compared with the period from 1930 to 1960. Temperatures in the region are also warming, with most increases in the spring, summer and autumn months.

Adjusting to this long drought period has been extraordinarily difficult for the people of the region. The stress caused by failure of rains and decrease in total seasonal rainfall on crop yields, and the resulting impacts on communities led to intensification and extensification of agriculture, migration of labour and households, and ultimately degradation of soil and conflict between land users (especially pastoralists and agriculturalists). The historical period of drought and decreased rainfall might be an indication of how a warmer and drier climate of the future, might trigger regional impacts.

Few integrated models have looked at the effects of climate change in the Sahel. One of the more innovative approaches is the Sahel syndrome model that includes the socially contingent effects of climate change. Ludeke, Moldehauer and Petschel-Held (1999) claim that the main advantage of their approach over "ceteris paribus" impact studies is that the investigation of the response of the observable inter-sectoral studies (syndromes) to climate change overcomes the difficulties in later systemic integration. The question of which pattern of closely interacting elements of social, economic and natural environment institute severe problems for humanity is solved in advance by the identification of the syndromes. This does not allow for totally new and dangerous complexes emerging under climate change, which may be important in calculating the social cost of carbon. The authors state that predictive world models based on first principles would have to be used for this.



Annex Figure 12. Observed annual rainfall anomalies for three African regions, 1900-1998, and model-simulated anomalies for 2000-2099
Model anomalies are for 10 model simulations the four HadCM2 simulations are the dashed curves. All anomalies are expressed with respect to observed or model-simulated 1961-1990 average rainfall. (Hulme *et al*., 2001).

In the case of the Sahel syndrome, Ludeke *et al.* (1999) looked at the sensitivity of the syndrome in respect to climate, using the climate sensitivity of the proneness or "disposition" of a region towards the Sahel syndrome. The core dynamic pattern of the Sahel syndrome is formed by a positive feedback loop consisting of the state variables rural poverty, increased agricultural activity and soil degradation. Existing rural poverty drives farmers to overuse their lands leading to soil degradation which reduces yields and thereby exacerbates rural poverty (as identified in several case studies, e.g. Kates and Haarman (1992), Leonard (1989), Reenberg and Paarup-Laursen (1997). The set of necessary conditions for the disposition to the Sahel Syndrome can be divided into socio-economic and natural dimensions. A fuzzy logic algorithm is applied to the qualitative arguments in the system which allows the reasoning to be mapped using quantitative indicators and avoids the need for explicit quantitative modelling. A detailed description is available in Cassel-Gintz *et al.*, 1997.

Results of the syndrome model for current conditions and for some climate scenarios indicate that large areas of the world have a high or very high disposition to the Sahel syndrome with respect to climate namely countries of Africa, Asia and South America (Ludeke et al. 1999). In Africa, Morocco, Algeria, the Sahel region countries of Guinea, Mali, Burkina Faso, Niger, Chad, Sudan, the east African countries of Kenya and Tanzania and also Mozambique, Madagascar and Zimbabwe show highly sensitive regions. An evaluation of the Sahel syndrome disposition under a double CO_2 climate (which might be expected between 2050 and 2100) using ECHAM3 and Hadley Centre scenarios allow regions to be identified explicitly where the Sahel syndrome would become worse in the future with climate change. The scenario results show good mutual agreement for an increase in disposition in several regions of the world. In particular, regions adjacent to those already affected by the syndrome such as countries in southern Africa and a broad strip directly south of the Sahel which has changed from low disposition to very high disposition. The western regions of the Sahel also increase their disposition from moderate to high.

Another approach for modelling climate change impacts in the region is to analyze the various processes and functions related to sustainable food security by Verhagen *et al.* (1993). This work is based on the results of the Netherlands project, Impact of Climate Change on Drylands (ICCD) that brought together scientists with anthropological, geographical and economic backgrounds (Dietz, Verhagen, and Ruben, 2001 and Van den Born, Schaeffer, and Leemans, 2000). This recognises the complex interrelations between ecological, material human and social capital and starts much more from an agricultural rather than a land use point of view. Crop models are used to determine crop yields under various environmental conditions and management practices. The focus of the work was on how climate change and in particular precipitation affected yield levels. Using historical climate data, patterns of societal responses to changing conditions were reconstructed. Demographic changes are the principal driving factors followed by farm technology and farm management. Each individual or group has a history of portfolios of options through time, called a pathway of chosen options. Nine portfolio options have been distinguished: storage of food, increasing food production, intensification of food production, marketing non-agricultural services, selling services (e.g. by attracting tourists), selling labour, social security arrangements, stealing and reducing food demand (through out migration, reducing natural population growth through lower birth rates and declining natural population growth through higher death rates).

Scenario analyses using a range of global circulation models show a wide variety of outcomes for 2050, with some consensus that most of dryland West Africa will become appreciably drier (with higher temperatures and lower precipitation). The consequences of these projections are an increase in high-risk environments for agriculture and a further southward shift of the arid and semi-arid zones. Simulation studies reveal a delay in the onset of the growing season and associated lower yields. Results from the ICCD project indicate an increase in drought risk across the region which in some areas changes from a light drought risk to extreme drought risk over the period 1990 to 2050.

The ICCD studies on decision-making showed clearly that a very wide range of factors has to be considered when investigating pathways of specific individuals or groups. The variables taken into account by decision makers cover a wider range than the household, village or district. Changes in behaviour resulted from the variability in rainfall in the 1970s and 80s. In general in the Sahel they found that there was a strategic attempt to develop a multi-locational and multi-sectoral household economy, both in agriculture and outside the sector. They recommend that more carefully focused field research is required to make up for the lack of data on a wide range of settings and social groups. Progress in analysing the process of decision making has to be supplemented by more quantitative assessments of the economic behaviour of people and more basic data gathering and field research. Linkages between individuals, village, regional and national levels need more attention.

Stephenne and Lambin (2001) have developed a simulation model of land-cover changes at a national scale for Sudano-Sahelian countries (SALU SAhelian Land-Use model). The specific purpose of the model was to generate backward and forward projections of land-use change over several decades at a national scale. The model represents a dynamic but simplified version of the current understanding of the processes of land-use change in the Sahelian region. The authors argue that to produce long-range projections require a good understanding of how climate variability and affects both land use and land cover. This information is gained through local case studies on land use dynamics which highlight how people make land use decisions in a specific situation.

A generalised understanding of the drivers of land use change that can be linked to regional scale patterns of change is gained through a comparative analysis of the case studies. The exogenous variables of the model are human population, livestock population, rainfall and cereal imports. These are defined for each year from the FAOstat database and the global monthly precipitation dataset. These drive yearly changes in land-use allocation. It consists of calculations for pastoral land, cropland and fuel wood extraction area.

Application of the model to Burkina Faso indicates that land use changes at two time frequencies: high as driven by climate variability and low as driven by demographic trends. The model predicts an increase in land degradation in the early 1990s. The rates of cropland expansion predicted by the model as a result of drought periods are consistent with rates measured for several case studies. Results under future climates have been calculated but are not yet published (Lambin, personal communication, 2004). The authors did not feel comfortable running the model under scenarios further in the future than 2015.

In their most recent work the SALU model was used to generate "what-if" scenarios to explore hypotheses on the relative role of driving forces of land-use change in the Sudano-sahelian countries of Africa (Stephenne and Lambin, 2004, in press). The model simulations provided very relevant insights to better understand the impact of a range of driving forces of land-use change. Rural population growth represents a larger stimulus for land-use change than urban population growth. Demographic variables have a greater impact on land use than recurring droughts. The demographic driving forces are slow variables while rainfall is a fast variable. Recurring droughts could be viewed as trigger events, and urban population growth and consumption as mediating factors, while rural population growth defines long-term trends. The timing of occurrence of drought with respect to transitions in land use has a major impact on land-use change. They also find that polices aimed at protecting pastoral land and supporting agricultural intensification both contribute to maintain pastoral activities. They summarise that by examining environmental, social and economic implications of various land-use scenarios, the modelling approach adopted in SALU can provide support for decision-making. The ICCD report on the impacts of climate change on drylands also discusses some of the issues around how households behave in relation to climate variability including increases in rainfall as well as decreases. Migration caused by drought is also discussed.

Influence diagrams and thought experiments for regional impacts in the Sahel

In this section we present a schema to reflect the behaviour of people and the environment in the Sahel in response to a reduction in rainfall (Annex Figure 13). This has been developed by Dr Tony Nyong, a lecturer at the University of Jos in Nigeria based on his regional knowledge plus his research into livelihoods, vulnerability and adaptation to climate change in West Africa (see www.aiaccproject.org). The issues are reflected in different ways by other schemas we have found in the literature in particular one by Annette Reenberg who has looked specifically at agricultural land-use dynamics in the Sahel. She proposes to develop a model which recognises land use pattern changes as event-driven (Reenberg, 2001, Annex Figure 14). A more universally applicable schema for rural households, migration and the rural environment is presented in Bilsborrow (2002, Annex Figure 15). This includes wider inputs and effects in the system but has fewer feedbacks.

Drawing upon these three influence diagrams (or thought experiments), we can construct a narrative of how climate change might lead to socially contingent effects in the Sahel. Drought is not a strange phenomenon to the West African Sahel. Any successful attempt at mitigating the impacts of future drought events in the Sahel must be grounded in a firm knowledge of the nature of drought vulnerability in the region.

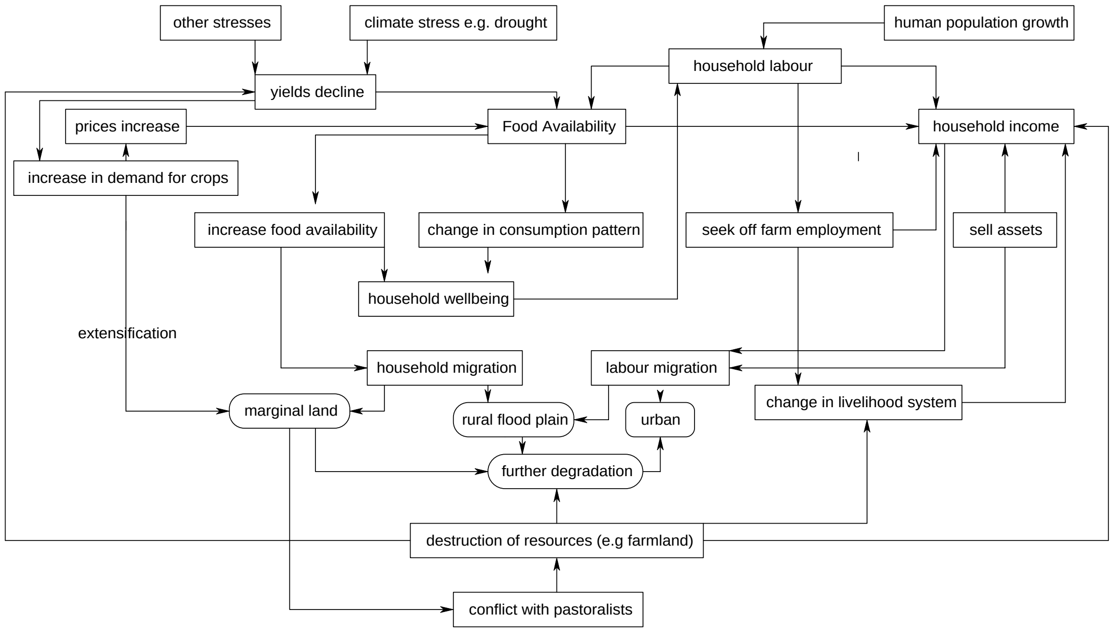
Drought is not the only cause of vulnerability in the Sahel. It acts with other stressors such as declining soil fertility, an unsustainable population growth, poor governance and pervasive poverty. These stressors, largely triggered by droughts, affect the household livelihood system in many ways. First, it leads to a decline in agricultural yield.

The decline in yields leads to an increase in grain price as more people now go after the limited quantity of products in the market. The decline in yield directly affects the amount of food available to the household. A reduction in household food availability means a reduction in per capita food consumption which could affect the well-being of the household and consequently the quality and size of the household labour. The size of the household labour, which is directly affected by the population growth rate, also affects the amount of food availability. It is hypothesized that the size of a household affects food availability in two ways: positively in that it increases the size of land that can be cultivated and hence leads to an increase in yield, negatively in that it increases the quantity of food consumed. In both ways, household income is affected. Increased cultivation increases the household income but greater consumption also reduces household income in that the quantity of food now sold is reduced as well as the fact that more money is required to sustain the household.

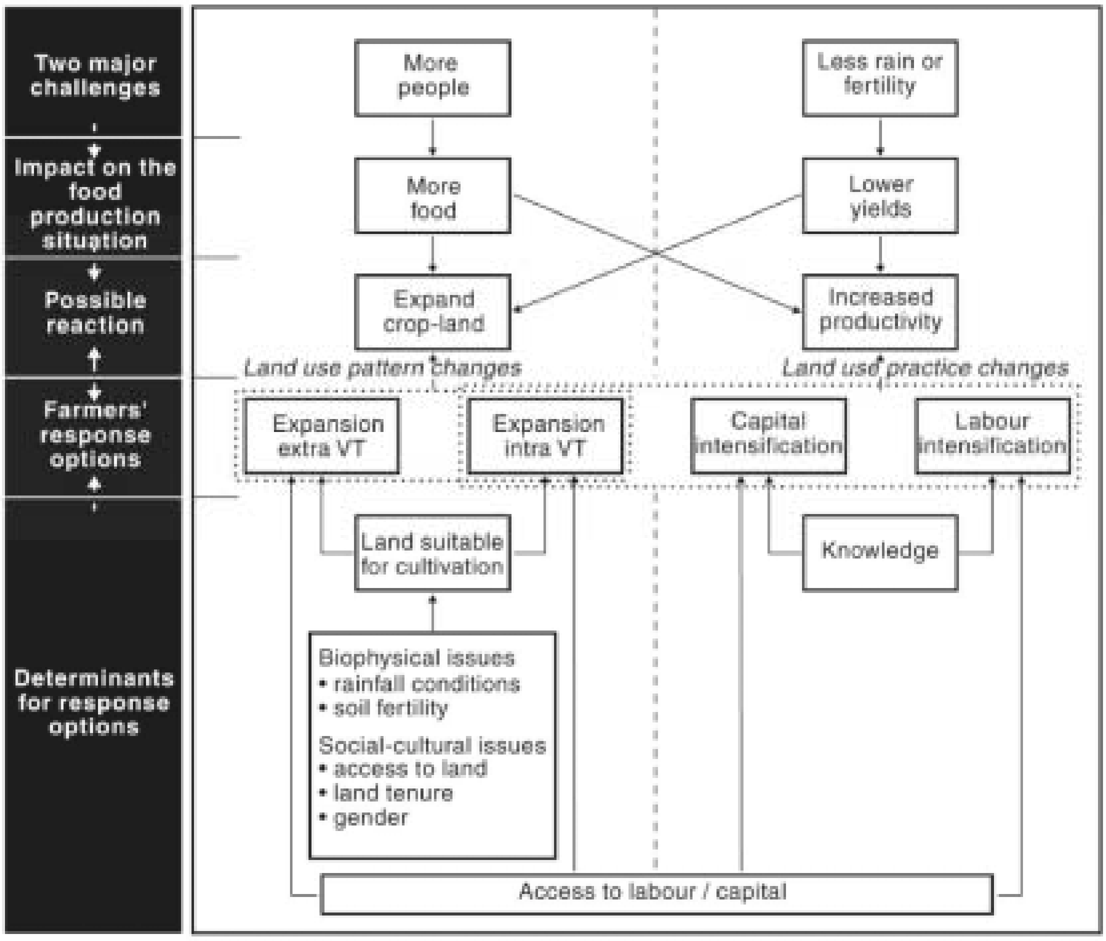
Where household income is negatively affected, certain household coping strategies may be implemented. First, a household may be forced to sell some of its assets to boost household income. Some of the assets may be what was required in the household's livelihood system. Where that happens, the household may be forced to change its livelihood system. This could have a further negative impact on household income.

A household may also consider that migration may be a viable coping strategy. Here, two types of migration are usually anticipated: labour migration where some members of the household go out to work and earn money, part of which is remitted to the household. They could move to the urban centres to seek non-farm employment, or move to other rural areas as hired agricultural labour. They may return later with more knowledge about agriculture to help improve future yields.

The second type of migration, which is usually a last resort, involves the entire household, which moves to marginal lands or to flood plains to make a living. This usually leads to further degradation and conflict. On the flood plains, the number of farming families soon exceeds the carrying capacities of the flood plains and leads to severe environmental degradation. Where this happens, there is a decline in yield and the farmers are now forced to seek other available lands and usually move to the marginal lands. Also, others end up homeless and destitute in the urban centres, which leads to pressure on the social infrastructure of the cities.

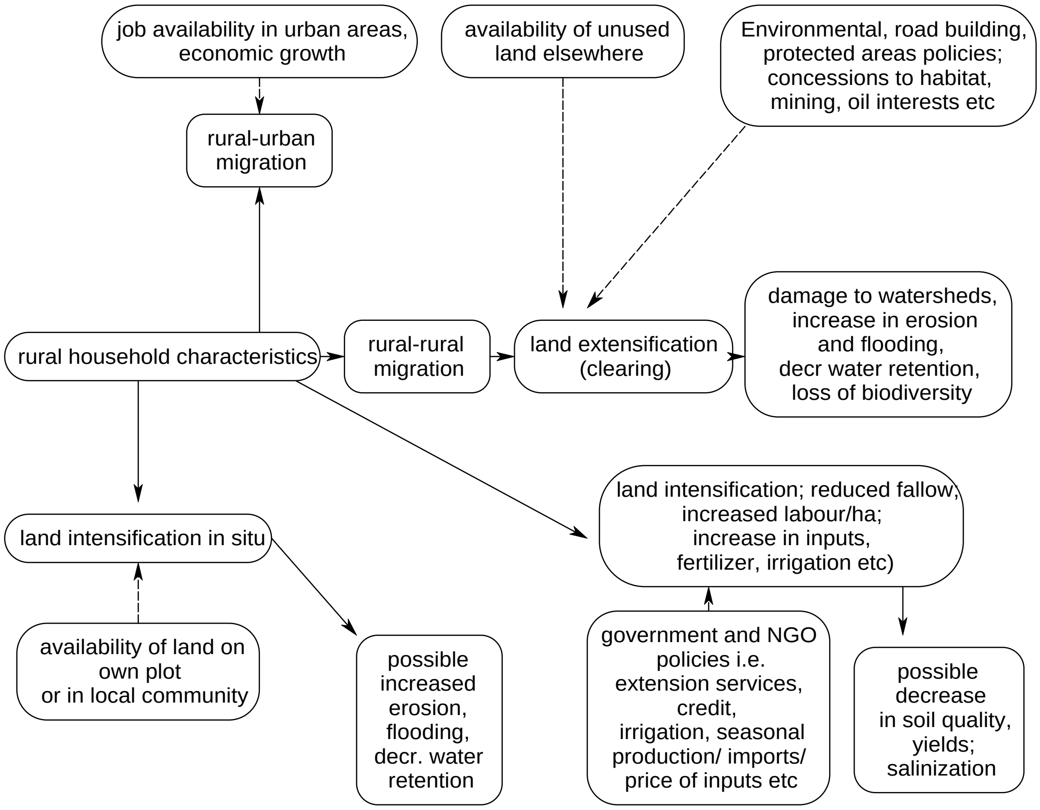


Annex Figure 13. Representation of resources, stresses and migration developed by the authors



Annex Figure 14. Farmers' response options to ensure food security vis-à-vis alterations in land use practice and land use patterns in the Sudan-Sahel region

VT refers to Village Territory. Source: Reenberg (2001).



Annex Figure 15. Rural household decision-making, migration and the rural environment
Source: Bilsborrow (2002)

The increase in grain prices means that many poor people (the majority of the rural population) cannot afford to buy from the market. They are therefore forced to seek ways of increasing their crop cultivation through agricultural extensification. This ultimately leads them to expand into marginal lands. Here, we find three groups of people who have been forced into cultivating marginal lands as a result of the droughts. Pastoralists traditionally occupy the marginal lands and the movement of farmers into these lands often leads to conflicts. These conflicts often result in the destruction of resources (farmlands, crops and livestock). The destruction could lead to a change in livelihood system, which would have a negative impact on household income. It would also directly lead to a further decline in crop/agricultural yield. This further decline in yield reinforces the increase in the price of agricultural produce. Where the conflicts are extended, human deaths are usually recorded and this affects the population.

A prototype multi-agent model of the Sahel drought-migration complex was developed to begin to operationalise the influence diagrams discussed above. The model has not been verified or validated due to funding constraints (the ICCD and PIK syndrome projects were both multi-year efforts with large teams). One result illustrates the kind of output that might be expected. With a normal climate (the present case) regional out-migration is relatively low—few households are forced to relocate to wetter regions. With a drier climate, the stresses on rural households accumulate and a larger number begin to migrate to wetter areas. This places the migrants in conflict with the existing residents.

Conclusion

What does this review of regional impacts of climate change imply for estimates of the social cost of carbon? First, we conclude that the conditions of multiple stresses related to the 1970s-1990s drought and dryness in the Sahel—leading to food insecurity, migration, changes in livelihoods and land use conflicts—might be both intensified and more widespread with climate change. Regional effects on economic growth and wellbeing could be significant and lead to quite high (non-marginal) estimates of the social cost of carbon.

Second, it does not seem likely that validated assessments of such regional effects (and quantification of their economic costs) are likely to be forthcoming soon. The uncertainties is regional climate predictions and underlying vulnerability leave open a wide range of plausible scenarios of future costs at this scale.

One next step would be to map the prevalence of such conditions where regional vulnerabilities and climatic risks could lead to socially significant impacts. A 'hot spots' approach of overlays is a simple approach, with dynamic, multi-agent models of vulnerability providing further insight into the processes that might lead to undesirable outcomes. Bounding exercises to provide end-points to the range of economic valuations would help identify the significance of these risks to global estimates of the social cost of carbon.