Review of Literature subsequent to IPCC AR4

AVOID:

Avoiding dangerous climate change

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

Author(s): Rachel Warren[1], Nigel Arnell[2], Pam Berry[3], John Caesar[4], Lynn Dicks[5], Robin Hankin[5], Jason Lowe[6], Robert Nicholls[7], Jesse O'Hanley[8], Jeff Ridley[4], Serban Scriecru[5], Peter Stott[4], Michael Vellinga[4], Paul van der Linden[4]

Institute: [1] Tyndall Centre, University of East Anglia, Norwich NR4 7TJ
[2] Walker Institute, University of Reading, Earley Gate, Reading
[3] Environmental Change Institute, University of Oxford, Dyson Perrins Building, South Parks Road, Oxford OX1 3QY
[4] Met Office Hadley Centre, FitzRoy Road, Exeter, EX2 3PB
[5] 4CMR, Dept of Land Economy, University of Cambridge, 19 Silver St., Cambridge
[6] Met Office Hadley Centre (Reading Unit), Department of Meteorology, University of Reading, Reading, RG6 6BB
[7] School of Civil Engineering and the Environment and Tyndall Centre, University of Southampton, Southampton SO17 1BJ
[8] Kent Business School, University of Kent, Canterbury CT2 7PE

Reviewer:

Institute: Tyndall Centre / Met Office Hadley Centre - -

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Key outcomes / non-technical summary

This report provides a review of the most relevant recent literature in the areas of climate science, impacts of climate change and climate change economics, with a focus on post IPCC Fourth Assessment report work. It also provides information on the key research gaps which might have a major impact on mitigation decisions.

- *Climate science*

The AR4 provided more definite statements of human influence on the climate system, and subsequent work has strengthened that further. The AR4 also highlighted greater complexity in many of the physical systems that climate models attempt to simulate. A large amount of post-AR4 research has focussed on better understanding of physical processes, including highlighting where model improvements are needed and where they are most robust. Risk assessments can be made using the information presented to-date but many of these are likely to be refined with improved models during AR5. This may impact on mitigation targets and impact assessments.

- *Impacts*

There have been many papers published since the AR4 on water, agriculture and health impacts. Many of these have added case studies from areas previously poorly-represented - specifically Africa and Central and South America – but few offer new insights into the effects of climate policy on these impacts. For agriculture, the tone of the post-AR4 literature on agricultural impacts is more pessimistic than that of the AR4, largely due to an increased understanding of the role of pests, extreme events, and changes in ozone concentrations, on either increasing the adverse effects of climate change or offsetting the positive effects. In the field of health impacts there has not been a great deal of progress in looking at the combined effects of climate change and local air quality issues. A number of local assessments of future sea level, including changes in extremes, have been published since the AR4 and these have tried to deal with the current uncertainty in the climate projections of sea level rise.

Since AR4 the number of projections of extinction risks which would result from future climate change has significantly increased. However, climate change induced extinctions would be significantly reduced by mitigation, and the first quantifications of these reductions are being made. Coral reefs, mountain and polar ecosystems and Mediterranean climate systems are the most vulnerable to climate change.

- *Economics*

The SRES scenarios are still broadly representative of plausible future ranges of future emissions without specific mitigation policy, but new scenarios are being developed. Assessments of the economic potential for and macroeconomic costs of mitigation of global greenhouse gas emissions have changed little since AR4. New studies cite costs of around 1% GDP, or even macroeconomic benefits, for stabilization at 445-710 ppm CO_2eq, or -2.3 to +2.5% GDP change for stabilization at 450-550 ppm. The carbon price necessary to achieve a particular stabilisation target remains very uncertain. There are large cost savings from including reductions in non-CO_2 gases in mitigation strategies, and these may be essential to reach the lower targets. Energy efficiency has a key role in mitigation though its efficacy is substantially offset by the rebound effect. The costs of inaction continue to be highly uncertain but literature now more strongly emphasizes potentially high costs including that due to extreme weather.

Early assessments show that the EU ETS is working to reduce European carbon emissions, but its effectiveness would be improved by auctioning the emissions allowances.

This report should be referenced as

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CONTENTS

1. INTRODUCTION

This document provides an assessment of recently published literature that has direct relevance to avoiding dangerous climate change and its impacts. The scope of the review is to cover climate change and its impacts on water resources, agriculture, ecosystems, human health, and coasts. The economics of avoiding dangerous climate change are also considered. The review focuses almost exclusively on refereed journal papers that were not included in the IPCC AR4, most of which were published subsequent to IPCC AR4.

Our approach has been to assemble a team of experts covering a wide range of specialisms. Each expert was asked to highlight only the most important literature not included in the AR4 from their research area. This forms the detailed review (with citations) in the appendices of this report and is intended to be used as a resource for those interested in more detail. The body of this report consist of an abridged version of the main points from the review, along with gaps in the literature and some suggestions on how to use the review information.

2. IMPLICATIONS OF THE REVIEW FOR POLICY MESSAGES AND MITIGATION NEGOTIATIONS

The purpose of this review is to be policy informative, not policy descriptive. However, we think it is useful to highlight some areas where the results might be most relevant to mitigation policy discussions.

The case for/against action

- The evidence base for a human influence on climate is now very strong and getting stronger. Examples now exist of local attribution of changing climate risk (e.g. the summer 2003 heat wave in Europe). Climate driven impacts on human and natural systems are being measured too. The move towards local information on systems of direct importance to the daily lives of individuals might help overcome the argument "I agree mankind is changing climate but I'm not seeing the effects in my country".
- The wider availability of future regional impact projections might also be useful in motivating some nations to act.
- Recent acceleration of several climate changes (e.g. the rate of sea level rise) is increasingly being used as an argument for urgent action. However, it is important to be aware that some counter evidence to the most extreme projections is emerging.

Choice of temperature and emission reduction targets

- While there is an increasing understanding of dangerous climate change, the trigger points remain highly uncertain. Considerable caution has to be applied to estimates that link impacts to temperature triggers, especially without uncertainty bars. Indeed, some types of dangerous impact may not simply be triggered by the amount of temperature rise; they may also depend on rate of change and/or concentration of CO_2. Thus, the science provides some room for manoeuvre when discussing a precise value for a temperature target, although, in general, there is a greater chance of triggering dangerous impacts at higher temperatures.
- There are remaining uncertainties in key climate parameters, such as climate sensitivity and the link between the carbon cycle and climate change. This means that the precise emissions pathway that will lead to a given future warming target is likely to change in the future. This implies a need for flexibility to alter future emission targets as the science progresses, possibly on a time-scale consistent with the IPCC report cycle (currently approximately every 5 years).

Achieving emission reductions

- Some integrated assessment models continue to use climate, impact and economic information that is out of date. This should be taken into account when evaluating particular scenarios.
- Mitigation potentials and carbon tax estimates remain uncertain. This is especially important to note when considering cost benefit analysis or the "cost optimum" mitigation solutions that are available from many integrated assessment models.
- Including land use is likely to be very important if the most optimistic targets are to be achieved. Increased understanding of impacts on natural carbon sinks suggests that the lifetime of any "natural" carbon offset estimate should be considered. Some areas that could provide near term offsets might not be sustainable in the future.

3. RECENT DEVELOPMENTS IN CLIMATE SCIENCE, IMPACTS AND ECONOMICS

3.1 CLIMATE SCIENCE

The IPCC AR4 benefited from longer observational records, which gave an increased climate change signal and enabled more definite attribution statement to be established. In addition, more climate models and more complex models were also available. This led to statements on the risks of a range of different warming levels and other climate changes. However, the increased focus on processes also highlighted the limitations that remain in projecting climate change and its impacts. A large amount of post-AR4 research has focussed on better understanding of physical processes, including highlighting where model improvements are needed and where they are most robust. Risk assessments can be made using the information presented to-date but many of these are likely to be refined with improved models during AR5. Understanding of "tipping points" is increasing but quantification of their trigger points is still very uncertain.

Detection and Attribution of Climate Change

Anthropogenically-forced temperature changes have now been detected on every one of the seven continents. Furthermore, changes in climate other than temperature have now been attributed to human influence, including hydrological quantities. Attribution analyses are also now extending to regional scales and to extremes.

Changes in Temperature and Rainfall Extremes

Human influence has at least doubled the risk of such a hot European summer as 2003, and by the 2040s projections show that summers over southern England could be at least as warm as 2003 on average 50% of the time. Large-scale climate variability has been shown to have a substantial influence upon local temperature extremes. Since our ability to predict changes in large-scale circulation patterns and teleconnections is currently limited, this has implications for our ability to project climate extremes.

Quantifying precipitation extremes remains a more challenging task than for temperature extremes. However, it has been shown that relative changes in the intensity of precipitation extremes tend to exceed the relative change in annual mean precipitation.

Recent Changes in Arctic Sea Ice

A minimum Arctic sea ice extent was observed in 2007. Most, but not all, climate models underestimate the observed sea ice trend over 1979-2006. However, it is not certain that the recent observed trend is exceptional. 20th Century simulations using the HadGEM1 model suggest that a similar trend may have occurred in the 1920s during an earlier warm period in the Arctic. However, the observations during this period are not considered good enough to evaluate this properly. A recent study attempted to use an apparently more robust feature of climate model results and predicted that the Arctic will be ice free during Septembers sooner than many of the climate models suggest on their own, but this is not projected to occur until after 2050 for a business as usual scenario emissions scenario.

Sea Level Rise and Ice Sheets

There has been an observed acceleration in sea level rise in recent years, but it is not yet clear if this will continue in the future. Current process models have only limited skill in making projections of the contribution to future sea level from ice sheets, but some lines of evidence indicate that the 21st century sea level increase is unlikely to exceed 2m.

Since the IPCC report several new studies have been initiated with the aim of producing more credible future sea level scenarios, with land ice dynamics and ice shelves accounted for, by the time of the next IPCC assessment.

The Atlantic Ocean Meridional Overturning Circulation

The IPCC AR4 concluded that "… it is very likely that the Atlantic Ocean Meridional Overturning Circulation will slow down during the course of the 21st century. A multi model ensemble shows an average reduction of 25% with a broad range from virtually no change to a reduction of over 50% averaged over 2080 to 2099." A key advance since AR4 is in the observations and it now appears that an apparent long-term weakening trend since the 1950s might actually have been natural variability. There has also been improved understanding of MOC processes and their inclusion in models. However, the picture is still unclear as to whether a collapse in the MOC is likely to occur under future business-as-usual emissions scenarios. The most complex climate models provide some conflicting evidence, and simpler models, which have been used to produce risk estimates, may not be adequate to represent the processes involved.

The Carbon Cycle
Since the AR4, it has been found that old growth forests continue to store carbon rather than being carbon neutral and tropical forests are increasing the amount of carbon which they store annually as a result of climate change experienced so far. However, several major carbon stocks in terrestrial ecosystems are at a high degree of risk from projected unmitigated climate change and land-use changes. There is further evidence that the efficacy of the ocean in removing carbon from the atmosphere is likely to decrease and for the Southern Ocean, a weakening of the carbon sink has been observed during the last two decades.

Many studies examine feedback processes operating in the terrestrial biosphere and the ocean but there are still only a small number of model simulations of the carbon cycle available using the most complex three dimension earth system models. A key issue that needs addressing is the size of the impact of other chemical species, such as nitrogen, on the climate-carbon cycle feedback.

Risk of Fire Activity
Models project further fire-related changes such as increased area burned, reduction in the mean age of the forest, and resultant changes in species composition and succession rates in tropical, temperate and boreal forests. These fires can act as a positive feedback on climate change because of the resultant long-term decrease in carbon storage. Significant increases in net ecosystem production (NEP) would be required over several decades to balance such carbon losses.

Climate Sensitivity
The AR4 concluded that the equilibrium sensitivity of the climate system to a doubling of CO_2 concentration in the atmosphere is likely to be in the range 2°C to 4.5°C, and is very likely to be above 1.5°C. Sensitivities above 4.5°C cannot be ruled out. There are currently a range of different estimates of the uncertainty in climate sensitivity, highlighting that the uncertainty estimates are themselves uncertain. Post AR4 it is still not yet clear which of these uncertainty estimates is most reliable.

Recent work by Hansen *et al.* (2008) reported that climate sensitivity should be viewed as having fast and slow components, the combination of which has a central estimate of 6°C. If this higher climate sensitivity were used in mitigation estimates it would imply a need for greater emission reductions than current IPCC WG3 estimates. However, it might not be relevant on time-scales of just a couple of centuries.

Reversibility of Climate Changes - Overshoot Scenarios
Some recent studies have discussed whether it is possible to temporarily cross potentially “dangerous” thresholds of atmospheric greenhouse gas concentrations (notably carbon dioxide) or temperature rise before returning quickly to lower safer levels in the future. Several post-AR4 studies now show that in overshoot scenarios, once a peak temperature is reached recovery is very slow, even with drastic subsequent emission reductions. The strong correlation between peak temperatures and cumulative emissions in mitigation scenarios has also been demonstrated, and this may lead to an approach to setting very long term (post 2050) targets.

Work on climate change reversibility has not been limited to atmospheric greenhouse gas concentrations and temperature. Recent work has further examined the irreversibility of Greenland ice sheet decline and long term committed warming to ecosystems.

3.2 CLIMATE IMPACTS

The IPCC AR4 presented new evidence showing the consistency between observed climate change and observed impacts, but there is still a lack of studies performing the type of formal detection and attribution studies used in climate science. Information is becoming available for more regions, but there are still gaps on many local impacts in some parts of the world.

The AR4 did summarize the impacts for particular temperature increases and mapped these on to stabilization temperatures, but it did not link this to particular mitigation pathways over the coming decades. This has since been attempted but a detailed integration of local climate change and impacts over the entire globe is still at a relatively early stage. Many current integrated assessment models still use impact information that pre-dates even the IPCC AR4.

Coastal systems

New results suggest that even if the upper estimates of sea level rise (up to 2m) are correct, adaptation would be a rational response for more developed coasts, where the threatened assets and populations are large. Recent assessments of long-term responses in the Thames estuary and the Netherlands support this view. Despite the global and regional models supporting the need and benefits of adaptation, many countries in Europe are ill prepared for these challenges at the present time.

Ecosystems

Observational and modeling based studies of both plants and animals in both terrestrial and marine systems continue to support the IPCC statement that approximately 20-30% of plant and animal species assessed so far are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2°C to 3°C above pre-industrial levels. There is increasing evidence of changes in phenology, abundance, morphology, and reproduction especially in temperate and arctic regions. This shows that the direction of changes projected by the extinction models is now supported even more strongly by observations than it was in AR4. There are also an increasing number of projections of extinction risks in the literature across an ever widening range of taxa and regions. Of particular concern is that over 20% of the wild relatives of peanut, potato and cowpea are at risk of climate-change induced extinction. These are an important source of genetic diversity for crop improvement. However, a number of other processes are occurring in ecosystems that are not included in these models and mean that projected extinctions might be underestimated.

Water resources

A great many papers have been published since the AR4 assessing the potential impacts of climate change on hydrological regimes and water resources. Whilst these have added case studies from areas previously poorly-represented - specifically Africa and Central and South America – there have been few new insights into the effects of climate policy on impacts on water resources, on the identification of critical thresholds or rates of change, or on impacts across the global domain. Only one study, for example, has compared impacts under different climate policies, demonstrating that considerable impacts remain after the successful implementation of a (relatively stringent) climate policy.

Agriculture and food security

There have also been many more published case studies into effects of climate change on crop productivity at an increasingly diverse number of sites. However, again there have been very few studies looking at climate policy effects. Overall, the tone of the post-AR4 literature is more pessimistic than that of the AR4, largely due to an increased understanding of the role of pests, extreme events, and changes in ozone concentrations, on either increasing the adverse effects of climate change or offsetting the positive effects.

Human health

Echoing the case with water resources and agriculture, since the AR4 there have been many new case studies into health impacts of climate change, but few new insights over an increased recognition of the effect of local conditions on actual impacts, and an increased concern with the combined effects of climate change and local air quality issues.

3.3 ECONOMICS OF MITIGATION

The IPCC assessment of climate change mitigation (Working Group 3) developed the concept of economic mitigation potential, which represents emission reductions that can occur in a realistic market situation, without economic losses and taking social non-market costs into account. It is lower than the technical mitigation potential, which calculates reductions possible with existing technology at any cost. The precise definition of these terms allowed clear comparison of the potential to reduce emissions across different sectors, timescales and levels of carbon price. The buildings sector had the highest economic mitigation potentials, especially at low carbon prices, while a synthesis of modeling studies showed cross sectoral emissions could be cut by between one fifth and a half by 2030, with carbon prices up to US$ 50/tCO_2-eq. Published assessments of mitigation potentials and economic costs of mitigation have not changed substantially since the Fourth Assessment, but the financial crisis has changed the economic backdrop dramatically. A notable deficiency in IPCC AR4 was the lack of using some of the latest climate science information from WG1 in the mitigation analysis of WG3.

Economic mitigation potentials

Some updates on technical mitigation potential have been produced since the IPCC AR4, for instance the updating of the McKinsey marginal abatement curve. However, assessments of the economic potential for mitigation of global GHG emissions have not changed greatly since AR4. Literature continues to emphasize the key role of energy efficiency in climate mitigation but also to highlight that the energy savings may be significantly offset (e.g. 26% in the UK and 52% globally) by the rebound effect whereby energy efficiency is offset by increased consumption.

Macroeconomic costs of mitigation

Studies of macroeconomic costs of mitigation continue to emphasize that these are relatively small e.g. the ADAM project range of -2.3 to +2.5% change in baseline GDP for stabilizing at 450-550 ppm CO_2-eq. Several new studies show costs of around 1% GDP, or even macroeconomic benefits, for stabilization of greenhouse gas concentrations between 710 and 445 ppm CO_2-eq.

Carbon prices necessary for greenhouse gas stabilisation

The carbon price necessary to achieve a particular stabilisation target remains uncertain. Recent global studies have estimated that stabilising at 550 ppm CO_2 eq requires a price of $50 - $100/t$CO_2$, while stabilising at 450ppm needs a carbon price between $100 and $500/t$CO_2$.

Cost reductions from including non-CO_2 mitigation

Studies continue to emphasize large cost savings from including non-CO_2 GHGs in mitigation strategies, especially when technological change is simulated. Abatement measures for non-CO_2 greenhouse gas emissions are amongst the most cost-effective in the short term (to 2020). Some authors argue that reductions of non CO_2 GHGs are essential in order to bring lower stabilization targets within reach. The most cost effective options involve reducing emissions of fluorinated gases and energy related methane.

Costs of inaction

Studies continue to highlight that there is high uncertainty about the damage costs due to climate change, and that these, and hence the 'optimal' levels of abatement calculated by some models, are strongly influenced by subjective choices of model parameters. Since the Stern Review, the balance of the literature has shifted towards emphasising potentially high costs, for example due to extreme weather events.

Land use

Incorporating land use changes such as reduced deforestation and degradation is a crucial part of a post-2012 agreement, without which targets are unlikely to be met. The costs of mitigation through land use change are comparable to costs of other mitigation options.

Financial crisis

The financial crisis is an opportunity to invest in climate change mitigation, through stimulus packages. If 20% of the global economic stimulus package was focused on mitigation, the investment would be similar to the estimated abatement costs required to stabilise greenhouse gases at 500 ppm. Climate policy is likely to increase the number of jobs in the medium term and possibly also in the short term.

Existing business-as-usual emissions scenarios

Emissions are increasing in China and India faster than previously expected. However, although some studies indicate that future global emissions may already exceed the range of the current IPCC emission scenarios, these studies may be flawed. Thus, at this time the SRES scenarios are still broadly representative of plausible ranges for future global emissions without climate policy. New baseline scenarios are being developed for the IPCC's Fifth Assessment Report, and a recent study developed a baseline that exceeds the SRES envelope by 2030.

Strategies and pathways to emission reduction

Developing countries must be as fully integrated as possible in a post-2012 climate agreement in order to maximize the chance of meeting challenging targets. Early assessments show that the EU ETS is working to reduce European carbon emissions, but is not yet as effective as it could be. It has been argued that emissions allowances should be auctioned, not freely allocated, after 2012. Loss of competitiveness due to carbon pricing, and consequent leakage of emissions outside EU borders, is likely to be small and confined to a few specific industrial sectors.

4. ASSESSMENT OF GAPS IN THE LITERATURE

Doherty *et al.* (2009) recently reported on the Global Climate Observing System program (GCOS), the World Climate Research Programme (WCRP), and the International Geosphere-Biosphere Programme (IGBP) summaries of the lessons learned through AR4 Working Groups I and II. The authors also highlighted several specific research themes that require further investigation. We have combined these gaps with those highlighted by the technical summary of IPCC AR4 (Working Group II) and the outputs of a one-day workshop held by 4CMR set up to identify gaps in the economics literature.

The table below shows gaps noted in the literature for climate science and climate impacts. The table also highlights some of the progress that has taken place or that is planned in order to fill these gaps.

RESEARCH GAP	PROGRESS AND/OR COMMENTS
Need to constrain the global climate sensitivity	There is a critical need to improve understanding of the processes involved in aerosol indirect forcing (e.g., aerosol transport, convective processes, cloud formation and dissipation) and to represent them reliably in climate models. At a minimum, an upper bound on aerosol indirect effect radiative forcing both for the past and near future should be determined through a combination of model comparisons and measurements.
Need to reduce uncertainties in sea level rise projections	An immediate community initiative should be established that uses physical process studies, observations, and syntheses to obtain a consensus on the possible nonlinear responses of ice sheets to climate change, including their influences on rates of sea level rise.
Efforts are needed to improve the ability of models to reproduce fundamental aspects of the climate system, such as circulation and precipitation patterns, El Niño, and seasonal variability, as well as to reproduce other impact-relevant variables such as extremes in temperature and precipitation.	Many modelling centres are developing new or improved versions of their climate models ahead of IPCC AR4. Many involve higher resolution and additional processes. It is important that more impact related quantities are included in model intercomparison projects.
In AR4 most impacts studies used only the A2 or B2 socioeconomic scenarios: the 'Fast Track' work originating from some members of this Consortium was the only study which comprehensively	In the AVOID project and in ongoing research a wider diversity of baselines is now being used, but much of this work is not yet published. The CIAS integrated assessment model and the QUEST GSI project will

addressed the full range of SRES scenarios	continue to deliver assessments over a range of socioeconomic scenarios in the future.
More detail required on projected climate and impacts and uncertainties therein at regional and local scales.	This still remains a significant gap, due to the difficulty of producing climate projections at such small scales that encapsulates the uncertainty. UKCP09 made a major advance in this direction but covers only the UK. The PRUDENCE study produced downscaled climate projections for Europe using a variety of coupled GCM/RCMs but neither of these works has yet been extended to examine impacts. The downscaled climate projections used in AVOID are state of the art and thus AVOID will be one of the few studies which uses a globally consistent method.
Land surface processes and biosphere–atmosphere interactions need to be included in regional projections of climate	Some new studies are appearing, as cited here, but most models still do not include these processes adequately. To assist progress, there is a need to develop and apply a consistent, harmonized set of scenarios of land use, land cover, and emissions databases to support both the climate and integrated assessment communities, with consistency across spatial and temporal scales, and considering both historic and future time scales.
Scenarios needed for abrupt climate change, including quantification of uncertainties	UKCP09 has produced an extreme sea level rise scenario. Literature on possible extreme sea level rises has grown (sea level rise section). NERC and EU funded projects are looking at aspects of MOC collapse and ice sheet changes. Further work needed.
Scenarios needs on a 10–30-yr time scale, including quantification of uncertainties.	In AR5 there will be a particular focus on this time-scale. On approach uses extended runs of decadal forecasting systems, such as those being evaluated in the ENSEMBLES project.
Scenarios for beyond 2100 (esp. for sea level rise) including quantification of uncertainties	Literature on extreme sea level rise beyond 2100 has grown. Whilst climate projections exist beyond 2100, socioeconomic projections are not feasible on this timescale. Impacts projections beyond 2100 are dependent on socioeconomics, except (to some extent) in the case of ecosystem impacts.
Tools and techniques needed to manage large quantities of data from climate model ensembles	Probabilistic models are being developed which encapsulate this uncertainty (e.g. the probabilistic version of MAGICC used in AVOID). The integrated model CIAS (also used in AVOID) can encapsulate climate model uncertainty and links it to impacts. Using the data from GCM ensembles will be more challenging.
Damages avoided by different levels of emission reduction	There is still almost no literature on this and AVOID is breaking new ground in producing it.
Better ability to project changes in precipitation	Observations and novel technology should be utilized to better understand variations in the hydrologic cycle, both in the very short term and sustained over decades,

	in particular with respect to extremes.
Better ability to project changes in extreme weather events	Improvements are needed to GCMs. Going to higher resolution will increase the computational cost of these model.
Better understanding of carbon cycle feedbacks needed, in particular for possible Amazon rainforest collapse	Efforts are needed to improve process modelling and understanding of feedbacks in the carbon cycle across the earth system. These will require 1) a denser and more evenly distributed network of sustained in situ and remote sensing observations of carbon-related variables on land, in the oceans, and in the atmosphere, and 2) improvements to carbon-cycle models.
Field studies to evaluate the impacts of climate change on human systems and ecosystems	There is some more literature in this area but more is still needed. Climate and impact-relevant observational data records should be 1) reprocessed (as needed) to reflect new knowledge and to improve the flagging of errors and estimation of biases, and 2) made available as global, gridded fields.
Adaptation not incorporated into climate change impact estimates	This continues to be a problem, but since adaptation is a policy choice a better method would be to show adaptation options and their costs. The coastal projections in AVOID WS1 adopt such an approach, as does the PAGE model.
Datasets must be expanded to include observations of climate change impacts on human and natural systems	Observations of impacts should especially be made 1) in regions that have been identified as being highly vulnerable and 2) in regions that represent both weak and strong adaptive capacity.
Datasets must be expanded to include autonomous and planned adaptation to climate change	As above
A systematic approach must be established specifically to monitor and assess vulnerability.	
What enhances resilience and what predisposes vulnerability to irreversible climate change impacts?	Limited understanding needs to be extended
Costs of climate change impacts	The literature is growing slowly but this is still a gap.
Costs of adaptation	The literature is growing but this is still uncertainty.

Although many of these research needs are focused on the requirements of adaptation planning, they also have implications for mitigation decisions and avoiding dangerous climate change. While the adaptation agenda is starting to focus more on the time scale of the next 30 years, mitigation advice and avoiding dangerous climate change also needs information on longer timescales, including on the reversibility of changes in atmospheric forcing, temperature and sea level rise.

Gaps in the economic literature

Some of these gaps were highlighted at a workshop organised by 4CMR and The Royal Society, during the Copenhagen Climate Congress in March 2009: *Mitigation of climate change: filling the knowledge gaps revealed by the Fourth Assessment Report.* Others have been suggested by economists at 4CMR.

- We need increased effort using and comparing the results of Integrated Assessment Models (IAMs), which couple dynamic models of the economy with models of climate change to inform climate policy. One new review of 30 existing IAMs finds that none of them yet incorporates all the features that would be considered best practice.
- Indirect economic impacts of climate change need further assessment.
- Co-benefits of mitigation (air quality, health, employment, biodiversity...) were emphasized in the AR4, but we still need to quantify and monetise them and integrate them into economic analyses.
- There is an inadequate treatment of risk and uncertainty.
- There is not enough assessment of stringent mitigation pathways, such as to stabilise at 400 ppm CO_2-eq.
- The economic baseline has changed, due to the financial crisis. As yet there is little assessment of how this affects mitigation costs.
- Research on political economy is weak and poorly integrated. We need to understand better how human systems behave and what can actually be delivered.
- Different instruments such as taxes/trading systems must be compared.
- Research on the economic potential of advanced mitigation technologies is needed.
- We need better emissions data and projections, especially for developing countries.
- The economic potential for negative emissions (e.g. biomass plus sequestration) remains to be thoroughly investigated.

5. CONCLUSIONS

There is clearly a great deal of information available on climate change and mitigation, both in the IPCC AR4 and subsequently. For instance, 33480 publications are listed in the ISI web of science database since 2007 with a topic that includes “climate”. This review presents a small subset of these publications, selected and interpreted by experts in climate change science, impacts assessment and climate mitigation economics.

The central message from the review is that although there is a lot of information available there are still unanswered questions on the amount of future warming for a given set of emissions and the precise impacts it will trigger. There is also uncertainty on the options available for action and how much they will cost. The consequence of this message is NOT that there is insufficient information to justify a global agreement on limiting climate change. There is strong evidence that climate is already changing, that impacts of climate change are likely to be predominantly negative, and that more severe impacts are likely to be encountered as warming continues. There is also a growing understanding of technologies to lower greenhouse gas emissions in the short and long terms. However, our results do imply that flexibility to adjust any future global agreement would be prudent as information gaps are filled in.

APPENDICES

A. CLIMATE CHANGE SCIENCE

The IPCC AR4 was a step forward on the third assessment report. Longer observational records and more observed quantities were analysed. The increasing climate change signal meant that more definite attribution results could be established. More climate models were available for the AR4, and more complex models were also available. This enabled more statements to be made on the risks of a range of different warming levels and other climate changes. However, the increased focus on processes also highlighted the limitations that remain in projecting climate change and its impacts.

In the following subsections we discuss recent progress in the areas of climate science that are most relevant to avoiding dangerous climate change. The concept of tipping points in the climate system has particular relevance to the issue of avoiding dangerous climate change. A post-AR4 review by Lenton *et al.* (2008) attempted to summarise current understanding in this area, looking at a range of physical systems. Their summary table is shown below and provides a useful indication of recent scientific understanding of some key system thresholds.

This work was extended by Kriegler *et al.* (2009), who attempted to provide probabilities for these dangerous climate changes using expert opinions as their input. Caution has to be placed on such a subjective approach. However, it is beyond the scope of this report to update the Lenton table using more objective methods so we instead highlight key issues in a range of relevant research areas. WS2 of AVOID will provide detailed objective information on many aspects of dangerous climate change.

We also draw the attention of the reader to the recent publication of the UKCP09 study (Murphy *et al.* 2009 and Lowe *et al.* 2009) which, although focused on the United Kingdom, highlights new techniques for estimating uncertainty in future climate change projections.

Table 1. Policy-relevant potential future tipping elements in the climate system and (below the empty line) candidates that we considered but failed to make the short list*

Tipping element	Feature of system, F (direction of change)	Control parameter(s), ρ	Critical value(s),† ρ_{crit}	Global warming†‡	Transition timescale,† T	Key impacts
Arctic summer sea-ice	Areal extent (−)	Local ΔT_{air}, ocean heat transport	Unidentified§	+0.5–2°C	~10 yr (rapid)	Amplified warming, ecosystem change
Greenland ice sheet (GIS)	Ice volume (−)	Local ΔT_{air}	+~3°C	+1–2°C	>300 yr (slow)	Sea level +2–7 m
West Antarctic ice sheet (WAIS)	Ice volume (−)	Local ΔT_{air}, or less ΔT_{ocean}	+~5–8°C	+3–5°C	>300 yr (slow)	Sea level +5 m
Atlantic thermohaline circulation (THC)	Overturning (−)	Freshwater input to N Atlantic	+0.1–0.5 Sv	+3–5°C	~100 yr (gradual)	Regional cooling, sea level, ITCZ shift
El Niño–Southern Oscillation (ENSO)	Amplitude (+)	Thermocline depth, sharpness in EEP	Unidentified§	+3–6°C	~100 yr (gradual)	Drought in SE Asia and elsewhere
Indian summer monsoon (ISM)	Rainfall (−)	Planetary albedo over India	0.5	N/A	~1 yr (rapid)	Drought, decreased carrying capacity
Sahara/Sahel and West African monsoon (WAM)	Vegetation fraction (+)	Precipitation	100 mm/yr	+3–5°C	~10 yr (rapid)	Increased carrying capacity
Amazon rainforest	Tree fraction (−)	Precipitation, dry season length	1,100 mm/yr	+3–4°C	~50 yr (gradual)	Biodiversity loss, decreased rainfall
Boreal forest	Tree fraction (−)	Local ΔT_{air}	+~7°C	+3–5°C	~50 yr (gradual)	Biome switch
Antarctic Bottom Water (AABW)*	Formation (−)	Precipitation–Evaporation	+100 mm/yr	Unclear¶	~100 yr (gradual)	Ocean circulation, carbon storage
Tundra*	Tree fraction (+)	Growing degree days above zero	Missing‖	—	~100 yr (gradual)	Amplified warming, biome switch
Permafrost*	Volume (−)	$\Delta T_{permafrost}$	Missing‖	—	<100 yr (gradual)	CH_4 and CO_2 release
Marine methane hydrates*	Hydrate volume (−)	$\Delta T_{sediment}$	Unidentified§	Unclear¶	10^3 to 10^5 yr ($>T_E$)	Amplified global warming
Ocean anoxia*	Ocean anoxia (+)	Phosphorus input to ocean	+~20%	Unclear¶	~10^4 yr ($>T_E$)	Marine mass extinction
Arctic ozone*	Column depth (−)	Polar stratospheric cloud formation	195 K	Unclear¶	<1 yr (rapid)	Increased UV at surface

N, North; ITCZ, Inter-tropical Convergence Zone; EEP, East Equatorial Pacific; SE, Southeast.

*See *SI Appendix 2* for more details about the tipping elements that failed to make the short list.

†Numbers given are preliminary and derive from assessments by the experts at the workshop, aggregation of their opinions at the workshop, and review of the literature.

‡Global mean temperature change above present (1980–1999) that corresponds to critical value of control, where this can be meaningfully related to global temperature.

§Meaning theory, model results, or paleo-data suggest the existence of a critical threshold but a numerical value is lacking in the literature.

¶Meaning either a corresponding global warming range is not established or global warming is not the only or the dominant forcing.

‖Meaning no subcontinental scale critical threshold could be identified, even though a local geographical threshold may exist.

A.1 Detection and Attribution of Climate Change

The IPCC fourth assessment report (AR4) came to a more confident assessment of the causes of global temperatures than previous reports and concluded that "most of the observed increase in global average temperatures since the mid-20th century is **very likely** due to the observed increase in anthropogenic greenhouse gas concentrations", (where very likely means> 90% probability of the statement being correct). This is an advance since the Third Assessment report, which concluded that "most of the observed warming over the last 50 years is **likely** to have been due to the increase in greenhouse gas concentrations" (where likely means > 66% probability). The AR4 also concluded that "discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes, and wind patterns." In addition AR4 reported that "it is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica".

Since the publication of AR4 in 2007, warming over Antarctica has been attributed to human influence (Gillett *et al.* 2008) meaning that **anthropogenically forced temperature changes have now been detected on every one of the seven continents**.

Changes in climate other than temperature have now been attributed to human influence. For example, Santer *et al.* (2006) have shown from satellite data that the atmosphere is getting moister, as predicted by models under global warming, and have attributed this moistening to human influence. Zhang *et al.* (2007) attributed **latitudinal redistribution of precipitation** to human influence. The magnitude of change in the observations could be greater than those simulated in climate models. Barnett *et al.* (2008) detected human-induced changes in the hydrology of the Western United States.

We now have a greater confidence in the conclusion that emissions have had a significant impact on the climate system, because an important caveat made at the time of AR4 has been removed. At the time of AR4 there were discrepancies between observed and modelled estimates of ocean heat content variability. This discrepancy has now been shown to be due to instrumental biases that have now been corrected (Domingues *et al.* 2008).

Thus, important advances have been made since the AR4, with attribution now extending beyond temperature variables and showing physical consistency between observed and simulated temperature and hydrological cycle changes, underscoring the reality of human effects on climate.

Attribution analyses are also now extending to regional scales and to extremes. New methodologies are being developed for detection of regional scale changes including better use of observations and models (Christidis *et al.* 2009) and the use of experiments forced by observed sea surface temperatures to calculate the changed probability of particular events, such as a flood or a heatwave, to human influence.

A.2 Changes in Temperature and Rainfall Extremes

The AR4 concluded that "it is very likely that hot extremes, heat waves and heavy precipitation events will continue to become more frequent". Frost days are projected to decrease in frequency, and growing season length to increase. Most GCMs predict drier summers and wetter winter conditions, so along with an increased risk of drought there is also an increased risk of short but heavy flood causing precipitation events.

(a) Temperature

A key area of progress since AR4 has been the finding that large-scale climate variability (e.g. the North Atlantic Oscillation (NAO), El Nino-Southern Oscillation (ENSO), and Pacific interdecadal variability) has a substantial influence upon temperature extremes (Kenyon and Hegerl 2008). In particular, the NAO is found to have a significant influence on extreme winter daily temperatures, causing changes of the same magnitude as projected changes in future extremes (Scaife *et al.* 2008). Since our ability to predict changes in large-scale circulation patterns and teleconnections is currently limited, this has implications for our ability to project climate extremes.

Brown *et al.* (2008) found that extreme daily maximum and minimum temperatures warmed for most regions since 1950. The largest positive trends were found over Canada and Eurasia where daily maximum temperatures warmed by around 1 to 3°C since 1950.

Human influence has at least doubled the risk of such a not European summer as 2003 (Jones *et al.* 2008). In this study simulated changes were consistent with observed changes over the recent period, and by the 2040s projections show that summers over southern England could be at least as warm as 2003 on average 50% of the time.

A key advance has been the first estimation of the potential for mitigation to avoid increases in extremes. If atmospheric CO_2 concentrations were stabilized at roughly 450ppm by the end of 2100 without an overshoot, the change in intensity of heat waves could be 55% less than in a reference scenario (Washington *et al.* 2009), with the biggest reductions in heatwave intensity found over the western United States, Canada, and much of Europe and Russia.

(b) Precipitation

Quantifying precipitation extremes remains a more challenging task than for temperature extremes. Annual to multi-decadal variability can contribute a significant level of uncertainty to future projections of local precipitation extremes in Europe (Kendon *et al.* 2008). It has been shown that relative changes in the intensity of precipitation extremes tend to exceed the relative change in annual mean precipitation (Kharin *et al.* 2007). For example, an increase of 6% in 20-year return values of 24 hour precipitation could be expected with each one degree of global warming.

A.3 Recent Changes in Arctic Sea Ice

A minimum arctic sea ice extent was observed in 2007, and this appears to have been the result of an abnormal atmospheric blocking pattern which maintained cloud free skies for several weeks in the summer. Recently there has been a great deal of interest in the observed decline in Arctic sea ice and the ability of models used in the IPCC AR4 to make credible climate change simulations of arctic ice.

Stroeve *et al.* (2007) compared the sea ice simulations in many of the GCMs used in AR4. They found that most climate models underestimate the trend over 1979-2006. However a few models, including HadGEM1, reproduce the observed trend well, where the linear trends in the model and observations are statistically indistinguishable. Stroeve *et al.* also noted that the models with better simulation of ice extent trends include relatively sophisticated sea ice physics, particularly the representation of variable ice thicknesses within a gridbox, that was introduced in HadGEM1. Improved sea ice physics has also been shown to have improved the mean Arctic sea ice simulation in HadGEM1 (McLaren *et al.* 2006).

It is also not certain that the recent observed trend is exceptional. 20th Century simulations using HadGEM1 suggest that a similar trend may have occurred in the 1920s during an earlier warm period in the Arctic. However the observations during this period are not considered good enough to evaluate this properly.

The majority of climate model projections for the 21st Century suggest an ongoing decreasing trend of ice extent, but do not suggest any obvious thresholds or rapid events. However, some models, such as a version of that from NCAR, show occasional rapid changes in ice extent, from which the ice does not recover. A recent study by Boé *et al.* (2009) attempted to use an apparently more robust feature of climate model results, the ratio of the future rate of sea ice decline to the past rate of decline, from 18 models and combine it with the observed rate of recent sea ice decline. While this study predicts that the Arctic will be ice free during Septembers sooner than many of the climate models suggest on their own, this is not projected to occur until after 2050 for a business as usual scenario emissions scenario.

A.4 Sea Level Rise and Ice Sheets

There has been an observed acceleration in sea level rise in recent years, but it is not yet clear if this will continue in the future. Current process models have only limited skill in making projections of the contribution to future sea level from ice sheets, but some lines of evidence indicate that the 21st century sea level increase is unlikely to exceed 2m. In contrast, Hansen (2007) believes that much larger sea level rise is possible (> 2m by 2100). Several new studies are attempting to make improved projections of the most likely future sea level but these are not yet complete. Against this backdrop of uncertainty there is a need to continue monitoring sea level and to ensure adaptation plans are in place to deal with any further acceleration in the rate of sea level rise.

The latest IPCC Fourth Assessment report (AR4) presents a range for global mean sea level rise over the 21st century based primarily on projections by an "ensemble of opportunity" of coupled climate models under a number of future SRES scenarios. This range is given as 0.18m to 0.59m. The major part of this sea level increase is attributed to thermal expansion. The remainder is provided by the melt of glaciers and ice caps, and small projected changes in the net contribution from the Greenland and Antarctic ice sheets. The AR4 noted that the uncertainty in the contribution of the ice sheets is relatively large, and provided a simple estimate of how much the recently observed increase in the contribution to sea level from ice sheets would make if this term continued to increase with rising temperatures. This suggested up to a further 17cm of sea level rise would be expected by the end of the 21st century. Crucially, The IPCC Synthesis Report made clear that due to the large and poorly quantified uncertainties, an upper bound for sea-level rise during the 21st century could not be reliably established.

Since the IPCC report several new studies have been initiated with the aim of producing more credible future sea level scenarios, with land ice dynamics and ice shelves accounted for, by the time of the next IPCC assessment. These studies include the EU funded ICE2SEA project and the US study called seaRISE. The most significant publications on sea level projections that have appeared since the IPCC report have focused on three key areas: Observational studies of sea level and the ice sheets, Model studies based on statistical techniques and Process model studies and constraints on sea level rise.

(a) Observational studies of sea level and the ice sheets

IPCC, 2007 noted a rate of sea level rise between 1961 and 2003 of approximately 1.8 mm/yr, with an increase to approximately 3.1mm/yr between 1993 and 2003. Similar accelerations of sea-level rise have been observed earlier in the 20th Century but they were followed by a subsequent decrease in the rate, giving the lower long-term average.

Recent satellite measurements have identified retreat of the Amundsen Sea, part of the West Antarctic Ice Sheet, has been thinning rapidly in the past two decades. Glacier flow rates have also been measured to be increasing in the Pine Island area of Antarctica. Gravity satellite measurements from the GRACE study estimate that Greenland and Antarctica are now losing mass at a rate of about 150 cubic kilometres annually. A recent study presented at the IOP conference in Copenhagen suggests that Greenland has been losing 265 cubic kilometres annually between 1995-2007, leading to sea level rises of 0.7+/-0.2 mm/yr (Mernild 2009). However, this must be balanced by evidence presented by Tavi Murray and colleagues at the AGU fall conference in 2008 (Kerr, 2009). These authors showed evidence of a recent slow down in a number of Greenland glaciers.

Thus, it is currently unclear if the recent acceleration in sea level rise will continue in the future. Further observation and improved process understanding are required to be confident that recent ice sheet changes represent a systematic acceleration, rather than a short-lived temporary change. Nonetheless, recent observations still raise major concerns in terms of increasing impacts and the need to adapt

(b) Model studies based on statistical techniques

A number of recent studies have used statistical techniques to estimate future sea level based on past changes. The most notable are Rahmstorf (2007) and Grinstead *et al.* (2009), with the former author providing an update on his work at the recent IOP conference in Copenhagen. These methods typically develop “transfer functions”, relating past temperature change to past sea level change. By combining these functions with future temperature projections from climate models it is possible to estimate future sea level rise. The most recent Rahmstorf work concluded that 21st century sea level rise would likely be in the range 75cm to 190cm.

While these type of studies do provide evidence that sea level may rise above the IPCC, 2007 projection range, they are not process based models and have a critical limitation. As Hansen (2007) points out, these types of projections assume that the balance of processes in the “tuning period”, typically the 20th century and part of the 19th century, must also apply during the 21st century. Whereas, current process understanding suggests that to achieve the largest sea level rise projected by these methods will require an increase in the ice sheet contribution relative to thermal expansion. Simulating this requires a more sophisticated modelling approach. Thus, the statistical methods are of limited use in addressing 21st century sea level rise.

(c) Process model studies and constraints on sea level rise

The volume of ice within the West Antarctic Ice Sheet available for relatively rapid collapse into the ocean has been considered as up to 6 m since the work of Mercer (1978) first raised this threat in 1978. A recent assessment of this volume using much better data, suggests that the volume available for collapse is only equivalent to 3.3 m of global sea-level rise (Bamber *et al.* 2009). While this reduces the available volume, it is still large enough to be of major concern, especially since the coasts of N America and the Indian Ocean would both experience a disproportionately large sea level rise due to changes in the earth's spin axis resulting from the movement of such a large volume of ice from Antarctica to the oceans.

Hansen (2007) 'finds it almost inconceivable' that climate change would not increase sea level by 'the order of metres' by 2100. He believes this largely because of his understanding of the dynamics of ice sheets, involving strong non-linearities and feedback processes which are not included in current models. Such non-linearities would include warming-induced loss of buttressing ice-shelves where glaciers meet the sea. A counter argument to Hansen is found in the palaeoclimatic work of Rohling *et al.* (2008) who examined sea level change in the last high stand of sea level about 100,000 years ago. During this period, ice masses and configuration of the ice sheets were similar to those existing today. Rohling *et al.* find a maximum rise in sea level during this analogue period of 1.6 +/-0.8 m/century

A modelling study of the kinematics of glaciers in Greenland and Antarctica have recently placed an upper limit of 2m upon sea level rise by 2100 (Pfeffer *et al.* 2008). This is based on an examination of the fluxes and discharges necessary to reach various sea level rise 'targets', and assuming that the velocity of glaciers cannot exceed the upper limit of that which has so far been observed. This particular study suggests that a 0.8m sea level rise by 2100 is the most likely value.

A recent study by Nick *et al.* (2009) applied a process based model to a single Greenland glacier, Helheim. The authors concluded that acceleration of the glacier's flow rate may be followed by a period of slower flow. From this they conclude that extrapolating recent observed increases in glacier characteristics might not give reliable sea level projections. Progress has also been made by Schoof (2007), who demonstrated a numerical technique for simulating a marine ice sheet grounding line, and predicted an instability (i.e. rapid sliding) should the bedrock slope downwards towards the ice sheet interior. Several modeling groups are now developing robust algorithms to include a two-dimensional description of the grounding line for inclusion in their general ice sheet models.

Thus, while an upper limit on 21st century sea level rise of around 2m is emerging from two different evidence sources, there is also evidence that the most likely sea level rise might be considerably lower. Current understanding also still suggests that increases in sea level rise initiated during the 20th and 21st century are likely to continue for at least several hundred years, even with significant mitigation of emissions taking place.

A.5 The Atlantic Ocean Meridional Overturning Circulation

The Atlantic Ocean has a Meridional Overturning Circulation (MOC), which transports large amounts of heat northwards in the Atlantic from the Equator. A key part of this is called the thermohaline circulation (THC) Disruption of the MOC would have a major impact on the Northern hemisphere climate, with likely detrimental impacts on human and animal systems. The IPCC AR4 concluded that "… it is very likely that the Atlantic Ocean Meridional Overturning Circulation will slow down during the course of the 21st century. A multi model ensemble shows an average reduction of 25% with a broad range from virtually no change to a reduction of over 50% averaged over 2080 to 2099."

The key advance since AR4 is in the observations: Cunningham *et al.* (2007) reported the results of the first-ever sustained monitoring of the MOC at 26°N through the RAPID array, quantifying the inter-seasonal variability of the MOC at this latitude. The results indicated that the five historical estimates of the strength of the MOC by Bryden *et al.* 2005 all fall within the (large) inter-seasonal variability. It was previously through, from 5 historical 'snapshot' observations, that a long-term weakening trend could be observed since the 1950s. The new result suggests that this might not in fact be the case. Similarly, Clarke at el. (2009) studied a palaeoclimatic cooling event 8.2 thousand years before present, and found no associated collapse in MOC. There are however, still many other palaeoclimatic events (such as the Younger Dryas) which were associated with MOC collapse.

Until the joint NERC-Met. Office RAPIT project delivers, there is still no systematic, formal risk assessment of THC shutdown, but new work has looked at how changes in other climate features such as Arctic sea ice might affect it. Such processes have different representations or are absent in GCMs.

Only a few GCMs are able to reproduce a state in which the THC remains shut down. One of these has recently been upgraded and can no longer sustain such a state, in common with most other GCMs (Yin and Stouffer 2007). Earth system models can reproduce such a state as a response to greenhouse gas emissions, and an important recent study (Mikolajewicz *et al.* 2007) found that the MOC collapsed in the high emission scenario (SRES A2) scenario, whilst under the low emission SRES B1 scenario, only a temporary weakening is predicted. The SRES A1B scenario brings the system close to its bifurcation point, with three out of five runs leading to a collapsed circulation. Scott *et al.* (2008) recently used a simplified 3D-coupled model to show that the stability of the MOC over the next 1000 years depends on the amount radiative forcing and the climate sensitivity. This updates earlier similar 2D work by Stocker and Schmittner. The MOC is less susceptible to collapse in the later 3D version.

In summary, the picture is still unclear as to whether a collapse in the MOC is likely to occur under future business-as-usual emissions scenarios. The most complex climate models provide some conflicting evidence, and simpler models, which have been used to produce risk estimates, may not be adequate to represent the processes involved.

A.6 The Carbon Cycle

Since the AR4, it has been found that (i) old growth forests continue to store carbon rather than being carbon neutral (Luyssaert *et al.*, 2008); and (ii) tropical forests, including old growth forests, are increasing the amount of carbon which they store annually as a result of climate change experienced so far (Phillips *et al.*, 2009; Lewis *et al.*, 2009). Several major carbon stocks in terrestrial ecosystems are at a high degree of risk from projected unmitigated climate change and land-use changes.

There are still only a small number of simulations of the carbon cycle available using the most complex three dimension earth system models, but this is set to change as modelling teams set up experiments ahead of AR5. A key issue that needs addressing is the size of the impact of other chemical species, such as nitrogen, on the climate-carbon cycle feedback.

Various studies of processes in different ecosystem types throw some light on how carbon cycle or other feedback processes (not included in many GCM simulations) might affect future climate change. For small amounts of climate change, a negative feedback might be expected, with additional carbon sequestered by vegetation, thus slightly reducing climate change (Bronson *et al.* 2009). Net primary production is modelled to have already increased (Del Grosso *et al.* 2008), and growing seasons and leaf area indices are generally predicted to increase for a small amount of climate change. However, albedo may decrease, causing a positive feedback, so overall effects of small climate change are unclear. For larger amounts of climate change, carbon cycle feedback processes noted in AR4 are expected to kick in which would slowly convert forest to grasslands, and so net primary production of grasslands and forests themselves would decrease significantly (De Boeck *et al.* 2008) and significantly exacerbate climate change.

Many studies examine feedback processes operating in forests.

(a) ***Amazon:*** Likely to contribute to positive feedback (i.e. increased climate change). Most models of the eastern Amazonia, particularly if corrected for their tendency to underestimate current rainfall, tend to demonstrate a reduction in dry season rainfall, which is widely expected to lead to dieback of 18% to 70% of the forest, or possibly conversion to a seasonal forest, depending on the model chosen, increasing its vulnerability to fire (Salazar *et al.* 2007; Cook & Vizy 2008, Malhi *et al.* 2008) and leading to a positive feedback on climate (Phillips *et al.*, 2008 and 2009). *Reducing deforestation would decrease vulnerability to fire*.

(b) ***Temperate regions:*** Overall effects unclear: processes of both positive and negative feedback. A high carbon uptake occurred during the autumn 2006 to spring 2007 warm period (Delpierre *et al.* 2009) but a subsequent hot summer would cancel this out (Granier *et al.* 2007; Reichstein *et al.* 2007; Vetter *et al.* 2008;

Scherrer *et al.* 2005). Temperate forest soil organic carbon may be released to the atmosphere as climate changes, depending on the type of forest (Rasmussen *et al.* 2008). Species composition of temporal and boreal forests changes with climate, for example in North America (Iverson *et al.* 2008) and in Siberia (MacDonald *et al.* 2008), and are likely to reduce carbon storage (Kellomäki *et al.* 2008, Kurz *et al.* 2008). Drought negatively affects deciduous temperate forest ecosystem productivity and thus its carbon balance (Noormets *et al.* 2008). The upward expansion of boreal forest might stimulate carbon sequestration in tree biomass (Kammer *et al.* 2009).

(c) ***Arctic & Montane****:* Large positive feedback expected. In the Arctic large reductions in carbon storage and fisheries services from aquatic ecosystems are expected (Wrona 2006). Some montane systems, particularly tropical montane cloud forest (Chang *et al.* 2008), high altitude bogs and some grasslands, such as those on the Tibetan Plateau (Yang *et al.* 2008), sequester large amounts of carbon in their soils, which are vulnerable to release by climate warming.

(d) ***Grasslands****:* Effects uncertain**.** New studies have looked at the feedback processes associated with the impact of climate change on grassland, but net effects remain uncertain. At regional and global scales, a changing climate may have a profound effect on the distribution of grasslands and savannahs. For example some models predict the replacement of Amazon tropical forest by savannahs (Salazar *et al.* 2007) whilst in Africa, savannahs which are a critical habitat for many of Africa's charismatic mega fauna, may be gradually taken over by forest and scrub if rainfall increases (Sankaran *et al.* 2005; Lucht *et al.* 2006; Blaum *et al.* 2007).

There is further evidence that the efficacy of the ocean in removing carbon from the atmosphere is likely to decrease. For the Southern Ocean, a weakening of the carbon sink has been observed during the last two decades and whether this trend may continue or reverse is uncertain (Le Quéré *et al.* 2007). Cox *et al.* (2002) projected that the ocean sink could peak by the end of the 21st century, and a new study now predicts that the ability of the oceans to absorb inorganic carbon could peak at around 5 Gt per year, and that this peak could be reached by the end of the 21st century (Cermeno *et al.* 2008). It is also thought that warming will lead to an additional decreased efficiency of ocean sink due to thermal stratification. Warming may enhance upwelling of nutrient rich waters along coastal areas which may positively or negatively affect ecosystems and hence the ability of these waters to absorb carbon (Harley *et al.* 2006; Svensson *et al.* 2005). Conversely, increased sea temperatures may inhibit upwelling and lead to dissolved oxygen deficiencies (Pörtner and Knust, 2007). The overall result is unclear.

Despite the advances in observation and modelling aspects of carbon cycle change there are still large gaps in our understanding of the interactions between climate change and the carbon cycle. For instance, nitrogen and ozone may have a significant impact on the climate-carbon cycle feedback (Thornton *et al.* 2007; Sokolov *et al.* 2008; Sitch *et al.* 2007). Key research requirements include better constraining of model simulated changes using observations, and improving our understanding of how other chemical cycles will impact on the carbon cycle on a global scale.

The uncertainty in carbon cycle modelling makes a major contribution to the total uncertainty in mitigation advice.

A.7 Risk of Fire Activity

Since the AR4, increased fire activity due to climate change arguably has already occurred (Achard *et al.* 2008).

Models project further fire-related changes such as increased area burned, reduction in the mean age of the forest, and resultant changes in species composition and succession rates in tropical, temperature and boreal forests (Kurz *et al.* 2008; Macias Fauria *et al.* 2008; McMillan *et al.* 2008). Examples include a doubling of area burned along with a 34-50% increase in fire occurrence is projected in parts of boreal forest by the end of this century (Girardin *et al.* 2008; Flannigan *et al.* 2009), and in increase in the number of days with fire danger conditions during the 21st century by a maximum of about 12-30% in Russia (Malevsky-Malevich *et al.* 2008). These fires will act as a positive feedback on climate change because of the resultant long-term decrease in carbon storage (Gough *et al.* 2008). Significant increases in net ecosystem production (NEP) would be required over several decades to balance such carbon losses (Kurz *et al.* 2008).

A.8 Climate Sensitivity

The AR4 concluded that the equilibrium sensitivity of the climate system to a doubling of CO_2 concentration in the atmosphere is likely to be in the range 2°C to 4.5°C, and is very likely to be above 1.5°C. Sensitivities above 4.5°C cannot be ruled out. There are currently a range of different estimates of the uncertainty in climate sensitivity, highlighting that the uncertainty estimates are themselves uncertain. Post-AR4, it is still not yet clear which of these uncertainty estimates is most reliable.

The most complex methodology is to combine 3D earth system model projections with a range of observational constraints, as in Murphy *et al.* (2004). Better understanding of cloud processes is needed to improve model estimates of climate sensitivity. Better observational estimates of climate sensitivity are likely to require improvements in ocean heat uptake measurement and, even more importantly, the better measurements of the magnitude of aerosol forcing (Andreae *et al.* 2005).

A recent estimate of climate sensitivity, using a new method that makes use of different response time scales in the earth system, was published by Schwartz (2007). His initial estimate was below the AR4's 1.5°C, but after criticism in the literature (e.g. Foster *et al.* 2008) a revised estimate of 1.9 ± 1.0 °C was produced (Schwartz 2008). This is more consistent with the AR4 but still below the central estimates of many of the studies reported therein.

There remains interest in how constant the climate sensitivity remains over time. Senior and Mitchell (2000) previously noted a change in sensitivity over time but a recent update by Williams *et al.* (2008) showed that taking a slightly different definition of radiative forcing reduces the apparent temporal variations in sensitivity. However, Brierley *et al.* (2009) present some conflicting evidence, showing a dependence of climate sensitivity in a GCM on the temperature.

Hansen *et al.* (2008) reported that climate sensitivity should be viewed as having fast and slow components. The fast component corresponds to the more usual view of climate sensitivity discussed above. The slow components are associated with long term changes associated with ice sheets and may not be relevant to projections of less than a few centuries. They are likely to be important when considering indefinite stabilisation. If this higher climate sensitivity were used in mitigation it would imply a need for greater emission reductions than current estimates.

For scenario projection using simple climate models the uncertainty distribution of climate sensitivity and the magnitude of the climate-carbon cycle feedback are both important. Huntingford *et al.* (2009) recently estimated that of these two uncertainties it is the climate sensitivity that dominates the total uncertainty. Therefore, continued efforts to reduce this uncertainty would be beneficial for mitigation studies.

A.9 Reversibility of Climate Changes - Overshoot Scenarios

Huntingford and Lowe (2007) discussed whether it is possible to temporarily cross potentially "dangerous" thresholds of atmospheric greenhouse gas concentrations (notably carbon dioxide, CO_2) or temperature rise before returning quickly to lower safer levels in the future. Such an overshoot policy might be deliberate, or may occur if society is unable to reduce emissions quickly enough to prevent a desired temperature target from being exceeded. Frame *et al.* (2006) highlight an interesting feature of climate system which means that the uncertainty in peak temperature is lower than in pure greenhouse gas concentration stabilization scenarios.

Several studies now show that in overshoot scenarios, once the peak temperature is reached, recovery is very slow, even with drastic subsequent emission reductions. This means that once overshooting of, for example, the 2°C target, occurs, it is likely to be many decades or even centuries before temperatures can be restored to below 2°C, even with very strong emission reductions.

For example: Matthews and Caldeira (2008) examined scenarios with large future emissions cuts using a single Earth system model of intermediate complexity (EMIC) and found that near-zero emissions were required to stabilize atmospheric near-surface temperature. It can be inferred that if extremely low emissions are needed for climate stabilization, then even lower (or zero) emissions will probably correspond to only very slow rates of recovery in global temperature.

Working Group 1 of the AR4 provides only limited coverage of `overshoot' scenario. For instance, Meehl *et al.* (2007) reported an experiment by Tsutsui *et al.* (2007) that prescribed reductions in atmospheric CO_2 concentrations by around 150 ppm over 100 years, and the associated derived temperature response gave a reduction of around 1 °C. While this used a complex climate model (the community climate system model), driving the model with prescribed CO2 concentrations again raises the question of whether such rapid reductions are actually feasible in terms of emissions.

IPCC AR4 WG1 also reported (in their figure 10.35) the results from five EMICs, and this same experiment set was analysed more fully later in Plattner *et al.* (2008). These authors used a scenario with emissions set to *zero* at 2100, by which time the atmospheric CO2 concentration had reached between 650 and 700 ppm. *Immediately following this extreme emissions reduction, atmospheric CO_2 concentration fell by only 50–100 ppm over 100 years. Further, between 2100 and 2300 the global average surface temperature levelled out in two of the models and began decreasing slightly in the other three.*

More recently, Solomon *et al.* (2009) also used an EMIC to derive long-term CO_2 and temperature response following emissions being set to zero. Their method also attempted to capture expected precipitation changes using a 'pattern scaling' method, although caution should be exercised as this methodology requires verification for long periods of slowly declining temperature.

Recently, Lowe *et al.* (2009) extended this work to more complex three dimensional earth system models, again finding slow atmospheric CO_2 and temperature decline rates. These authors then used large ensembles of simulations with a simple coupled climate–carbon cycle model to make probability estimates for the amount of time for which the global surface temperature might exceed critical warming thresholds. For a multi-gas emissions scenario that peaks emissions in 2015 before adjusting to a long-term reduction rate of 3% per year, there is around a 55% probability of exceeding a 2°C target above pre-industrial levels. Possibly of more importance is that ***we find a 30% probability that we would remain above this warming level for at least 100 years, and a 10% probability that the 2°C threshold may be exceeded for up to 300 years.*** The implications of this very slow rate of atmospheric CO_2 and temperature reduction for such a drastic emissions cut have considerable implications for the climate change debate.

Furthermore, House *et al.* (2008) showed that further emissions reductions beyond 2050 would also be needed to limit long-term temperature increases. Allen *et al.* (2009) demonstrated the strong correlation between peak temperatures and cumulative emissions in mitigation scenarios. **All of these studies imply that long term emission reduction, beyond 2050, will be required to constrain future warming.**

Work on climate change reversibility has not been limited to atmospheric greenhouse gas concentrations and temperature. For instance there has been significant work carried out on the reversibility of ice sheet deglaciation. The AR4 states that there is a global temperature rise threshold, between 1.9ºC to 4.6ºC (Gregory and Huybrechts, 2006), above which the Greenland ice sheet surface mass balance becomes negative. If the threshold temperature is sustained it will lead to the irreversible decline of the ice sheet and a sea level rise of approximately 7m. New work on the irreversibility of Greenland ice sheet decline (Ridley *et al.*, submitted), looks at the capacity of the ice sheet to recover should global temperatures return to pre-industrial. It is found that if between 15% and 45% of the ice volume is lost during a warming period, then the ice sheet will obtain a steady state at 80% of its pre-industrial volume. If more than 45% of the ice sheet is lost then the final equilibrium state is 20% of the pre-industrial volume. Since the period of time of elevated temperatures determines the degree of ice sheet ablation, an early mitigation effort can prevent a permanent sea-level rise.

A further advance has applied the concept of committed warming to ecosystems (Jones *et al.* 2009). Looking at the HadCM3C model, these authors found that the full ecosystem response to a driving global climate change (atmospheric CO_2 increase and warming) is unlikely to occur until at least several decades after the driving climate change occurred. Furthermore, it implies that the eventual change locked into forest systems may not be detectable in advance. When the climate is restored to more favourable conditions the model predicts that forests do eventually recover but the time-scale is much longer than that over which they are projected to decline.

References

Allen M.R., Frame D.J., Huntingford C., *et al.* 2009: Warming caused by cumulative carbon emissions towards the trillionth tonne. NATURE Volume: 458 Issue: 7242 Pages: 1163-1166.

Andreae MO, Jones CD, Cox PM 2005: Strong present-day aerosol cooling implies a hot future. NATURE Volume: 435 Issue: 7046 Pages: 1187-1190.

Bamber, J.L. *et al.*, 2009. Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet. Science, 324, 901-903.

Barnett *et al.* 2008: Human-induced changes in the hydrology of the Western United States, Science, doi: 10.1126/science.1152538.

Blaum, N., Rossmanith, E., Popp, A. & Jeltsch, F. 2007: Shrub encroachment affects mammalian carnivore abundance in arid rangelands. Acta Oecologica 31: 86-92.

Boé, J., Hall, A. and Qu, X. 2009: September sea-ice cover in the Arctic Ocean projected to vanish by 2100. Nature Geoscience 2, 341 – 343. Published online: 15 March 2009 | doi:10.1038/ngeo467.

Brierley CM, Thorpe AJ, Collins M. 2009: An example of the dependence of the transient climate response on the temperature of the modelled climate state. Atmospheric Science Letters Volume: 10 Issue: 1 Pages: 23-28.

Bronson, D.N.R., Gower, S.T., Tanner, M. & van Herk, I. 2009: Effect of ecosystem warming on boreal black spruce bud burst and shoot growth. Global Change Biology 15: 1534-1543.

Brown, S.J., Caesar, J., and Ferro, C.A.T. 2008: Global changes in extreme daily temperature since 1950, J. Geophys. Res., 113, D05115, doi:10.1029/2006JD008091.

Bryden et al 2005: "Slowing of the Atlantic meridional overturning circulation at 25° N", Nature, 438, p 655-657, doi:10.1038/nature04385.

Cermeno P, Dutkiewicz S, Harris RP, *et al.* 2008: The role of nutricline depth in regulating the ocean carbon cycle. *Proceedings of The National Academy Of Sciences Of The United States of America* Volume: **105** Issue: **51**.

Chang, S-C., Tseng, K-H., Hsia, Y-J., Wnag, C-P, Wu, J-P. 2008: Soil respiration in a subtropical montane cloud forest in Taiwan. Agricultural and Forest Meteorology, 148: 788-798.

Christidis, N, P. A. Stott, F. W. Zwiers, H. Shiogama, T. Nozawa. 2009. Probabilistic estimates of recent changes in temperature: a multi-scale attribution analysis. Clim. Dyn., doi 10.1007/s00382-009-0615-7.

Clarke *et al.* 2009: "Freshwater Discharge, Sediment Transport, and Modeled Climate Impacts of the Final Drainage of Glacial Lake Agassiz" J Climate, 22, 45-62.

Cook, K.H. and Vizy, E.K. 2008: Effects of twenty-first-century climate change on the Amazon rain forest. Journal of Climate 21: 542-560.

Cox P.M., Betts R.A., Collins M., *et al.* 2002: Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoretical and Applied Climatology*. Volume **78** Issue: 1-3, Pages: 137-156.

Cunningham *et al.* 2007: "Temporal variability of the Atlantic meridional overturning circulation at 26.5 degrees N", Science, doi: 10.1126/science.1141304, 317, p. 935-938.

De Boeck, H.J., Lemmens, C.M.H.M., Zavalloni, C., *et al.* 2008: Biomass production in experimental grasslands of different species richness during three years of climate warming. Biogeosciences 5: 585-594.

Del Grosso, S, Parton W., Stohlgren, T., Zheng, D.L., Bachelet, D., Prince, S., Hibbard, K., Olson , R. 2008: Global potential net primary production predicted from vegetation class, precipitation, and temperature. Ecology, 89, 2117-2126.

Delpierre, N., Soudani, S., Francois, C., *et al.* 2009: Exceptional carbon uptake in European forests during the warm spring of 2007: a data-model analysis. Global Change Biology 15: 1455-1474.

Doherty S. J. *et al.* 2009: Lessons Learned from IPCC AR4: Scientific Developments Needed to Understand, Predict, and Respond to Climate Change. Bulletin of the American Meteorological Society. Volume 90, Issue 4 April 2009: pp. 497–513 DOI: 10.1175/2008BAMS2643.1.

Domingues, C. M. *et al.*, 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature, 453, 1090-1093.

Flannigan, M., Stocks, B., Turetsky, M., & Wotton, M. 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology* 15: 549-560.

Foster G., Annan J.D., Schmidt G.A., Mann M.E. 2008: Comment on "Heat capacity, time constant, and sensitivity of Earth's climate system" by S. E. Schwartz. Journal Of Geophysical Research-Atmospheres Volume: 113 Issue: D15 Article Number: D15102.

Frame D.J., Stone D.A., Stott P.A., *et al.* 2006: Alternatives to stabilization scenarios. Geophysical Research

Letters Volume: 33 Issue: 14 Article Number: L14707.

Gillett, N. P., D. A. Stone, P. A. Stott, T. Nozawa, A. Yu. Karpechko, G. C. Hegerl, M. F. Wehner and P. D. Jones. 2008. Attribution of polar warming to human influence. Nat. Geosci., 1, 750-754.

Girardin, M.P. & Mudelsee, M. 2008: Past and future changes in Canadian boreal wildfire activity. *Ecological Applications* 18: 391-406.

Gough, C.M., Vogel, C.S., Schmid, H.P. & Curtis, P.S. 2008: Controls on annual forest carbon storage: Lessons from the past and predictions for the future. *BioScience* 58: 609-622.

Granier A., Reichstein M., Breda, N., *et al.* 2007: Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003. Agricultural and Forest Meteorology 143: 123-145.

Gregory, J.M. & Huybrechts, P., 2006, Ice-sheet contributions to future sea-level change. Phil. Trans. Royal Soc. A, **364**, 1709-1731.

Grinsted, A., Moore, J., Jevrejeva, S. Reconstructing sea level from palaeo and projected temperatures. http://www.iop.org/EJ/volume/1755-1315/6 Earth and Environmental Science 6 (2009) 012001

Hansen, J.E. 2007: *Environ. Res. Lett.* 2. 024002 doi:10.1088/1748-9326/2/2/024002.

Hansen J., M. Sato, P. Kharecha, D. Beerling, R. Berne, V. Masson-Delmotte, M. Pagani, M. Raymo, D. L. Royer, J. C. Zachos 2008: Target atmospheric CO2: Where should humanity aim? Open Atmos. Sci. J., vol. 2, pp. 217-231. DOI: 10.2174/1874282300802010217.

Harley, C.D.G., Hughes, A.R., Hultgren, K.M., *et al.* 2006: The impacts of climate change in coastal marine systems. Ecology Letters 9: 228-241.

House J, Huntingford C, Knorr W, Cornell S E, Cox P M, Harris G R, Jones C D, Lowe J A and Prentice C I 2008: What do recent advances in quantifying climate and carbon cycle uncertainties mean for climate policy? Environ. Res. Lett. 3 044002.

Huntingford C., Lowe J.A., Booth B.B.B., *et al.* 2009: Contributions of carbon cycle uncertainty to future climate projection spread. Tellus Series B-Chemical And Physical Meteorology Volume: 61 Issue: 2 Pages: 355-360.

Huntingford C. and Lowe J. 2007: Overshoot scenarios and climate change. Science 316 829.

Iverson L.R., Prasad A.M., Matthews S.N., Peters M. 2008: Estimating potential habitat for 124 eastern US tree species under siz climate scenarios. Forest Ecology and Management 254, 390-406.

Jones, C., J. Lowe, S. Liddicoat, and R. Betts 2009: Committed terrestrial ecosystem changes due to climate change. Nature Geoscience 2, 484 – 487. Published online: 9 | doi:10.1038/ngeo555.

Jones, G. S., P. A. Stott, and N. Christidis, Human contribution to rapidly increasing frequency of very warm Northern Hemisphere summers, J. Geophys. Res., 113,D02109, doi:10.1029/2007JD008914, 2008.

Kammer, A., Hagedorn, F., Shevchenko, I., *et al.* 2009: Treeline shifts in the Ural mountains affect soil organic matter dynamics. Global Change Biology 15: 1570-1583.

Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K.T., & Strandman, H. 2008: Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. Philosophical Transactions of the Royal Society B, Biological Sciences 363: 2341-2351.

Kendon, E.J., Rowell, D.P., Jones, R.G. and Buonomo, E. 2008: Robustness of Future Changes in Local Precipitation Extremes, J. Climate, 21, 4280–4297, DOI: 10.1175/2008JCLI2082.1.

Kenyon J. and Hegerl G.C. 2008: Influence of modes of climate variability on global temperature extremes, J.Climate, 21, 3872-3889, DOI: 10.1175/2008JCLI2125.1.

Kerr, R. A., 2009. Galloping glaciers of Greenland have reined themselves in. Science, 323, 458.

Kharin, V.V., Zwiers, F.W., Zhang, X. and Hegerl, G.C. 2007: Changes in temperature and precipitation extremes in the IPCC Ensemble of Global Coupled Model Simulations. J. Climate, 20,1419–1444.

Kriegler E, Hall JW, Held H, *et al.*, 2009: Imprecise probability assessment of tipping points in the climate system. Proceedings Of The National Academy Of Sciences Of The United States Of America Volume: 106 Issue: 13 pp: 5041-5046.

Kurz, W.A., Stinson, G. & Rampley, G. 2008: Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? Philosophical Transactions of the Royal Society B, *Biological Sciences* 363: 2261-2269.

Le Quéré, C., C. Rödenbeck, E.T. Buitenhuis, T. J. Conway, R. Langenfelds, A. Gomez, C. Labuschagne, M. Ramonet, T. Nakazawa, N. Metzl, and N. Gillett, M. Heimann, 2007: Saturation of the Southern ocean CO_2 sink due to recent climate change, Science, **316**, DOI:10.1126/ science.1136188, 1735-1738.

Lenton TM, Held H, Kriegler E, *et al.* 2008: Tipping elements in the Earth's climate system. Proceedings Of The National Academy Of Sciences Of The United States Of America Volume: 105 Issue: 6 Pages: 1786-1793.

Lewis, S.L., Lopez-Gonzalez, G., Sonke, B., *et al.* (2009) Increasing carbon storage in intact African tropical forests. Nature 457: 1003-1006.

Lowe J.A., Huntingford C., Raper S.C.B., *et al.* 2009: How difficult is it to recover from dangerous levels of global warming? Environmental Research Letters Volume: 4 Issue: 1 Article Number: 014012.

Lucht, W., Schaphoff, S., Erbrecht, T., Heyder, U. & Cramer, W. 2006: Terrestrial vegetation redistribution and carbon balance under climate change. Carbon Balance and Management 2006, 1: 6.

Luyssaert, S., Schulze, E.-D., Börner, A., *et al.* (2008) Old-growth forests as global carbon sinks. Nature 455: 213-215.

MacDonald, G.M., Kremenetski, K.V. & Beilman, D.W. 2008: Climate change and the northern Russian treeline zone. Philosophical Transactions of the Royal Society B, Biological Sciences 363: 2285-2299.

Macias Fauria, M., & Johnson, E.A. 2008: Climate and wildfires in the North American boreal forest. Philosophical Transactions of the Royal Society B, *Biological Sciences* 363: 2317-2329.

Malevsky-Malevich, S.P., Molkentin, E.K., Nadyozhina, E.D. & Shklyarevich, O.B. 2008: An assessment of potential change in wildfire activity in the Russian boreal forest zone induced by climate warming during the twenty-first century. Climatic Change 86: 463-474.

Malhi, Y., Roberts, T.J., Betts. R.A., Killeen, T.J., Li, W.H. & Nobre, C.A. 2008: Climate change, deforestation, and the fate of the Amazon. *Science* **319**, 169-172

Matthews H.D. and Caldeira K. 2008: Stabilizing climate requires near-zero emissions Geophys. Res. Lett. 35 L04705.

McLaren, A.J. *et al.*, 2006: Evaluation of the sea ice simulation in a new coupled atmosphere-ocean climate model HadGEM1:. *J. Geophys. Res.,* **111**, doi:10.1029/2005JC003033.

McMillan, A.M.S., Winston, G.C., & Goulden, M.L. 2008: Age-dependent response of boreal forest to temperature and rainfall variability. Global Change Biology 14: 1904-1916.

Mercer J., 1978:West Antarctic Ice Sheet and CO2 Greenhouse Effect: a threat of disaster *Nature* **271** 321-325.

Mernild, S. 2009: Increased Greenland melt extent 1995-2007. http://www.iop.org/EJ/volume/1755-1315/6 Earth and Environmental Science 6. 012035. *non-peer reviewed literature*

Mikolajewicz *et al.* 2007:: " Long-term effects of anthropogenic CO2 emissions simulated with a complex earth system model", Clim Dyn, 28, p599-633, doi 10.1007/s00382-006-0204-y.

Murphy JM, Sexton DMH, Barnett DN, *et al.* 2004: Quantification of modelling uncertainties in a large ensemble of climate change simulations. NATURE Volume: 430 Issue: 7001 Pages: 768-772.

Murphy, J., D. Sexton, G. Jenkins, P. Boorman, B. Booth, K. Brown, R. Clark, M. Collins, G. Harris, L. Kendon. 2009: UKCP09: Climate change projections, ISBN 978-1-906360-02-3, Version 2, amended July 2nd 2009, Met Office Hadley Centre.

Nick, F. M., *et al.*, 2009. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. Nature Geoscience, DOI:10.1038, published on-line January 11, 2009.

Noormets, A., McNulty, S.G., DeForest, J.L., Sun, G., Li, Q. & Chen, J. 2008: Drought during canopy development has lasting effect on annual carbon balance in a deciduous temperate forest. New Phytologist 179: 818-828.

Phillips, O.L., Lewis, S.L., Baker, T.R., Chao, K.T., & Higuchi, N. (2008). The changing Amazon forest. *Phil. Trans. Roy. Soc* ***B*** **363** 2369-2375.

Phillips, O.L., Aragão, L.E.O.C., Lewis, S.L., *et al.* 2009: Drought sensitivity of the Amazon rainforest. Science 323: 1344-1347.

Plattner G-K et al 2008 Long-term climate commitments projected with climate–carbon cycle models J. Clim. 21 2721–51.

Pörtner, H.O. & Knust, R. 2007: Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315: 95-97.

Pfeffer et al, 2008: Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise *Science* Vol. 321. no. 5894, pp. 1340 – 1343.

Rahmstorf, S., 2007: A semi-empirical approach to projecting future sea-level rise. Science, 315, 368-370.

Rasmussen, C., Southard, R.J. & Horwath, W.R. 2008: Litter type and soil minerals control temperate forest soil carbon response to climate change. Global Change Biology 14: 2064-2080.

Reichstein, M., Ciais, P., Papale, D., *et al.* 2007: Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: a joint flux tower, remote sensing and modelling analysis. Global Change Biology 13: 634-651.

Ridley, J., Gregory, J.M., Huybrechts, P. & Lowe, J., Submitted, Thresholds for irreversible decline of the Greenland ice sheet, Cli. Dyn.

Rohling, E.J., Grant K, Hemleben C, *et al.* 2008: New constraints on the timing of sea level fluctuations during early to middle marine isotope stage 3. Paleoceanography Volume: **23** Issue: **3** Article Number: PA3219.

Salazar, L.F., Nobre, C.A. & Oyama, M.D. 2007: Climate change consequences on the biome distribution in tropical South America. Geophysical Research Letters 34: L09708.

Sankaran, M., Hanan, N.P., Scholes, R.J., *et al.* 2005: Determinants of woody cover in African savannas. Nature 438: 846-849.

Santer, B. D., C. Mears, F. J. Wentz, K. E. Taylor, P. J. Gleckler, T. M. L. Wigley, T. P. Barnett, J. S. Boyle, W. Bruggemann, N. P. Gillett, S. A. Klein, G. A. Meehl, T. Nozawa, D. W. Pierce, P. A. Stott, W. M. Washington, M. F. Wehner, 2006. Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. Proc. Nat. Acad. Sci., 103, 13905-13910, 10.1073/pnas.0602861103.

Scaife AA, Folland CK, Alexander LV, Moberg A, Knight JR. 2008:, European climate extremes and the North Atlantic Oscillation, J. Climate 21, 72–83.

Scherrer, S.C., Appenzeller, C., Liniger, M.A. & Schär, C. 2005: European temperature distribution changes in observations and climate change scenarios. Geophysics Research Letters 32: L19705.

Schoof C, 2007, Marine ice-sheet dynamics. Part 1. The case of rapid sliding, Journal of Fluid Mechanics, **573**, 27-55.

Schwartz S.E. 2007: Heat capacity, time constant, and sensitivity of Earth's climate system. Journal Of Geophysical Research-Atmospheres Volume: 112 Issue: D24 Article Number: D24S05.

Schwartz S.E. 2008: Reply to comments by G. Foster *et al.*, R. Knutti *et al.*, and N. Scafetta on "Heat capacity, time constant, and sensitivity of Earth's climate system". Journal Of Geophysical Research-Atmospheres Volume: 113 Issue: D15 Article Number: D15105.

Scott et al 2008: "Relative roles of climate sensitivity and forcing in defining the ocean circulation response to climate change", Clim Dyn, 30, p.441-454, doi: 10.1007/s00382-007-0298-x.

Senior CA, Mitchell JFB 2000: The time-dependence of climate sensitivity. Geophysical Research Letters Volume: 27 Issue: 17 Pages: 2685-2688.

Sitch S, Cox PM, Collins WJ, *et al.* 2007: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. NATURE Volume: 448 Issue: 7155 Pages: 791-4.

Sokolov AP, Kicklighter DW, Melillo JM, *et al.* 2008: Consequences of considering carbon-nitrogen interactions on the feedbacks between climate and the terrestrial carbon cycle. Journal of Climate Volume: 21 Issue: 15 Pages: 3776-3796.

Solomon S, Plattner G-K, Knutti R and Friedlingstein P 2009 Irreversible climate change due to carbon dioxide emissions Proc. Natl Acad. Sci. 106 1704–9.

Stroeve J. *et al.*, 2007: Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.,* **34**, L09501, doi:10.1029/2007GL029703.

Svensson, C.J., Jenkins, S.R., Hawkins, S.J. & Åberg, P. 2005: Population resistance to climate change: modelling the effects of low recruitment in open populations. Oecologia, 142: 117-126.

Thornton PE, Lamarque JF, Rosenbloom NA, *et al.*2007: Influence of carbon-nitrogen cycle coupling on land model response to CO2 fertilization and climate variability. Global Biogeochemical Cycles Volume: 21 Issue: 4 Article Number: GB4018.

Tsutsui J, Yoshida Y, Kim D-H, Kitabata H, Nishizawa K, Nakashiki N and Maruyama K 2007 Long-term climate response to stabilized and overshoot anthropogenic forcings beyond the twenty-first century Clim. Dyn. 28 199–214.

UKCP09: Lowe, J.A., Tom Howard, Anne Pardaens, Jonathan Tinker, Geoff Jenkins, Jeff Ridley, Met Office, James Leake, Jason Holt, Sarah Wakelin, Judith Wolf, Kevin Horsburgh, Proudman Oceanic Laboratory, Tim Reeder, Environment Agency, Glenn Milne, Sarah Bradley, 2009: University of Durham, Marine Climate Change Partnership, Marine & coastal projections, ISBN 978-1-906360-03-0.

Vetter M., Churkina, G., Jung, M., *et al.* (2008) Analyzing the causes and spatial pattern of the European 2003 carbon flux anomaly using seven models. Biogeosciences 5: 561-583.

Washington, W. M., R. Knutti, G. A. Meehl, H. Teng, C. Tebaldi, D. Lawrence, L. Buja, and W. G. Strand 2009:, How much climate change can be avoided by mitigation?, Geophys. Res. Lett., 36, L08703, doi:10.1029/2008GL037074.

Williams KD, Ingram WJ, Gregory JM 2008: Time variation of effective climate sensitivity in GCMs. Journal of Climate Volume: 21 Issue: 19 Pages: 5076-5090.

Wrona, F.J., Prowse, T.D., Reist, J.D., Hobbie, J.E., Levesque, L.M.J. & Vincent, W.F. 2006:

Yang, Y., Fang, J., Tang, Y., Ji, C., Zheng, C., He, J., Zhu, B. 2008: Storage, patterns and controls of soil organic carbon in the Tibetan grasslands. Global Change Biology, 14:1592-1599.

Yin and Stouffer 2007: "Comparison of the Stability of the Atlantic Thermohaline Circulation in Two Coupled Atmosphere-Ocean General Circulation Models" J Climate,20, 4293-4315. DOI: 10.1175/JCLI4256.1.

Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott, T. Nozawa, 2007: Detection of human influence on twentieth-century precipitation trends, Nature, doi: 10.1038/nature06025.

B. CLIMATE CHANGE IMPACTS

B.1 Coastal System Impacts and Adaptation

The IPCC AR4 reported that sea level rise is projected to cause large losses of coastal ecosystems such as wetlands, mangroves and salt marshes e.g. the Sundarbans in Bangladesh (EEA, 2008; Gopal and Chauhan 2006). These ecosystems have a key role in protecting coastlines from erosion and storms, and thus further increases the impacts of sea level rise. Slow growing species such as corals, may be especially vulnerable. Also highly impacted will be intertidal communities, where steep topography and anthropogenic structures (e.g. sea wall defences), may prevent the inland migration of mudflats and sandy beaches (Harley *et al.* 2006) and hence may become unable to sustain for example, large populations of migratory shore birds which depend upon them. The UK is of high international importance for its migratory shorebirds.

At key post-AR4 insight is that even with large rises in sea level of up to 5-m/century, it would still be economically rational to protect some of our more developed coasts. This conclusion is supported empirically by both responses to submergence in subsiding cities, and the Thames Estuary 2100 (2009) and Delta Commission 2008 (see below). However, this would not protect smaller assets on other parts of the coastline, or the coastal ecosystems: indeed, protecting one section of coastline might increase impacts in another. Losses of coastal wetlands, salt marshes and mangroves as a result of sea level rise will remove the coast's natural means of protecting the land against the erosive forces of the sea.

A case study of the Thames Estuary under the same extreme 5-m/century scenario illustrated the potential for institutional paralysis which could hinder an adaptive response (Lonsdale *et al.* 2008). Hence a universal retreat from the shore in response to a large sea-level rise does not appear inevitable, which is counter to most interpretations of such a scenario, but the uncertainties remain large.

At the regional scale, the available DIVA results have had important inputs into the EU Green paper on adaptation (European Commission, 2007), as they emphasised the great benefits and need for coastal adaptation within Europe. However, national assessments across Europe show that most European countries are not preparing adequately for impacts and adaptation needs in their coastal zones (Tol *et al.* 2008). There are exceptions, and major adaptation plans have been published for the Thames Estuary (TE2100, 2009) and the Netherlands (Delta Commission, 2008). These studies deliberately took a long-term view and considered large rises of several metres and even more, as they were testing the sensitivity of the different adaptation decisions to the magnitude of sea-level rise. The Dutch study projected a local sea level rise of between 65cm and 1.3 m (Advice to the Dutch Cabinet, 2008). The TE2100 study projected a most likely range up to approximately 90cm, but also suggested a low probability high impact increase of up to 2m could not be ruled out. In both cases, the conclusion is that we can adapt to large rises in sea level. Further, in both cases the defences are going to be upgraded in a manner that will allow further upgrades as required. Innovative elements will also be included, such as the diversion of the Rhine tributary to a new channel near Rotterdam to separate the issues of flood defence, water management and the operation of Europort.

At sub-national scales, the Tyndall Centre for Climate Research has demonstrated the capacity to look quantitatively at the trade-off between erosion and coastal flooding within a single sub-cell (sub-cell 3b in Norfolk) (Dawson *et al.* 2009). Increased cliff protection against erosion leads to a lower sediment supply, and hence increased flood risk in coastal lowlands (or greater beach nourishment costs to manage this risk). As erosion management is under the control of coastal managers, this suggests that they do have some policy levers to respond to climate change. This work illustrates a class of modelling tool that might be developed to support the development of third generation shoreline management plans.

Significantly improved estimates of regional and global impacts of sea-level rise are expected to be available for the IPCC Fifth Assessment based on the Dynamic and Interactive Vulnerability Assessment (DIVA) model (DINAS-COAST Consortium, 2006). High end sea-level rise scenarios have been investigated as part of the Atlantis Project using the FUND model (Nicholls *et al.* 2008).

B.2 Ecosystems and Biodiversity

We review in turn statements made in IPCC AR4 and examine how the new literature stands in relation to these statements:

B.2.1 Approximately 20-30% of plant and animal species assessed so far are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3°C above pre-industrial levels

Biodiversity underpins ecosystem services to humans such as flood prevention, water purification, food supplies, sources of medical drugs, coastal protection, and biogeochemical cycles such as the carbon and nitrogen cycles. Its loss, therefore, contributes significantly to dangerous climate change. **Observational and modelling based studies continue to support the IPCC statement (1).**

(a) ***There is increased evidence to support it from observations*****:** Since AR4 the validity of the modelling methods used to project potential extinctions has been further enhanced by continued observations of climate-induced changes in species distributions and in their altitudinal ranges. Poleward shifts in polar and boreal ecosystems are the greatest (Callaghan *et al.* 2007; McDonald *et al.* 2008). For many organisms, poleward expansion is observed to be slower than warm climate retreat, leading to an overall reduction in range (Foden *et al.* 2007). Elevational range shifts have been recorded for plants (Kelly and Goulden 2008; Vittoz *et al.* 2008), butterflies (Wilson *et al.* 2007), and trees (Gehrig-Fasel *et al.* 2007; Beckage *et al.* 2008) but the advance of the tree line is still too slow for species to track climate change (Devictor *et al.* 2008). Thus extinctions as a consequence of range changes are particularly projected for mountains (Colwell *et al.* 2008) and Arctic areas.

New projections show how achievement of the 2°C target would prevent most projected bird extinctions: (i) if global temperature rises by 6.4°C above 1990 (the upper end of the IPCC 2007 range) 30% of Western Hemisphere landbirds could become extinct with 20% more at risk of extinction. (ii) constraining temperature rise to 4°C reduces this to 15% extinct and 20% more at risk of, whilst constraining it to 1.8°C (about 2°C above pre-industrial, i.e. the EU 2°C target) reduces it to 2% with a further 20% at risk (Sekercioglu *et al.* 2007). (iii) Avian diversity in Europe is expected to fall by 23% with endemic species facing likely extinction for global temperature rises of 3°C above pre-industrial. (iv) this fall reduces to 6% with a 2°C rise (Huntley *et al.* 2008; Virkkala *et al.* 2008).

Since the AR4, numerous studies have more firmly demonstrated marked changes in marine and freshwater ecosystems. Sea temperature rises have generally triggered a northward movement of warm-water species and a similar retreat of colder-water species, as fast as 15-50km per decade (Wethey and Woodin, 2008; Sabatés *et al.* 2006; Hiddink and ter Hofstede 2008; Perry *et al.* 2005). Species can also retreat to deeper cooler water (Dulvy *et al.* 2008).

Some projected biome shifts have been better quantified, in particular the poleward spread or shift of temperate and boreal forests in the Northern Hemisphere high latitudes, and a substantial degradation of vegetation type in the tropics (e.g., increase of drought tolerant deciduous tree coverage at the expense of evergreen trees), especially in portions of west and southern Africa and South America (Alo and Wang 2008; Wolf *et al.*2008).

(b) *There are an increasing number of projections of extinction risks in the literature. Of particular concern are:* Over 20% of the wild relatives of peanut, potato and cowpea are at risk of climate change induced extinction (Jarvis *et al.* 2008). These are an important source of genetic diversity for crop improvement.

Salmon will disappear from many rivers as climate changes (Crozier *et al.* 2008; Battin *et al.* 2007). Climate change will expand ranges of downstream species and decrease upstream ones (Durance and Ormerod 2007; Buisson *et al.* 2008).

If emissions are not reduced, 78% of European butterflies could lose more than half their current range by 2080s (Settele *et al.* 2008).

B.2.2 Most vulnerable ecosystems include coral reefs, the sea-ice biome, polar ecosystems, mountain ecosystems and Mediterranean-climate ecosystems

Coral reef systems continue to be impacted by climate change. Sharp declines in the abundance and extent of coral reefs associated with increased bleaching and disease events have now been shown to be driven in large part by elevated sea surface temperatures (Parmesan 2006; Lough 2008). Moreover, increased ocean acidification associated with higher levels of atmospheric CO_2 concentrations has been linked with inhibiting coral formation and reductions in the growth rate of crustose coralline algae (Guinotte and Fabry 2008), which will likely have major implications for the future viability of coral reef systems. A significant proportion of coral species have been identified as being susceptible to climate change (Foden *et al.* 2008) with possibly one third of coral reefs already facing elevated extinction risk today based on their current rates of decline and the IUCN red list criteria (Carpenter *et al.* 2008). Hoegh-Guldberg *et al.* (2007) reviews the latest work on coral reefs, including a new coral ecosystem model simulation, and again emphasizes that widespread reef erosion will inevitably occur if CO_2 concentrations exceed 450 ppm, leading to vastly reduced biodiversity and loss of coral-associated fish and invertebrates, whilst levels of 500 ppm would reduce coral reefs to crumbling frameworks with very few corals.

The southern Mediterranean and its ecosystems have now been identified as particularly vulnerable to water stress and desertification processes under climate change conditions (Gao and Giorgi 2008; Schröter *et al.* 2005; Berry *et al.* 2007; Sánchez de Dios *et al.* 2009), as a consequence of large projected decreases in precipitation and glacier meltwater, and consequent drought stress (Giorgi and Lionello, 2008; Beniston *et al.* 2007; Gao and Giorgi 2008; Metzger *et al.* 2008). Observational, modelling and experimental studies indicate that mountain conifers, butterflies, amphibians and temperate trees are particularly at risk (Wilson *et al.* 2007; Benito Garzón *et al.* 2008; Gomez-Aparico *et al.* 2008).

Tundra and Arctic/Antarctic are still considered the most vulnerable to climate change, with large potential losses of tundra (Wolf *et al.* 2008). A pan-Arctic greening of the tundra has been observed (Tape *et al.* 2006). Whilst spread of forest northwards (or upwards) would help increase carbon sequestration in biomass (Tømmervik *et al.* 2009), this is not sufficient to counter emissions from thawing of the permafrost. Warming and changes in the state of the ground are still expected to affect species such as lemming, musk ox and reindeer, and dramatic population reductions are occurring (Callaghan *et al.* 2007) with natural population cycles of voles and lemmings no longer observed in some areas which disrupts the ecology of their predators such as snowy owls, skuas, ermines and weasels (Callaghan *et al.* 2007).

Clarke *et al.* (2007) found marked decreases of ice-associated biota over the past few decades in conjunction with contractions of winter sea ice habitat (Clarke *et al.* 2007) which may have serious negative impacts on mammals (Learmonth *et al.* 2006; Simmonds and Isaac 2007) and penguins (Jenouvrier *et al.* 2009), as changes in the timing and extent of sea ice separate these animals from their food supply (Moline *et al.* 2008). Rising sea surface temperatures have been implicated as a significant cause for the reduced abundance in Arctic areas of several charismatic marine mammals like the narwhal, beluga and polar bear, mediated via changes in prey distribution and abundance (Simmonds and Isaac 2007). Conversely, species richness of fish in the North Sea has actually increased over the past 22 years in response to higher water temperatures (Hiddink and ter Hofstede 2008), indicating that climate change can also have positive effects within certain areas.

Modelling studies continue to emphasize the sensitivity of mountains in both temperate, Mediterranean and tropical regions to climate change, including cloud forest (EEA, 2007; Nogués-Bravo *et al.* 2007; Karmalkar *et al.* 2008; Bravo *et al.* 2008), due to changes in both temperature and precipitation. Mountain species are often range restricted with limited dispersal abilities and are therefore especially sensitive to climate change (Vittoz and Engler 2007; Engler and Guisan 2009), especially in the tropics (Wake and Vredenburg 2008), with most vulnerable species being endemics (Meine 2007), and also high elevation and poorly dispersing species (Engler *et al.* 2009).

B.2.3 There is increasing evidence of experienced and projected effects of changes in climate variability

Observed changes in climate variability such as floods and droughts have been shown to be already having impacts on desert ecosystems. For example, population reductions (Thibault and Brown 2008), displacement (Kelly and Goulden 2008) and local extinction of certain desert species (Foden *et al.* 2007) have been detected. This highlights the potential future impacts of warming-induced change in climate variability, which will also affect community composition (Miriti *et al.* 2007), fire dynamics and may assist the establishment of invasive species (Bradley 2009).

European temperate woodlands are now considered to be particularly vulnerable to drought with some species, such as beech, possibly being particularly vulnerable (van der Werf *et al.* 2007; Verbeeck *et al.* 2008; Gärtner *et al.* 2008; Meier and Leuschner 2008; Robson *et al.* 2009). Drought often will interact negatively with other ecological processes (St. Clair *et al.* 2008) and is predicted to have a major impact on the future species composition of forests (Geßßler *et al.* 2007).

In Europe and Russia, projections of reduced summer flows will stress many riparian areas (EEA, 2008) causing declines in migrating fish.

B.2.4 There is increasing evidence of experienced and projected effects of climate-change facilitated spread of invasive species and diseases

Climate change is regarded as important factor in facilitating spread of invasive species and diseases, contributing to the decline and displacement of native biota (Byrnes *et al.*, 2007; Occhipinti-Ambrogi, 2007). Rare and invasive species observed in grasslands in California following major El Niño events (Hobbs *et al.*, 2007) which may serve as a proxy for a climate-changed world. Rahel & Olden (2008) make projections of invasive fish species as climate warms.

B.2.5 There is increasing evidence of changes in ecosystem composition and function, including nutrient cycling, productivity, and community dynamics (Bertin 2008; Oloffson *et al.* 2009).

Species composition of communities has been observed changing in the Alps (Pauli *et al.* 2007; Vittoz *et al.* 2008; Vittoz *et al.* 2009) on a sub-Antarctic island (Le Roux and McGeoch 2008), and in coastal marine food webs (Byrnes *et al.* 2007). Changes in small mammal communities have also been observed due to differential rates of species' altitudinal movement (Moritz *et al.* 2008). With climate change, European farmland bird species with northerly ranges have declined as have long-distance migratory birds, whilst wetland birds and species with southerly ranges have increased (Lemoine *et al.* 2007a, 2007b). Migrant butterflies have increased in parts of the UK (Sparks *et al.* 2007) but decreased in the Mediterranean (Wilson *et al.* 2007); composition and abundance of macro-invertebrates and fish has changed (Burgmer *et al.* 2007; Durance and Ormerod 2007; Daufresne and Boet 2007). Such changes have also been simulated in the laboratory for plants (Lloret *et al.* 2009). Whilst varying gains and losses in abundance of certain species and overall diversity occur, there are local extinctions of high priority species like salmon (Bertin 2008; Brander 2007).

B.2.6 There is increasing evidence of changes in phenology, abundance, morphology, and reproduction (Rosenweig *et al.* 2008) especially in temperate and arctic regions (Adrian *et al.* 2006)

An extended growing season affects albedo and feedbacks between land and atmosphere (Peñuelas *et al.* 2009) but the overall influence of these feedbacks on climate is uncertain. Unsynchronized phenological changes for different species have resulted in reductions in populations due to mismatches between predators and their prey e.g. first insect appearance and the migrant bird arrival (Both *et al.* 2007). Temporal mismatches may occur among mutualistic partners, e.g. plants and pollinators although research in this area is limited (Hegland *et al.* 2009, Memmott *et al.* 2007).

New phenological changes have been seen in trees, plants and fungi (Gange *et al.* 2007; Kauserud *et al.* 2008; Pudas *et al.* 2008; Peñuelas *et al.* 2009; Moreno-Rueda *et al.* 2009, Franks and Weis 2009); in amphibians (Carroll *et al.* 2009; Kusano and Inoue 2009); and in the spring migration of birds (Zalakevicius *et al.* 2006; Gordo, 2007; Rubolini *et al.* 2007; van Buskirk *et al.* 2009). Changes are stronger at higher northern latitudes (Colwell *et al.* 2008). As in AR4, changes to the warming climate have confirmed its discernible influence on many biological systems.

Many marine species now appear earlier in their seasonal cycles (e.g., plankton blooms in the North Sea) (EEA, 2008) and this together with the changes observed in marine primary productivity will disrupt marine food webs e.g. via the altered timing and abundance of a key food supply, namely krill in the Southern Oceans (Frederikson *et al.* 2006; Koeller *et al.* 2009). This will affect many bird species and economically important fish stocks such as cod (Beaugrand *et al.* 2003). Life-cycle changes have also been observed in other marine species, including turtles (Mazaris *et al.* 2008). Climate change-induced alterations of ecological interactions and biological processes have been suggested as likely causes for the loss of inter-tidal community diversity in the Pacific Northwest (Smith *et al.* 2006).

B.2.7 Ocean acidification
A key consequence of increases in the amount of carbon dioxide dissolved in the ocean is greater ocean acidity. New work has highlighted the impacts of low ocean pH on molluscs and various plankton species, (Riebesell 2008; Zeebe *et al.* 2008). Impacts on oysters and mussels will impact commercial aquaculture (Gazeau *et al.* 2007). Brown algae and seagrasses are expected to benefit from higher CO_2 concentrations (Guinotte and Fabry 2008). A major programme to study the impacts of ocean acidification has recently been initiated in the UK with funding from NERC and Defra.

B.3 Water Resources
Since the publication of the AR4 there have been literally hundreds of published studies into the impacts of climate change on hydrological regimes and water resources. Virtually all of these have been relatively conventional impact assessments, exploring the consequences of (generally) SRES climate scenarios for hydrological behaviour. Most significantly, the new literature adds impact studies from areas previously poorly represented – specifically Africa and Central and South America.

Whilst these additional studies have thrown light on potential impacts in previously unstudied areas, this review focuses on the relatively few studies that have (i) taken a global perspective, (ii) explicitly compared "business-as-usual" and policy climate scenarios, (iii) or sought to identify critical climate thresholds or rates of change.

Adam *et al.* (2009) used the AR4 climate model set to explore in a systematic way potential changes in the timing of streamflow due to reductions in snowfall and snowmelt, concluding that decreased snowpack produces decreases in warm-season runoff in many mid- to high-latitude areas where precipitation changes are either moderately positive or negative in the future projections. The greatest changes are at the boundaries of areas that currently experience substantial snowfall. No published studies have yet examined the implications of the AR4 climate scenarios for global water resources scarcity, although a number are currently in preparation.

Rockstrom *et al.* (2009) used an old climate scenario (HadCM2) with A2 socio-economic assumptions and demonstrated that the estimated impacts of climate change on water scarcity depended on how water was used; by 2050, approximately 59% of the world's population was exposed to "blue water shortage" (i.e. irrigation water shortage), but a substantially smaller proportion (36%) was exposed to water shortage if "green water" (water in the soil) was also taken into account.

Fischer *et al.* (2007) simulated future global irrigation demands without climate change and under two climate models and two emissions scenarios (representing "no policy" (SRES A2) and "mitigation" (SRES B1)), using the FAO agro-ecological zones model. By 2080, the mitigation scenario produced withdrawals approximately 40% lower than those under the no policy reference scenario, with operating costs $8-10 billion per year lower (i.e. $16-17 billion extra per year, compared with the situation without climate change, compared to $24-27 billion extra per year under the reference scenario). In this case, climate policy reduces, but does not eliminate the impacts of climate change. There have been no other published studies which have explicitly compared impacts under reference and policy scenarios.

No published studies have yet clearly identified critical thresholds for water resources impacts – largely because these will be context-specific – and so far only one has attempted to characterise generalised sensitivity of hydrological behaviour to change in order to identify impact areas "hotspots". Preston and Jones (2008) used a very simple hydrological model applied across Australia with climate patterns derived from a number of AR4 climate models to estimate change in runoff per degree of global warming. They noted high uncertainty, but also identified consistently high sensitivity to change (large reductions per degree of warming) in coastal West Australia and Southeast Queensland. Preston and Jones (2008) noted the limiting assumptions with the methodology adopted, but it does provide an example of an attempt to generalise impact assessment results away from the raw driving climate projections to draw general conclusions about rates of change.

B.4 Agriculture and Food Security

The AR4 identified a number of key gaps in knowledge of the potential consequences of climate change for “food, fibre, forestry and fisheries”. In terms of the characterisation of “dangerous” climate change and of climate policy, the most important gaps are in (i) understanding of the effect of enriched CO_2 concentrations on crop productivity, particularly for non-cereal crops, (ii) understanding the combined effects of elevated CO_2 and climate change on pests, weeds and disease, (iii) understanding the role of changes in extreme events on productivity, and (iv) identifying highly-vulnerable micro-environments and households. As with the water sector, since the AR4 many more case studies of potential changes in agricultural (primarily grain crop) productivity, but relatively few studies have made significant advances in the key general gaps relevant to the understanding of thresholds and the effects of policy. Tubiello *et al.* (2007) provide a good overview of the scientific understanding of crop and pasture response to climate change, using much the same material as reviewed in the AR4. Whilst the general conclusions are, unsurprisingly, similar to those in the AR4, Tubiello *et al.* (2007) place greater emphasis on the potential for changes in pests, weeds and disease, and extreme events, to offset the generally positive effect of CO_2 enrichment on crop productivity; the tone is therefore rather less “positive” than the AR4 assessment. This less positive tone is supported by new research published by Lobell *et al.* (2008), which takes a probabilistic approach using the AR4 climate model results to estimate likelihoods of crop production changes *by 2030* in developing world regions; results suggest greater negative impacts in the short term than implied in the AR4.

Tubiello *et al.* (2007) reemphasise the AR4 conclusion that, under unstressed conditions, CO_2 enrichment tends to increase crop yields (5-20% at 550 ppm CO_2). More recent modelling studies, however, cast doubt on the generality of the effect of CO_2 enrichment (e.g. Challinor and Wheeler (2008a), who modelled the effect of CO_2 enrichment on groundnut productivity under unstressed and water-stressed conditions), and Lobell and Field (2008) concluded that current observational data were not sufficient to constrain the uncertainty in the estimated effects of enrichment.

Since the AR4 there has been more evidence on the (generally adverse) effect of extreme events and other drivers on crop productivity. Challinor and Wheeler (2008b), for example, showed using a crop simulation model, that the CO_2 stimulation of groundnut productivity in India was more than offset by the projected increased frequency of high temperature extremes. A series of studies (Reilly *et al.* (2007), Van Dingenen *et al.* (2009) and Booker *et al.* (2009)) have demonstrated that elevated ozone concentrations can substantially reduce crop productivity, particularly at the regional scale, potentially offsetting CO_2 enrichment effects. The impacts, however, are dependent on the rate of future air quality improvements, and therefore are influenced by pollution control policy.

B.5 Human Health

The AR4 concluded that climate change will tend to increase the burden of disease and ill-health through increased malnutrition, increased exposure to extreme events, changes in the range of some infectious disease vectors, and the effects of high temperatures on cardio-respiratory morbidity and mortality. Since the AR4 there have been a number of studies which have examined in more detail a number of specific potential challenges to human health, although much of the literature simply calls for new research to be undertaken to help clarify uncertainties and the potential magnitude of change.

There are, however, two emerging issues relevant to the identification of “dangerous” climate change and the effects of climate policy. The first relates to controversy over the effect of higher temperatures on mortality. Bosello *et al.* (2006) – not cited in the AR4 chapter on human health – claimed that increased temperatures would *reduce* heat-related mortality – by up to 800,000 deaths per year in 2050 - as reductions in cold-weather mortality more than offset increases in hot-weather mortality. This assertion was strongly disputed by Ackerman and Stanton (2008), who claimed that there was no substantial evidence for such a reduction, and that Bosello *et al.* (2006) relied on empirical relationships between temperature and mortality that neither accounted appropriately for geographic variability in tolerance nor for the countervailing effect of human adaptation to gradual changes in average temperature. For instance, Gosling *et al.* (2009a) demonstrated the importance of considering adaptation in assessments of the impacts of climate change on heat-related mortality – allowing for adaptation to a 2°C warming in mean temperatures reduced heat-related mortality in the 2080s by approximately half that of no adaptation, for cities including London, Lisbon and Sydney. More generally, Meze-Hausken (2008) emphasised that human thresholds of tolerance to increased temperature were very varied, depending on local context (often cultural), and varied over time. For instance, the "threshold temperature" at which heat-related mortality becomes discernible can vary according to age (Hajat *et al.* 2007), temporally (Davis *et al.* 2003), and by latitude (Gosling *et al.* 2009b). Furthermore, considering that heat-related mortality impacts have been shown to vary by location for the same greenhouse gas emissions scenarios (Gosling *et al.* 2009a), estimates of the impact of climate change on heat-related mortality therefore need to be locally-calibrated.

The second issue refers to the linkages between air quality and climate change, and parallels the interest in agriculture. Kinney (2008) drew attention to the benefits of improving air quality for the impacts of climate change on human health, but noted the small number of studies.

References

Ackerman, F. and E. A. Stanton (2008). "A comment on "Economy-wide estimates of the implications of climate change: Human health"." *Ecological Economics* 66(1): 8-13.

Adam, J. C., A. F. Hamlet, *et al.* (2009). "Implications of global climate change for snowmelt hydrology in the twenty-first century." *Hydrological Processes* 23(7): 962-972.

Adrian, R., Wilhelm, S. & Gerten, D. (2006) Life-history traits of lake plankton species may govern their phenological response to climate warming. Global Change Biology 12: 652-661.

Advice to the Dutch cabinet 3rd September 2008, http://www.deltacommissie.com/en/advies

Alo, C.A. & Wang, G. (2008) Potential future changes of the terrestrial ecosystem based on climate projections by eight general circulation models. Journal of Geophysical Research G, Biogeosciences 113: G01004.

Battin, J., Wiley, M.W., Ruckelshaus, M.H., Palmer, R.N., Korb, E., Bartz, K.K. & Imaki, H. (2007) Projected impacts of climate change on salmon habitat restoration. Proceedings of the National Academy of Sciences USA 104: 6720-6725.

Beaugrand, G., Brander, K., Lindley, J.A., Souissi, S. & Reid, P.C. (2003) Plankton effect on cod recruitment in the North Sea. Nature 426: 661-664.

Beckage, B., Osborne, B., Gavin, D.G., Pucko, C., Siccama, T. & Perkins, T. (2008) A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. Proceedings of the National Academy of Sciences USA 105: 4197-4202.

Beniston, M., Stephenson, D.B., Christensen, O.B., *et al.* (2007) Future extreme events in European climate: an exploration of regional climate model projections. Climatic Change 81: 71-95.

Benito Garzón, M., Sánchez De Dios, R., & Sainz Ollero, H. (2008) Effects of climate change on the distribution of Iberian tree species. Applied Vegetation Science 11: 169-178.

Berry, P.M., Jones, A.P., Nicholls, R.J. & Vos, C.C. (Eds) (2007) Assessment of the vulnerability of terrestrial and coastal habitats and species in Europe to climate change. Annex 2 of Planning for biodiversity in a changing climate - BRANCH project Final Report. Natural England, Peterborough, UK.

Bertin, R.I. (2008) Plant phenology and distribution in relation to recent climate change. Journal of the Torrey Botanical Society 135: 126-146.

Booker, F., R. Muntifering, *et al.* (2009). "The Ozone Component of Global Change: Potential Effects on Agricultural and Horticultural Plant Yield, Product Quality and Interactions with Invasive Species." *Journal of Integrative Plant Biology* 51(4): 337-351.

Bosello, F., R. Roson, *et al.* (2006). "Economy-wide estimates of the implications of climate change: Human health." *Ecological Economics* 58(3): 579-591.

Both, C. & te Marvelde, L. (2007) Climate change and timing of avian breeding and migration throughout Europe. Climate Research 35: 93-105.

Bradley, B.A. (2009) Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. Global Change Biology 15: 196-208.

Brander, K.M. (2007). Global fish production and climate change. Proceedings of the National Academy of Sciences USA 104: 19709-19714.

Bravo, D.N., Araújo, M.B., Lasanta, T. & Moreno, J.I.L. (2008) Climate change in Mediterranean mountains during the 21st century. Ambio 37: 280-285.

Buisson, L., Thuiller, W., Lek, S., Lim, P. & Grenouillet, G. (2008) Climate change hastens the turnover of stream fish assemblages. Global Change Biology 14: 2232-2248.

Burgmer, T., Hillebrand, H. & Pfenninger, M. (2007) Effects of climate-driven temperature changes on the diversity of freshwater macroinvertebrates. Oecologia 151: 93-103.

Byrnes, J.E., Reynolds, P.L. & Stachowicz J.J. (2007) Invasions and extinctions reshape coastal marine food webs. PLoS ONE 2: e295.

Callaghan, T.V, Björn, L.O., Chapin III, F.S., *et al.* (2007). Arctic tundra and polar desert ecosystems. In: Arctic climate impacts assessment, Symon, C. Arris, L. & Heal, B. (Eds). Cambridge University Press, Cambridge.

Carpenter, K.E., Abrar, M., Aeby, G., *et al.* (2008) One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 321: 560-563.

Carroll, E.A., Sparks, T.H., Collinson, N. & Beebee, T.J.C. (2009) Influence of temperature on the spatial distribution of first spawning dates of the common frog (*Rana temporaria*) in the UK. Global Change Biology 15: 467-473.

Challinor, A. J. and T. R. Wheeler (2008a). "Crop yield reduction in the tropics under climate change: Processes and uncertainties." *Agricultural and Forest Meteorology* 148(3): 343-356.

Challinor, A. J. and T. R. Wheeler (2008b). "Use of a crop model ensemble to quantify CO2 stimulation of water-stressed and well-watered crops." *Agricultural and Forest Meteorology* 148(6-7): 1062-1077.

Clarke, A., Murphy, E.J., Meredith, M.P., King, J.C., Peck, L.S., Barnes, D.K.A. & Smith, R.C. (2007) Climate change and the marine ecosystem of the western Antarctic Peninsula. Philosophical Transactions of the Royal Society B-Biological Sciences 362: 149-166.

Climate change effects on aquatic biota, ecosystem structure and function. Ambio 35: 359-369.

Colwell, R., Brehm, G., Gilman, A., & Longino, J. (2008) Global warming and elevational shifts, and lowland biotic attrition in the wet tropics. Science 5899: 258-261.

Crozier, L.G., Zabel, R.W. & Hamlett, A.F. (2008) Predicting differential effects of climate change at the population level with life-cycle models of spring Chinook salmon. Global Change Biology 14: 236-249.

Daufresne, M. & Boet, P. (2007) Climate change impacts on structure and diversity of fish communities in rivers. Global Change Biology 13: 2467-2478.

Davis, R. E., P. C. Knappenberge *et al.* (2003) “Changing heat-related mortality in the United States.” *Environmental Health Perspectives* 111:1712–1718.

Dawson R.J., Dickson M, Nicholls R. J., Hall J, Walkden M, Stansby P K, Mokrech M., Richards J., Zhou J., Milligan J, Jordan A, Pearson S, Rees J, Bates P.D., Koukoulas S, Watkinson A., (2009). "Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change." Climatic Change, DOI 10.1007/s10584-008-9532-8

Delta Commission, 2008 http://www.deltacommissie.com/en/advies (accessed 31 May 2009)

Devictor, V., Julliard, R., Couvet, D. & Jiguet, F. (2008) Birds are tracking climate change, but not fast enough. Proceedings of the Royal Society B, Biological Sciences 275: 2743-2748.

DINAS-COAST Consortium, 2006. DIVA 1.5.5. Potsdam Institute for Climate Impact Research, Potsdam, Germany, CD-ROM. Available at http://www.pik-potsdam.de/diva.

Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmuller, V., Dye, S.R. & Skjoldal, H.R. (2008) Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. Journal of Applied Ecology 45: 1029-1039.

Durance, I. & Ormerod, S.J. (2007) Climate change effects on upland stream macroinvertebrates over a 25-year period. Global Change Biology 13: 942-957.

EEA, European Environmental Agency (2007) Europe's environment: the fourth assessment. EEA Report No 1/2007, Copenhagen.

EEA, European Environmental Agency (2008) Impacts of Europe's changing climate - 2008 indicator-based assessment. EEA Report No 4/2008, Copenhagen.

EEA, European Environmental Agency (2008) Impacts of Europe's changing climate - 2008 indicator-based assessment. EEA Report No 4/2008, Copenhagen.

Engler, R. & Guisan, A. (2009) MIGCLIM: Predicting plant distribution and dispersal in a changing climate. Diversity and Distributions, 1-12.

Engler, R., Randin, C.F., Vittoz, P., Czáka, T., Beniston, M., Zimmermann, N.E. & Guisan, A. (2009) Predicting future distributions of mountain plants under climate change: does dispersal capacity matter? Ecography 32: 34-45

European Commission, 2007. Green Paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - Adapting to climate change in Europe options for EU action. Technical report, European Commission.

Fischer, G., F. N. Tubiello, *et al.* (2007). "Climate change impacts on irrigation water requirements: Effects of mitigation, 1990-2080." *Technological Forecasting and Social Change* 74(7): 1083-1107.

Foden, W., Mace, G., Vié, J.-C., *et al.* (2008) Species susceptibility to climate change impacts. In: Vié, J-C. Hilton-Taylor, C. & Stuart, S.N. (Eds). The 2008 Review of The IUCN Red List of Threatened Species. IUCN, Gland, Switzerland.

Foden, W., Midgley, G.F., Hughes, G.O., *et al.* (2007) A changing climate is eroding the geographical range of the Namib Desert tree Aloe through population declines and dispersal lags. Diversity and Distributions 13: 645-653.

Franks, S.J. & Weis, A.E. (2009) Rapid evolution of flowering time by an annual plant in response to a climate fluctuation. Proceedings of the National Academy of Sciences USA, 104: 1278-1282.

Frederiksen, M., Edwards, M., Richardson, A.J., Halliday, N.C. & Wanless, S. (2006) From plankton to top predators: bottom-up control of a marine food web across four trophic levels. Journal of Animal Ecology 75: 1259-1268.

Gange, A.C., Gange, E.G., Sparks, T.H. & Boddy, L. (2007) Rapid and recent changes in fungal fruiting patterns. Science 316: 71.

Gao, X. & Giorgi, F. (2008) Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. Global Planetary Change 62: 195-209.

Gärtner, S., Reif, A., Xystrakis, F., Sayer, U., Bendagha, N. & Matzarakis, A. (2008) The drought tolerance limit of *Fagus sylvatica* forest on limestone in southwestern Germany. Journal of Vegetation Science 19: 757-768.

Gazeau, F., Quiblier, C., Jansen, J.M., Gattuso, J.P., Middleburg, J.J., & Heip, C.H.R. (2007) Impact of elevated CO2 on shellfish calcification. *Geophysical Research Lett.* **34** 21-28

Gehrig-Fasel, J., Guisan, A. & Zimmermann, N.E. (2007) Tree line shifts in the Swiss Alps: climate change or land abandonment? Journal of Vegetation Science 18: 571-582.

Geßßler, A., Keitel, K., Kreuzwieser, J., Matyssek, R., Seiler, W. & Rennenberg, H. (2007) Potential risks for European beech (*Fagus sylvatica* L.) in a changing climate. Trees-Structure and Function 21: 1-11.

Giorgi, F. & Lionello, P. (2008) Climate change projections for the Mediterranean region. Global Planetary Change 63: 90-114.

Gómez-Aparicio, L., Pérez-Ramos, I.M., Mendoza, I., *et al.* (2008). Oak seedling survival and growth along resource gradients in Mediterranean forests: Implications for regeneration in current and future environmental scenarios. Oikos 117: 1683-1699.

Gopal, B. & Chauhan, M. (2006) Biodiversity and its conservation in the Sundarban Mangrove Ecosystem. Aquatic Sciences 68: 338-354.

Gopal, B. & Chauhan, M. (2006) Biodiversity and its conservation in the Sundarban Mangrove Ecosystem. Aquatic Sciences 68: 338-354.

Gordo, O. (2007). Why are bird migration dates shifting? A review of weather and climate effects on avian migratory phenology. Climate Research 35: 37-58.

Gosling, S. N., J. A. Lowe and G. R. McGregor (2009a). “Climate change and heat-related mortality in six cities Part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change.” *International Journal of* ***B****iometeorology* 53(1):31-51.

Gosling, S. N., J. A. Lowe *et al.* (2009b) “Associations between elevated atmospheric temperature and human mortality: a critical review of the literature.” *Climatic Change* 92:299–341.

Guinotte, J.M. & Fabry, V.J. (2008) Ocean acidification and its potential effects on marine ecosystems. Year in Ecology and Conservation Biology 1134: 320-342.

Hajat, S., R. S. Kovats, and K. Lachowycz (2007) “Heat-related and cold-related deaths in England and Wales: who is at risk?” *Occup Environ Med* 64:93-10.

Harley, C.D.G., Hughes, A.R., Hultgren, K.M., *et al.* 2006: The impacts of climate change in coastal marine systems. Ecology Letters 9: 228-241.

Hegland, S., Nielsen, A., Lázaro, A., Bjerknes, A. & Totland, Ø. (2009) How does climate warming affect plant-pollinator interactions? Ecology Letters 12: 184-195.

Hiddink, J.G. & ter Hofstede, R. (2008) Climate induced increases in species richness of marine fishes. Global Change Biology 14: 453-460.

Hobbs, R.J., Yates, S. & Mooney, H.A. (2007) Long-term data reveal complex dynamics in grassland in relation to climate and disturbance. Ecological Monographs 77: 545-568.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J. *et al.* (2007) Coral reefs under rapid climate change and ocean acidification. Science 318: 1737-1742.

Huntley, B., Collingham, Y.C., Willis, S.G., Green, R.E. (2008) Potential impacts of climate change on European breeding birds. *Plos One* January 2008 issue 1 e1439.

Jarvis, A., Lane, A., Hijmans, R. (2008) The effect of climate change on crop wild relatives. *Agricultural Ecosystems and Environment*, 126: 13-23.

Jenouvrier, S., Caswell, H., Barbraud, C., Holland, M., Strœye, J., Weimerskirch, H. (2009) Demographic models and IPCC climate projections predict the decline of an emperor penguin population. *Proceedings of the National Academy of Sciences*, 106: 1844-1847.

Karmalkar, A.V., Bradley, R.S. & Diaz, H.F. (2008). Climate change scenario for Costa Rican montane forests. Geophysical Research Letters 35: L11702

Kauserud H, Stige LC, Vik JO, Økland RH, Høiland K, Stenseth NC. 2008. Mushroom fruiting and climate change. Proceedings of the National Academy of Sciences USA, 105, 3811-3814

Kelly, A.E. & Goulden, M.L. (2008) Rapid shifts in plant distribution with recent climate change. Proceedings of the National Academy of Sciences USA 105: 11823-11826.

Kinney, P. L. (2008). "Climate Change, Air Quality, and Human Health." *American Journal of Preventive Medicine* 35(5): 459-467.

Koeller, P., Fuentes-Yaco, C., Platt, T., *et al.* (2009) Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Science 324: 791-793.

Kusano, T. & Inoue, M. (2009). Long-term trends toward earlier breeding of Japanese amphibians. Journal of Herpetology 42: 608-614.

Le Roux, P.C. & McGeoch, M.A. (2008) Changes in climate extremes, variability and signature on sub-Antarctic Marion Island. Climatic Change 86: 309-329.

Learmonth, J.A., MacLeod, C.D., Santos, M.B., Pierce, G.J., Crick, H.Q.P. & Robinson, R.A. (2006) Potential effects of climate change on marine mammals. Oceanography and Marine Biology 44: 431-464.

Lemoine, N., Bauer, H.-G., Peintinger, M. & Böhning-Gaese, K. (2007a). Effects of climate and land-use change on species abundance in a Central European bird community. Global Ecology and Biogeography 21, 495-503.

Lemoine, N., Schaefer, H.-C. & Böhning-Gaese, K. (2007b) Species richness of migratory birds is influenced by global climate change. Global Ecology and Biogeography 16: 55-64.

Lloret, F., Peñuelas, J., Prieto, P., Llorens, L. & Estiarte, M. (2009) Plant community changes induced by experimental climate change: Seedling and adult species composition. Perspectives in Plant Ecology and Systematics 11: 53-64.

Lobell, D. B. and C. B. Field (2008). "Estimation of the carbon dioxide (CO2) fertilization effect using growth rate anomalies of CO2 and crop yields since 1961." *Global Change Biology* 14(1): 39-45.

Lobell, D. B., M. B. Burke, *et al.* (2008). "Prioritizing climate change adaptation needs for food security in 2030." *Science* 319(5863): 607-610.

Lonsdale K., Downing T.E., Nicholls R. J., Parker D, Vafeidis A.T., Dawson R, Hall J, 2008: "Plausible responses to the threat of rapid sea-level rise in the Thames Estuary." Climatic Change, 91, 145-169

Lough, J.M. (2008) 10th anniversary review: a changing climate for coral reefs. Journal of Environmental Monitoring 10: 21-29.

Mazaris, A., Kallimanis, A., Sgardelis, S. & Pantis, J. (2008) Do long-term changes in sea surface temperature at the breeding areas affect the breeding dates and reproduction performance of Mediterranean loggerhead turtles? Implications for climate change. Journal of Experimental Marine Biology and Ecology 367: 219-226.

Meier, I.C. & Leuschner, C. (2008) Genotypic variation and phenotypic plasticity in the drought response of fine roots of European beech. Tree Physiology 28: 297-309.

Meine, C. (2007) Threats to biodiversity in Bulgaria. Available from: http://rmportal.net/tools/biodiversity-support-program/17-conserving-biological-diversity-in-bulgaria-the-national-biological-diversity-conservation-strategy.

Memmott, J., Craze, P.G., Waser, N.M., and Price, M.V. (2007) Global warming and the disruption of plant-pollinator interactions. *Ecology Letters* **10**, 710-717

Metzger, M.J., Bunce, R.G.H., Leemans, R. & Viner, D. (2008) Projected environmental shifts under climate change: European trends and regional impacts. Environmental Conservation 35: 64-75.

Meze-Hausken, E. (2008). "On the (im-)possibilities of defining human climate thresholds." *Climatic Change* 89(3-4): 299-324.

Miriti, M.N., Rodriguez-Buritica, S., Wright, S.J., and Howe H.F. (2007) Episodic death across species of desert shrubs. *Ecology* **88** 32-36

Moline, M.A., Karnovsky, N.J., Brown, Z., Divoky, G.J., Frazer, T.K., Jacoby, C.A., Torrese, J.J. & Fraser, W.R. (2008) High latitude changes in ice dynamics and their impact on polar marine ecosystems. Year in Ecology and Conservation Biology 2008, 1134: 267-319.

Moreno-Rueda, G., Pleguezuelos, J. & Alaminos, E. (2009) Climate warming and activity period extension in the Mediterranean snake Malpolon monspessulanus. Climatic Change 92: 235-242.

Moritz, C., Patton, J.L., Conroy, C.J., Parra, J.L., White, G.C. & Beissinger, S.R. (2008) Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. Science 322: 261-264.

Nicholls R. J., Tol R.S.J., Vafeidis A.T., (2008). "Global estimates of the impact of a collapse of the West Antarctic ice sheet: an application of FUND." Climatic Change, 91, 171-191

Nogués-Bravo, D., Araújo, M.B., Martinez-Rica, J.P. & Errea, M.P. (2007) Exposure of global mountain systems to climate change. Global Environmental Change 17: 420-428.

Occhipinti-Ambrogi, A. (2007) Global change and marine communities: alien species and climate change. Marine Pollution Bulletin 55: 342-352.

Olofsson, J., Oksanen, L., Callaghan, T., Hulme, P., Oksanen, T., Suominen, O. (2009) Herbivores inhibit climate-driven shrub expansion on the tundra. Global Change Biology: 15

Parmesan, C. (2006) Ecological and evolutionary responses to recent climate change. Annual Review of Ecology Evolution and Systematics 37: 637-669.

Parmesan, C. (2007) Influences of species, latitudes and methodologies on estimates of phenological response to global warming. Global Change Biology 13: 1860-1872.

Pauli, H., Gottfried, M., Reiter, K., Klettner, C. & Grabherr, G. (2007) Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994-2004) at the GLORIA*master site Schrankogel, Tyrol, Austria. Global Change Biology 13: 147-156.

Peñuelas, J., Rutishauser, T. & Filella, I. (2009) Phenology Feedbacks on Climate Change. Science 324: 887-888.

Perry, A.L., Low, P.J., Ellis, J.R. & Reynolds, J.D. (2005) Climate change and distribution shifts in marine fishes. Science 308: 1912-1915.

Preston, B. L. and R. Jones (2008). "A national assessment of the sensitivity of Australian runoff to climate change." *Atmospheric Science Letters* 9(4): 202-208.

Pudas, E., Leppälä, M., Tolvanen, A., Poikolainen, J., Venäläinen, A., & Kubin, E. (2008) Trends in phenology of Betula pubescens across the boreal zone in Finland. International Journal of Biometeorology 52: 251-259.

Rahel F.J. and Olden, J.D., (2008) Assessing the effects of climate change on aquatic invasive species. Conservation biology 22, 521-533.

Reilly, J., S. Paltsev, *et al.* (2007). "Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone." *Energy Policy* 35(11): 5370-5383.

Riebesell, U. (2008) Climate change: Acid test for marine biodiversity. Nature 454, 46-47

Robson, T.M., Rodríguez-Calcerrada, J., Sánchez-Gómez, D. & Aranda, I. (2009) Summer drought impedes beech seedling performance more in a sub-Mediterranean forest understory than in small gaps. Tree physiology 29: 249-259.

Rockstrom, J., M. Falkenmark, *et al.* (2009). "Future water availability for global food production: The potential of green water for increasing resilience to global change." *Water Resources Research* 45.

Rosenzweig, C., Karoly, D.J., Vicarelli, M., *et al.* (2008) Attributing physical and biological impacts to anthropogenic climate change. Nature 453: 353-357.

Rubolini, D., Møller, A.P., Rainio, K. & Lehikoinen, E. (2007). Intraspecific consistency and geographic variability in temporal trends of spring migration phenology among European bird species. Climate Research 35: 135-146.

Sabatés, A., Martín, P., Lloret, J. & Raya, V. (2006) Sea warming and fish distribution: the case of the small pelagic fish, *Sardinella aurita*, in the western Mediterranean. Global Change Biology 12: 2209-2219.

Sánchez de Dios, R., Benito-Garzón, M. & Sainz-Ollero, H. (2009) Present and future extension of the Iberian submediterranean territories as determined from the distribution of marcescent oaks. Plant Ecology: 1-17.

Schröter, D., Cramer, W., Leemans, R., *et al.* (2005) Ecosystem service supply and vulnerability to global change in Europe. Science 310: 1333-1337.

Sekercioglu, C.H., Schneider, S.H., Fay, J.P., and Loraire, S.R. (2007) Climate change, elevational range shifts, and bird extinctions. *Conservation Biology* 22, 1, 140-150.

Settele, J. *et al.* (2008) Climatic Risk Atlas of European Butterflies. *Biorisk* **1**, special issue.

Simmonds, M.P. & Isaac, S.J. (2007) The impacts of climate change on marine mammals: early signs of significant problems. Oryx 41: 19-26.

Smith, J.R., Fong, P. & Ambrose, R.F. (2006) Dramatic declines in mussel bed community diversity: response to climate change? Ecology 87: 1153-1161.

Sparks, T.H., Dennis, R.L.H., Croxton, P.J., Cade, M. (2007) Increased migration of Lepidoptera linked to climate change, European Journal of Entomology: 104, 139-143

St. Clair, S.B., Sharpe, W.E. & Lynch, J.P. (2008) Key interactions between nutrient limitation and climatic factors in temperate forests: a synthesis of the sugar maple literature. Canadian Journal of Forest Research 38: 401-414.

Tape, K., Sturm, M. & Racine, C. (2006) The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. Global Change Biology 12: 686-702.

TE2100 (Thames Estuary 2100), 2009. http://www.environment-agency.gov.uk/research/library/consultations/106100.aspx (accessed 31 May 2009)

Thibault, K.M. & Brown, J.H. (2008) Impact of an extreme climatic event on community assembly. Proceedings of the National Academy of Sciences USA 105: 3410-3415.

Tol R.S.J., Klein R.J.T., Nicholls R. J., (2008). "Towards sucessful adaptation to sea-level rise along Europe's coasts." Journal of Coastal Research, 24 (2), 432-450.

Tømmervik, H., Johansen, B., Riseth, J.A., Karlsen, S.R., Solberg, B. & Høgda, K.A. (2009) Above ground biomass changes in the mountain birch forests and mountain heaths of Finnmarksvidda, northern Norway, in the period 1957-2006. Forest Ecology and Management 257: 244-257.

Tubiello, F.N., Soussana, J-F., Howden, S.M. (2007) Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences* 104(50: 19686-19690.

van Buskirk, J., Mulvihill, R. & Leberman, R. (2009) Variable shifts in spring and autumn migration phenology in North American songbirds associated with climate change. Global Change Biology 15: 760-771.

van der Werf, G.W., Sass-Klaassen, U.G.W. & Mohren, G.M.J. (2007) The impact of the 2003 summer drought on the intra-annual growth pattern of beech (*Fagus sylvatica* L.) and oak (*Quercus robur* L.) on a dry site in the Netherlands. Dendrochronologia 25: 103-112.

Van Dingenen, R., F. J. Dentener, *et al.* (2009). "The global impact of ozone on agricultural crop yields under current and future air quality legislation." *Atmospheric Environment* 43(3): 604-618.

Verbeeck, H., Samson, R., Granier, A., Montpied, P. & Lemeur, R. (2008) Multi-year model analysis of GPP in a temperate beech forest in France. Ecological Modelling 210: 85-103.

Virkkala, R., Heikkinen, R.K., Leikola, N. & Luoto, M. (2008) Projected large-scale range reductions of northern-boreal land bird species due to climate change. Biological Conservation 141: 1343-1353.

Vittoz, P. and R. Engler (2007) Seed dispersal distances: a typology based on dispersal modes and plant traits. Botanica Helvetica 117: 109-124.

Vittoz, P., Bodin, J., Ungricht, S., Burga, C.A. & Walther, G.-R. (2008) One century of vegetation change on Isla Persa, a nunatak in the Bernina massif in the Swiss Alps. Journal of Vegetation Science 19: 671-680.

Vittoz, P., Randin, C., Dutoit, A., Bonnet, F. & Hegg, O. (2009) Lower impact of climate change on subalpine grasslands in the Swiss Northern Alps? Global Change Biology 15: 209-220.

Wake, D.B., & Vredenburg, V.T. (2008) Are we in midst of the sixth mass extinction? A view from the world of amphibians. Proceedings of the National Academy of Sciences USA 105: 11466-11473.

Wethey, D.S. & Woodin, S.A. (2008) Ecological hindcasting of biogeographic responses to climate change in the European intertidal zone. Hydrobiologia 606: 139–151.

Wilson, R.J., Gutiérrez, D., Gutiérrez, J. & Monserrat, V.J. (2007) An elevational shift in butterfly species richness and composition accompanying recent climate change. Global Change Biology 13: 1873-1887.

Wolf, A., Callaghan, T.V., Larson, K. (2008) Future changes in vegetation and ecosystem function of the Barents Region. Climatic Change 87: 51-73.

Yang, Y., Fang, J., Tang, Y., Ji, C., Zheng, C., He, J., Zhu, B. (2008) Storage, patterns and controls of soil organic carbon in the Tibetan grasslands. Global Change Biology, 14:1592-1599.

Zalakevicius, M., Bartkeviciene, G., Raudonikis, L. & Janulaitis, J. (2006) Spring arrival response to climate change in birds: a case study from eastern Europe. Journal of Ornithology 147: 326-343.

Zeebe, R.E., Zachos, J.C., Caldeira, K., and Tyrell, T. (2008) Oceans: Carbon emissions and acidification. *Science* **321**, 51-52.

C. ECONOMICS OF CLIMATE CHANGE MITIGATION

We review in turn several of the statements made in IPCC AR4 WGIII and ask if new literature throws light on these statements.

C.1 With current climate change mitigation policies and related sustainable development practices, global greenhouse gas emissions will continue to grow over the next few decades

Recent literature continues to support this statement. Raupach *et al.* (2007) present an analysis showing that emissions are observed to be increasing faster than expected. However, the period of observed increases in emissions is considered too short to establish a trend break (van Vuuren and Riahi 2008; Schiermeier 2008). Subsequent to the 2007 results, the global financial crisis has developed, bringing many countries into recession. Historically this has caused significant reductions in emissions in the short term (but not the deep sustained emission cuts necessary to significantly reduce warming).

Pielke, Wigley and Green (2008) suggest that the IPCC SRES scenarios hugely underestimate future emissions without mitigation action. However, their analysis is flawed. It uses a 'frozen technology' scenario as a baseline, which is, according to others eminent in the field, an unrealistic thought experiment (Schiermeier 2008). The assumption in the IPCC scenarios that technological change will continue as it has historically done is entirely reasonable, based on principles thoroughly grounded in the literature, and agreed by panels of experts.

There is agreement that emissions in Asia (China and India) are increasing faster than expected, but this was acknowledged in the IPCC AR4. Although Raupach *et al.* (2007) appears to show that emissions are growing faster than in the A1FI SRES scenario, recent analysis of the emissions data by the committee on climate change (Smith *et al.* 2008) has revealed that the actual emissions were still below the SRES A1B scenario in 2007. The IPCC noted that the highest populations assumed in the SRES scenarios were now larger than the highest UN projections. Hence the SRES scenarios still represent reasonable plausible ranges for future global emissions.

There is general consensus in the utility of generating new baselines, however, and in the Fifth Assessment a completely different approach to scenario building will be used. Some new baselines already exist, for example, Garnaut, Howes, Jotzo and Sheehan (2008) present a new business-as-usual scenario, created for the Garnaut climate change review in Australia, with emissions that are 11% higher in 2030 than in SRES A1FI.

C.2 Both bottom-up and top-down studies indicate there is substantial economic potential for the mitigation of global GHG emissions over the coming decades that could offset the projected growth of global emissions or reduce emissions below current levels

An assessment using a variety of models finds similar results to AR4 (Hoogwijk *et al.* 2008). In particular carbon prices of 50\$/tCO_2 induced a 29-46% drop in global CO_2-eq emissions by 2030, using a wide range of simulation and optimisation models which use very different approaches (the AR4 range, for comparison, is 20-52% by 2030).

C.3 In 2050 global average macro-economic costs for multi-gas mitigation towards stabilisation between 710 and 445 ppm CO_2-eq are between a 1% gain to a 5.5% decrease of global GDP

Recent studies have also found that macroeconomic costs of mitigation are relatively small. For example Stern (2007) found that stabilization at 550 ppm CO_2 would cost ~1% GDP (+/- 3%) by 2050. (IEA, 2008) finds that reducing global CO_2 emissions by 50% from 2005 levels by 2050 (sufficient to stabilize at ~500 ppm CO_2 eq) will require an investment of 1.1% of global GDP to 2050. McKinsey (2009) estimates costs of less than 1% of GDP for a 35% reduction relative to 1990 by 2030. Other models simulating the UK or EU alone suggest similar GDP reductions of 0.7-1.1% by 2050 for a 60% emission reduction, 1.5-2% for an 80% reduction, or 0.55-0.8% for a 20-30% reduction by 2020 (Strachan, Pye, and Kannan, 2009).

A comparison of five energy-environment-economy models, carried out as part of the ADAM project[1], found that costs of stabilising at 400-550 ppm CO_2-eq range from -2.3 to 2.5% of baseline GDP in 2100. This is the

[1] www.adamproject.eu. The ADAM results will be published in a forthcoming special issue of the Energy Journal, and a book to be launched at the COP 15 in December, and published in 2010 (Knopf *et al.*, 2010). The summary results referred to here have already been published in a report (Edenhofer & Stern, 2009).

first time such results have been compiled across several models for stabilisation scenarios lower than 450 ppm.

One of the ADAM models, E3MG, developed at the University of Cambridge, predicts economic benefits of mitigation, resulting in increased GDP relative to baseline by 2100 (see also (Barker, Scrieciu and Foxon, 2008). One other model (RICE FAST IMCP) reported in the IPCC AR4 also show GDP above baselines for mitigation at global and national levels under some assumptions. E3MG predicts greater benefits from more stringent mitigation with gains of 1.3% above baseline in 2100 for the 550 ppm CO_2-eq case, and 2.1% for the 400 ppm case. This is in contrast to most findings in the literature, which find costs increasing for more stringent mitigation.

The key differences between E3MG and other models are that it includes other mitigation measures, such as the recycling of revenues collected from auctioning permits and regulations to support the deployment of electric cars, as well as pricing carbon to stimulate low-carbon technologies and energy efficiency. It also captures the under-employed and unemployed resources existent in the global economic system, which can be drawn into more productive uses and accelerate growth through the investments needed to decarbonise the world economy. Many studies that show GDP losses neglect trade and competitiveness benefits of moving to a low carbon economy, or do not allow recycling of revenues from carbon pricing, or benefits from the growth of low carbon industries.

There is recognition that these ‘costs’ for mitigating climate change should not be considered as net costs. They might be thought of as investments or a re-direction of economic activity and employment (IEA 2008), and may not actually reduce GDP. Some costs can be balanced against reduced fuel costs, for example.

C.4 Modelling studies consistent with stabilization at around 550 ppm CO_2-eq by 2100 show carbon prices rising to 20-80 US$/t$CO_2$ by 2030 and to 30-155 US$/t$CO_2$ by 2050. Studies that take into account induced technological change lower these price ranges to 5-65 US$/t CO_2-eq in 2030 and 15-130 US$/t$CO_2$ in 2050

There are significant uncertainties regarding the level of carbon pricing necessary to achieve a particular cut in emissions. The level of carbon prices for a specific stabilisation target depends not only on baseline emissions and the assumed world fossil fuel prices and costs of new technologies (Strachan *et al.* 2009), but also on the portfolio of mitigation policies being implemented.

In 2008, the International Energy Agency (IEA, 2008) doubled its 2006 estimate of the marginal costs to bring CO_2 emissions to 2005 levels by 2050 (consistent with stabilization at roughly 550 ppm CO_2-eq) pricing this at up to US$50/t$CO_2$. The increased price was due to increased emissions, engineering costs and the declining value of the dollar. This falls within the price range quoted by the IPCC for this level of mitigation.

The same study estimates a cost of 200-500 US$/t$CO_2$ for an 80% reduction by 2050, which is far greater than any marginal costs quoted by the IPCC, but also represents stringent mitigation to a level not considered in this context.

Barker *et al.* (2008) show that a carbon price of only $100/t$CO_2$ may bring about a 50% cut in emissions relative to 2000 by 2050 if, in addition to the carbon price, regulatory measures and incentives are used to encourage deployment of low-carbon technologies. In that study, a carbon price alone led to a mere 16% reduction in emissions by 2050 (stabilization at 550 ppm CO_2-eq).

McKinsey (2009), using the marginal abatement cost approach, estimates that a pathway to stabilization at 500 ppm CO_2-eq can be achieved at carbon prices less than $60 US$/tCO_2 eq.

(Gerlagh 2007) found stabilization costs could be reduced by 50% or more when technological change is accounted for. However, empirical research on the effect of environmental policy on technology is still not particularly well tied to efforts to model with induced technological change ((Pizer and Popp 2008); Kahouli-Brahmi 2008), so these results must be interpreted with caution.

Since institutional structure creates strong barriers to change, and technology policy is important to promoting technological change (Kohler *et al.* 2007), as is knowledge sharing between nations (Bosetti, Carraro, Massetti, and Tavoni 2008).

C.5 Multi-gas emission scenarios can meet climate targets at substantially lower costs.

The IPCC found that carbon prices were reduced 30-85% in 2100 when non-CO_2 gases are included. The literature continues to support this view. In particular the Energy Modeling Forum EMF-21 work, which was one strong basis of the IPCC Fourth Assessment, has now been extended to assess the costs of non-CO_2 abatement allowing for technological development beyond 2020 (Lucas, den Elzen, Olivier, and Gisjen 2007). This reduced non-CO_2 mitigation costs by 3-21% in 2050 and 25-35% in 2050. In the shorter term, the cost saving from employing non-CO_2 mitigation options was very high in this study. The overall cost of climate policy was cut by 85% in 2010 relative to a CO_2 only approach.

Some authors argue that non-CO_2 abatement options are necessary to bring lower stabilisation targets within reach. For example, (M. G. J. den Elzen, Lucas, and van Vuuren 2008) assess regional abatement costs for stabilisation at 450ppm and 550ppm CO_2-eq. They find that non-CO_2 reductions and energy efficiency options are the most cost-effective sources of emission reductions in the short term, especially in the former Soviet Union and Asia. CO_2 reductions become dominant between 2020 and 2050.

Another marginal costs analysis (Den Elzen, Lucas and Gisjen 2007) suggests that, when non-CO_2 abatement options are included, the cost of achieving the European emission reduction target of 20% by 2020 is 0.05-0.24% of GDP.

The most important non-CO_2 abatement options in the short term are likely to involve the fluorinated gases (eg HFCs, PFCs) and methane emissions generated during coal mining and oil and gas production (Lucas, van Vuuren, Olivier and den Elzen 2007).

C.6 Energy efficiency options for new and existing buildings could considerably reduce CO_2 emissions with net economic benefit. Many barriers exist against tapping this potential, but there are also large co-benefit. 30% of the projected GHG emissions from buildings could be avoided by 2030

Literature continues to support this view with McKinsey (2009) finding that energy efficiency can contribute the largest abatement potential between now and 2030. IEA (2008b) estimate that energy efficiency improvements in buildings could contribute 17% of emission reductions that could be made by 2050.

New estimates of the size of the rebound effect, where energy efficiency measures are accompanied by an increase in consumption, have been published. It has been estimated to potentially offset 52% of the total energy saving globally, from a mix of energy efficiency measures proposed by the IEA (Dagoumas and Barker 2009). In the UK, the rebound effect could offset 26% of the total savings from UK energy efficiency measures to 2010 (Barker, Ekins and Foxon 2007).

C.7 The Costs of Inaction. Statement in IPCC AR4: '...the economically optimal timing and level of mitigation depends upon the uncertain shape and character of the assumed damage cost curve'

It has long been known that social costs of carbon (i.e. damage costs) and hence the implied optimal stabilization level can be manipulated by changing key parameters such as discount rates, equity weighting, the way in which damage is represented, and so on (see IPCC AR4, WGIII, Figure 3.39). Stern argues strongly for the selection of certain parameter values in this debate, and these arguments still hold. Inevitably the range of estimates of the costs of inaction in the recent literature continues to be wide because different institutions use different parameter values. For example, OECD (2008) found that estimates of the economic costs of climate change vary widely, with the Stern assessment falling at the top of the range.

Discussion continues in the literature about the sensitivity of climate change damage cost assessments to underlying assumptions and estimated parameters (e.g. (Anthoff, Hepburn and Tol 2009; Nordhaus 2007). (Tol and Yohe 2009) show that manipulating parameters in a simplified Stern-like model can diminish the damage estimates by 84% or increase them by 900%.

Hof, Den Elzen and van Vuuren (2008) carry out a sensitivity study on the analysis in the Stern review and show that values chosen for abatement and damage costs influence the economically optimal mitigation path as strongly as the discount rate leading to a wider range of 'optimal' stabilisation targets (520ppm-800ppm CO_2-eq) than recommended by Stern (450-550 ppm), depending on the assumptions. These results confirm the position of the IPCC and do not significantly advance the debate.

There is agreement that choosing to reduce greenhouse gas emissions is a political and ethical choice, and economics should be used to assess the cost-effectiveness of different routes to doing so (Ackerman, DeCanio, Howarth and Sheeran 2009; Barker 2008; Barker, Scriecіu and Taylor 2008; Dietz and Stern 2008).

Recent analyses provide the following insights:

a. Hope (2009) deduces an optimal emissions path by balancing climate damages against abatement and adaptation costs, using the PAGE model. He finds optimal emission reductions of 54% (66%) in Annex 1 countries and 58% (86%) in non-Annex 1 countries, relative to 2000, by 2020 (2060 in brackets). This analysis produces a social cost of carbon of $63/tC, lower than the Stern figure of $300/tC, largely due to the use of market exchange rates instead of purchasing power parity.
b. Extreme events can contribute to a non-linear increase of inaction costs with global mean temperature rise (Hallegate 2009; Hallegate, Hourcade and Dumnas 2007; Webersik, Esteban and Shibayama 2009, Webersik *et al.* 2009).
c. Losses due to extreme events have been difficult to quantify owing to the need to separate the component of the increase due to increased frequency or severity of weather events, versus increasing stocks at risk due to rising GDP. However, progress has now been made in this area: for example, Schmidt et al (2009a, b) show that in the USA some 25% of the increase can be attributed to climate change, and that this component has been increasing by 4%/year since 1971.
d. Delaying policy by 10 years will dramatically increase its costs (McKinsey 2009).
e. New since the Fourth Assessment Report are estimates of a 20% reduction in outdoor worker productivity in Delhi for a local 2°C temperature rise (Kjellstrom and Lemke 2009) and 0.1-0.5% GDP loss in Germany due to heat stress impacting on worker productivity by 2100 under a medium emissions scenario (A1B) (Hubler, Klepper, Peterson 2008).

More generally, criticisms of the cost-benefit approach continue in the literature (Hof, Den Elzen and van Vuuren, 2008; Weitzman 2009). Specifically, Weitzman (2009) emphasizes the difficulty of including high impact, low probability catastrophes. Such events are not well-characterised in terms of probability or cost, but with any reasonable notion of risk aversion the need to avoid such events will dominate the calculation of the benefits of action. Stern (2007) did include such impacts in his analysis, however.

C.8 Land Use Change: AR4 found that 'including land use mitigation options as abatement strategies provides greater flexibility and cost-effectiveness for achieving stabilisation'

Currently there is a particular opportunity to act on the above statement through the negotiations on REDD (Reduced Emissions from Deforestation and Degradation). The Bali Action Plan commits to reducing emissions from deforestation and degradation, but indicates no preferred financing mechanism. There is widespread agreement (Eliasch 2008; Hepburn and Stern 2008) that providing funds for avoided deforestation will be a crucial aspect of a post-2012 climate change deal. Furthermore, it has been shown that action on land use change is central to obtaining the EU 2°C target (Warren *et al.* in review).

Avoided deforestation has been demonstrated to be a cost effective mitigation option. Stern (2007) estimates that to completely halt deforestation could have a marginal cost of up to $30 tCO_2eq^{-1}. The European Commission has assessed the cost of halving deforestation by 2020 somewhere between US$3 billion and $250 billion (Bozmoski and Hepburn 2009). Similarly Kindermann *et al.* (2008) use three land use models with a range of estimates of forest cover and carbon storage in forests to estimate costs of halving deforestation by 2030. They find values of US$17-28 billion, or $10-21 tCO_2^{-1}, which compare favourably with the range of costs for other mitigation options. Obviously transaction costs and institutional barriers raise costs in practice, but there are similar barriers to other mitigation options that might not be included in their cost estimates.

C.9 The financial crisis and its effect on mitigation

The current economic situation is an opportunity to invest in mitigation. (Bowen, Fankhauser, Stern and Zhengelis 2009) evaluate 23 measures for tackling climate change that could form part of a fiscal stimulus. They find energy efficiency and some transport measures have high potential for short term economic advantage and mitigation. If a 'green' stimulus made up 20% of the global stimulus package, the investment would compare well to amounts required to reach the low-carbon trajectory necessary to avert dangerous climate change, as estimated by McKinsey *et al.* (2009). Pollitt and Junankar (2009) show that using a proportion of the fiscal stimulus packages for low carbon investments could help alleviate the negative influence on recovery of a return to high oil prices. Fankhauser *et al.* (2008) find that climate policy could have either a positive or negative effect on employment in the short term, but in the medium term, analyses generally show increased numbers of jobs in the wider economy.

C.10 Strategies and pathways to emissions reduction

From a global perspective, Kyoto has achieved little, and some authors point to fundamental flaws in its approach. Helm (2008) for example urges that international agreements should be based on consumption, not production. The UK claims a reduction of 15.7% in emissions since 1990, by 2005. But if aviation, shipping and goods manufactured elsewhere are taken into account, UK emissions had increased by around 19% since 2003. Barrett (2008) points out that the current agreement is weak on enforcement. M. den Elzen and Hohne (2008) argue that the slow pace of climate policy and the steady increase in global emissions now make it 'almost unfeasible to reach the relatively low global emission levels in 2020 needed to meet [a stabilisation target of] 450 ppm CO_2-eq.'

According to World Energy Outlook for 2008 (IEA, 2008), more than half of global CO_2 will be emitted in developing countries by 2010.

Lutz and Meyer (2009) provide economic evidence that developing countries must be fully involved in the post-2012 reduction targets, otherwise the targets will not be met. They model a hybrid tax and permit approach, using the global econometric simulation model GINFORS.

In their simulation, costs of mitigation to the EU27 can be twice or only half as high, depending on the allocation of allowances, the treatment of auctioning revenues and the use of flexible mechanisms. For example, if credits from Clean Development Mechanism (CDM) projects can be used to cover up to 50% of carbon emission allowances, the EU could reduce emissions by 30% by 2020, for the same cost as reducing by 20% without the CDM. The other advantage of employing flexible mechanisms is that demand for clean, low carbon technologies will then grow outside as well as within Europe, improving export prospects for Europe.

The European Union Emissions Trading Scheme (EU ETS) is a central pillar of European climate policy and should be a demonstration to other nations of how carbon trading can be effective. Since the implementation phase (Phase II) only began in 2008, the literature on whether this policy has been successful is limited. In general, it provides a very cautious welcome, but argues that there is a lot to learn before the policy functions as it should.

Put simply, the EU ETS is not delivering the kind of carbon prices that other economic studies indicate are required to stabilise greenhouse gases at 550ppm. Over the period 2005-2007, the price reached a maximum of €32.85 tCO_2^{-1} (Ellerman and Buchner 2008). In recent months, the allowance price has been hovering around €15 tCO_2^{-1} (www.pointcarbon.com). This low price is partly as a result of the financial crisis, which began in October 2008 and has caused a substantial drop in demand for fossil fuel energy and manufactured products.

(Skjaerseth and Wettestad 2008) discuss the institutional and political differences between nations that have hampered implementation of the EU ETS, and led to only moderate and mixed success. They highlight decentralized management of the scheme, hurried implementation, prior climate policies in particular nations and inclusion of too many CDM credits, as causes of its ineffectiveness in certain cases. The UK is identified as the clear front runner in Europe in implementing the EU ETS. The UK needed 17.7% fewer permits than it was allocated in the first reporting period for 2005.

Ellerman and Buchner (2008) make a first attempt to analyse whether the EU ETS has worked, and actually reduced carbon emissions in Europe. Their tentative analysis suggests that in the first two years of the trial period, European CO_2 emissions were reduced by between 50 and 100 million tonnes each year as a result of the EU ETS. This is between 1 and 2% of the total carbon dioxide emissions for the EU27 in those years. However, for the first part of this period, the allowance price was between €18 and 32 tCO_2^{-1}, and rising.

A report by Climate Strategies (Neuhoff *et al*, 2008) compiles evidence on the effectiveness of the EU ETS, and argues that beyond 2012, most emissions allowances should be auctioned rather than freely allocated. Without this revision, the EU ETS is not expected to deliver its objectives.

The most serious argument in favour of freely allocating allowances could be the need to avoid leakage. However, existing analyses of the effects of cost increases due to carbon prices show that leakage problems are only likely in a narrow range of sectors and products, rather than being an economy wide problem (Barker *et al.* 2007; Fankhauser, Sehlleier and Stern 2008). For example, Barker, Junankar, Pollitt, and Summerton, (2007) show that carbon leakage in response to environmental tax reforms in Europe is **small**, and in some cases is even negative because of exported low carbon technologies. (Lutz and Meyer 2009) find that in the case of unilateral EU climate policy (permit trading and carbon taxes), reduced economic competitiveness will lead to a small reduction in the GDP of the EU27 in 2020, of 0.55%.

Neuhoff *et al.* (2008) provide evidence that in the UK only 1% of all economic activities will face cost increases over 4%, as a result of carbon prices of €20 tCO_2^{-1} imposed by the ETS. Indirect costs, due to higher electricity prices, are below 2% for 99% of economic activities. The manufacturing sectors most affected by cost increases are: lime, cement, iron and steel, refined petroleum, fertiliser and aluminium. Free allocations of emissions allowances could be tailored to these sectors, or the leakage problem could be addressed by other means such as State Aid or border adjustments. However, Reinaud (2009) points out that substantial falls in competitiveness and leakage in response to European climate policies have not been identified, even in these sectors. Also, such analyses are usually based on prices in particular sectors, and do not account for the 'first-mover' advantages to Europe in developing new technologies (Reinaud, 2009).

Finally, the OECD report of Burniaux *et al.* (2009) sets out key steps towards reaching a single international carbon price. These are: 1) remove fossil fuel subsidies and 2) link regional carbon markets. The report highlights regulation, technical standards on energy efficiency and research and development policy as important in encouraging mitigation.

References

Ackerman, F., DeCanio, S., Howarth, R., & Sheeran, K. (2009). Limitations of integrated assessment models of climate change. Climatic Change. DOI 10.1007/s10584-009-9570-x.

Anthoff, D., Hepburn, C., & Tol, R. S. J. (2009). Equity weighting and the marginal damage costs of climate change. Ecological Economics, 68(3), 836-849.

Barker, T. (2008). The economics of avoiding dangerous climate change. An editorial essay on the Stern Review. Climatic Change, 89(3-4), 173-194.

Barker, T., Ekins, P., & Foxon, T. (2007). The macroeconomic rebound effect and the UK economy. Energy Policy, 35, 4935-4946.

Barker, T., Junankar, S., Pollitt, H., & Summerton, P. (2007). Carbon leakage from unilateral Environmental Tax Reforms in Europe, 1995-2005. Energy Policy, 35(12), 6281-6292.

Barker, T., Scrieciu, S., & Foxon, T. (2008). Achieving the G8 50% target: modelling induced and accelerated technological change using the macro-econometric model E3MG. Climate Policy, 8, S30-S45.

Barker, T., Scrieciu, ?., & Taylor, D. (2008). Climate Change, social justice and development. Development, 51(3), 317- 324.

Barrett, S. (2008). Climate treaties and the imperative of enforcement. Oxford Review of Economic Policy, 24(2), 239-258.

Bosetti, V., Carraro, C., Massetti, E., & Tavoni, M. (2008). International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. Energy Economics, 30, 2912-2929.

Bowen, A., Fankhauser, S., Stern, N., & Zhengelis, D. (2009). An outline of the case for a 'green' stimulus. London: Grantham Research Institute for Climate Change and the Environment.

Bozmoski, A., & Hepburn, C. (2009). The interminable politics of forest carbon. Oxford: Smith School of Enterprise and the Environment.

Burniaux, J-M., Chateau, J., Dellink, R., Duval, R., Jamet, S. (2009) The Economics of Climate Change Mitigation: How to Build the Necessary Global Action in a Cost-effective Manner. OECD Economics Dept Working Papers, No 701, OECD Publishing. doi:10.1787/224074334782

Dagoumas, A., & Barker, T. (2009). The macroeconomic rebound effect and the global economy. Energy efficiency. Published on-line, doi 10.1007/s12053-009-9053-y.

den Elzen, M., & Hohne, N. (2008). Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets. Climatic Change, 91(3-4), 249-274.

den Elzen, M., Lucas, P. L., & Gisjen, A. (2007). Exploring European countries' emission reduction targets, abatement costs and measures needed under the 2007 EU reduction objectives Netherlands Environmental Assessment Agency.

den Elzen, M. G. J., Lucas, P. L., & van Vuuren, D. P. (2008). Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO2-equivalent concentrations. Climatic Change, 90(3), 243-268.

Dietz, S., & Stern, N. (2008). Why economic analysis supports strong action on climate change: a response to the Stern Review's critics. Rev Environ Econ Policy, ren001.

Edenhofer, O., & Stern, N. (2009). Towards a Global Green Recovery: Recommendations for Immediate G20 Action: Postdam Institute for Climate Impact Research (PIK).

Eliasch, J. (2008). Climate Change: Financing Global Forests. London, UK: Her Majesty's Stationery Office.

Ellerman, A. D., & Buchner, B. K. (2008). Over-allocation or abatement? A preliminary analysis of the EU ETS based on the 2005-06 emissions data. Environmental & Resource Economics, 41(2), 267-287.

Fankhauser, S., Sehlleier, F., & Stern, N. (2008). Climate change, innovation and jobs. Climate Policy, 8(4), 421-429.

Garnaut, R., Howes, S., Jotzo, F., & Sheehan, P. (2008). Emissions in the Platinum Age: the implications of rapid development for climate-change mitigation. Oxford Review of Economic Policy, 24(2), 377-401.

Gerlagh, R. (2007). Measuring the value of induced technological change. Energy Policy, 35(11), 5287-5297.

Hallegatte, S. (2009). Roadmap to assess the economic cost of climate change with an application to hurricanes in the United States. Hurricanes and Climate Change, 361-386. Proceedings of Summit, Cambodia, May 27-30 2007.

Hallegatte, S., Hourcade, J. C., & Dumas, P. (2007). Why economic dynamics matter in assessing climate change damages: illustration on extreme events. Ecological Economics, 62(2), 330-340.

Helm, D. (2008). Climate-change policy: why has so little been achieved? Oxford Review of Economic Policy, 24(2), 211-238.

Hepburn, C., & Stern, N. (2008). A new global deal on climate change. Oxford Review of Economic Policy, 24(2), 259-279.

Hof, A. F., den Elzen, M. G. J., & van Vuuren, D. P. (2008). Analysing the costs and benefits of climate policy: value judgements and scientific uncertainties. Global Environmental Change - Human and Policy Dimensions, 18(3), 412-424.

Hoogwijk, M., van Vuuren, D. P., Boeters, S., Blok, K., Blomen, E., Barker, T., *et al.* (2008). Sectoral Emission Mitigation Potentials: Comparing Bottum-Up and Top-Down Approaches: Ecofys.

Hope, C. (2009). How deep should the deep cuts be? Optimal CO2 emissions over time under uncertainty. Climate Policy, 9(1), 3-8.

Hubler, M., Klepper, G., & Peterson, S. (2008). Costs of climate change: the effects of rising temperatures on health and productivity in Germany. Ecological Economics, 68(1-2), 381-393.

IEA. (2008a). Energy Technology Perspectives 2008. Paris, France: International Energy Agency (IEA).

IEA, (2008b). Energy Efficiency Policy Recommendations, Available at: http://www.iea.org/G8/2008/G8_EE_recommendations.pdf [Accessed May 5, 2009].

Kahouli-Brahmi, S. (2008). Technological learning in energy-environment-economy modelling: a survey. Energy Policy, 36(1), 138-162.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., *et al.* (2008). Global cost estimates of reducing carbon emissions through avoided deforestation. Proceedings of the National Academy of Sciences of the United States of America, 105(30), 10302-10307.

Kjellstrom, T., & Lemke, B. (2009). Loss of worker productivity due to projected climate change, Presented to IARU conference Climate change: global risks, challenges and decisions. Copenhagen, 10-12 March 2009.

Knopf, B., Edenhofer, O., Barker, T., Bauer, N., Baumstark, L., Criqui, P., *et al.* (2010). The economics of low stabilisation: implications for technological change and policy. In M. Hulme & H. Neufeldt (Eds.), Making climate change work for us: ADAM synthesis book. Cambridge Cambridge University Press.

Kohler, J., Barker, T., Pan, H., Agnolucci, P., Ekins, P., Foxon, T., *et al.* (2007). New lessons for technology policy and climate change: investment for innovation. Climate Policy, 7(2), 156-161.

Lucas, P. L., van Vuuren, D. P., Olivier, J. G. J., & den Elzen, M. G. J. (2007). Long-term reduction potential of non-CO2 greenhouse gases. Environmental Science & Policy, 10(2), 85-103.

Lutz, C., & Meyer, B. (2009). Environmental and economic effects of post-Kyoto carbon regimes: Results of simulations with the global model GINFORS. Energy Policy, 37(5), 1758-1766.

McKinsey. (2009). Pathways to a low carbon economy: McKinsey and Company.

Neuhoff, K., Matthes, F. C., Betz, R., Dröge, S., Johnston, A., Kudelko, M., *et al.* (2008). The role of auctioning for emissions trading. Cambridge, UK: Climate Strategies.

Nordhaus, W. (2007). Critical assumptions in the stern review on climate change. Science, 317(5835), 201-202.

OECD. (2008). Costs of inaction on key environmental challanges: OECD.

Pielke, R., Wigley, T., & Green, C. (2008). Dangerous assumptions. Nature, 452(7187), 531-532.

Pizer, W. A., & Popp, D. (2008). Endogenizing technological change: Matching empirical evidence to modeling needs. Energy Economics, 30, 2754-2770.

Pollitt, H., & Junankar, S. (2009). The impact of oil prices on the global economic recovery: a report to the Foreign and Commonwealth Office. Cambridge: Cambridge Econometrics.

Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G., *et al.* (2007). Global and regional drivers of accelerating CO2 emissions. Proceedings of the National Academy of Sciences of the United States of America, 104(24), 10288-10293.

Reinaud, J. (2009). Trade, Competitiveness and Carbon Leakage: Challenges and Opportunities. London: Chatham House.

Schiermeier, Q. (2008). Nature 452, 508-509 doi:10.1038/452508a

Schmidt, S. Kemfert, X., and Hoppe, P. (2009a) The impact of socioeconomics and climate change on tropical cyclone losses in the USA. Regional Environmental Change DOI 10.1007/s10113-008-0082-4

Schmidt, S. Kemfert, X., and Hoppe, P. (2009b) Tropical cyclone losses in the USA and the impact of climate change - a trend analysis based on data from a new approach to adjusting storm losses. Environmental Impact Assessment Review¸in press.

Skjaerseth, J. B., & Wettestad, J. (2008). Implementing EU emissions trading: success or failure? International Environmental Agreements-Politics Law and Economics, 8(3), 275-290.

Smith, S., Goldborne, N., Lowe, J. A., Gohar, L. (2008). Projecting global emissions, concentrations and temperatures. Technical annex to chapter 1 of "Building a low-carbon economy – the UK's contribution to tackling climate change". http://www.theccc.org.uk/reports/building-a-low-carbon-economy/technical-appendices.

Stanton, E. A., Ackerman, F., & Kartha, S. (2009). Inside the Integrated Assessment Models: four issues in climate economics. Climate and Development, Forthcoming (accepted).

Stern, N. (2007). The economics of climate change: the Stern review Cambridge: Cambridge University Press.

Strachan, N., Pye, S., & Kannan, R. (2009). The iterative contribution and relevance of modelling to UK energy policy. Energy Policy, 37(3), 850-860.

Tol, R. S. J., & Yohe, G. W. (2009). The Stern Review: a deconstruction. Energy Policy, 37(3), 1032-1040.

Van Vuuren, D.P., and Riahi, K. (2008) Do recent emission trends imply higher emissions forever? Climatic Change 91 237-248

Webersik, C., Esteban, M., & Shibayama, T. (2009). The economic impact of future increases in tropical cyclones in Japan, Climate change: global risks, challenges and decisions. Copenhagen: International Alliance of Research Universities (IARU).

Weitzman, M. L. (2009). On modeling and interpreting the economics of catastrophic climate change. Review of Economics and Statistics, 91(1), 1-19.