Met Office Hadley Centre

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Tyndall°Centre for Climate Change Research

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AVOID – providing key research on avoiding dangerous climate change

AVOID – Avoiding dangerous climate change

An updated review of developments in climate science research since the IPCC Fourth Assessment Report

Living With Environmental Change LWEC

An updated review of developments in climate science research since the IPCC Fourth Assessment Report

Peter Good[1], Simon N. Gosling[2], Dan Bernie[1], John Caesar[1], Rachel Warren[3], Nigel W. Arnell[2], and Jason A. Lowe[1]

[1] Met Office Hadley Centre, Exeter, UK
[2] Walker Institute, University of Reading, Reading, UK
[3] Tyndall Centre, University of East Anglia, Norwich, UK

Contents

Glossary

AEROCOM	Aerosol Comparisons between Observations and Models
AMOC	Atlantic Meriodional Overturning Circulation
AR4	Fourth Assessment Report (of the IPCC)
AR5	Fifth Assessment Report (of the IPCC)
AVOID	Avoiding Dangerous Climate Change research programme
BoM	Bureau of Meteorology (of Australia)
C3 crops	Crops that produce a three-carbon compound during photosynthesis, including agricultural crops such as rice, wheat, soybeans, potatoes and vegetables.
C4 crops	Crops that produce a four-carbon compound during photosynthesis, mainly of tropical origin, including the agriculturally important crops maize, sugar cane, millet and sorghum.
C4MIP	Coupled Carbon Cycle Climate Model Intercomparison Project
CCC	Committee on Climate Change
CDF	Cumulative Density Function
CMIP3	Phase 3 of the Coupled Model Intercomparison Project
CO_2	Carbon Dioxide
CSIRO	Commonwealth Scientific and Research Organization (of Australia)
DALYS	Disability-Adjusted Life-Years
DECC	Department of Energy and Climate Change (UK)
Defra	Department for Environment, Food and Rural Affairs (UK)
DIVA	Dynamic Interactive Vulnerability Assessment
ECS	Equilibrium Climate Sensitivity
ENSO	El Niño Southern Oscillation
EU	European Union
FACE	Free-Air Carbon dioxide Enrichment
FAO	Food and Agriculture Organization (of the United Nations)
FD	Forbush decreases
FEEDME	Food Estimation and Export for Diet and Malnutrition model
GCM	Global Climate Model
GDP	Gross Domestic Product
GHCN	Global Historical Climatology Network
GIS	Geographical Information Systems

GISS	Goddard Institute for Space Studies (of the National Aeronautics and Space Administration, USA)
GLAM	General Large Area Model for annual crops
GPS-RO	Global Positioning System – Radio Occultation
GRACE	Gravity Recovery and Climate Experiment
IAP RAS	Institute of Atmospheric Physic, Russian Academy of Sciences
IDAG	International Ad Hoc Detection and Attribution Group
IMAGE	Integrated Model to Assess the Greenhouse Effect
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MIROC	Model for Interdisciplinary Research on Climate
MOC	Meridional Overturning Circulation
N_2O	Nitrous Oxide
NAO	North Atlantic Oscillation
NCDC	National Climatic Data Center (of the National Oceanic and Atmospheric Administration, USA)
NEP	Net Ecosystem Production
NERC	Natural Environment Research Council (UK)
PDF	Probability Density Function
ppm	Parts per million
QUEST-GSI	Quantifying and Understanding the Earth System – Global Scale Impacts
RCP	Representative Concentration Pathway
RH	Relative Humidity
SLR	Sea Level Rise
SRES	Special Report on Emissions Scenarios (of the IPCC)
SST	Sea Surface Temperature
TAR	Third Assessment Report (of the IPCC)
TCR	Transient Climate Response
TCWV	Total Column Water Vapour
THC	Thermohaline Circulation
TSI	Total Solar Irradiance
UV	Ultraviolet radiation
WAIS	West Antarctic Ice Sheet

Executive Summary

Background

This report presents a review of new climate science literature since the first Committee on Climate Change report (CCC, 2008), which will be relevant to the Committee's assessment of whether or not UK emissions targets should be updated. The CCC 2008 report drew largely upon the contents of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) published in 2007, with the addition of some relevant post-AR4 work. Here we provide an updated review of climate change, covering developments in understanding of the physical climate system and climate change impacts since the IPCC AR4 to early 2010.

We draw our findings predominantly from recent peer-reviewed literature of studies which suggest an increase, or decrease, in risk of a particular impact of climate change, or through a better understanding of physical processes relating to the climate response to emissions. In general we have focused on studies which present a global perspective on climate change assessments, although in the absence of this for some sectors, regional and national studies are cited when required. Almost all the work cited has been peer-reviewed and published prior to April 2010, although we include a small number of relevant studies which are either in press (having passed peer-review) or are progressing through the peer-review process with an expectation of publication. Each of these studies is clearly indicated in the text.

In particular we seek to highlight studies which demonstrate whether or not recent assessments show a changed risk of damage to human or natural systems compared with the conclusions of the IPCC AR4. In addition to new literature on scientific understanding we have consulted with experts in a number of the areas discussed in this report, to ensure that we present an up to date view.

The review highlights a number of themes which apply to both the climate and impacts sectors considered:

1. A movement towards probabilistic methods of impacts assessment and/or the consideration of climate modelling uncertainty.

2. A move towards assessing the potential benefits that could be accrued under different climate change mitigation scenarios relative to a business as usual reference scenario.
3. Several uncertainties still remain that are linked to understanding the association between climate and natural or human systems.
4. Increasing recognition that temperature is not the only impact metric.

Whether recent impact assessments show a changed risk of damage to human or natural systems since the IPCC AR4 depends upon the impact sector.

We also consider interactions between potentially abrupt climate changes which have been a neglected area of research until recently. These interactions have the potential to increase the severity of the consequences of climate change, but in most cases we are currently unable to quantify these interactions.

Summary of findings

This section presents a brief overview of relevant new literature for each sector, beginning with the large-scale physical climate system, and moving onto climate impacts. **Tables 1 and 2** provide a summary of changes since IPCC AR4 in the different sectors considered, and also the possible changes for a 2°C or 4°C global temperature change.

Observed climate change and projected trends

- Since the AR4, warming over Antarctica has been attributed to human influence and there is now a broader range of evidence to attribute other changes in climate to human influence including regional temperatures, and the effects of external forcing on changes in the hydrological cycle, the cryosphere, atmospheric circulation changes, oceanic changes, and changes in extremes.
- Post-AR4 analyses of internal climate variability indicate that the recent apparent slowdown in global warming is not inconsistent with a continued warming trend of around 0.2°C per decade.
- Observing systems still do not allow a full diagnosis of the energy balance of the climate system, but there is an indication that since 1998 energy may have gone into warming the oceans rather than the surface.

- Post-AR4 work does not substantially change the previous estimates of urbanization-related uncertainty on global temperature trends. Some regional temperature observing networks (e.g. China) show evidence of urban warming in recent decades, but the large-scale non-urban warming trend is larger.
- Surface specific humidity has increased and the trends are consistent with a majority of fully coupled GCMs. There are inconsistencies over the southern hemisphere, although this is a region of greater uncertainty in both observations and models.
- Recent changes in surface specific humidity and total column water vapour aloft have been attributed in part to human causes.
- There remains large uncertainty over the exact magnitude of the effect of solar variability on the Earth's climate.

Processes affecting the relationship between emissions and temperature

Statistical issues relating to choosing temperature and emissions targets

- Focusing on the median predicted warming for mitigation and business as usual scenarios has advantages over considering the probability of exceeding a fixed target.
- New results focusing on cumulative emissions add extra confidence to the simple climate model simulation results presented in the first CCC report in 2008.

Climate sensitivity

- This remains the largest quantifiable uncertainty in determining temperature from emissions using simple climate models.
- A recent review of climate sensitivity estimates found that they were all consistent with the IPCC AR4 conclusion that climate sensitivity is very likely to be greater than 1.5℃ and likely to be between 2℃ and 4.5℃.
- Higher climate sensitivities are difficult to rule out, though a climate sensitivity of over 6℃ is very unlikely.

Biogeochemical feedbacks

- Carbon cycle – climate interaction provides a positive feedback but the magnitude remains uncertain.
- Different climate forcing agents (e.g. CO_2, N_2O, ozone, aerosol) can affect the health of vegetation in very different ways, with implications for the amount of carbon storage.
- Reducing the atmospheric concentration of CO_2 may take a very long time due to the carbon cycle feedbacks, which may have implications for concentration "overshoot" targets.

Large-scale components of the climate system

Ice sheets

- The melting of the Greenland ice sheet is still considered one of the potential thresholds for rapid and/or irreversible change though more likely to occur for medium and high warming scenarios.
- Rapid loss of the west Antarctic ice sheet (WAIS) is thought possible though it remains difficult to quantify thresholds for this.

Sea ice

- There is now less concern about imminent Arctic sea ice collapse as observed summer sea ice extent has recently recovered after 2007 back to the long-term trend, although estimates suggest it is thinner than before.
- It is still considered likely that sea ice decline would be reversible, although associated impacts of a temporary loss (e.g. on biodiversity) may not be.
- When IPCC AR4 models are adjusted to fit the observations they suggest that the Arctic becomes free of sea ice earlier than the raw model results for a business as usual scenario. However there are still large uncertainties in modelling contemporary sea ice mass budgets, partly as a result of a lack of observational validation.

Sea level rise

- Although there are predictions of sea level rise in excess of IPCC AR4 values, these typically use semi-empirical methods that suffer from limited physical validity.
- There is evidence to suggest that increases significantly above 1m have a low probability of occurring, but cannot be ruled out.
- Linking sea level rise projections to temperature must be done with caution because of the different response times of these two climate variables to a given radiative forcing change.
- Recent studies suggest that 30-40% of future sea level rise could be avoided in a 2℃ world compared with a 4℃ world.

Atlantic meridional overturning circulation

- Recent studies have shown a large variability in the strength of the MOC on daily to seasonal timescales, which casts doubt on a previous report suggesting an observed decrease in MOC transport.
- Large uncertainties still remain in the probability of complete shutdown. But one study, for a temperature increase of 4.5℃ by 2100, suggested that the probability of a complete shutdown was 10%.

Tropical forests

- Observational evidence from recent Amazon events gives further confidence in our understanding of the susceptibility of forest to drought, but the results from modelling studies on forest dieback are mixed, emphasising the large uncertainty.
- Climate change may increase the vulnerability of forests to fire.

Accelerated emissions from wetlands, terrestrial permafrost and ocean hydrates

- There is additional confidence that these are important processes which were missing from AR4 GCMs, which could have a significant effect on warming for given emissions. The risk is expected to increase with large-scale warming, with early model results suggesting additional warming of the order of several percent.
- Model simulations suggest possible self-sustaining feedback of decomposition of organic-rich permafrost in northeast Siberia.

- However, since modelling is at an early stage, large uncertainties remain.

Climate extremes

- A recent observational study has found that extreme daily maximum and minimum temperatures have warmed over most regions, with increases of 1°C to 3°C since 1950 over some regions.
- Human influence has at least doubled the risk of the type of summer experienced over Europe in 2003. By the 2040s, summers over southern England could be at least as warm as 2003 on average 50% of the time.
- The first GCM study to estimate the potential for mitigation to avoid climate change indicates that, under a mitigation scenario, the change in intensity of heat waves could be 55% less than under a business as usual scenario.

Impacts of climate change on human and natural systems

This review of climate change impacts covers the six main impact sectors: coastal system impacts and adaptation, ocean acidification, ecosystems and biodiversity, water resources and desertification, agriculture and food security, and human health. It follows the chapters of the IPCC AR4 Working Group II "Impacts, adaptation and vulnerability" publication.

Coastal system impacts and adaptation

- New research agrees with the IPCC AR4 conclusion that south-east Asia will be the most highly affected region under climate change scenarios but the large differences in methodological approaches between studies means it is not possible to say whether new research presents a change in the magnitude of risk relative to what was presented by the IPCC AR4.
- The global economic damage caused by Sea Level Rise (SLR) could be around 400,000 million $US/year for a 0.71m SLR in 2100 and around 330,000 million $US/year for a 0.49m SLR. These correspond to temperature increase of 4°C and 2°C respectively.

- Recent European studies are not in agreement as to whether climate change will have a positive or negative impact on coastal tourism.

Ocean acidification

- New research agrees with the IPCC AR4 statement that surface ocean pH has decreased by approximately 0.1 units relative to pre-industrial levels and is predicted to decrease by up to a further 0.3-0.4 units by 2100.
- Mitigation that limits global warming to a 2℃ target would reduce the magnitude of the decline in pH to 0.16 from pre-industrial levels, but this still represents a substantial decline in ocean surface pH.
- Post-IPCC AR4 studies add to the evidence-base that some calcifying organism species demonstrate a resistance to increased CO_2 and others demonstrate a negative response.
- Inconsistencies between studies mean that the IPCC AR4 statement that ocean acidification will have a detrimental impact on marine organisms requiring calcium carbonate still remains at medium confidence.

Ecosystems and biodiversity

- Tropical ecosystems have been added to the list of those most vulnerable, alongside polar, mountain, coral reefs and Mediterranean systems.
- One third of coral reef species are already at risk of extinction and bleaching events will become annual once ocean temperatures have fully responded to the present day CO_2 concentration.
- There is increasing evidence to support the IPCC AR4 statement that 20-30% of plant and animal species are at increasingly high risk of extinction as global mean temperatures exceed a warming of 2-3℃ above pre-industrial levels.
- There is greater confidence in the modelling projections for drying in the Amazon under climate change.

Water resources and desertification

- Recent research does not suggest a major change in the risk of climate change on water resources relative to the IPCC AR4.
- A recent study shows substantial decreases of around 25% in average annual runoff for the Mediterranean and central South America for 2°C warming and around 40% for 4°C warming.
- New research shows that mitigation could lower, but not eliminate, the impacts of climate change on water resources.
- New research is consistent with the IPCC AR4 projections that the percentage cover of land experiencing extreme drought at any one time could rise from 1% at present-day to 30% by the end of the century,

Agriculture and food security

- Recent probabilistic impacts assessments generally suggest declines in crop productivity with climate change, which are less optimistic than those presented by the IPCC AR4.
- New research suggests that the effect of CO_2 enrichment on crop productivity is less optimistic than presented by the IPCC AR4.
- Mitigation policies aimed at limiting global-mean temperature rise to 2°C could reduce exposure to undernourishment by 30-50% relative to a business as usual scenario, and crop production losses could be cut by 70-100%.

Human health

- New research shows that for 2°C warming there could be 4 million extra heat-related deaths and around 6 million less cold-related deaths, although the aggregation of mortality to the global level hides important regional variations.
- Previous assessments of heat-related mortality are likely underestimates because they do not consider the role of changing temperature variability with climate change.
- New research shows that for 4°C warming, summertime heat-related mortality could increase more than threefold from present-day levels for some cities.
- The role of climate change on malaria may be greater than previously expected, but it should be noted that malaria

incidence is affected by numerous factors other than the average temperature.

There is a need to be cautious as it is difficult to quantify the risk implied in much of the scientific literature. This is illustrated by the expert elicitation exercise of Kriegler et al. (2009) which showed substantial variation in how different experts estimated the change in probabilities of abrupt change in different elements of the climate system, such as the collapse of the Greenland ice sheet. It is also particularly difficult to assess if new literature published during the period of just a few years represents a genuine change in risk. Scientific understanding is subject to a degree of fluctuation, particularly with regards to less well understood aspects such as potential thresholds for rapid climate change.

Uncertainties remain in the understanding of particular physical processes and mechanisms within the climate systems, as well as distinct uncertainties about the magnitude of some climate change impacts on human and natural systems.

The recent research reviewed in this report supports the previous conclusion of CCC that it is not possible to define an obvious maximum temperature target. Overall scientific understanding of many elements of the physical climate system and the impacts of climate change has improved. Progress has also been made in robustly quantifying the remaining uncertainty in climate projections and impacts.

This review finds that without any global mitigation action many projected impacts of climate change will be severe, and that significant levels of adaption are likely to be required in many sectors even with urgent and rapid global emissions reductions.

Figure 1 summarises, relative to what was reported in the AR4; (1) whether the degree of the severity of the impacts sectors we considered has changed, (2) whether the degree of understanding of those impacts has changed, and (3) whether the confidence in those impacts projections has changed. We acknowledge that this schematic is subjective and representative only of the views of the authors, but it makes an attempt to summarise and assess post-AR4 developments in climate change impacts science.

For the components of the climate system covered in chapters 2 and 3 there is currently less agreement between the consulted experts about the relative changes since AR4. Therefore we have not included a figure to summarise these chapters of the report.

In producing **Figure 1**, we assessed (1) by comparing pre- and post-AR4 impacts estimates for similar degrees of global-mean warming, (2) by evaluating what new knowledge post-AR4 research has added to current knowledge, and (3) by considering the degree of consensus across impacts estimates of post-AR4 findings. For instance, **Figure 1** demonstrates that we suggest that post-AR4 research shows no change in the severity of the projected impacts of climate change on ocean acidification because new research tends to confirm the magnitudes of results of previous studies, that increased atmospheric CO2 increases ocean acidity and that this has a detrimental effect on some marine organisms. However, there has been a considerable increase in the understanding of the effects of increased ocean acidification on marine organisms, with new studies shedding light on the varied responses of various organisms to this stress. Given that new research on the effects of ocean acidification on marine organisms can show varied responses for the same organism across studies, it is not possible to say whether there has been an increase or decrease in confidence of this impact sector relative to what was know at the time of the publication of the AR4.

It should be noted that we do not seek to quantify the magnitude of “more” and “less” on the axes of **Figure 1**. The axes are relative because there are several complexities and uncertainties associated with forming an absolute scale upon which all impact sectors can be placed. Nevertheless, the extreme ends of each axis may be seen as representative of ground-breaking new developments in understanding, or of major changes in the sign of the severity of impacts, since the AR4. The main conclusion to be drawn from **Figure 1** is that the level of changed risk of damage to human or natural systems since the AR4 depends upon the impact sector, although we find an overall increased risk to human health, ecosystems and biodiversity and agriculture and food security.

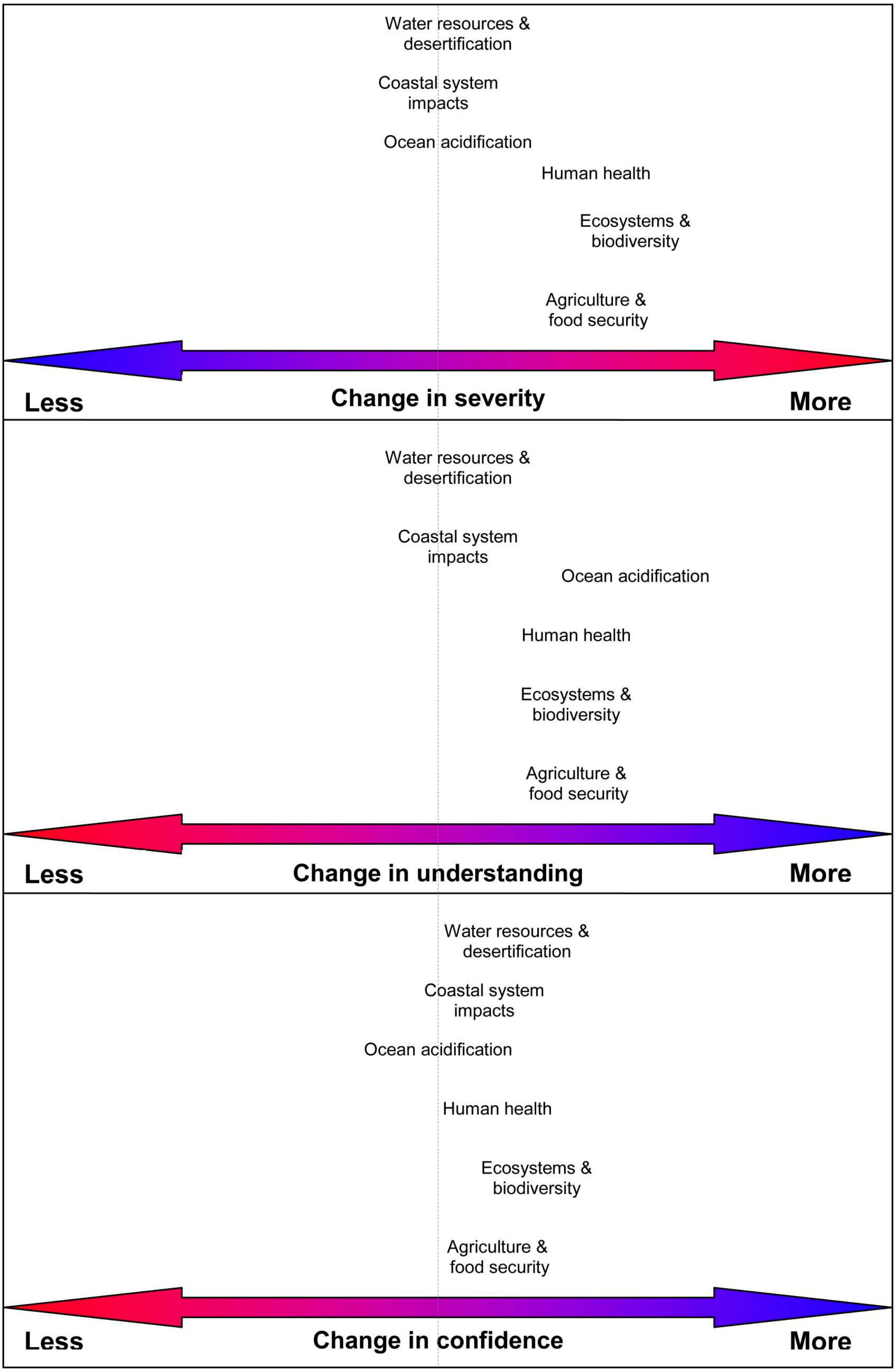

Figure 1: Change in severity, understanding and confidence in projections for post-AR4 climate impacts science. Note that this figure is subjective and represents the views of the authors.

Table 1: Summary of post-IPCC AR4 work on large-scale components of the climate system for worlds with a global-mean temperature approximately 2℃ and 4℃ warmer than present. The results presented here are estimates based upon post-AR4 studies, i.e. they are not incremental upon the quantitative estimates presented in the AR4 but are new overall projections at these temperatures.

Climate sector	AR4 Level of scientific understanding	Post AR4 research	Change in understanding	Impact with 2℃ rise	Impact with 4℃ rise
Arctic Sea Ice	Medium	A few key papers	Better understanding of variability, trends and physical processes, though uncertainty remains. Use of observational constraints on projections suggests that ice free summer conditions may occur sooner than documented by AR4; but there is less concern about a more rapid imminent collapse.	Minimum summer sea ice extent projected to reduce by 35-70% depending on whether observational constraints are applied. Mean thickness reduced leading to an increase in inter annual variability of ice extent.	Median projections, constrained by observations, suggest frequent ice free summer conditions by 2100 under an SRES A1B scenario.
Ice Sheets	Low	Several key papers	Improving models and understanding of dynamics and processes. Possible existence of multiple stable states found for Greenland, suggesting that it may not be able to recover from partial melting.	Greenland ice sheet: unlikely to collapse based on AR4 threshold. West Antarctic: mechanisms for rapid collapse are possible, relating to retreat of the grounding line, though threshold for such a change are currently difficult to estimate.	Greenland ice sheet: considered at risk of significant mass loss through surface melting, though over relatively long time scales. Higher probability of ice loss from accelerated outlet glacier or ice stream flow.

Sea level rise	Low-Medium	A large number of key papers	Sea level rise varies non-linearly with temperature but the range for the 21st Century remains uncertain. Now acknowledged that high end sea level rise estimates (2m by 2100) may be difficult to rule out.	Moving from a 4℃ world trajectory to a 2℃ world trajectory might avoid around one third of 21st Century sea level rise.	Sea level rise of 2m cannot be ruled out but an increase of more than 1m is unlikely.
Atlantic Meridional Overturning Circulation	Low-Medium	Several key papers.	Improved observations and high frequency variability cast doubt on previously reported slow down. Modelling studies still inconclusive.	Considered unlikely to collapse although some slow down is possible.	Expert elicitation puts chance of collapse at 10% for moderate to high warming, but modelling results are inconclusive.
Tropical Forests	Low-Medium	Several key papers	New evidence of susceptibility to drought. A growing number of model studies show feedbacks from non-CO_2 forcing agents such as N_2O and ozone. Old growth forests have been found to sequester carbon rather than being carbon neutral, which increases the need to ensure that mechanisms to avoid	One study suggests a 20% decrease in the coverage of broad leaf trees, though modelling studies are inconsistent.	Up to 80% reduction in coverage of broad leaf trees is found in one modelling study.

			deforestation include pristine old growth forest.		
Methane emissions from wetlands	Low	A few key papers	Now recognised as being closely related to recent methane variability. If release is substantially realised this may lead to an increase in anthropogenic warming by several percent. Process-based models being developed.	Significant uncertainty in this developing area precludes any present estimation of potential thresholds or risk.	
Carbon emissions from terrestrial permafrost	Low	A few key papers	Some evidence of thawing permafrost has been observed. Improving understanding of processes but large uncertainties remain in the size of the carbon store, the possible timescale for release, and the temperature threshold for any potential release.	Significant uncertainty in this developing area precludes any present estimation of potential thresholds or risk.	
Ocean methane hydrates	Low	A few key papers	Large uncertainties in the size and location of stores. Likelihood and time scale of release very uncertain.	Significant uncertainty in this developing area precludes any present estimation of potential thresholds or risk.	

<table>
<tr><td>Tropical climate system</td><td>Medium</td><td>One key paper</td><td>Understanding of how ENSO will respond to climate change has not developed.</td><td colspan="2">Despite none of the AR4 models indicating an abrupt change in the behaviour of ENSO, such behaviour cannot be ruled out owing to the pervasive bias of these models in representing present day ENSO variability.</td></tr>
<tr><td>Extremes</td><td>Low-Medium</td><td>Several key papers on global changes</td><td>Large-scale variability has been shown to have a significant impact on extremes. Our, presently poor, ability to predict such variability limits ability to predict change in extremes.

First study including mitigation effects on extremes has been published.

It remains unclear whether the recent change in the frequency of tropical storms is larger than the natural variability.</td><td colspan="2">A study has shown that a mitigation scenario (global mean warming of approximately $2°C$) avoids 55% of the increase in heat waves under a $4°C$ scenario.

Projections indicate a decrease in frequency of tropical storms.

Mid-latitude storms are projected to increase in intensity but decrease in frequency.</td></tr>
<tr><td>Interactions between potentially abrupt changes</td><td>Low</td><td>One key paper</td><td>First major expert elicitation exercise on possible interactions.</td><td>Incomplete understanding of individual elements makes assessment of interactions difficult, particularly the determination of particular thresholds.</td><td>Incomplete understanding of individual elements makes assessment of interactions difficult, particularly the determination of particular thresholds.</td></tr>
</table>

Table 2: Summary of post-IPCC AR4 impact estimates for each impact sector, for worlds with a global-mean temperature approximately 2°C and 4°C warmer than present. The results presented here are estimates based upon new post-AR4 studies, i.e. they are not incremental upon the quantitative estimates presented in the AR4 but are new overall projections at these temperatures.

Impact sector	**AR4 Level of scientific understanding**	**Post AR4 research**	**Change in understanding**	**Impact with 2°C rise**	**Impact with 4°C rise**
Sea level rise impacts	Good	One key paper	New research confirms south-east Asia as a highly vulnerable region.	The global economic damage caused by SLR could be around 330,000 million $US/year for a 2°C world.	New research suggests that for a 1m SLR that around 56 million people would be impacted and 1.86% of total coastal wetlands would be lost. The global economic damage caused by SLR could be around 400,000 million $US/year for a 4°C world.
Ocean acidification from increased atmospheric CO_2	Medium	A few key papers	Increasing evidence to support the magnitude of projected changes presented in the AR4.	A reduction in global mean ocean surface pH to 7.95, an additional doubling of the currently observed acidification.	A reduction in global mean ocean surface pH to 7.81, an additional quadrupling of the currently observed acidification.
Impact of ocean acidification on marine organisms	Medium	Several key papers	There is more detail on how different species might respond to ocean acidification, based upon laboratory studies.	Post-IPCC AR4 studies add to the evidence-base that the response of calcifying organisms to ocean acidification is varied, with some species demonstrating a resistance to increased CO_2 and others demonstrating a negative response. Inconsistencies between studies mean that there has been no	

				increase in confidence that ocean acidification will have a detrimental impact on marine organisms.	
Water resources	High	A few key papers	New findings support the magnitude of the projections for global water scarcity presented in the IPCC AR4. New results include a more comprehensive treatment of climate modelling uncertainty.	Approximately 59% of the world's population exposed to "blue water shortage" (i.e. irrigation water shortage). 36% exposed to "green water shortage" (water in the soil). Decreases of around 25% in average annual runoff for the Mediterranean and central South America relative to present. Population exposed to an increase in water scarcity assuming a business as usual population scenario at 2050, based upon 4 climate models, is 0.570 – 1.960 billion.	Decreases of around 40% in average annual runoff for the Mediterranean and central South America relative to present. Percentage of the global population that experiences an increase in water scarcity under the SRES A1B population scenario (year 2080) is 5-29% (range across 21 forcing climate models).
Terrestrial ecosystems	Medium	Several key papers	Tropical systems are now found to be at risk for low levels of temperature rise. New evidence is showing how synergies between fire, drought, pests and bioclimatic changes can impact forest ecosystems.	IPCC AR4 stated 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 to 3°C above pre-industrial levels'. Since AR4, increasing evidence now supports this statement. New findings show that substantial impacts are expected in tropical regions for small amounts of global temperature rise.	IPCC AR4 gave a few examples of large extinction risks expected, with 50% of protected areas unable to fulfil their current conservation objectives. Since then synergistic effects of changes in fire, drought, and pests have been found to be likely to exacerbate impacts in both forest and freshwater ecosystems.

				One study has proposed a 2℃ limit to protect Amazon rainforest.	
Marine ecosystems	Medium	Several key publications	New studies suggest dramatic 60% turnovers in assemblages of fish species for moderate climate changes. More quantitative estimates of sensitivity of coral reefs to climate change.	60% turnover in marine assemblages of fish species, most pronounced in polar regions, for global temperature changes close to 2℃.	There are still few studies for this temperature rise, but in view of large impacts at 2℃ and ocean acidification effects, very large impacts might be expected.
Desertification	Medium-High	Several key papers	Observations and model projections are consistent with AR4, but more detail is now available. New knowledge highlights a critical risk area for drought in south and south-eastern Europe under climate change. This risk can be greatly reduced by mitigation.	Up to 10-fold reductions in return rates of the 100-year drought in the Mediterranean region.	
Agriculture and food security	Medium	Several key papers	Increased evidence for the potential benefits of mitigation policy. The potential effects of CO_2 enrichment for crop yields are now considered less optimistic than presented in the IPCC AR4 because of the offsetting of increased yields by yield reductions	Mitigation policies aimed at limiting global-mean temperature rise to 2℃ could reduce exposure to undernourishment by 30-50% relative to a business as usual scenario, and crop production losses could be cut by 70-100%. Crop production loss in India could be 10-40% despite the beneficial effects of higher CO_2 on crop growth, with losses of 4-5 million	

			due to warmer temperatures, increased pests and weeds, and increased ozone. There has been a shift towards a probabilistic method of impacts assessment.	tonnes of wheat for every rise of 1℃. The IPCC statement that global yields of C3 crops will be unaffected in a 2℃ warmer world now appears optimistic, although within a fairly wide uncertainty range - global losses from climate change outweighing gains from CO_2 enrichment in a sub-2℃ warmer world are now considered unlikely for wheat (<33% chance), likely for barley (>66% chance) and virtually certain for maize (>99% chance).	
Human health	Medium	Several key papers	Previous assessments of heat-related mortality are likely underestimates because they do not consider the role of temperature variability with climate change and/or mortality displacement adequately.	Globally, 4 million extra heat-deaths and around 6 million less cold-related deaths in the year 2100 relative to present - hence thermal stress reduces by around 2 million deaths due to warmer winters. The IPCC AR4 showed that for an approximately 2℃ warmer world than present, 5-6 billion people would be at risk of dengue as a result of climate change (based upon projections from 4 climate models) In sub-Saharan Africa, climate change could cause 95,000 extra deaths from malaria in the year 2050 under a climate change scenario that results in a 2℃ warmer world in 2100.	Annual summertime heat-related mortality could increase by more than threefold from present-day levels for cities including Boston, Budapest, Dallas, Lisbon, London and Sydney. In the absence of adaptation, global deaths due to malaria could increase from around 1 million in 2000 to around 1.1million in 2050 under a climate change scenario that results in a 4℃ warmer world in the year 2100 - limiting warming to 2℃ reduced malaria health risks by about only 2% and the impact reduces by around 50% if adaptation is considered.

1. Introduction

The first part of the report (sections 2 and 3) focuses on change in the large-scale physical climate system. We start with some discussion on statistical issues relating to the choice of temperature and emissions targets. We then review progress relating to general processes affecting the amount of global warming for given emissions. The report then goes on to focus on potential changes in the large-scale climate system. This latter section generally relates to systems where research is at an earlier stage, with consequently larger potential for substantial advances but also greater caveats about scientific uncertainty. A summary of the bibliographic search process used is given in Appendix A, and a description of the expert consultation process is given in Appendix B.

The second part of the report (sections 4 to 10) focuses on changes in climate impacts. A recent and useful review by Füssel (2009) presents an updated assessment of the risks from climate change based on research published since the Intergovernmental Panel on Climate Change Fourth Assessment Report (hereafter referred to as IPCC AR4). Füssel's article is largely devoted to reviewing research developments in climate science (e.g. modelling of abrupt events and potential thresholds, tropical cyclones, carbon cycle feedbacks) but the section on climate change impacts is relatively brief and focuses largely on impacts on biodiversity hotspots. With this in mind, here we present a much-needed updated review of the impacts of climate change published since the IPCC AR4. It is anticipated that the review will be useful in aiding the policy-making process. Given that literally hundreds of articles have been published since the IPCC AR4 on climate change impacts, we aim to answer the question of whether recent climate change impact assessments show a changed risk of damage to human or natural systems relative to what is presented in the IPCC AR4. Even with this focus, the magnitude of studies that could potentially be included remains large, so we generally only include studies that have taken a global perspective, although in some cases, in the absence of any studies covering such a large geographic domain, we include national or regional impacts assessments (e.g. for the impact of climate change on coastal tourism). The impacts sectors we consider broadly follow the sectors considered by Working Group II of the IPCC AR4 and more specifically the impacts sectors considered by the UK Committee on Climate Change in setting the 2050 emissions target (CCC, 2008):

- coastal system impacts and adaptation,
- ocean acidification,
- ecosystems and biodiversity,
- water resources and desertification,
- agriculture and food security,
- human health.

This second part of the report is structured into sections for each impact sector respectively, and at the end of each section we summarise the evidence for whether there is a changed risk of damage relative to what was reported in the IPCC AR4. The use of the terms “likely” and “unlikely” are <u>not</u> used in the same sense as the IPCC AR4 but instead reflect a qualitative consensus from the recent scientific literature and opinion of the research community at the present time. A summary of the bibliographic search process is given in Appendix A.

1.1. Observed climate change

To conclude the introduction, we discuss post-AR4 work which relates to issues surrounding the observational climate record and the projection of future temperature trends. The IPCC AR4 (Solomon et al., 2007) concluded that “it is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica”. Stott et al. (2010) review more recently published evidence to report that, since the AR4, warming over Antarctica has also been attributed to human influence and there is now a broader range of evidence to attribute other changes in climate to human influence. They discuss post-AR4 research which shows significant human-induced changes on regional temperatures, and the effects of external forcing on changes in the hydrological cycle, the cryosphere, atmospheric circulation changes, oceanic changes, and changes in extremes.

1.1.1. The 1000-year temperature record

Reconstructions of northern-hemisphere average temperatures over the last 1000 years have been produced independently from a range of direct and indirect data. These include data extracted from tree rings, ice cores and documentary sources as well as a number of instrumental records from the 18th Century onwards. Uncertainty in the temperature record arising from the use of indirect data and the reduced spatial coverage at periods further into the past have been rigorously examined and documented in the production of such temperature reconstructions.

The reconstructions show that while there have been some fluctuations in average temperature over the last 1000 years, the impact of human activities during the last century remains clear and without precedent in at least the last 1000 years.

While research to improve the accuracy of past temperature reconstructions is ongoing, there is a consensus in the scientific community that the predominant features of the temperature record are robust. This consensus is supported by the conclusions of the recent Muir Russell inquiry (Muir Russell et al., 2010). It finds no basis for any claims of scientific impropriety by the University of East Anglia (UEA) Climatic Research Unit or grounds to doubt its contribution to the development of the 1000-year temperature record.

1.1.2. Short term reduction in warming trend

Much recent attention has focused on the apparent reduction of the warming trend over the last decade (Easterling, 2009). The variation in global mean temperature trend estimates for 2000-2009 from the leading surface temperature datasets, 0.05˚C per decade (HadCRUT3 - Brohan, 2006), 0.12˚C per decade (GISS - Hansen, 2001) and 0.07˚C per decade (NCDC - Smith, 2008) shows that short-period trends are uncertain. Nevertheless, these figures are substantially less than the 0.18˚C per decade measured between 1981-2005. Furthermore, projections of climate change suggest global temperatures should rise at a rate of 0.2˚C per decade for the next 20 years. In light of this, there is, at least superficially, a discrepancy between observed and expected rates of recent global temperature rise.

It is understood that climate can vary without any change in climate forcing agents. This ‘internal climate variability’ relates to the capacity for the oceans to store huge amounts of heat. Climate models are also able to produce such variability. For instance an analysis of the IPCC Special Report on Emissions Scenarios (SRES) A2 scenario simulations of the first half of the 21st century, provided for the IPCC AR4, found that 10% of decadal trends were negative despite their long term trends having substantially more warming than observed over the last 30 years (Easterling, 2009). Another analysis found that even when the annual variability caused by the El Niño–Southern

Oscillation (ENSO) was taken account of, trends of 10 years in length with no warming were not inconsistent with an ensemble of climate models chosen to have a long-term warming trend of 0.2˚C per decade (Knight, 2009). Climate indices have been used to suggest a synchronization of the leading modes of internal climate variability may have caused the reduction in warming (Swanson, 2009), although the authors admit this is "purely speculative".

Even though the observed reduction in recent global temperature rise is consistent with internal variability, there are other hypotheses which might explain it in part. Solar activity has reduced from a maximum in 2000 to a minimum in 2008-9, possibly to its lowest level since the 1930s (Lockwood, 2010). The associated small reduction in the Sun's brightness is suggested to have offset much of the anthropogenic warming over the 2002-2008 period (Lean, 2009), although there remains uncertainty about the exact magnitude of the influence of the sun on global temperatures (see section on solar activity and climate). In addition, an observed change in the concentration of water vapour in the stratosphere (Solomon, 2010) may have reduced the rate of decadal warming by a quarter from that of greenhouse gases alone. Formal detection and attribution studies, that have been used to deduce the contributions to climate change over the last century (e.g. International Ad Hoc Detection and Attribution Group (IDAG), 2005), have not been applied to the changes over just the last 10 years. A further contribution to the reduced observed trend may be an artefact of the temperature data. The fraction of marine surface temperature observations made using buoys rather than from ships increased dramatically in recent years, introducing an artificial cooling of several hundredths of a ˚C per decade over the last 10 years (Thompson et al., 2008).

Evaluating the contributions of forcing factors and internal variability to global temperature changes over the last 10 years is limited by the currently available observing systems, which do not allow a full diagnosis of the energy balance of the climate system (Trenberth, 2010). Despite this, one analysis of the Earth's energy balance using observations and models (Murphy, 2009) suggests that since 1998 energy may have gone into the oceans rather than warming the surface. Analyses of oceanic observations have been used to initialise climate models in order to predict the internal variability of the climate system in addition to its response to forcing agents. One such study using full-depth information hints at decreased warming between 2005 and 2010 (Smith, 2007). Another, using surface conditions alone, suggests that the decade following 2005 may be cooler than 1996-2005 due to internal changes in the ocean (Keenlyside, 2008), although the effect of using only surface initialisation on this analysis has been questioned (Dunstone, 2010).

1.1.3. Urban influences

The potential effects of urban heat islands on estimates of global near-surface temperature trends have been reduced to a low level by avoiding (Brohan et al., 2006; Jones and Moberg, 2003; Peterson et al., 1997) or adjusting (Hansen et al., 2001) urban temperature measurements. Peterson et al. (1999) found that global rural temperature series and trends were very similar to those based on the full Global Historical Climatology Network (GHCN) data set. Some regional temperature observing networks (e.g. China: Jones et al., 2008) show evidence of urban warming in recent decades, but even in these regions the large-scale non-urban warming trend is greater. Comparisons of windy weather with calm weather air temperature trends for a worldwide set of observing sites suggest that global near-surface temperature trends have not been greatly affected by urban warming trends (Parker, 2006) ; this is supported by comparisons with marine surface temperatures (Parker, 2010).

Because the Earth is about 70% ocean, the urbanization-related uncertainty on global overall temperature trends was assessed by Trenberth et al. (2007) for IPCC AR4 to be only 0.002°C per decade. More recent augmented estimates of urban warming for China (Jones et al., 2008) do not substantially increase these estimates because of the avoidance or adjustment of urban observations in the global series cited by Trenberth et al. (2007). Furthermore, urban China is developing at a greater rate than most other parts of the world and is only a small fraction of the land surface. Because the urban heat island is mainly a night time phenomenon, its influence on global trends of land air temperature at night since 1900 are likely to be about double those on mean temperature, i.e. 0.012°C per decade.

1.1.4. Observed water vapour increase

There has been debate over the ability of climate models to accurately simulate the observed patterns of atmospheric water vapour. Atmospheric humidity has historically been less well observed than temperature. Land surface observations are sparse prior to 1973 and recording biases degrade the marine data pre-1982. There is no up to date surface monitoring record. Vertical profile data from radiosondes are compromised by progressive developments in instrumentation and by changes in recording of cold or dry extremes (McCarthy et al., 2009). Satellites have provided total column water vapour (TCWV) over the oceans from microwave sensors reliably from the late 1980s and upper tropospheric relative humidity (RH) from infrared sounders from 1979 and microwave sounders from 1994. However, cloud contamination leads to major dry biases for infrared sounders; and orbital drift, instrument degradation and instrument changes remain major issues for all satellite-based climate records. Global positioning system radio occultation (GPS-RO) has become a viable monitoring option for TCWV since 1997 (Wang et al., 2007). Regardless, much effort has been invested in quantifying recent changes in humidity and comparing with state of the art Global Climate Models (GCMs).

Increasing surface specific humidity (*q*) is globally pervasive (Dai 2006, Willett et al., 2008, Willett et al., 2010). Over land, recent trends are concurrent with the majority of fully coupled all forcings GCMs for the Globe, Tropics and Northern Hemisphere. However, for the Southern Hemisphere (a region of greater uncertainty both in the observations and models), the observations show no trend while the models show a moistening comparable with that of the Northern Hemisphere. Decreases in RH over land since 2000 have been noted contradicting earlier findings of quasi-stationarity (Simmons et al., 2010). This is consistent with the slower warming rate of the oceans (the main source of atmospheric moisture) relative to the land over recent years. Aloft, significant changes in TCWV over the oceans have been observed and are encompassed within the spread of trends simulated by all forcings GCMs (Santer et al., 2007; Mears et al., 2007). Despite varying biases in climate model mean state, all state of the art models simulate about the same water vapour feedback and fractional change in water per degree of surface warming at the surface (Willett et al., 2010) and aloft (John and Soden 2007). Biases are largest in the upper troposphere. Essentially, recent changes in *q* at the surface and TCWV aloft are attributable to human causes (Mears et al., 2007; Santer et al., 2007; Willett et al., 2007). Observed changes can only be reproduced by climate models that include anthropogenic forcings - natural forcings alone are an insufficient explanation.

1.1.5. Solar activity and climate

There has been debate regarding whether changes in solar activity have contributed to changes in global temperature. The IPCC AR4 concluded that the scientific understanding of the impact of changes in solar irradiance on climate was "low" (Forster, 2007) and that a re-evaluation of the changes in total solar irradiance (TSI) suggested a smaller radiative forcing impact over the twentieth century than reported in previous IPCC reports. A number of reconstructions of TSI produced since the IPCC AR4 support this view (e.g. Krivova, 2007 and Tapping, 2007). In the IPCC AR4 it was reported that the increase in TSI during the first half of the 20th century may have contributed to the observed warming in global mean temperatures (Hegerl, 2007) based on detection and attribution studies using climate simulations with the previously larger increase in TSI. A reduction in the secular change of TSI in reconstructions over the 20th century is likely to reduce the confidence of an attribution of a solar contribution to early 20th century warming.

Empirical analyses since the IPCC AR4 (Trenberth, 2007) continue to suggest that the global surface temperature response to the 11 year solar cycle may be larger than estimated from climate model simulations (Hegerl, 2007). The range in observed global mean temperatures due to the solar cycle have been estimated to be between 0.1^{o}C (Lean, 2008) and 0.2^{o}C (Camp, 2007) but other studies suggest that these results may not be robust (Benestad, 2009 and Stott, 2009). It is unlikely that changes in solar irradiance over the last 30 years or so could significantly contribute to the observed temperature trend as different measures of solar activity do not show coincident changes with temperatures (Lockwood, 2007). Indirect influences on climate via ozone caused by ultraviolet radiation (UV) variations over a solar cycle were reported in the IPCC AR4 (Forster, 2007) and subsequent studies have added to the evidence of a solar influence on circulation changes such as the North Atlantic Oscillation (NAO; Matthes, 2006) and amplifying effects on tropical Pacific climate (Meehl, 2009).

There is a speculative link between the changes in the Sun's magnetic field (which influences cosmic ray intensity at the Earth) and variations in cloud coverage (see discussion in Forster, 2007). Inhomogeneities in satellite reconstructions of global cloud coverage (Norris, 2007) probably produced spurious correlations with the measured cosmic ray variations. There is some support for some localised association of cosmic rays with cloud coverage (Harrison, 2008) although the magnitude of the influence may be very small (Pierce, 2009). Rapid changes in the Sun's magnetic field over a few days can rapidly decrease the amount of cosmic rays reaching Earth, so called Forbush decreases (FD). A study looking at just 6 of these FD events suggested a correlation with rapid changes in cloud cover (Svensmark, 2009). However other studies (e.g. Kristjansson, 2008; Laken, 2009 and Calogovic, 2010) found no such association when either looking at the same events or a larger sample.

Separating the potential impacts of direct and indirect influences of the Sun (which by their very nature tend to co-vary) on climate as well as distinguishing these from other forcing factors that often vary coincidentally with solar activity (e.g. volcanic eruptions) remains challenging (Ingram, 2006; Lockwood, 2010).

2. Processes affecting the relationship between emissions and global temperature

2.1. Statistical issues relating to choosing temperature and emissions targets

2.1.1. Median warming vs. probability of exceeding 2°C

The 2008 CCC report focused on how the median warming could be kept to a level of around 2°C and, given our current understanding of uncertainty in the link between emissions of greenhouse gases and warming, would give a high probability of the temperature not reaching 4°C.

Here we contrast the approach taken by the CCC with that of limiting warming to 2°C with at least a 50% chance (e.g. the aim of the European Union (EU)). The main drawback with quoting a probability for a given temperature level is that deviations from 50% are difficult to place in context. For instance, is a 45% probability of meeting the target very different from 50%? By focusing on the result in terms of temperature it becomes more straightforward to place results in context.

Figure 2 shows a cumulative distribution function of warming for a scenario that gives a median warming near to 2°C and a very low probability of exceeding 4°C. First it is apparent that there is an approximate linear region between around 20% and 80% probability. What is more important is the steepness of this curve, where a small change in temperature corresponds to a large change in probability. A less than 1°C of warming in this part of the diagram corresponds to sixty percentage points. This means we can place differences in probability of exceeding a given temperature target in terms of relevant temperature differences. For instance, natural interannual variability in global mean temperature of ±0.2°C corresponds to around ±15 percentage points on the probability axis. The uncertainty coming from the choice of aerosol emission ratio, or choice of alternative climate sensitivity uncertainty distributions, each correspond to a range of at least 0.4°C or 30 percentage points on the probability axis. Additionally, if we consider the uncertainty in temperature thresholds for triggering accelerated or irreversible change then the spread along the probability axis is even larger (e.g. for Greenland entering a state of irreversible deglaciation a temperature range of around 1.9

to 4.6℃ was reported in the last IPCC assessment – see section 3.1). Taken together, this implies that a 45% chance of meeting a 2℃ warming target is likely to have a median warming only a little above 2℃, and within natural variability and our understanding of other uncertainties.

It is also important to highlight that we have less confidence in the tails of this distribution, especially the upper tail. The physical climate system feedback processes for such large amounts of warming have not been investigated in as much detail as those at lower temperatures. Further, when considering stabilisation scenarios the upper tail of the warming distribution is strongly dependent on the upper tail of the climate sensitivity distribution. Numerous studies have highlighted that this remains uncertain (e.g. Roe and Baker, 2008).

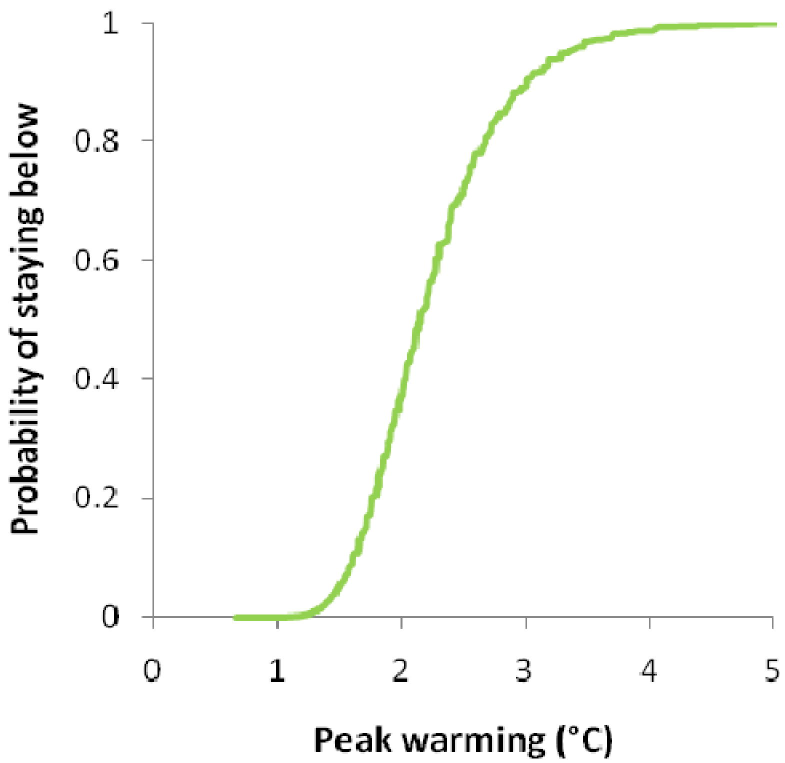

Figure 2: Cumulative Density Function (CDF) of warming to 2100 for an example mitigation scenario with a median warming of 2℃ and very low probability of exceeding 4℃.

We thus conclude that the approach of requiring the median warming to be in the region of a given temperature threshold (for instance 2℃) appears logical. It is also reasonable to require the higher temperature threshold (such as 4℃) falls within the upper tail of a cumulative distribution of warming, but less reasonable to attempt to place a precise probability on this upper temperature.

2.1.2. Use of cumulative emissions

A development since the first CCC report is the publication of a number of studies relating to cumulative emissions of greenhouse gases (especially CO_2) directly to either likely warming (Allen et al., 2009b) or the probability of exceeding 2℃ (Meinshausen et al., 2009).

For a scenario with global emissions peaking in 2016 followed by a year on year reduction of 4%, the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) predicts a median peak warming of 2.1℃ and a 57% chance of exceeding 2℃. Using the findings of the cumulative emissions studies highlighted above, Meinshausen et al. estimate the chance of exceeding 2℃ as 60%. Interpreting the findings of Allen et al. and applying to the same scenario implies a maximum warming of 1.8℃ assuming zero emissions after 2100 (or 2.4℃ assuming a higher value for the emissions floor), although this also assumes a balance between non-CO_2 gases and negative aerosol forcing. Similarly, though precise estimates are difficult for the tails of the distribution, the cumulative emissions approach of Allen et al. suggests that the likelihood of exceeding 4℃ for this scenario is less than 5% while the simulation with MAGICC puts the chances of exceeding 4℃ at 1%.

2.1.3. Committed warming

The IPCC AR4 and several modelling studies (e.g. Meehl et al., 2005) discuss the issue of committed warming. The committed warming for constant forcing, estimated for stabilisation at year 2000, is typically of the order of an extra 0.5℃ by 2100. A key study (Ramanathan and Feng, 2008) raised the issue that, since stabilising CO_2 in the atmosphere would likely need very low emissions, anthropogenic emissions of sulphur would be much lower today and so the constant forcing scenario should be modified to remove the sulphate aerosol component. When this is done the studies estimated an eventual commitment warming with greenhouse gases stabilised in 2005 of 1.4 to 4.3℃. However, we suggest that a more appropriate approach, which was not considered, would also remove shorter lived greenhouse gases from the committed term, which would tend to lower the committed warming. Further work is needed to investigate this in detail but we note that many fairly arbitrary choices on what to include in the fixed forcing can lead to very different projected committed temperatures.

There has been recent discussion about the idea of a zero emissions commitment (Matthews and Weaver, 2010 and **Figure 3**), which might be used in preference to the committed warming for constant forcing. This follows from the fact that in several climate model experiments that suddenly set emissions to zero (e.g. Lowe et al., 2009) the temperature remains stable or declines slowly. This is a consequence of the slow decline in atmospheric CO_2 being compensated for the continued adjustment of the climate system to earlier forcing changes. The zero emission commitment is probably better discussed in the context of biogeochemical feedbacks, which determine the rate of atmospheric CO_2 decline.

2.2. Changes in understanding of forcing

Our understanding of greenhouse gas forcing has changed little since the IPCC AR4 (Forster et al., 2007) and the CCC (2008) report. However, there has been some progress in research on specific components of the radiative forcing.

New research shows that radiative forcing by linear aircraft contrails is quite small, perhaps even smaller than indicated in AR4, but contrail-induced cirrus is still very uncertain (Haywood et al., 2009; Lee et al., 2009).

Some evidence on black carbon aerosols suggests that this positive forcing is larger than in AR4 – a review paper is being prepared on this, but we are unable to cite it at this stage. Regarding aerosols in general, AR4 used AEROCOM (Aerosol Comparisons between Observations and Models) to obtain the uncertainty in forcings. However, it is likely that this does not capture all of the uncertainties. There has been no major progress on aerosol indirect effects and the uncertainty range remains large,

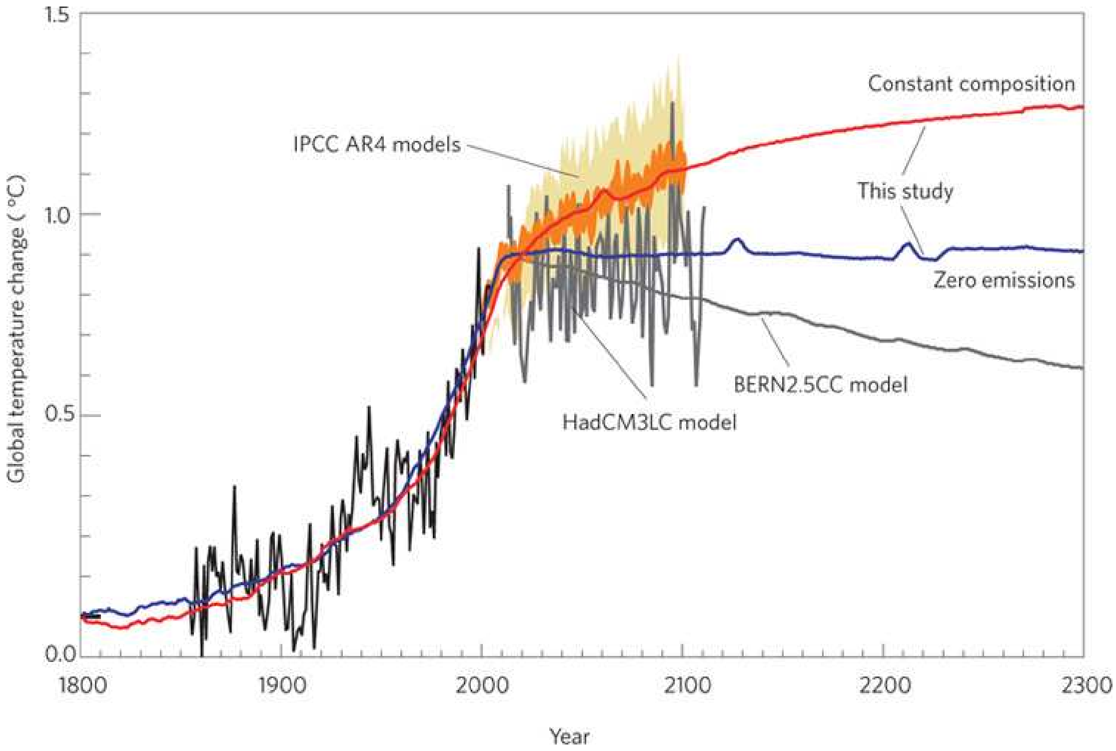

Figure 3: Constant-composition commitment (red line) represents the future warming associated with current atmospheric carbon dioxide concentrations, and zero-emissions commitment (blue line) represents the warming commitment from past carbon dioxide emissions (simulated here by the UVic Earth System Climate Model). Also shown are the constant-composition commitments simulated by the Intergovernmental Panel on Climate Change fourth assessment report (IPCC AR4) models (orange line, multimodel mean; yellow shading, range spanned by models), the zero-emissions commitment simulated by the HadCM3LC and BERN2.5CC models (grey lines) and historical temperature data (black line). Constant atmospheric carbon dioxide concentrations lead to continued warming for many centuries, whereas the elimination of carbon dioxide emissions leads to approximately stable or decreasing global temperature. Source: Matthews and Weaver (2010).

2.3. Climate response to given greenhouse concentration change

The temperature response to a change in greenhouse gas concentrations can be measured in different ways. These differ according to whether greenhouse gas concentrations are assumed to be fixed or time-varying, and to which physical feedbacks are allowed to respond.

Equilibrium Climate Sensitivity (ECS) is the global equilibrium surface warming after a doubling of atmospheric CO_2 concentration (Knutti and Hegerl, 2008). Most estimates of climate sensitivity keep fixed the slowly varying land surface properties such as ice sheets. Various estimates of climate sensitivity were reviewed by Knutti and Hegerl (2008), who found that they are consistent with the IPCC AR4 conclusion that it is very likely (>90% probability) to be greater than 1.5°C and likely (more than 66% probability) to be between 2°C and 4.5°C.

One issue is that high ECS may be fundamentally hard to rule out partially because of the long time scale involved in realising a high degree of warming. A promising way forward was demonstrated by Annan and Hargreaves (2006), who suggested that this range can be more tightly constrained by combining multiple lines of observational evidence (from recent greenhouse warming, volcanic cooling and the climate of the last glacial maximum). They estimate a 5-95% interval of 1.5-4.5°C for a doubling of carbon dioxide concentration. They find that a climate sensitivity of greater than 6°C is very unlikely. However, some caution is advised given that such an approach relies on assumptions about the independence of the different lines of evidence (Knutti and Hegerl, 2008).

Recent work has examined whether the climate sensitivity might be higher due to slowly varying climate components. Hansen et al. (2008) attempted to quantify the response allowing for feedbacks from changes in ice sheets and other land surface properties. They use paleoclimate data to estimate an eventual warming of around 6°C for a doubling of carbon dioxide concentration. Lunt et al. (2010) applied a combined modelling and data approach to Pliocene paleoclimate to infer that inclusion of the longer-term components could increase climate sensitivity by around 30-50%.

The Transient Climate Response (TCR; as defined in AR4) is the global mean temperature change which occurs at the time of carbon dioxide doubling when the CO_2 concentration is increased by 1% each year until the doubling is reached. Transient climate response is generally lower than equilibrium climate sensitivity, since the response of the longer time scale components of the climate response have not yet been fully realized.

An advantage of the TCR from a policy perspective is that it may be able to better constrain the value of TCR compared to ECS and therefore better predict the peak long term warming arising from a particular emissions scenario. Frame et al. (2006) found that the maximum warming in a scenario where greenhouse gas concentrations peak then gradually reduce is more closely constrained by observable anthropogenic warming. That is, high values of maximum warming under peaking scenarios are easier to rule out than high ‘climate sensitivities’. This is because high sensitivity models take a long time to come into equilibrium.

A disadvantage of using TCR is that it mixes together the response of different elements of the climate system which work on fundamentally different time scales such as ocean diffusivity and radiative forcing. Progress may be made in constraining the behaviours of such individual components, thereby leading to a better diagnosis of the ECS.

- A review of various estimates of climate sensitivity found that they were all consistent with the IPCC AR4 conclusion that climate sensitivity is very likely to be greater than 1.5℃ and likely to be between 2℃ and 4.5℃.

2.4. Biogeochemical feedbacks

The terrestrial biosphere plays a major role in the regulation of atmospheric composition, and hence climate, through multiple interlinked biogeochemical cycles. Although carbon cycle-climate interactions have been a major focus, other biogeochemistry feedbacks are also important in modulating future climate change (Arneth et al., 2010).

There has not yet been a major published update on the Carbon Cycle Climate Model Intercomparison Project (C4MIP), which provided an estimate of carbon cycle uncertainty for the CCC (2008) analysis and other studies. However, model runs currently taking place using the Representative Concentration Pathway (RCPs) for the IPCC Fifth Assessment Report (AR5) will provide a significant update. Further processing of results from the EU ENSEMBLES project could also be used for this purpose, but so far have not been.

The AR4 concluded, based largely on C4MIP, that rising atmospheric CO_2 concentration increases land carbon uptake by stimulating plant productivity (concentration carbon feedback) while it is diminished by carbon losses with warmer temperatures (the climate-carbon feedback) leading to less uptake and possibly becoming a net source (Friedlingstein et al., 2006). While concentration carbon feedback has a four times greater effect on land carbon storage, the climate carbon feedback remains the larger source of uncertainty (Gregory et al., 2009). However, a number of recent studies indicate that other biogeochemical effects on the carbon cycle have a significant impact on the climate.

Modelling based research into the effects of nitrogen biogeochemistry on the carbon cycle (Sokolov et al, (2008); Thornton et al., (2009); Bonan and Levis (2010)) suggest that it has a significant impact on the carbon cycle. Its inclusion is found to decreases the concentration affect on carbon uptake (reducing the negative feedback thereby amplifying CO_2 increase) and also decreases the climate carbon loss due to temperature effects (reducing the positive feedback thereby damping CO_2 increases). Whist the range of the impact varies between studies, they agree that the magnitude of the impacts on the concentration-climate feedback is more significant, such that the overall impact of nitrogen biogeochemistry on the terrestrial carbon-cycle is to amplify climate change.

Sitch et al. (2007) find that increases in ozone concentration leads to a significant suppression of the global land-carbon sink as plant productivity is affected by increases in ozone concentrations. As a result more carbon dioxide accumulates in the atmosphere, with the suggestion that the resulting indirect radiative forcing caused by this ozone affect on plants could contribute more to global warming than the direct radiative forcing due to tropospheric ozone increases themselves. Again this will act to increase the rate of climate change.

Other more recent papers have also shown that different climate forcing agents (e.g. CO_2, ozone and aerosol) can have very different effects on the earth system (Huntingford et al., 2010[1]; Collins et al., 2010[1]) supporting the emerging consensus that different agents can affect the health of vegetation in very different ways, with consequences for the amount of carbon stored by the land surface as well as other ecosystem services.

[1] In press as of November 2010.

A key policy-relevant issue raised by another four recent studies (Matthews and Caldeira, 2008; Solomon et al., 2008; Lowe et al., 2009, Frölicher and Joos, 2010) is that reducing the atmospheric concentration of carbon dioxide may take a very long time, due to the nature of carbon cycle feedbacks. This means that if the atmospheric CO_2 concentration overshoots a 'safe' target, reducing the concentration back to acceptable levels can take a long time.

- Non-CO_2 forcings, such as ozone, may affect the availability of carbon storage on land.
- Though uncertainties remain large, omission of terrestrial carbon–nitrogen dynamics may lead to an underestimate of reductions in carbon emissions required to meet particular atmospheric CO_2 target.

3. Large-scale components of the climate system

Large scale climate changes and their associated impacts may have potentially significant and undesirable impacts on human and natural systems. Whilst these are often associated with rapidly changing elements of the climate system, more gradual changes in many systems can also be important. Large uncertainty remains about the probability of occurrence and magnitude of such potential changes and impacts. The CCC (2008) report relied heavily on Lenton et al. (2008) which was one of a small number of post-IPCC AR4 papers available at the time. We also use two recent reviews assessing risks from climate change (Smith et al., 2009; Fussel, 2009). There is also further evidence that the earth system exhibits critical thresholds (Dakos et al, 2008), and that changes can be very abrupt (Brauer et al., 2008; Steffensen et al., 2008). Rockström et al. (2009a) have included climate change as one of their nine key ‘planetary boundaries’ which they suggest need to be observed to remain in a ‘safe operating space’ for human beings. Climate change is one of three boundaries which they believe to have been transgressed, although other commentators have questioned their chosen description of a “dangerous” threshold for this phenomenon (Allen, 2009).

The systems reviewed here are: ice sheets, sea ice, sea level rise, the Atlantic meridional overturning circulation (AMOC), tropical forests, and carbon release from wetlands, permafrost, and ocean methane hydrates. We also discuss large-scale variability in the tropics, associated with the ENSO, climate extremes (including heat waves, precipitation extremes and wind storms), and end with the relationships and interactions between various abrupt climate change mechanisms.

3.1. Ice Sheets

There are two issues relating to changes to ice sheets; one being the rate of change, and the other being whether the change might be reversible or not.

Some studies have assessed whether ice sheets could undergo rapid mass loss. From a policy perspective, substantial reduction in ice sheet volume and consequent sea level rise may occur even if these systems are not formally classified as potentially susceptible to *rapid* change. The physical mechanisms of change in ice sheets are different than for sea ice and it is less likely that critical thresholds could be ruled out for ice sheets (Notz, 2009). Of various possible climate thresholds considered by Kriegler et al. (2009), melting of the Greenland ice sheet was assessed as the hardest to rule out for medium and high warming scenarios. Abrupt loss of the west Antarctic ice sheet (WAIS) is thought possible, although it is hard to quantify any threshold (Notz, 2009).

The CCC (2008) report highlighted concern that the summer melt of the Greenland ice sheet had accelerated, and could lead to high rates of sea level rise. Also that beyond some temperature thresholds the Greenland and West Antarctic ice sheets will commence irreversible melting. These would eventually increase global sea level by up to 12m over a period of several centuries. Models suggested Greenland could start irreversible melting as a result of sustained global warming of 1.9-4.6℃ implying that collapse would be unlikely at a warming of 2℃ and likely at 4℃. Factors governing melting of the West Antarctic ice sheet are less well understood. Recent observations have shown rapid local losses from both ice sheets, highlighting the inadequacy of current models.

Various recent studies add confidence that substantial loss of ice sheets is a possible effect of anthropogenic interference. There have been further reports of observed acceleration of many Greenlandic outlet glaciers, probably associated with warming (Rignot & Kanagaratanam, 2006; Van de Wal et al., 2008; Joughin et al., 2008a). In addition, mass loss in Greenland has been observed to be migrating northward (Khan et al., 2010). Present-day losses from both Greenland and Antarctica are now approximately equivalent to 1.5 mm/yr sea level rise, with roughly equal contributions from the WAIS and Greenland, whilst the East Antarctic ice sheet remains in balance (Velicogna, 2009, van den Broeke et al., 2009). These losses have been accelerating during the GRACE measurement period (Velicogna, 2009). Speed up of the Pine Island Glacier in West Antarctica continues unabated (Rignot, 2008). The AR4 report did attempt to take some account of the observed acceleration in its estimate of sea level rise by 2100, although it is still unclear what the recent observed changes imply for long-term future ice sheet loss (Nick et al., 2009). Furthermore, new observations suggest that there may be a natural cycle of increase and decrease in the rates of ice sheet loss (Kerr, 2009), so short-term trends should not necessarily be extrapolated into the future.

The community has developed a better understanding of the causes of observed ice thinning in Greenland. There is a background signal attributable to increased melt (a consequence of higher air temperatures) and predictions of this signal are now starting to converge with observations (for instance from the Gravity Recovery and Climate Experiment (GRACE) satellite; van den Broeke, 2009). Increased surface melting is responsible for over half the recent increase in mass loss (van den Broeke, 2009) and responds rapidly to changes in air temperature. Very high thinning rates close to the margin have been attributed to both enhanced lubrication by melt water and ice berg calving. Recent research shows that, while the mechanism for the former (drainage of large supraglacial lakes) is realistic (Das et al., 2008), it does not contribute greatly to thinning (Joughin et al., 2008b; van der Wal 2008). Spatial analysis of the pattern of thinning (Sole et al., 2008) suggests that the calving mechanism is more important, and this has been shown to be the cause of thinning for the three largest glaciers in Greenland (Howat et al., 2007; Joughin et al., 2004; Joughin et al., 2008b). This has the important implication that the present large local rates of thinning close to the margin may cease once the ice sheet retreats from contact with the ocean (Sole et al., 2008). Progress is being made in the modelling of calving (Nick et al., 2008), and links to ocean circulation changes (analogous to that thought to be triggering change in West Antarctica) have been postulated (Holland et al., 2008).

The most recent paleoproxy estimate of sea level highstand during the Eemian is 6.6-8 m (Kopp, 2009) with the likelihood that most of this rise emanated from Antarctica. Global temperature rise during the Eemian was about 2ºC above pre-industrial and comparable with projections for 2100. The origin of the warming however, was insolation-driven rather than temperature-driven, and the ice sheets may respond somewhat differently to these forcings. The estimated potential contribution to sea level rise from WAIS melt has been reduced down to around 3.3m over a sub-millennial timescale (Bamber et al., 2009).

Paleoproxy studies have also indicated the possibility that small changes in forcing (albeit with quite large changes in ocean temperature) can lead to sudden retreat of the WAIS (Naish et al., 2009; Pollard and DeConto, 2009). A mechanism to bring warm water onto the Antarctic continental shelf, where it can melt the base of the ice shelves, has been identified (Toma et al., 2008). The consequent retreat of the grounding line, glacial speed-up and increased mass loss from the ice sheet, has long been established. Recent field observations (Scott et al., 2009) confirm a previous mechanism by which thinning of the ice shelf can affect ice deep within the ice-sheet interior over decadal time scales (Payne et al., 2004).

Concerning reversibility of ice sheet loss, one model study incorporating a state of the art ice sheet model has found evidence for multiple stable states, representing effectively irreversible loss, even if global climate returns to its pre-industrial state (Ridley et al., 2010). This demonstrates that a simple link between temperature thresholds and abrupt or irreversible change in particular elements of the climate systems is not always appropriate. Other studies suggest that Greenland ice sheet loss may be reversible (e.g. Lunt et al., 2004).

There is still large uncertainty in ice sheet response to warmer climate (Oerlemans et al., 2006) and the consequent sea level rise.

- The melting of the Greenland ice sheet is considered one of the more likely to occur abrupt changes for medium and high warming scenarios.
- Rapid mass loss from the west Antarctic ice sheet (WAIS) is thought possible though it is hard to quantify thresholds for this.

3.2. Sea Ice

Following previous concern, highlighted in the previous CCC report (2008), about the imminent collapse of Arctic summer sea ice (Stroeve et al., 2007), summer sea ice extent recovered back to the long-term trend line in 2009 (Fetterer et al., 2009), though estimates of thickness suggest that it is significantly thinner as a result of being largely composed of thin first year ice. It has been argued that the dip in 2007 was not particularly unusual in the context of the observational record (e.g. Notz, 2009), especially given that variability might be expected to increase as the sea ice thins (Goosse et al., 2009; Notz, 2009). However, abrupt reductions in future Arctic summer sea ice extent are seen in projections from several CMIP3 (Phase 3 of the Coupled Model Intercomparison Project) models (Holland et al., 2006). It is still considered likely that sea ice decline would be reversible (Notz et al., 2009), although some consequences of a temporary, but complete, seasonal loss of sea ice (e.g. for biodiversity) might be irreversible.

Methods combining observational constraints with model projections suggest that summer sea ice may disappear earlier than predicted by many (but not all) AR4 models, probably before the end of the century under a mid-range non-mitigation emission scenario (Wang and Overland, 2009; Boe et al., 2009). However, though model skill has improved, caution is advised, given remaining imperfections in the models. AR4 models show large uncertainty, in terms of differences in contemporary sea ice mass budgets, partly due to a lack of relevant observations to validate models (Holland et al., 2010) although some models, such as HadGEM2, are now able to replicate many aspects of the observed long-term trend and interannual variability. Despite uncertainty over the timing of routinely ice-free summer Arctic conditions, it is still thought very likely that this would occur with a 4°C warming.

- There is now less concern about imminent Arctic sea ice collapse as, following the record low of 2007, observed summer sea ice extent has recently recovered back to the long-term trend, although estimates suggest it is thinner. It is still considered likely that sea ice decline would be reversible, although associated impacts of a temporary loss (e.g. on biodiversity) may not be.
- Many of the AR4 models suggest that summer sea ice may disappear earlier than predicted, probably before the end of the century under a mid-range emissions scenario, but there are still large uncertainties in modelling contemporary sea ice mass budgets, partly as a result of a lack of observational validation.

3.3. Sea level rise

The IPCC AR4 concluded that, at the time, understanding was too limited to provide a best estimate or an upper bound for sea level rise (SLR) in the twenty-first century. However, a range of sea level rise excluding accelerated ice loss effects was published, ranging from 0.19m to 0.59m by the 2090s (relative to 1980-2000), for a range of scenarios (SRES B1 to A1FI). The IPCC AR4 also provides an illustrative estimate of an additional SLR term of up to 17cm from acceleration of ice sheet outlet glaciers and ice streams, but did not suggest this would be an upper value.

A recent development in sea level prediction is the proliferation of a range of semi-empirical methods. Rather than modelling the different processes that contribute to sea level rise and summing them, these semi-empirical methods obtain a quantitative relationship between past global sea level and temperature change (Rahmstorf, 2007; Vermeer, M. & Rahmstorf, 2009; and Grinsted et al., 2010) or radiative forcing (Jevrejeva et al., 2010), typically derived from the last century or so, but sometimes longer. The approach is loosely based on an understanding of physical processes, but the relationship is determined by statistical methods. The general assumption is that the relationship between sea level rise and temperature (or forcing) will hold in the future and for a much greater range of warming than occurred during the period from which it was calibrated. If this assumption is valid, it allows estimates of future sea level rise to be calculated directly from climate model predictions of global warming. Several studies give projections in the range of one to two metres by 2100, much greater than the IPCC projection ranges. It is thus critical to ask whether semi-empirical approaches can be used to provide robust projections suitable for planning purposes.

There has already been some concern about the statistical validity of these approaches (Holgate et al., 2007; Schmith et al., 2007; and Rahmstorf, 2007), but it is also important to consider what semi-empirical methods imply regarding possible contributions to sea level rise. It seems unlikely that semi-empirical methods can predict large dynamical changes in ice sheets, if they have been calibrated against observations from recent centuries, because the evidence suggests that the contribution of ice sheets to sea level rise was small before the last couple of decades. Of the projected future sea level rise, a proportion would be contributed by the melting of glaciers and ice caps (excluding Greenland and the Antarctic), but even their total loss would be unlikely to produce more than around 40cm of rise, and their contribution could be considerably less (Raper and Braithwaite, 2006). According to current understanding of the rate at which the deep ocean takes up heat, it is also unlikely that thermal expansion could be large enough to bring the total twenty-first-century sea level rise to almost two metres. Combined, the loss of ice from glacial melting and thermal expansion of the ocean do not produce such a large future sea level rise as predicted by semi-empirical models, and since the tuning period means it is unlikely these methods contain much information on large ice sheet changes we should ask where the extra SLR originates.

Adding up the estimates of the various observationally derived contributions to historic sea level rise, which all have uncertainties, we find that their sum may fall short of the measured total sea level rise (IPCC AR4). The semi-empirical methods assume that any difference is due to a missing contribution that will increase with global warming. Though that assumption may be correct, without understanding/identifying the physical processes that may make up this shortfall in sea level, there is little in the way of supporting evidence.

Thus, we conclude that although there are predictions of sea level rise in excess of IPCC AR4 values, these typically use semi-empirical methods that suffer from limited physical validity. The approach taken in the Thames Estuary 2100 study (Lowe et al., 2009) concluded that increases in sea level during the 21st century up to 2m can not be ruled out. However, there is evidence to suggest (e.g. Pfeffer et al., 2008) that increases significantly above 1m have a low probability of occurring (see Lowe and Gregory, 2010, for a recent discussion). Linking sea level rise projections to temperature must also be done with caution because of the different response times of these two climate variables to a given radiative forcing change.

Recent work by van Vuuren et al. (2010[1]) estimated that for a 2°C world global mean SLR could be 0.49m above present levels which is well within the range projected by the IPCC AR4. Their estimate for a 4°C world was 0.71m, suggesting around 40% of the future increase could be avoided by mitigation. Similar results were obtained by the AVOID programme which found around a third of 21st century sea level rise could be avoided by moving from a scenario leading to a 4°C world to one leading to a 2°C world.

3.4. Atlantic 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."

Schneider et al. (2007) analysed AR4 models and found that predictions of MOC change (weighted by skill to represent current day fields) showed that

[1] In press as of November 2010.

the MOC will weaken by 25-30% by the year 2100. Recent monitoring (Cunningham et al., 2007; Kanzow et al., 2007) has revealed large variability in the strength of the MOC on daily to seasonal timescales. This significant variability casts doubt on a previous report of decreases in MOC transport from several hydrographic sections (Bryden et al., 2005), though it does not explain the observed water mass changes below 3000m. Recent results based on radar altimeter and Argo data also suggest that there has been no slowdown, at least over the altimeter era (1993-present; Willis, 2010). In contrast, two ocean state estimation studies (Wunsch & Heimbach, 2006; Balmaseda et al., 2007) do indicate a slow down. It has been suggested, based on model studies, that anthropogenic aerosols have slowed the weakening of the MOC and such weakening would only become significant several decades into the 21st century (Delworth & Dixon, 2006).

Regarding the possibility of shutdown, a recent study (Swingedouw et al., 2007) with one climate model found that additional melt from Greenland could lead to complete Atlantic Meriodional Overturning Circulation (AMOC) shutdown in a CO_2 stabilisation experiment. However, a previous study with a different model (Ridley et al., 2005) had found no effect from similar levels of meltwater input. Mikolajewicz et al. (2007) showed results from an earth system model with atmospheric and ocean GCMs which produces a complete shutdown under a high emission scenario, but not before 2100.

Reversibility following shutdown is a key issue for the AMOC. Hofmann & Rahmstorf (2009) showed that hysteresis still occurs in a new low-diffusivity model. This is contrary to previous theoretical arguments that hysteresis is a product of diffusivity of the low-resolution simplified ocean models used to perform the long-term integrations required to investigate this issue.

There is further evidence that a bias in ocean fresh water transport seen in various climate models may make the MOC overly stable in current models (Weber et al., 2007). Hofmann & Rahmstorf (2009) also suggested that fundamental model selection bias could lead to models being too stable against MOC shutdown. The influence of Greenland melting on the AMOC is not a new idea, but large uncertainty remains: this effect combines two poorly understood systems.

There is some new work on the impacts of AMOC weakening. Two studies (Vellinga and Wood, 2007; Kuhlbrodt et al., 2009) found sea level rise of several tens of cm along parts of the North Atlantic coast (see also Landerer et al., 2007; Yin et al., 2009). They find that regional cooling would partially offset the greenhouse gas warming, and various other impacts may be substantial but hard to quantify such as change in tropical precipitation patterns and change in ocean currents leading to declining fish stocks and ecosystems (Schmittner, 2005).

Large uncertainty remains in the probability of a complete MOC shutdown (Kriegler et al., 2009, Zickfeld et al., 2007). However, for the high temperature corridor of Kriegler (centred on 4.5℃ by 2100, 6.5℃ by 2200), the probability of complete shutdown was assessed to be at least 10%. Comparable results were found by the exercise reported by Zickfeld et al. (2007). It is thought unlikely that the AMOC would significantly weaken with 2℃ warming.

- Recent studies have shown a large variability in the strength of the MOC on daily to seasonal timescales, which casts doubt on a previous report suggesting an observed decrease in MOC transport.
- Large uncertainties still remain in the probability of complete shutdown. But one study, for a temperature increase of 4.5℃ by 2100, suggested that the probability of a complete shutdown was 10%.

3.5. Tropical forests

Recent research has focused on the Amazon, with mixed information regarding the possibility of forest dieback, and a few new studies on timescales of change, reversibility and the influence of other forms of anthropogenic interference. There is consensus that temperature is not the only important metric for impacts in this sector.

Various studies address the possibility of forest dieback. Tropical forests, including old growth forests in the Amazon and Africa, are increasing the amount of carbon which they store annually as a result of climate change (Phillips et al., 2009; Lewis et al., 2009). But recent observations of the Amazon response to the 2005 drought have demonstrated that the Amazon forest is vulnerable to possible future drying (Philips et al., 2009).

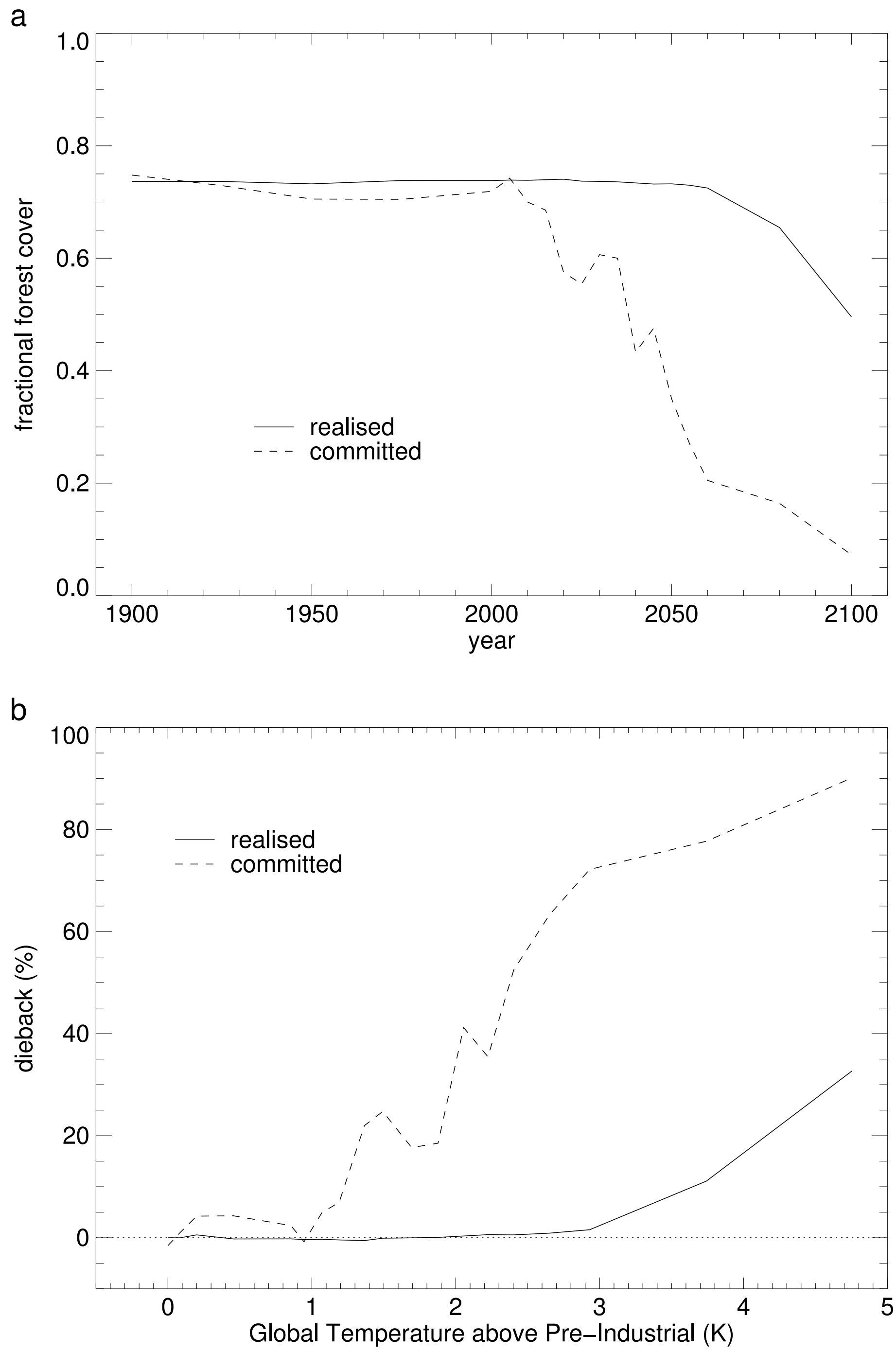

Figure 4: (a) Fractional tree cover (represented as fractional coverage of broadleaf trees in the region 40°–70° W, 15° S–5° N) as it evolves dynamically through the SRES A2 simulation and the committed state corresponding to each year. (b) The same information plotted as the percentage of complete die-back as a function of global mean temperature rise above pre-industrial (defined as 0 for the original, pre-industrial forest cover, and 100 for complete loss of tree cover in this region). Source: Jones et al. (2009).

Following on from the original Met Office Hadley Centre (HadCM3LC model) result of extensive dieback, the drying pattern over Amazon seen in HadCM3LC has been found to be plausible because it may be currently masked by aerosol forcing (Cox et al., 2008). Sitch et al. (2008) applied patterns of climate change from HadCM3LC to different vegetation model formulations. They found that loss of some Amazon forest is robust to different vegetation model formulations. On the other hand, they found significant uncertainty in the amount of forest loss.

Lapola et al. (2009) provide further information on model uncertainty: when patterns of climate change from GCMs other than HadCM3LC are used, the Amazon forest response is highly dependent on assumptions about the (highly uncertain) CO_2 fertilization effect (which in their vegetation model prevents dieback under climate change patterns from most GCMs). There is some evidence, however, to suggest that the CO_2 fertilization effect may not persist for more than a few years (Leakey et al., 2009) and that the benefit may be significantly reduced by concurrent fertilization of vines, which can shorten the lifespan of trees (Phillips et al., 2002).

Jones et al. (2009) investigated issues of timescales of dieback and reversibility (**Figure 4**). They showed that transient earth system model simulations to 2100 can substantially underestimate the long term committed forest loss (in simulations where forest loss occurs). Thus a threshold can be crossed before the impacts are apparent. They found that in one model (HadCM3LC), the global temperature threshold for forest dieback is as low as 2°C. They also showed that timescales for regrowth can be very long, although there are uncertainties due to model-dependent strength of vegetation-climate coupling.

There is also increasing recognition that anthropogenic effects other than greenhouse warming are critical for the forest. Interactions between effects of climate change and human activity in the forest (e.g. deforestation and associated increased fire risk, currently absent from GCMs) are very important. Combined effects may be larger than the sum of individual influences. Golding and Betts (2009) and Malhi et al. (2009) showed that climate change may increase vulnerability to fire, arguing that regional management may be critical in determining the forest fate. Owing to the long-term decrease in carbon storage that results, fires will act as a positive feedback on climate change (Gough et al., 2008). Lapola et al. (2009) also emphasised the critical and uncertain role of CO_2 fertilization in forest projections.

Large uncertainties remain. Malhi et al. (2009) demonstrated that there is substantial uncertainty in rainfall projections: there is a large spread and model simulations of present-day rainfall over Amazon are rather poor. A large spread in vegetation model responses to a given climate change pattern was found by Sitch et al. (2009) and Lapola et al. (2009).

We discuss further aspects of the climate change impact on forests in section 6.7.

- Observational evidence from recent Amazon events suggests a susceptibility to drought, but the results from modelling studies on forest dieback are mixed, emphasising the large uncertainty.
- Climate change may increase the vulnerability of forests to fire.

3.6. Accelerated carbon release

In this section we consider carbon release from wetlands, ocean hydrates and terrestrial permafrost. The amount of carbon stored is known to be large, but the exact amounts are highly uncertain. There is also the potential for positive feedbacks in the system which implies the potential to destabilise a greater amount of carbon.

3.6.1. Wetlands

Methane emissions from wetlands are a potentially important natural feedback on anthropogenic climate change which is absent from AR4 GCMs. Wetlands are the dominant natural source of methane globally, and emit 100-231 Tg methane per year (Denman et al., 2007) – about 17-40% of the present-day methane budget. Changes in wetlands emissions are thought to be largely controlled by the water table depth and surface temperature (Bloom et al., 2010). Though their significance has still not been robustly quantified, wetland emissions could increase the warming response to anthropogenic emissions through the additional radiative forcing from methane and its long-lived oxidation product, carbon dioxide. This process may also undergo rapid change (wetlands emissions can be switched on or off), and there is some possibility of direct mitigation through drying of managed wetlands.

Recent studies have increased our confidence that wetlands emissions represent an important process missing from AR4 GCMs. Additionally, recent observational studies have led to increased confidence that tropical and boreal wetlands emissions have played a significant role in atmospheric methane variability over paleoclimate and recent timescales (Fischer et al., 2008; Dlugokencky et al., 2009; Bloom et al., 2010). Bloom et al. (2010) report an increase in Arctic wetland emissions over 2003–2007 due to warming of mid-latitude and Arctic wetland regions. However, this is a very short time period, so it is hard to interpret in terms of future change, and the increase in emissions is small when considered in a global context and compared to other sources of methane. In terms of potential future change, Ise et al. (2008) found that feedbacks between organic carbon content and soil thermal and hydrological properties could accelerate loss of peat.

Two recent studies with the Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS) climate model of intermediate complexity, but featuring different wetlands schemes (Eliseev et al., 2008 and Volodin, 2008), added to evidence from a previous paper (Gedney et al., 2004) that wetlands emissions have the potential to significantly increase anthropogenic warming by several percent.

However, uncertainties remain large (O'Connor et al., 2010[1]) and relate to a number of factors including: the present-day global distribution and budget of emissions; sensitivity of emissions to changes in temperature and precipitation (and sulphate deposition); regional patterns of climate change in wetland areas; and a lack of process-based modelling and understanding, especially in the tropics and regarding possible future changes in methane sinks.

- Wetland emissions could increase the warming response to given anthropogenic emissions through additional radiative forcing from methane and its long-lived oxidation product, carbon dioxide.
- There is increased confidence that tropical and boreal wetlands emissions have played a significant role in atmospheric methane variability over paleoclimate and recent timescales.

[1] In press as of November 2010.

3.6.2. Ocean hydrates

Some recent studies have addressed the issue of the plausibility of substantial methane release from ocean hydrates. There have recently been isolated observations of methane gas escaping from the seabed along the West Spitsbergen continental margin. This release may be due to warming of the West Spitsbergen current over the past 30 years (Westbrook et al., 2009) and is supported by process-based modelling (Reagan and Moridis, 2009).

Methane gas venting to the atmosphere from sediments of the East Siberian Arctic seas have been reported (Shakhova et al., 2010), although there is no direct evidence to establish whether this release is due to anthropogenic climate change or represents an ongoing adjustment to flooding during the last deglaciation.

Shallow water hydrates are the most vulnerable and could release significant amounts of methane as a result of as little as a 1˚C increase in seafloor temperature (Reagan and Moridis, 2008). Model studies (Reagan and Moridis, 2007; Archer et al., 2009) have indicated that there is potential for human activity to cause a significant fraction of ocean methane hydrates to be melted, and for the consequent impact on the severity of anthropogenic global warming. Thresholds for hydrate release and the severity of such a release are, however, very poorly quantified (e.g. Archer et al., 2009). Archer (2007) suggested that any such release is most likely to take place on time scales of millennia or longer. This is because methane hydrates are stored in sediment columns which provide thermal insulation from anthropogenic warming. However, the possibility of much more rapid release cannot currently be ruled out.

Substantial uncertainties remain, affecting the amount and timescale of methane release (Archer et al., 2009; O'Connor et al., 2010[1]). These include: the amount of methane stored in ocean hydrates (the uncertainty range is around an order of magnitude, 500-3000 GtC (Archer et al., 2007)); where it is concentrated geographically; the magnitude of future ocean warming at these locations; how the warming will propagate through the sediment column; and how much of the methane will escape the sea floor to reach the ocean and atmosphere. Archer et al. (2009) suggest that all these uncertainties have a very large influence on the potential climate impacts.

[1] In press as of November 2010.

- Recent studies have found evidence of methane release from ocean hydrates in West Spitsbergen and the East Siberian Arctic seas.
- Shallow water hydrates are the most vulnerable and could release significant amounts of methane as a result of as little as a 1˚C increase in sea floor temperature.
- Substantial uncertainties remain, affecting the amount and timescale of methane release.

3.6.3. *Terrestrial permafrost*

Schuur et al. (2008) estimate that there is about 1672 PgC stored in northern circumpolar permafrost areas. Permafrost thawing, through anthropogenic warming, could release large amounts of additional carbon into the atmosphere, either directly or indirectly, by modifying wetlands emissions (Schuur et al., 2008; Zhang et al., 2009). This would lead to an increase in the rate of anthropogenic warming. This release has the potential to be very abrupt, potentially on the timescale of decades, although timescales are very uncertain.

Regarding confidence in whether such a release is possible, recent observations suggest that high-latitude permafrost regions are experiencing thawing (Jorgenson et al., 2006). The permafrost model of Khvorostyanov et al. (2008) for the Yedoma region of eastern Siberia simulated a release of 75% of the 500GtC stock over 3-4 centuries through a self-sustaining feedback, at an average release rate about one third of the current rate of CO_2 emission from fossil fuel burning.

There is still substantial uncertainty regarding the timescales of release (O'Connor et al., 2010[1]). Methane hydrates in permafrost could destabilise and release methane to the atmosphere on a timescale of decades to centuries if the hydrate becomes exposed through coastal erosion (Shakhova et al., 2005), but timescales as long as millennia are possible. The self-sustaining feedback simulated for the Yedoma region by Khvorostyanov et al. (2008) would be irreversible even if global temperatures were reduced to present-day levels. The risk of methane release from permafrost may also be increased if rapid sea ice loss occurs (Lawrence et al., 2008).

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[1] In press as of November 2010.

Again, large uncertainties exist regarding the amount of carbon stored in peat and permafrost (Hugelius and Kuhry, 2009); in important complex vertical and horizontal variations in permafrost properties; different mechanisms of permafrost loss; whether carbon is released as CO_2 or methane; and the indirect effect on wetlands emissions and their interaction with fire.

- Permafrost thawing through anthropogenic warming could release large amounts of additional carbon into the atmosphere either directly or indirectly by modifying wetlands emissions
- Recent observations suggest that high-latitude permafrost regions are experiencing thawing, but there is high uncertainty over the timescale of release.

3.7. Tropical climate system

In addition to the more frequently referred to potential abrupt changes to the climate system, such as a rapid loss of Arctic sea ice, a number of other large-scale climate processes could also undergo rapid change. One of these is the tropical climate system and the El Niño Southern Oscillation. Latif and Keenlyside (2009) concluded that, at this stage of understanding, we do not know how global warming will affect the tropical Pacific climate system. None of the AR4 models they analysed showed rapid changes in behaviour. However, a threshold of abrupt change cannot be ruled out because, while they are better than the previous generation of models (Reicheler and Kim, 2008), these same models all show large biases in simulating contemporary tropical pacific, and disagree on the sign of change in ENSO-like response.

- Uncertainty remains over how climate change will affect the tropical Pacific climate system, including the El Niño Southern Oscillation.

3.8. Extremes – temperature, precipitation and wind storms

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 key area of progress since AR4 has been the finding that large-scale climate variability (e.g. the North Atlantic Oscillation (NAO), El Niño-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 over Europe, 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 have warmed by around 1°C to 3°C since 1950. Human influence has at least doubled the risk of such a hot 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 450 parts per million (ppm) by the end of 2100 without an overshoot, approximately equivalent to a 2°C world, the change in intensity of heat waves could be 55% less than in a business as usual reference scenario, which corresponds to around 4°C (Washington et al., 2009). The biggest reductions in heat wave intensity are found over the western United States, Canada, and much of Europe and Russia. This is broadly consistent with results (Caesar, 2010[1]) using data from the EU ENSEMBLES project where the global mean number of days exceeding the upper 90th percentile of daily temperatures is seen to increase from a baseline of around 36 days per year in 1861-1890 to around 200 days per year in 2100 under a business as usual (4°C change) and 130 under a 450 ppm mitigation scenario (2°C change). This equates to avoiding 43% of this increase by mitigation.

[1] Work done using EU ENSEMBLES data as part of Workstream 2 of the AVOID programme. Not yet published, available from http://www.avoid.uk.net.

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.

For tropical cyclones there is some consensus developing from the two sides of the debate in a review paper by Knutson et al. (Nature 2010).
They conclude that it remains uncertain whether past changes in tropical cyclone activity have exceeded natural variability and that model predictions indicate a globally averaged shift towards stronger storms with a decreased frequency of tropical cyclones.

Studies on mid-latitude storms have been reviewed in Ulbrich et al. (2009). They concluded that in the Northern Hemisphere winter the models predict fewer storms with some local increases in intense storms. In the Southern Hemisphere the models show a southward shift in the storm track.

- Observational studies have found that extreme daily maximum and minimum temperatures have warmed over most regions, with increases of 1℃ to 3℃ since 1950 over some regions.
- Human influence has at least doubled the risk of the type of summer experienced over Europe in 2003. By the 2040s, summers over southern England could be at least as warm as 2003 on average 50% of the time.
- The first GCM study to estimate the potential for mitigation to avoid climate change indicates that under a 2℃ mitigation scenario the change in intensity of heat waves could be 55% less than under a 4℃ business as usual scenario.

3.9. Interactions between potentially abrupt changes

Interactions between different systems that may exhibit thresholds for rapid change could significantly affect the overall risk of abrupt climate change. Given the high uncertainty about individual elements, quantifying the change in risk from interactions is extremely difficult, although Kriegler et al. (2009) do address this issue (**Figure 5**).

The loss of the Greenland ice sheet would lead to increased global warming. As well as increased impacts, this causes a general increase in the risk of other abrupt changes being triggered. Greenland ice sheet loss may also have more direct effects, which would increase the risk of other rapid changes. One example is that freshwater input from the melting of the Greenland ice sheet could increase the risk of AMOC shutdown. Another is that sea level rise could increase the risk of destabilising the Antarctic ice sheet through retreat of the grounding line. Regional climate change in key regions, such as the Arctic or the Amazon basin, could have a large influence on crossing critical thresholds in those regions, but also in other parts of the world.

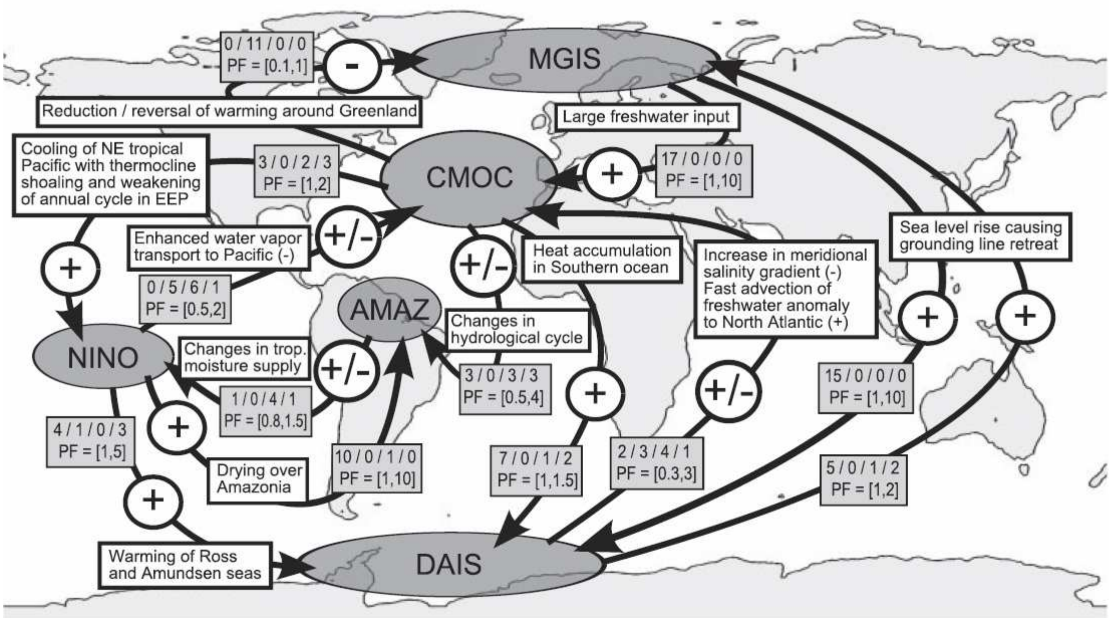

Figure 5: Sketch of main interactions between potential thresholds from the expert consultation study of Kriegler et al. (2009). CMOC=reorganisation of AMOC, AMAZ=Amazon rainforest dieback, NINO=shift of ENSO, MGIS=melting of Greenland ice sheet, DAIS=disintegration of West Antarctic ice sheet. Pairs of thresholds (A, B) are connected if at least 5 experts judged that some effect of triggering A on the probability of triggering B exists, and that they outnumbered experts who saw no effect of A on B.

4. Coastal system impacts and adaptation

4.1. Sea level rise impacts

A highly cited study in the IPCC AR4 is Nicholls (2004), which assessed the global scale impact of sea level rise (SLR) associated with 4 SRES emissions scenarios and a single climate model on the average annual number of people flooded and amount of coastal wetlands lost. Under the A1FI scenario (equivalent to approximately a 4℃ warmer world than present in 2100), global-mean SLR was estimated as 34cm in the 2080s relative to present, and was shown to be associated with an additional 63-102 million people flooded (assuming the level of protection remains at present-day levels) and an additional 5-20% loss of coastal wetlands. Assuming adaptation protection measures consistent with Gross Domestic Product (GDP) reduced the number of people flooded to 6-10 million. Similarly, modelling of all coastal wetlands (but excluding sea grasses) by McFadden et al. (2007) suggested global losses from 2000 to 2080 of 33% and 44% given a 36 cm and 72 cm rise in sea level, respectively.

There is little evidence post-IPCC AR4 that the international community has seriously considered the implications of SLR for population location and infrastructure in many developing countries. An important study that addresses this caveat is presented by Dasgupta et al. (2009), which assessed the consequences of prescribed SLR (1-5m in 1m increments with no other climate changes) for 84 developing countries, assuming that levels of protection remain at present-day levels. Their results were extremely skewed, with severe impacts limited to a relatively small number of countries. For these countries (e.g., Vietnam, A.R. of Egypt, The Bahamas), however, the consequences of SLR are potentially catastrophic. For instance, in A.R. Egypt, 28,498 km^2 of agricultural land (13.09% of the nation's total); 24,953 km^2 of urban areas (5.52% of the nation's total); and 24,015 km^2 of wetlands (6.55% of the nation's total) would be submerged in case of 1m SLR (e.g. see **Figure 6**). As a result, an estimated 6.44% of GDP would be lost. For many other countries, including some of the largest (e.g., China), the absolute magnitudes of potential impacts are very large. At the other extreme, many developing countries experience limited impacts. At the regional level, impacts were most severe for East Asia and the Middle East and North Africa (**Figure 7**).

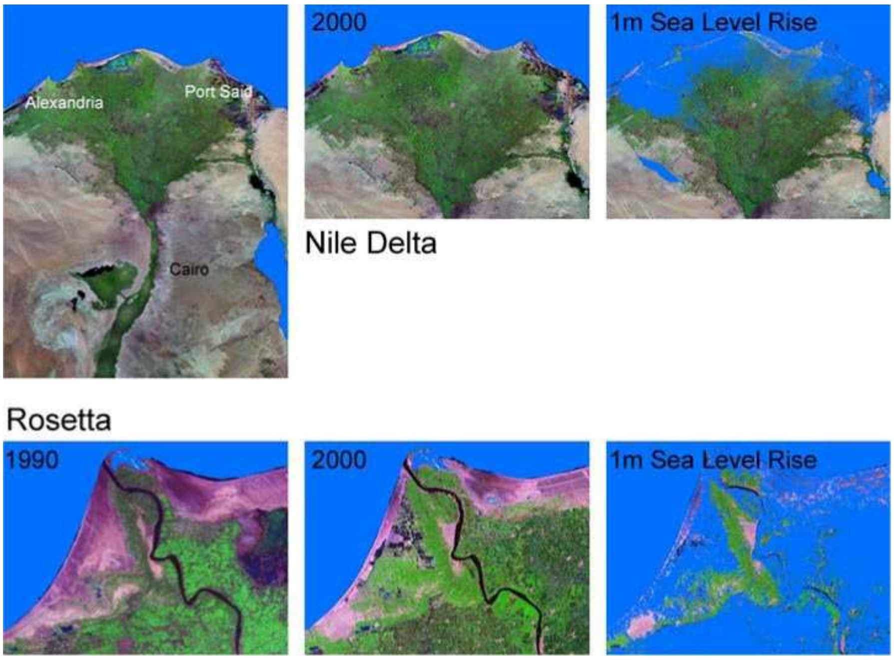

Figure 6: Inundation zones for 1-m SLR in the Nile Delta and Rosetta, in A.R. of Egypt. Source: Dasgupta et al. (2009), p. 386.

The analyses suggest that planning for adaptation should begin immediately and that international resource allocation strategies should recognize the skewed impact distribution they document. Some countries will be little-affected by SLR, while others will be so heavily impacted that their national integrity may be threatened.

It is interesting to compare the results presented by Dasgupta et al. (2009) with the results presented by Nicholls (2004). For a 1m SLR, Dasgupta et al. (2009) estimated that around 56 million people would be impacted and 1.86% of total coastal wetlands would be lost. In contrast, Nicholls (2004) estimated that for a lower SLR of 34cm, 63-102 million people would be flooded and 5-20% of wetlands would be lost. Although Nicholls (2004) did also consider future adaptations, if we consider the results above (which are for the cases where both studies assume present-day levels of protection), the differences in impact between studies are large, especially given Dasgupta et al. (2009) considered a greater magnitude of SLR. The differences are perhaps more likely due to the methodological approaches each study applied, rather than due to climate change.

For instance:

- Nicholls (2004) applies the SRES emissions scenarios to compute SLR consistently, whereas Dasgupta assumes uniform global SLR of 1,2,3,4, and 5m.
- Nicholls (2004) applies SRES population projections and downscales them whereas Dasgupta et al. (2009) uses current population and notes that increased effects due to greater population on coasts is neglected.
- Dasgupta et al. (2009) only investigates the impacts of SLR for developing countries whereas Nicholls (2004) considers impacts globally.
- The two studies use very different methodologies for estimating population affected by SLR and wetlands lost, even though both studies in some cases use the same data (e.g. CIESIN). Simply, Dasgupta et al. (2009) used a Geographical Information System (GIS) to overlay exposure datasets (population, wetlands etc.) with inundation zones, whereas Nicholls (2004) used more statistically-based methods.

Both studies note their limitations, e.g. Nicholls (2004) states clearly that the wetlands model overestimates national losses and that it is hard to validate the model. Importantly, however, although the magnitudes of the impacts differ, both studies agree that south-east Asia will be the most highly affected region. Whilst the impacts presented by Dasgupta et al. (2009) are of a lower magnitude than those presented by Nicholls (2004), the large differences in methodological approach means it is not possible to say whether the Dasgupta et al. (2009) study objectively presents a change in the magnitude of risk relative to what Nicholls (2004) presents.

van Vuuren et al. (2010[1]) attempted to put an economic value on the impact of global SLR. By using the DIVA (Dynamic Interactive Vulnerability Assessment) model with climate change scenarios they show that the global economic damage caused by SLR equates to around 400,000 million $US/year for a world 4°C warmer than present in 2100, and around 330,000 million $US/year for a 2°C world. These correspond to global mean SLRs of 0.71m and 0.49m respectively. The results are comparable to costs presented

[1] In press as of November 2010.

by Dasgupta et al. (2009), who showed that the economic damage caused by a 1m global mean SLR could be around 220,000 million $US.

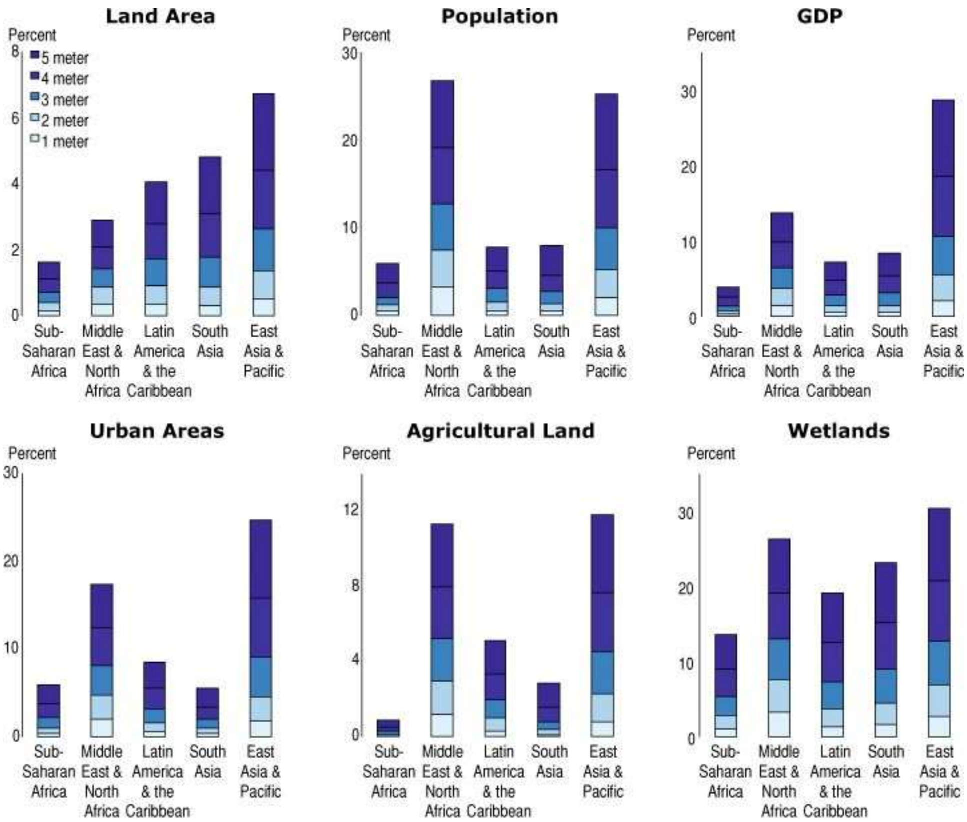

Figure 7: Percentage of various sectors in different regions impacted by prescribed amounts of SLR. For the land area sectors, the percentages indicate the total percentage for the sector that would be submerged for a given SLR. For instance, with 5m SLR, approximately 9% of all urban areas would be submerged and approximately 4% of all agriculturual land would be submerged. Source: Dasgupta et al. (2009), p. 384.

4.2. Adaptation to coastal impacts

A key post-AR4 insight regards the retreat versus protection issue of coastal adaptation. Recent studies suggest that even with large rises in sea level of up to 5m/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 (TE2100, 2009) and Delta Commission 2008 (Kabat et al., 2009; Delta Commission 2008). 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 SLR 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 an extreme 5m/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 SLR 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 emphasized 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 different adaptation decisions to the magnitude of SLR. The Dutch study projected a local SLR of between 65cm and 1.3 m (Delta Commission, 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 defenses 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.

More recently, van Vuuren et al. (2010[1]) have used the DIVA model to assess globally, both damage and adaptation costs (in terms of raising dikes and replenishing beaches) of SLR, associated storm surges and socio-economic development under a reference and business as usual scenario respectively, taking into account coastal erosion (both direct and indirect), forced migration, coastal flooding (including rivers) and salinity intrusion into deltas and

[1] In press as of November 2010.

estuaries. Van Vuuren et al. (2010) found that the sum of damage and adaptation costs was highest for the business as usual scenario and lowest for the mitigation scenario with adaptation. Independent from the level of mitigation, adaptation reduced global overall costs rather effectively, which suggests a necessity for engaging in adaptation even under ambitious mitigation. For SLR, the study found that more damages could be avoided through an adaptation-only strategy than through a mitigation-only strategy, and even without SLR, adaptation would be cost-effective in order to protect the assets situated in the floodplain, which increase due to socio-economic development alone.

However, as the TE2100 project has shown, coastal defence by engineering is expensive and needs continued close attention if disasters are to be prevented. As such, simply leaving the land to inundation could work in coastal regions that are only sparsely inhabited. The Netherlands Delta Commission propose that rather than being a financial burden, coastal protection can be seen as a push to boost technological innovation, and to invest in the development of long-lasting and sustainable infrastructure (Kabat et al., 2010). They propose that, for the Netherlands, climate change can be an opportunity for societal and economic growth and evolution, moving the country into a sustainable future. Of course, the studies cited so far refer to countries in the developed world (UK and Netherlands). The IPCC AR4 acknowledged that a lack of adaptive capacity is often the most important factor that creates a hotspot of human vulnerability (Nicholls et al., 2007). Developing nations may have the societal will to relocate people who live in low-lying coastal zones or to improve coastal defences but without the necessary financial resources, their vulnerability is much greater than that of a developed nation in an identical coastal setting.

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) using a simple 2D raster-based inundation model called LISFLOODFP (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.

Another sub-national scale study with a UK focus is presented by Mokrech et al. (2008). Within the RegIS project, potential impacts of climate change for East Anglia and North West England were explored up to the 2050s using four socio-economic scenarios to represent plausible futures, which included changes in urban land use as well as adaptive responses to flooding comprising dike upgrade and realignment options. The results indicated that future climate will increase flood risk in both regions and that East Anglia is more vulnerable to climate change than North West England at the present level of protection, especially in the extensive coastal lowlands of the Fens and Broads because of the combined effects of SLR and increased river flows. The study concludes that although the present adaptive policy of upgrading defences in East Anglia will reduce the impacts of flooding, the policy is not effective in the case of more extreme climate change scenarios by the 2050s, in which case more extensive adaptation would be required.

4.3. Coastal ecosystems

The IPCC AR4 reported that SLR 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 SLR. The IPCC AR4 acknowledges that human development patterns also have an important influence on biodiversity among coastal system types. For instance, large-scale conversions of coastal mangrove forests to shrimp aquaculture have occurred during the past three decades along several of the world's coastlines (Nicholls et al., 2007). The additional stresses associated with climate change could lead to further declines in mangroves forests and their biodiversity. An important post-IPCC AR4 finding is that management choices associated with coastal ecosystems can have a *greater* potential impact on habitat viability than climate change. For instance, Richards et al. (2008) investigated the potential impacts and adaptations to future climate and socio-economic scenarios for three habitat types (saltmarsh, coastal grazing marsh, and fluvial grazing marsh) and selected species in floodplains in East Anglia and North West England. They found that management choices, which can be linked to socio-economic futures, have a greater potential impact on habitat viability than climate change. The choices society makes will therefore be key to protection and conservation of biodiversity. The analyses also showed that coastal grazing marsh is the most vulnerable habitat to SLR, although there is a scope for substituting losses with fluvial grazing marsh.

Recent work that assesses the impact of climate change on coral reefs is detailed in Section 6.2.2. Notably, one third of coral reef species are already at risk of extinction and a limit of 350ppm for CO_2 concentrations in the atmosphere has been proposed to safeguard reefs, and bleaching will become annual with today's concentration of CO_2 of 387 ppm (Hoegh-Guldberg et al., 2007; Veron et al., 2009).

Despite increasing scientific and public concerns on the potential impacts of global ocean warming on marine biodiversity, very few empirical data on community-level responses to rising water temperatures are available other than for coral reefs. Two recent studies in coastal south-eastern Australia, an area forecast to be a 'hotspot' for future warming, address this, and suggest less severe impacts associated with climate change than are expected for coral reefs. Stuart-Smith et al. (2010) describes changes in temperate sub-tidal reef communities over decadal and regional scales in the region, which has undergone considerable warming in recent decades. Analyses of biotic communities revealed few changes with time, although some species-level responses could be interpreted as symptomatic of ocean warming. These included fishes detected in Tasmania only in recent surveys and several species with warmer water affinities that appeared to extend their distributions further south. The most statistically significant changes observed in species abundances, however, were not related to their biogeographical affinities. The research suggests that the study encompassed a relatively stable period following more abrupt change, and that community responses to ocean warming may follow nonlinear, step-like trajectories. Figueira and Booth (2010) show that rising ocean temperatures in the region are resulting in a higher frequency of winter temperatures above survival thresholds for eight species of juvenile coral reef fish - current warming trajectories predict 100% of winters will be survivable by at least five of the study species as far south as Sydney (34°S) by 2080.

4.4. Coastal tourism

Climate change may influence coastal tourism directly via the decision-making process by influencing tourists to choose different destinations and indirectly as a result of SLR and resulting coastal erosion (Agnew and Viner 2001). The

IPCC AR4 concludes that climate change will have a ‘strong’ impact on coastal tourism and recreation, with major adverse effects likely for the Caribbean, Mediterranean, Florida, Thailand and Maldives (Nicholls et al., 2007). However, despite the importance of coastal tourism to the global economy, the magnitudes of the likely impacts of climate change on beach visits and coastal tourism are currently poorly understood, but post-IPCC AR4 research is addressing this. For instance, using a case study of the coastline at East Anglia, UK, Coombes et al. (2009) modelled the potential impacts under four future climate change scenarios. Their results suggest that climate change will result in a net increase in visitors with the positive effects of warmer and drier weather outweighing the negative influences of reductions in beach width due to SLR. A more recent study for the same region shows that whilst higher temperatures due to climate change are expected to increase visitor numbers, warmer weather may encourage greater participation in low impact activities such as bathing, thus reducing the impact of increased tourist numbers on the coastal environment (Coombes and Jones, 2010).

On a larger spatial scale, a European review by Moreno and Amelung (2009) has shown that with respect to climate, the Mediterranean is likely to remain Europe's prime region for summer-time beach tourism for at least the next 50 years and that coastal managers in Mediterranean destinations are advised to focus some of their attention on other climate change impacts such as SLR or water availability, and include environmental quality and diversification of activities in their deliberations. In stark contrast, Kundzewicz et al. (2008) suggest that the impacts of climate change on beach holidays in the Mediterranean are likely to be serious and largely adverse due to greater drought and fire risk, more flash floods, higher personal heat stress and more tropical diseases (e.g. malaria).

4.5. Summary of new findings since the IPCC AR4

- The IPCC AR4 showed that under the A1FI scenario (equivalent to approximately a 4°C warmer world than present in 2100), global-mean SLR was estimated as 34cm in the 2080s relative to present, and was shown to be associated with an additional 63-102 million people flooded (assuming the level of protection remains at present-day levels) and an additional 5-20% loss of coastal wetlands (Nicholls, 2004).
- New research (Dasgupta et al., 2009) suggests that for a 1m SLR that around 56 million people would be impacted and 1.86% of total coastal

wetlands would be lost. Both studies agree that south-east Asia will be the most highly affected region but the large differences in methodological approach means it is not possible to say whether the Dasgupta et al. (2009) study objectively presents a change in the magnitude of risk relative to what Nicholls (2004) and the IPCC AR4 present.

- The global economic damage caused by SLR could be around 400,000 million $US/year for a 4℃ world in 2100 and around 330,000 million $US/year for a 2℃ world. These correspond to global mean SLRs of 0.71m and 0.49m respectively (van Vuuren et al., 2010[1]).
- Recent studies suggest that even with large SLR of up to 5m/century, it would still be economically rational to protect some of our more developed coasts (TE2100, 2009; Kabat et al., 2009; Delta Commission, 2008; Mokrech et al., 2008).
- Whilst it may be economically viable to protect some parts of the developed coastline, smaller assets on other parts of the coastline or the coastal ecosystem would suffer in the absence of protection in those areas. Furthermore, protecting one section of coastline might increase impacts in another and an important post-IPCC AR4 finding is that management choices associated with coastal ecosystems can have a *greater* potential impact on habitat viability than climate change (Richards et al., 2008) so adaptive measures need to be taken with care.
- Research into community-level responses to rising water temperatures has increased since the IPCC AR4. Evidence from south-eastern Australia suggests community responses to ocean warming may follow nonlinear, step-like trajectories and that rising ocean temperatures in the region are resulting in a higher frequency of winter temperatures above survival thresholds (Figueira and Booth 2010; Stuart-Smith et al., 2010).
- New research is shedding light on the magnitudes of the likely impacts of climate change on beach visits and coastal tourism, particularly within the UK and Mediterranean, but the studies are not in agreement as to whether the impacts will be positive or negative (Coombes et al., 2009; Coombes and Jones, 2010; Moreno and Amelung, 2009; Kundzewicz et al., 2008). Also, whilst this new research has focused on tourism in European countries, it is important

[1] In press as of November 2010.

to note that the IPCC AR4 concludes that several small island states are likely to suffer as a result of rising sea level due to climate change, e.g. the Maldives, which will have a secondary impact on tourism (Nicholls et al., 2007).

5. Ocean acidification

In this section we firstly describe the main conclusions on ocean acidification from the IPCC AR4. Then we review the post-IPCC AR4 evidence from modelling studies for the impacts of increased atmospheric CO_2 concentrations on ocean acidification and then the evidence for the biological impacts of increasing acidification of the oceans on marine organisms.

5.1. Conclusions from the IPCC AR4

Anthropogenic emissions of CO_2 have increased the atmospheric concentration of CO_2 from 280ppm to approximately 390ppm (IPCC 2007a), higher than any time in at least the last 650,000 years. While much of these emissions have remained in the atmosphere, leading to global warming, much is sequestered in trees and plants and an estimated 25-50% of emissions are absorbed by the ocean (Zeebe et al., 2008) which acts as a buffer for emissions of CO_2 and limits global warming. A key consequence of increases in the amount of carbon dioxide dissolved in the ocean is greater ocean acidity. Modelling studies and measurements cited in the IPCC AR4 suggest that the absorption of CO_2 by the ocean has already decreased the pH of the ocean surface by 0.1 since 1750 (IPCC, 2007a), making it more acidic than at any time in the last 25 million years. Much of the IPCC AR4 conclusions on the impacts of climate change on ocean acidification are based solely upon a study by Caldeira and Wickett (2003), which showed that surface ocean pH has decreased by around 0.1 units due to absorption of anthropogenic CO_2 emissions relative to pre-industrial (1750) levels and is predicted to decrease by up to a further 0.3-0.4 units by 2100.

Although the resultant changes in ocean chemistry are well understood, the biological impacts of increasing acidification of the oceans on marine organisms, ecosystems and biogeochemical cycling are all still poorly understood (IPCC, 2007b; Legge and Tyrell, 2009[1]). This is despite research into the consequence of increased ocean acidification as a result of rising atmospheric CO_2 concentrations growing rapidly over the past decade. The IPCC AR4 concludes that, with *medium* confidence, ocean acidification will impair a wide range of planktonic and shallow benthic marine organisms that use aragonite to make their shells or skeletons, such as corals and marine snails (pteropods), with significant impacts particularly in the Southern Ocean, where cold-water corals are likely to show large reductions in geographical range this century (Fischlin et al., 2007). This is because a coral reef represents the net accumulation of calcium carbonate ($CaCO_3$) produced by corals and other calcifying organisms but calcification rates decline with increases in ocean acidification, which means reef-building capacity also declines. Ocean acidification impacts on oysters and mussels will impact commercial aquaculture and lead to significant economic loss. For instance, Gazeau et al. *(*2007) demonstrate that the calcification rates of the edible mussel (Mytilus edulis) and Pacific oyster (Crassostrea gigas) decline linearly with increasing CO_2 – mussel and oyster calcification may decrease by 25 and 10%, respectively, by the end of the century, following the IPCC IS92a scenario (740 ppmv in 2100). Whilst new work has highlighted the impacts of low ocean pH on molluscs and various plankton species, (Riebesell 2008; Zeebe et al., 2008), experimental studies have shown that these organisms are less sensitive to ocean acidification than corals (Gazeau et al., 2007). At the same time, oceanic acidification has been projected to trigger marine oxygen holes (Hofmann and Schellnhuber, 2009); marine areas depleted in oxygen currently occur as a result of pollution, and cause 'dead zones'.

A key issue concerns the timescales at which the impacts of ocean acidification are projected to occur. For instance, Feely et al. (2004) showed that the cold surface waters in low-latitude regions will begin to become undersaturated with respect to aragonite only when atmospheric CO_2 reaches 1,200 ppm, more than four times the pre-industrial level ($4xCO_2$) of 280 ppm. In contrast, Orr et al. (2005) suggest that some polar and subpolar surface waters will become undersaturated at $2xCO_2$, probably within the next 50 years. This is much sooner than previously thought; Kleypas et al. (1999) suggested a timescale of hundreds of years was required.

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[1] This citation has not been peer-reviewed but given that the citation refers to a literature review, we are confident in referring to the paper here.

5.2. Post-IPCC AR4 studies assessing the impact of climate change on ocean acidification

An important post-IPCC AR4 study used an earth system model of intermediate complexity to show how consideration of climate change affects predicted changes in ocean pH (Cao et al., 2007). Under a CO_2 emission scenario derived from the WRE1000 CO_2 stabilisation concentration pathway and a *constant climate*, Cao et al. (2007) projected a reduction by 2500 in surface ocean pH of 0.47 relative to a pre-industrial value of 8.17. They then repeated the experiment but this time with the consideration of climate change under climate sensitivities of 2.5°C and 4.5°C respectively; the reduction in projected global mean surface pH was little different from the simulation with a constant climate, at about 0.48 and 0.51 respectively. The results suggest that future changes in ocean acidification caused by emissions of CO_2 to the atmosphere are largely independent of the amounts of climate change, which confirms the findings of an earlier study by McNeil and Matear (2006). This is an important finding because it confirms the atmospheric concentration of CO_2 is a major driver of ocean acidification, regardless of the global mean temperature. Furthermore, the results presented by Cao et al. (2007) agree with the findings of Caldeira and Wickett (2003), which are summarized in the IPCC AR4; at around 788 ppm CO_2 Cao et al. (2007) showed that ocean pH declines by about 0.3 from pre-industrial levels.

Since, the IPCC AR4, some studies have addressed the potential impacts that could be avoided if certain emissions mitigation policies are applied. For instance, Mathews et al. (2009) used the University of Victoria Earth System Climate Model (UVic ESCM) version 2.8, an intermediate-complexity global model of the coupled climate-carbon system, to investigate how climate engineering may affect surface ocean pH and the degree of aragonite saturation. Future CO_2 emissions were specified until the year 2100 from the SRES A2 scenario and climate engineering was implemented at the year 2010 of the simulation as a uniform reduction of incoming solar radiation. The study showed that climate engineering could slow ocean pH decreases somewhat relative to the non-engineered case, but would not affect the level of aragonite saturation due to opposing responses of pH and aragonite saturation to temperature change. Bernie et al. (2010) used a combination of simple and complex coupled-carbon General Circulation Model (GCM) to examine the projected changes in global ocean surface pH from a range of non-mitigation and mitigation policy global emissions scenarios produced under the UK AVOID programme. The study suggested that without mitigation, ocean pH could decrease from a pre-industrial (year 1750) level of 8.16 (8.07 in present day) to 7.67 (10th and 90th percentiles of 7.74 and 7.58 respectively) by 2100, assuming a fossil-fuel intensive SRES A1FI-type future, or for an SRES A1B future, 7.81 (7.86, 7.71). Both of these projected ranges of global mean ocean surface pH are without precedent in at least the last 25 million years. However, Bernie et al. (2010) showed that pH could be maintained at 8.00 (8.02, 7.96) under a mitigation policy with peaking global emissions in 2016 and post-peak reduction of 5% per year to a low long-term emissions floor (6 Gt CO_2 equivelent/yr). Whilst this represents a considerable reduction in the magnitude of the pH decrease relative to the non-mitigation scenarios, it still represents a significant further acidification relative to pre-industrial levels.

5.3. Improved regional detail of impacts

The post-IPCC AR4 literature provides a more regionally detailed overview of the impacts of ocean acidification because previously, the majority of studies focused either on global average conditions (Caldeira and Wickett, 2003) or on low-latitude regions (Kleypas et al., 1999). For instance, Feely et al. (2009) have published estimates based on the SRES A2 emissions scenario where atmospheric CO_2 levels could approach 800 ppm near the end of the century. The associated impact is a surface water pH drop from a pre-industrial value of about 8.2 to about 7.8 by the end of this century, increasing the ocean's acidity by about 150% relative to the beginning of the industrial era. Their projections indicate that aragonite undersaturation will start to occur by about 2020 in the Arctic Ocean and 2050 in the Southern Ocean. By 2050, all of the Arctic will be undersaturated with respect to aragonite, and by 2095, all of the Southern Ocean and parts of the North Pacific will be undersaturated. However, it is important to note that these estimates are based solely upon climate change projections from a single climate model (CCSM3) and emissions scenario (SRES A2), such that uncertainties in the projections due to climate modelling uncertainty were not considered.

5.4. Post-IPCC AR4 evidence provides more details on the varied responses of marine organisms to ocean acidification

The study of the impact of ocean acidification on marine organisms has grown rapidly over the past 10 years, especially since the IPCC AR4, which concluded with *medium* confidence that ocean acidification would negatively affect some marine organisms. The majority of studies focus on calcifying marine organisms. At the publication of the IPCC AR4, it was known that various calcifying organisms respond differently to ocean acidification, with some organisms appearing to be unaffected by ocean acidification (Buitenhuis et al., 1999) and some negatively affected (Riebesell et al., 2000). Evidence published since the IPCC AR4 supports this, although now there is an improved understanding of the different ways in which calcifying organisms may respond, for instance, in terms of how their growth, fertility, metabolism and calcification rates are affected by acidification, and the importance of assessing the impacts of acidification not only upon calcification, but upon the whole life cycle of the organism, has been recognized (Ries et al., 2009; Hendriks et al., 2010; Rodolfo-Metalpa et al., 2010; Wood et al., 2008; Iglesias-Rodriguez et al., 2008).

Ries et al. (2009) investigated the effects of CO_2-induced ocean acidification on calcification in 18 marine organisms. Species were selected to span a broad taxonomic range. The study showed that 10 of the 18 species studied exhibited reduced rates of net calcification and, in some cases, net dissolution under elevated CO_2. However, in seven species, net calcification actually *increased* under the intermediate and/or highest levels of CO_2, and one species showed no response at all. These varied responses may reflect differences amongst organisms in their ability to regulate pH at the site of calcification. Similarly, on the basis of a meta-analysis of 372 available published experimental assessments, Hendriks et al. (2010) showed that some marine biota may be resistant to ocean acidification because acidification effects differed considerably across taxonomic groups and functions, but the magnitude of the changes were, overall in their opinion, modest for acidification levels within the ranges projected by the IPCC AR4 during this century. Their results showed that calcification rate, the most sensitive process responding directly to ocean acidification, will decline by 25% at elevated CO_2 values of 731–759 ppm but that processes such as growth, metabolism, survival and fertility were relatively unaffected by acidification (see **Figure 8**). Similar to the findings of Ries et al. (2009), they found that some organisms showed enhanced growth under elevated CO_2.

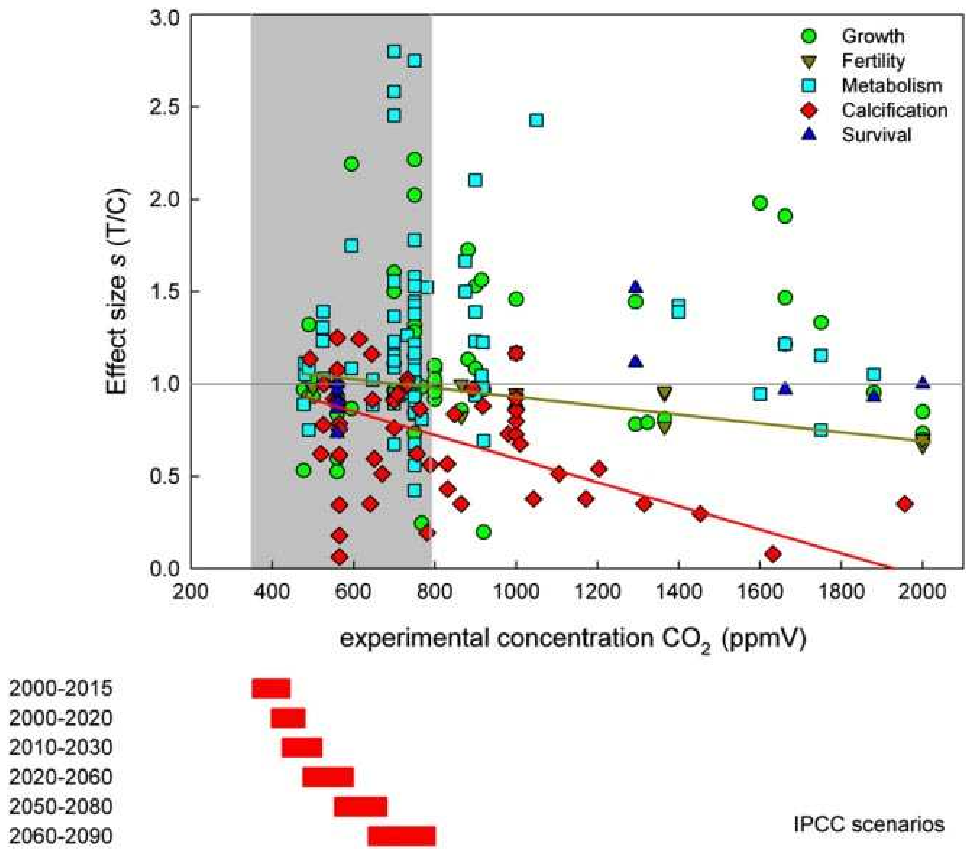

Figure 8: The relationship between the effect size, s (treatment/control), of biological responses, assessed by different processes, to experimental CO_2 concentration manipulation over the range 477–2000ppm CO_2. If s<1, then acidification has a negative impact, and if s>1 then acidification has a positive impact. The shaded area and lower part of the graph shows the future CO_2 values projected under different IPCC scenarios. Source: Hendriks et al. (2010), p. 162.

Indeed, there is now increasing evidence that the relationship between increased ocean acidification and the calcification rates of various marine organisms is complex, but importantly this is an issue of high debate. A good example is provided by Iglesias-Rodriguez et al. (2008a), a study published in the leading academic journal Science, which presented laboratory evidence that calcification and net primary production in the coccolithophore species *Emiliania huxleyi* are significantly increased by high CO_2 partial pressures - they showed that over the past 220 years there has been a 40% increase in average coccolith mass, which correlates with rising atmospheric CO_2 partial pressures. Iglesias-Rodriguez et al. (2008a) suggested that both photosynthesis and calcification increased by 100 to 150% over a CO_2 range from 280 to 750 ppm. However, this result was rigorously contested by Riebesell et al. (2008) because the result contradicts several previous studies that show ocean acidification had the opposite effect on the species (e.g. Riebesell et al., 2000; Sciandra et al., 2003; Leonardos and Geider, 2005). Nevertheless the authors justify their methodology and argue convincingly for the validity of their study (Iglesias-Rodriguez et al., 2008b). However, further to this justification, Turley (pers. comm.) reports that the study was invalid due to the age of the sample. Interestingly, a number of other studies corroborate with the results presented by Iglesias-Rodriguez et al. (2008a). Rodolfo-Metalpa et al. (2010) showed using the Mediterranean zooxanthellatemcoral *Cladocora caespitosa*, that an increase in CO_2 partial pressure in the range predicted for 2100 (around 700ppm), did not reduce its calcification rate. Wood et al. (2008) showed using the ophiuroid brittlestar *Amphiura filiformis* as a model calcifying organism, that some organisms can increase the rates of many of their biological processes in response to ocean acidification (in this case, metabolism and the ability to calcify to compensate for increased seawater acidity). However, Wood et al. (2008) showed that this came at a substantial cost (muscle wastage) and is therefore unlikely to be sustainable in the long term.

A very useful review of the inconsistency of the impact of ocean acidification on the *Emiliania huxleyi* species reported in various studies (e.g. Iglesias-Rodriguez et al., 2008a, Leonardos and Geider, 2005) is presented by Ridgwell et al. (2009). They show that different investigators have used different strains of *E. huxleyi* and that much of the incongruence between observed responses across studies could result from differing ecological adaptation (ecotypes). Additionally, the strains used in different studies were in culture for differing periods, ranging from several years to decades, and may have partially adapted after capture to the chemical conditions in the stock medium which are significantly different from sea water. Thus, the intra-species variability across experiments on *E. huxleyi* may be analogous to less controversial interspecific variability that has been reported amongst obviously different species. Ridgwell et al. (2009) argue that *E. huxleyi* should be regarded as a diverse assemblage of genotypes with highly variable calcification characteristics and ecological adaptations, which means the substantial variability in degree of calcification between genotypes suggests that future changes in genotype assemblage could be important.

A most interesting empirical study has been a survey of marine organisms surrounding volcanic vents which emit large amounts of CO_2 off the coast of Italy. Away from the vents, where normal pH values of 8.1-8.2 existed, a typical rocky shore community with abundant calcareous organisms is found; as a vent is approached, the community shifts to one lacking scleractinian corals and with significant reductions in sea urchin and coralline algal abundance. Close to vents pH values were typically 7.8–7.9 (minimum 7.4–7.5). At intermediate distances shells of the animals were soft and pliable. The mean pH decline is thus comparable to that projected for high emission scenarios in 2100 (Hall-Spencer *et al.,* 2008).

It is important to acknowledge that whilst these post-IPCC AR4 studies add to the evidence base that ocean acidification has *varied* impacts, the results still show acidification to have a negative impact on *some* organisms. Indeed, the IPCC AR4 concluded with *medium* confidence that ocean acidification would negatively effect various marine organisms, and given the results of the studies cited above, it is not possible to state with a higher degree of confidence the magnitude of the impact that ocean acidification will have on marine organisms and how resistant they will be to increased ocean acidification.

Very little research into the potential impacts of ocean acidification on fish is included in the IPCC AR4 but new research is shedding light on this area. Otoliths are aragonite structures that fish use for hearing and balance. Checkley et al. (2009) has shown that the otoliths of fish grown in water with high CO_2 were significantly larger than those of fish grown under present day CO_2 conditions. Many marine species appear to navigate towards suitable habitats using olfactory stimuli but Munday et al. (2009) showed that increased CO_2 can affect the olfactory system of larval clownfish and that the impairment of this sense may have serious consequences for fish populations. However, in a recent review of the impact of ocean acidification on fish, Legge and Tyrell (2009[1]) conclude that more research is necessary to better understand the impact of ocean acidification on this large and commercially important group of organisms.

[1] This citation has not been peer-reviewed but given that the citation refers to a literature review, we are confident in referring to the paper here.

5.5. Modelling evidence for the potential for catastrophic impacts of ocean acidification

Global scale studies published since the IPCC AR4 suggest potentially catastrophic effects of ocean acidification on global coral reefs. For instance, Cao and Caldeira (2008) showed that at a 450ppm stabilisation level, only 8% of existing coral reefs will be surrounded by water that is greater than 3.5 times saturated with respect to their skeleton materials compared to more than 98% before the industrial resolution. Veron (2008) identified carbon cycle changes in general and ocean chemistry in particular as the primary causes of the five known mass extinction events, each of which has left the globe without living reefs for at least four million years. The study concludes that the prospect of ocean acidification is potentially the most serious of all predicted outcomes of anthropogenic carbon dioxide increase and that acidification has the potential to trigger a sixth mass extinction.

Another study shows that at today's level of around 387 ppm, allowing a lag-time of 10 years for sea temperatures to respond, most reefs world-wide are committed to an irreversible decline and that the progressive onset of ocean acidification will cause reduction of coral growth and retardation of the growth of high magnesium calcite-secreting coralline algae (Veron et al., 2009). If CO_2 levels are allowed to reach 450 ppm (due to occur by 2030-2040 at the current rates), reefs will be in rapid and terminal decline from ocean acidification and other environmental impacts. The results confirm the findings of Veron (2008), that damage to shallow reef communities will become extensive with consequent reduction of biodiversity followed by extinctions and that should CO_2 levels reach 600 ppm, reefs will be eroding geological structures with populations of surviving biota restricted to refuges, with domino effects following which affect many other marine ecosystems.

5.6. Summary of new findings since the IPCC AR4

- New research supports findings from the IPCC AR4 that future changes in ocean acidification caused by emissions of CO_2 to the atmosphere are largely independent of the amounts of climate change, and that for a 3-4℃ warmer world than present, ocean pH could decline by about 0.3-0.4 from pre-industrial levels (Cao et al., 2007; Matear, 2006; Caldeira and Wickett, 2003; Bernie et al., 2010).
- New studies have shown that mitigation could reduce the magnitude of projected pH decreases relative to non-mitigation scenarios, but even with mitigation, the pH decrease still represents a significant further

acidification relative to pre-industrial levels (Mathews et al., 2009; Bernie et al., 2010).

- Post-IPCC AR4 evidence adds to the evidence-base that the response of calcifying organisms to ocean acidification is varied, with some species demonstrating a resistance or even growth under increased CO_2 whilst others decline. However some of the species that experience growth do so at the expense of muscle strength (Ries et al., 2009; Iglesias-Rodriguez et al., 2008; Hendriks et al., 2010; Rodolfo-Metalpa et al., 2010; Wood et al., 2008).
- There is increasing evidence that ocean acidification could potentially result in a mass extinction of worldwide coral species (Cao and Caldeira, 2008; Veron 2008; Veron et al., 2009). It is important to acknowledge that whilst the results of these studies suggest ocean acidification has *varied* impacts, their results still show acidification to have a negative impact on some organisms, and as such it is not possible to state with a higher degree of confidence than given by the IPCC AR4 (medium confidence) the magnitude of the impact that ocean acidification will have on marine organisms in general and how resistant they will be to increased ocean acidification.
- Research into the impact of ocean acidification on fish has grown since the IPCC AR4, with the impacts generally being shown as detrimental (Checkley et al., 2009; Munday et al., 2009; Legge and Tyrell, 2009), but there is a need to quantify the magnitude of the possible impact.

6. Ecosystems and biodiversity

6.1. Risk of extinctions

The IPCC stated 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 to 3°C above pre-industrial levels” (Fischlin et al., 2007).”

Biodiversity underpins ecosystem services to humans such as flood prevention, soil erosion 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 to the concept of *dangerous* climate change. New work such as Allesina et al. (2009) discusses how species extinctions undermine the robustness of an ecosystem's functioning even if there are no secondary extinctions, and introduces the idea of 'tipping points' as extinction rates rise.

Observational and modelling based studies continue to support the above IPCC statement. Since the IPCC 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; MacDonald et al., 2008, Colwell et al., 2008, Furgal & Prowse 2009). In many organisms, poleward expansion is observed to be slower than warm climate retreat, leading to a reduction in range (Foden et al., 2007). Elevational range shifts have been recorded for plants (Kelly & 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.

Since the IPCC 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 & Woodin, 2008, Sabatés et al., 2006; Hiddink & ter Hofstede, 2008, Perry et al., 2005). Species can also retreat to deeper cooler water (Dulvy et al., 2008).

There are increasing numbers of projections of extinction risks in the post-IPCC AR4 literature. Extensive new work projects a more holistic picture of impacts on marine systems. In addition to existing projections or observations of regional changes in net primary production or the distributions of various fish species in particular regions (Byrnes et al., 2007, Brierley & Kingsford 2009, Brander 2010), new work has now projected the global distribution of fish. Cheung et al. (2009) project that, by 2050, dramatic species turnovers of 60% of the present biodiversity will occur. Although species richness of fish in the North Sea has actually increased over the past 22 years in response to higher water temperatures (Hiddink & ter Hofstede, 2008) which might be considered a positive effect, large ecological disturbances can disrupt ecosystem services where species invasions is intense, for example in the polar regions (Cheung et al., 2009). Brander (2010) discusses how fisheries management needs to include effects of natural climate variability which causes regime shifts: this will be even more important under climate change. 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 & Ormerod, 2007, Buisson et al., 2008). Also, modelling of the changes in the distributions of 27 northern land bird species in the 21st century suggests that over two thirds of them will lose much of their climatic space by 2080 (Virkkala et al., 2008). Climate change also has the potential to greatly impact on crops - 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.

6.2. Highly vulnerable ecosystems

The IPCC AR4 found that the most vulnerable ecosystems include coral reefs, the sea-ice biome, polar ecosystems, mountain ecosystems and Mediterranean-climate ecosystems. Whilst evidence of the sensitivity of these ecosystems continues to accumulate, a major new finding since the IPCC AR4 is that tropical species are now also considered at high risk, as well as cold-blooded species in desert regions. The high diversity in the tropics means that this represents an increase in the projected impacts on biodiversity overall.

6.2.1. Tropical ecosystems

New work based on three different methodologies has suggested that species in the *tropics* are more vulnerable (Wright et al., 2009, Deutsch et al., 2009), because they already live close to their thermal tolerance. Wright et al. (2009) compare distances to cool refuges, finding that 20% of tropical mammal species would have to travel over 1000km to a cool refuge under a moderate climate change scenario compared with only 4% of small-ranged extratropical mammal species. Deutsch et al. (2009) show how due to physiological constraints tropical insect abundance may decline rapidly for quite small climate changes, whereas in temperate regions, insect abundance might be expected to increase with warming. A new approach using combined behavioural and biophysical modelling has also drawn attention to the high risks to terrestrial *ectotherms* such as insects, frogs, lizards and turtles in tropical and desert regions such as Australia (Kearney et al., 2009).

6.2.2. Coral reef systems

The IPCC AR4 concluded that reef-building corals are under stress on many coastlines and that reefs have deteriorated as a result of a combination of anthropogenic impacts such as overfishing and pollution from adjacent land masses, together with an increased frequency and severity of bleaching associated with rises of sea surface temperature (SST) of short duration above summer maxima due to climate change (Nicholls et al., 2007). The IPCC AR4 also suggests that an intensification of tropical storms could have devastating consequences on the reefs themselves. There is now increasing evidence to support this. For example, Crabbe (2008) set out to test the hypothesis that hurricanes and tropical storms limit the recruitment and subsequent survival of massive non-branching corals on the barrier reef off the coast of Belize in the Gulf of Honduras. There were significantly more non-branching massive corals recruited in non-hurricane years (mean 7.7) than in hurricane years (mean 3.8). The study concludes that hurricanes and severe storms limited the recruitment and survival of massive non-branching corals and marine park managers may need to assist coral recruitment in years where there are hurricanes or severe storms.

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 detailed review of the impact of ocean acidification on corals is provided in a separate section of this review. Generally, 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 International Union for Conservation of Nature (IUCN) red list criteria (Carpenter et al., 2008). Anthony et al. (2008) assess the relative sensitivity of different coral genera to increasing temperatures and acidification respectively. 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 450ppm, due to a combination of impacts of rising sea surface temperatures and acidification, leading to vastly reduced biodiversity and loss of coral-associated fish and invertebrates, whilst levels of 500ppm would reduce coral reefs to crumbling frameworks with very few corals.

Global climate model results imply that thermal thresholds will be exceeded more frequently with the consequence that bleaching will recur more often than reefs can sustain, perhaps almost annually on some reefs in the next few decades (Hoegh-Guldberg, 2005). The IPCC AR4 acknowledges that adaptation or acclimatisation might result in an increase in the threshold temperature at which bleaching occurs but the extent to which the thermal threshold could increase with warming of more than a couple of degrees remains very uncertain (e.g. Hughes, 2003). Indeed, the ability of corals to respond to warming temperatures by adapting or acclimatising to changing conditions has been a central topic of debate for over a decade (Baker et al., 2008). For example, a study by Berkelmans (2009) indicates that coral bleaching temperature thresholds on some reefs in the central Great Barrier Reef have increased over time, and suggests that acclimatisation is the most likely mechanism for these changes - however, whilst moving one species to another part of a reef resulted in acclimatisation, when the same species was moved to another part of a the reef, it failed to acclimatise. Baker et al. (2008) discuss the potential mechanisms by which corals might acclimatise to warmer temperatures, but this is still speculative. The suggestion that reefs might acclimatise is partly based on their partial recovery following bleaching events. Importantly, however, recovery after bleaching is not a *full recovery* and leads to a changed ecosystem (McClanahan, 2000) and/or reduced diversity (Lambo and Ormond, 2006). More recently, Veron et al. (2009) showed that reefs are already committed to an irreversible decline at today's CO_2 concentrations of 387ppm with bleaching becoming annual once ocean temperatures have responded fully to this concentration. At higher concentrations of 550-560 ppm, ocean acidification would lead to aragonite saturation levels incompatible with coral growth throughout the world, except possibly in a few parts of the Pacific. At intermediate concentrations of 450ppm, a combination of effects of acidification and sea surface temperature rise is projected to lead to the widespread decline of reef-building corals and the thousands of species on which they depend. They propose that a limit of 350 ppm CO_2 is required for the protection of coral reef ecosystems. This is based on the empirical relationship between observed CO_2 concentrations and the frequency and effects of bleaching events related to elevated sea surface temperature rise worldwide to date. Furthermore, the increasing frequency of bleaching events worldwide, and the mortality that often accompanies them, are often seen as compelling *prima facie* evidence that corals are unable to adapt or acclimatize quickly enough to compensate for climate changes (Jones, 2008). Rising sea levels and increasing storm intensity are likely to exacerbate these impacts during the 21st century (Veron et al., 2009).

6.2.3. The southern Mediterranean

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; 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). In particular the central and southern portions of the Iberian, Italian, Hellenic and Turkish peninsulas, parts of southeastern Europe, Corsica, Sardinia and Sicily may become dry and arid (Beniston et al., 2007; Gao and Giorgi, 2008; Metzer et al., 2008). Observational, modelling and experimental studies indicate that mountain conifer species, butterflies, amphibians and temperate trees are particularly at risk in this area (Wilson et al., 2007; Benito Garzón et al., 2008).

6.2.4. The tundra and Arctic/Antarctic

The tundra and Arctic/Antarctic are still considered the most vulnerable to climate change, with large potential losses of tundra (Tape et al., 2006; Wolf et al., 2008; Furgal and Prowse, 2009; Graae et al., 2009) and numerous examples of trophic (i.e. predator-prey) mismatch (Post et al., 2009). 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. Sea-ice-dependent species such as polar bears, walrus, seals and birds are declining (Clarke et al., 2007, Post et al., 2009) whilst lemming, musk ox and reindeer, have shown dramatic population crashes following ice-crusting after increasingly frequent freeze-thaw events (Callaghan et al., 2007). This may have serious negative impacts on higher trophic levels, particularly 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 begin to impose spatial separations between energy requirements and food availability (Moline et al., 2008). Vole and lemming cycles are no longer observed in some areas which have cascading effects on their predators such as snowy owls, skuas, ermines and weasels (Callaghan et al., 2007). Rising sea surface temperatures are reducing abundance of cold-adapted marine mammals like the narwhal, beluga and polar bear, mediated via changes in prey distribution and abundance (Simmonds & Isaac, 2007). Polar bears are projected to lose 68% of their summer habitat under a multi-model mean projection based on the A1B scenario in the 2090s (Durner et al., 2009); however, as the authors note, with sea ice declining faster than model projections this is likely to occur much earlier than the 2090s.

6.2.5. Mountain regions

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; Bravo et al., 2008; Karmalkar 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 the most vulnerable species being endemics (Meine, 2007), and also high elevation and poorly dispersing species (Engler et al., 2009). However, Willis and Bhagwat (2009) suggest that extinction rates may be less than previously projected in mountainous regions, because the varied topography provides small refugia in an otherwise unsuitable climate. They also mention that rates may be underestimated in flatlands. 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 (Wang et al., 2008), sequester large amounts of carbon in their soils, which are vulnerable to release by climate warming (Dise, 2009).

6.3. Increased post-IPCC AR4 evidence of the effects of changes in climate variability

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). Drought will often also interact negatively with other ecological processes (St. Clair et al., 2008) and is therefore 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 (Wrona, 2006; EEA, 2008) causing declines in migrating fish.

6.4. Effects of climate change on the spread of invasive species, pests and diseases.

There is increased post-IPCC AR4 evidence of experienced and projected effects of climate-change facilitated spread of invasive species and of pests and diseases. Rare and invasive species have been 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 and Olden (2008) make projections of invasive fish species as climate warms. Also, Raffa et al. (2008) attribute some of the massive outbreaks of tree-killing forest insects which have been observed particularly in boreal forests to climate change.

6.5. Increasing evidence of changes in ecosystem composition and function

There is increasing post-IPCC AR4 evidence of changes in ecosystem composition and function (e.g., nutrient cycling, productivity, and community dynamics; Bertin, 2008; Olofsson et al., 2009). In particular regime shifts have already occurred in several marine food webs (Byrnes et al., 2007; Alheit et al., 2009) as a result of (observed) changes in sea surface temperature and (separately) of natural climate variability, showing how future climate change will analogously affect species composition and hence ecosystem functioning and potentially biogeochemical cycles.

Changes in species composition of communities has been observed in several locations in widely different ecosystem types (Blaum et al., 2007; Pauli et al., 2007; Le Roux and McGeoch, 2008; Moritz et al., 2008; Vittoz et al., 2009). In European farmland bird communities, species with northerly ranges have declined, and long-distance migratory birds have also all declined. Wetland birds and species with southerly ranges have increased over time as climate has changed (Lemoine et al., 2007a, b). As climate has changed, migrant butterflies have increased in parts of the UK (Sparks et al., 2007), but decreased in the Mediterranean (Wilson et al., 2007). Altered composition and abundance of macro-invertebrates (Burgmer et al., 2007; Durance and Ormerod, 2007) and fish assemblages has been clearly observed over the last 15-25 years (Daufresne and Boet, 2007). Whilst varying gains and losses in the abundance of certain species and overall diversity occur, local extinctions of high priority species like salmon have been observed (Brander, 2007). 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 (Kellomaki et al., 2008, Kurz et al., 2008).

6.6. Changes in phenology, abundance, morphology, and reproduction

There is increasing post-IPCC AR4 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 feedbacks between land and atmosphere and atmospheric chemistry as well as albedo (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 arrival of migrant birds (Parmesan, 2007). Temporal mismatches may occur among mutualistic partners (Hegland et al., 2009). Plants and their pollinators may be decoupled (Memmott et al., 2007). There is new evidence of observed impacts of heat stress in mammals, and further projections of future impacts through consideration of physiological constraints of the mammalian reproductive system (Vors and Boyce, 2009; Hansen, 2009).

New phenological changes have been seen in trees, plants and fungi (Gange et al., 2007; Kauserud et al., 2008; Pudas et al., 2008; Moreno-Rueda et al., 2009); in amphibians (Carroll et al., 2009; Kusano and Inoue, 2009); and in the spring migration of birds (Both and Marvelde, 2007; Gordo, 2007; Rubolini et al., 2007; van Buskirk et al., 2009). Changes are stronger at higher northern latitudes (Colwell et al., 2008). As shown in the IPCC 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). Together with observed changes in marine net primary productivity (Behrenfeld et al., 2006), there will likely be a cascading effect on the structure of marine food webs e.g. via the altered timing and abundance of krill in the Southern Oceans (Frederikson et al., 2006; Koeller et al., 2009) including 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).

6.7. Climate change impact on forest ecosystems

6.7.1. Fire activity

Since the IPCC 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 projected doubling of area burned along with a 34-50% increase in fire occurrence in parts of boreal forest by the end of this century (Girardin et al., 2008; Flannigan et al., 2009), and an 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) and within two decades fire management agencies may not be able to maintain their current levels of effectiveness (Flannigan et al., 2009). A completely new approach to projecting future fire occurrence, ‘global pyrogeography’ has been developed which is capable of simulating current fire distribution and produces results consistent with the above projections (Krawchuk et al., 2009). It highlights that whilst fire is projected to increase dramatically in boreal regions, it is projected to decrease in other regions. Some of the projected decrease is due to climate-change induced vegetation changes such as desertification (and hence loss of material to burn) in some regions, whilst some is due to genuinely lower risks in, for example, tropical

Africa. An important caveat of all the studies is that they do not include the increase in fire due to pest outbreaks in forest, which could be a major driver of fire. Wherever fire regime changes occur, they are likely to alter at a rate that exceeds the natural adaptive capacity of many species. There is a need to include such effects in studies of impacts of climate change on biodiversity, since each species is naturally adapted to a particular fire regime within an ecosystem.

6.7.2. Forests and carbon

Since the IPCC 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 (Phillips et al., 2008; 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. Net primary production is modelled to have already increased (Del Grosso et al., 2008) and growing seasons and leaf area indices are generally projected to increase under most climate model scenarios over most of the globe for small amount of climate change. Whilst additional carbon may be sequestered by vegetation (Bronson et al., 2009), albedo may decrease, so the overall effects are unclear. However, large amounts of climate change feedback processes noted in the IPCC AR4 are expected to kick in which would slowly convert forest to grasslands.

6.7.3. Feedback processes

A large number of studies have continued to look at feedback processes operating in forests, for regions including the Amazon, temperate regions, the Arctic, grasslands, and marine environments. Below we review each region in turn.

Since the IPCC AR4, Malhi et al. (2009) have shown how most of 19 climate models examined underestimated precipitation in the Amazon region. When corrected for their tendency to underestimate current rainfall, the models still tended to demonstrate a reduction in dry season rainfall, which is widely expected to lead to dieback. 18% to 70% of the forest could be lost, or possibly be converted to a seasonal forest, depending on the climate model chosen, increasing its vulnerability to fire (Salazar et al., 2007; Cook and Vizy, 2008; Malhi et al., 2008; Huntingford et al., 2008; Betts et al., 2008) and leading to a positive feedback on climate. Reducing deforestation would reduce the risk of fire. Lapola et al. (2009) used a dynamic global vegetation model to show how CO_2 fertilisation effects might buffer the forest against drying: whilst enhanced CO_2 reduces water requirements, the CO_2 fertilisation effect itself was found only to occur in the first 1-2 years of tree growth in the Duke FACE experiments. There are however, already observations that enhanced CO_2 is increasing the prevalence of vines in tropical forests which has a deleterious effect on the trees, shortening their lifespan. Hence, this buffering effect on the trees is not likely to be seen in practise. Adams et al. (2009) identify observed *increased* Amazon die-off of tree species in response to the combination of increased temperatures and increased drought frequency. A substantial degradation of vegetation type in the tropics generally (e.g. increase of drought tolerant deciduous tree coverage at the expense of evergreen trees), has been identified especially in portions of west and southern Africa and South America (Alo and Wang, 2008; Wolf et al., 2008). A recent analysis of the 2005 Amazon drought (Phillips et al., 2009) identified that drought stricken areas have lost forest biomass, confirming through observations what had previously been a theoretical process. Using one model, Jones et al. (2009) found a 2°C limit for an onset of significant loss of forest cover in Amazonia, using an analysis of long-term committed changes rather than static simulations. This analysis takes into account the dynamics of changes in terrestrial vegetation, which mean that ecosystems can be committed to change long before any changes are actually observed.

For temperate regions, whilst the autumn 2006 to winter 2007 record warm period followed by an exceptionally warm spring in Europe, led to higher net carbon uptake (Delpierre et al., 2009) a subsequent hot summer cancelled this out (Granier et al., 2007; Reichstein et al., 2007; Vetter et al., 2008). Temperate forest soil organic carbon may be released to the atmosphere as climate changes, depending on the type of forest (Rasmussen 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). Raffa et al. (2008) note the widespread death of many tree species in multiple forest types that has affected over 10 million hectares since 1997, and a recent review collated more than 150 references that document 88 examples of forest mortality worldwide that were driven by climatic water/heat stress since 1970 (Allen et al. 2010). Allen et al. (2010)

suggests that the observed events form an emerging global pattern which may be at least partly attributed to climate change. It is suggested that future increase in drought is likely to exacerbate this emerging global trend of forest decline. In combination with afore-mentioned climate-change induced increases in tree-killing forest insects, and increases in fire, it is clear that projections of climate change impacts on forests are now considerably larger than described in the IPCC AR4.

In the Arctic large reductions in carbon storage and fisheries services from aquatic ecosystems are expected (Wrona, 2006).

New studies have looked at the feedback processes associated with the impact of climate change on grasslands, 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 (Lucht et al., 2006).

Warming may enhance ocean upwelling of nutrient rich waters along coastal areas which may positively or negatively affect ecosystems (Harley et al., 2006, Svensson et al., 2005). Conversely, increased sea temperatures may inhibit upwelling and lead to dissolved oxygen deficiencies (Pörtner & Knust, 2007). The overall result may be a reduction in upwelling and reduced productivity (Harley et al., 2006). Interactions between these two competing effects make predictions regarding increases or decreases in coastal productivity difficult to ascertain.

6.8. Combined climate change impacts on ecosystems

Since the IPCC AR4, new work has developed which simulates the impacts of *combinations* of climate changes and their impacts upon ecosystems, generally showing larger impacts than previously. For example, Adams et al. (2009) identify *increased* die-off of tree species in response to the combination of increased temperatures and increased drought frequency; whilst Mooij et al. (2009) find that climate-induced shifts in key aquatic species can reduce the resilience of the process which maintains lakes in a clear state (known as the macrophyte dominated state) – (Eutrophication has already converted many lakes from their clear state to their turbid state, leading to declines in biodiversity and ecosystem functioning).

6.9. Summary of new findings since the IPCC AR4

- Tropical ecosystems have been added to the list of those most vulnerable, alongside polar, mountain, coral reefs, and Mediterranean systems.
- There are new projections for impacts in marine systems, showing dramatic turnovers of 60% of fish assemblages under climate change, which could disrupt marine ecosystem functioning.
- New work is emerging on the consequences of synergistic impact of fire, drought, pests, and direct climate change on forests, leading to the projection of more severe impacts of climate change on forests than in IPCC AR4. Other work is emerging on synergistic impacts in freshwater systems, also showing increased impacts.
- One third of coral reef species are already at risk of extinction and a limit of 350ppm for CO_2 concentrations in the atmosphere has been proposed to safeguard reefs. Bleaching will become annual with today's concentration of CO_2 of 387 ppm.
- There is increased evidence of observed climate change impacts on reproduction in wild animals, and upon ecosystem composition and function.
- There is evidence that observed changes in climate variability are impacting on ecosystems.
- There is increasing evidence of experienced and projected effects of climate-change facilitated spread of pests and diseases.
- Old growth forests have been found to sequester carbon rather than being carbon neutral, which increases the need to ensure that mechanisms to avoid deforestation include pristine old growth forest. Tropical forests have been found to be increasing the amount of carbon which they sequester annually.
- There is increasing evidence from observations and models to support the statement made in the IPCC AR4 that 20-30% of plant and animal species are at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3°C above pre-industrial levels.
- There is greater confidence in the modelling projections for drying in the Amazon under climate change, and observations of the response

to a recent drought confirm this. A 2°C limit has been proposed to safeguard the Amazon from commitment to such a transformation.

7. Water resources and desertification

7.1. Global water resources and climate modelling uncertainty

The IPCC AR4 concludes that globally, climate change will have an overall net negative impact on water resources (high confidence) and that the beneficial impacts of increased annual runoff in other areas will be tempered by the negative effects of increased precipitation variability and seasonal runoff shifts on water (Kundzewicz et al., 2007). The most severe impacts are projected for arid and semi-arid areas, e.g. the Mediterranean basin, western USA, southern Africa, and north-eastern Brazil. Since the publication of the IPCC 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 taken a global perspective and/or address the issue of uncertainty in the projections. Somewhat surprisingly, there are only a few studies that have approached the issue of climate change impacts on water resources with a global perspective.

Rockstrom et al. (2009) used an older climate model (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 (typical of a world in which global mean temperature is just below 2°C warmer from present), 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. However, it should be noted that the above projections are based solely upon climate simulations from a single climate model. The projections are likely to be different if the climate scenarios are taken from different climate models. Indeed, a comparison of different sources of uncertainty in flood statistics in two UK catchments by Kay et al. (2006[1]) led to the conclusion that climate model uncertainty is the largest source of uncertainty, followed by the emissions scenarios, and finally hydrological modelling uncertainty. Despite this few studies published since the IPCC AR4 have addressed the role of climate model uncertainty. This is an important research gap because as shown by Meehl et al. (2007), the agreement between climate models with respect to projected changes of temperature is much higher than with respect to changes in precipitation. An exception is provided by Preston and Jones (2008), a study which attempted to characterise generalized 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 12 IPCC 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.

In a similar manner, the Natural Environment Research Council (NERC) QUEST-GSI project is presently assessing the impact of climate change scenarios from 21 IPCC AR4 climate models on global runoff and water resources for several degrees of mean global temperature change. Preliminary results show that hydrological simulations forced by climate change patterns from 21 climate models included in the IPCC AR4 show substantial decreases of around 25% in average annual runoff for the Mediterranean and central South America for a global mean temperature rise of 2℃ relative to present, and around 40% for a 4℃ rise (Gosling et al., 2010a; see **Figure 9**). Importantly, there is high agreement across the 21 climate change projections from different climate models regarding the simulated changes in runoff across the Mediterranean, but there is less agreement with the projected changes for South America. The same study shows that the uncertainty range due to climate modelling uncertainty associated with the percentage of the global population that experiences an increase in water scarcity in a 2℃ warmer world in the 2080s under the SRES A1B population scenario is 4-29% (see **Figure 10**).

[1] This citation has not been peer-reviewed.

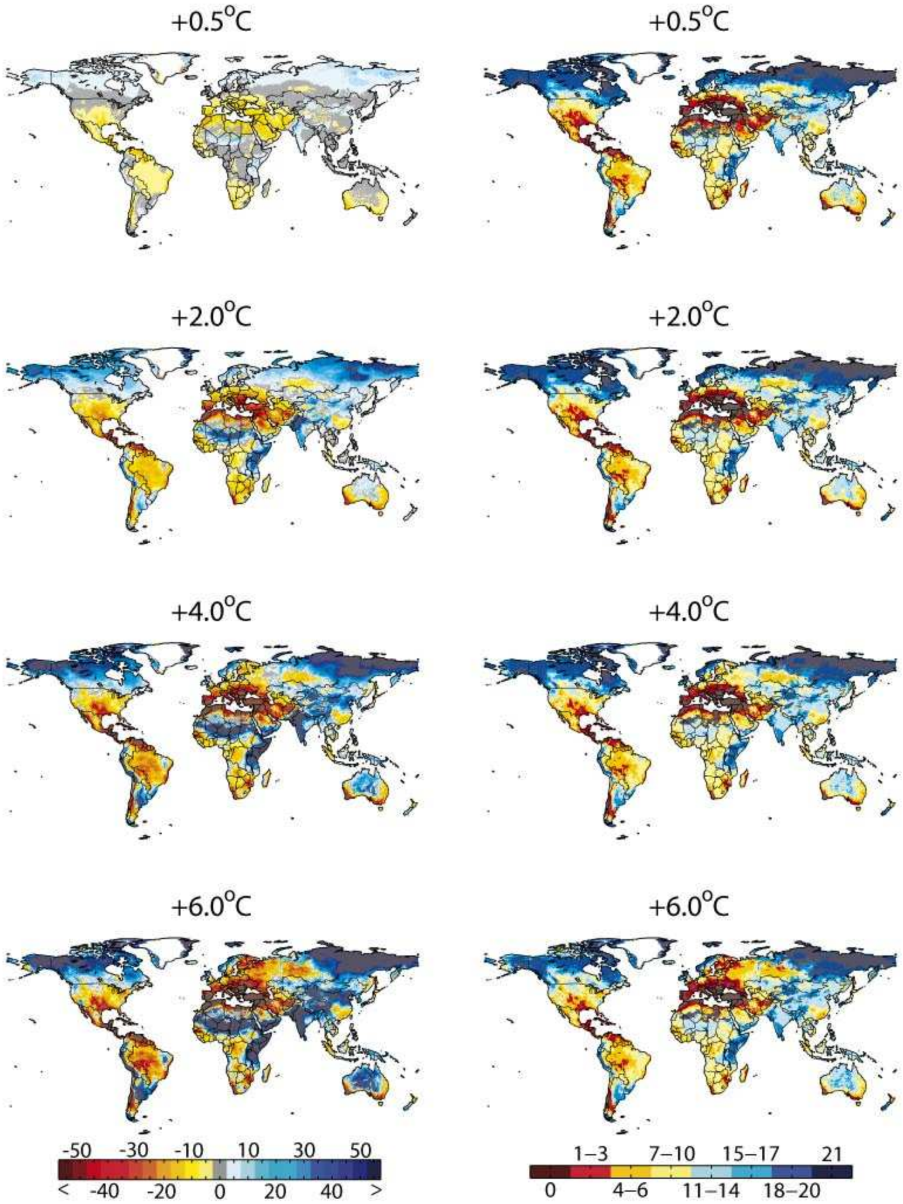

Figure 9: The left panels show the ensemble-mean of percentage change in mean annual runoff relative to present when the Mac-PDM.09 global hydrological model is forced by climate projections from the patterns of climate change from 21 climate models for 0.5℃ , 2.0℃, 4.0℃ and 6.0℃ prescribed increases in global-mean temperature from present. The right panels show the number of climate models that result in an increase in mean annual runoff for the same prescribed increases in global-mean temperature. Source: Gosling et al. (2010a).

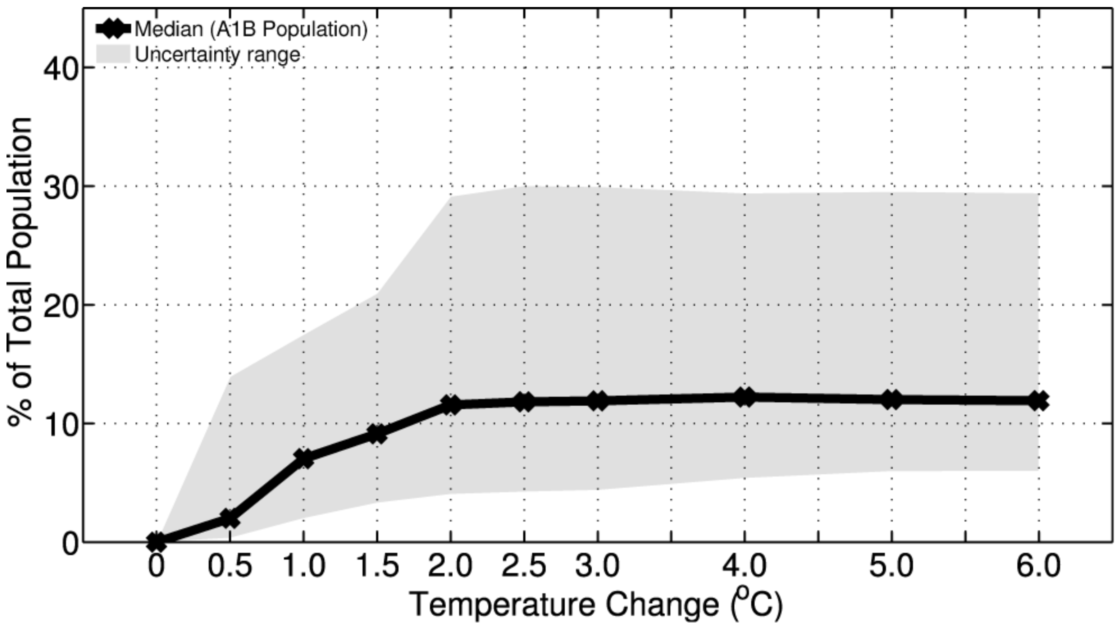

Figure 10: Percentage of the global total population that might experience an increase in water resources stresses with climate change for different global-mean temperature rises relative to present (1961-1990). For each temperature, population is assumed to follow the SRES A1B scenario and the year to be 2080. The uncertainty range reflects the range in projections from using climate projections from 21 different climate models included in the IPCC AR4. The solid line shows the median value across the 21 models. Source: Gosling et al. (2010a).

Whilst the results presented by Preston and Jones (2008) and Gosling et al. (2010a) do not necessarily show a change in the risk of climate change impact on water resources (e.g. Australia and the Mediterranean are also highlighted as 'hotspots' in the IPCC AR4), they do represent an important move towards a more complete treatment of climate modelling uncertainty in water resources modelling, which is an important development since the IPCC AR4, where the maximum number of climate models included in a cited water resources impact study was six (Arnell, 2004). A typical example of the kind of projections that are now becoming possible is presented in **Figure 10** which shows the range of the percentage of the global population that might experience an increase in water resources stress with climate change for different global-mean temperature rises relative to present (1961-1990) based upon climate projections from 21 climate models included in the IPCC AR4.

Other new studies suggest no change in risk from the IPCC AR4. Hayashi et al. (2010) estimated that in 2050 under the SRES B2 population scenario, the global total number of people living in water-stressed basins will be approximately threefold compared with that of the late twentieth century due to population growth, in the absence of climate change, based upon climate projections from a single climate model. This is similar to the results found by Arnell (2004) and presented in the IPCC AR4 (Kundzewicz et al., 2007) for the year 2055 under the same population scenario. Furthermore, the simulations with climate change from Hayashi et al. (2010) support the findings of the IPCC AR4 that the number of people living under decreased water stress will be higher than those for whom it increases. For instance, in the year 2100 under the B2 emissions and population scenario, Hayashi et al. (2010) estimated the number of people who undergo increasing water stress due to climate change to be 1.2 billion, while the number of people who will undergo decreasing water stress was estimated as 3.0 billion. Based upon climate projections from six climate models and the same population and emissions scenario, Arnell (2004) estimated the values to be in the ranges of 0.670–1.538 and 1.788–3.138 respectively. The hydrological model that was applied by Arnell (2004) in the IPCC AR4 has recently been updated by Gosling and Arnell (2010) and used in the EU-funded ADAM project to make further water resources simulations under climate change scenarios - results presented by Arnell et al. (2010b) for simulated increases in water resources stress in 2050 based upon 4 climate models and a business as usual scenario (typical of a 2℃ warmer world than present) give a range of 0.570 – 1.960 billion, which includes the estimates presented by Hayashi et al. (2010) and that is slightly wider than the range presented by Arnell (2004). Based upon new research, there appears to be no evidence to suggest a change in the risk from the impacts presented in the IPCC AR4 of global water resources stresses due to climate change.

A new approach to considering the role of climate modelling uncertainty is to use climate projections from perturbed parameter ensembles. Work in progress at the Met Office Hadley Centre and Walker Institute, University of Reading is currently exploring this. This research is novel because all previous assessments of the role of climate model uncertainty have applied climate projections from the IPCC AR4 models, whereas the application of a perturbed parameter ensemble allows for a more systematic consideration of climate modelling uncertainty.

7.2. Benefits of mitigation

Another important post-IPCC AR4 development is the consideration of the potential ‘benefits’ that certain mitigation policy scenarios might have on water scarcity. No published studies which have explicitly compared impacts under reference and policy scenarios are included in the IPCC AR4, but new research is addressing this. A study by 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 United Nations Food and Agriculture Organization (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. Work being carried out under the AVOID programme, funded by the UK Department of Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (Defra), is assessing global climate change impacts for several sectors associated with a set of policy scenarios with different emissions peaks, rates of reduction and emissions floors. For instance, Arnell et al. (2010a[1]) shows that climate change has the potential to increase water resources stresses for many millions of people but that the climate policies evaluated reduce the effects of climate change, with the earlier the peak in emissions, the greater the reduction. There is, however, considerable uncertainty in the numbers of people adversely affected by climate change and “saved” by climate policy, largely due to differences in projected changes in precipitation between the 21 different climate change patterns considered. For example, by 2100 policies which peak emissions in 2016 avoid between 20 and 55% of the adverse effects of climate change, with the range largely due to differences in projected change in rainfall (and hence water resources) in southern Asia. The effect of uncertainty due to differences between climate models is larger than uncertainty due to either uncertainty in change in temperature for a given emissions scenario, or uncertainty in future socio-economic characteristics. Similar to the results presented by Fischer et al. (2007), Arnell et al. (2010a[1])

[1] This paper has not yet been peer-reviewed but the hydrological model applied in the paper has been described and validated by Gosling and Arnell (2010) and applied in Gosling et al., (2010), so this reference can be considered robust. The application of climate change mitigation scenarios in this manner is also sparse in the literature, so the inclusion of this citation provides a useful addition.

concluded that whilst mitigation policy reduced the magnitude of the impact of climate change on water resources, it does not eliminate it. A similar study presented by Arnell et al. (2010b) for the ADAM project, presents the same conclusion based upon water resources projections using climate simulations from 4 climate models and scenarios that lead to a 2℃ and 4℃ warmer world than present respectively. Interestingly, in stark contrast to the findings of Fischer et al. *(*2007) and Arnell et al. (2010a,b), Hayashi et al. (2010) found that global CO_2 emission reductions will *increase* the number of people who undergo increasing water stress due to climate change, relative to present. Based upon climate projection patterns from a single climate model (MIROC 3.2 hires), they showed that globally at the year 2100, with CO_2 stabilisation occurring at 650ppm, around 1.2 billion people experience an increase in water stress due to climate change; at 450ppm stabilisation it is around 1.7 bullion. Hayashi et al. (2010) give no explanation for why water stress increases with reduced CO_2 and the result is somewhat surprising given, (1) that their reference scenario simulations (SRES B2) give similar estimates to those presented by Arnell (2004), and, (2) Arnell et al. (2010a,b) simulated water resources stress under mitigation scenarios using a very similar hydrological model and water resources model to that used in Arnell (2004).

7.3. Desertification

The IPCC AR4 projected that drought-affected areas are likely to increase in extent in the future. Widespread decreases in precipitation were projected for summer in most northern mid-latitudes, except for eastern Asia, and the risk of summer drought was thought likely to increase in central Europe, the Mediterranean area, and southern areas of Australia. In particular the IPCC AR4 projected that the percentage cover of land experiencing extreme drought at any one time would rise from 1% at present-day to 30% by the end of the century under an SRES A2 scenario.

Since the IPCC AR4, Sheffield and Wood (2008) projected future global drought in the 21st century using a suite of 8 climate models for the A2, A1B and B2 emission scenarios. A global decrease in soil moisture was found with regional hotspots in the Mediterranean, West Africa, central Asia, Central America, and mid-latitude North American regions. However, significant changes were not seen to occur for several decades, except for the Mediterranean region. In a global analysis using a single climate model only, Hirabayashi et al. (2008) found very significant increases in hydrological drought over North and South America, central and southern Africa, the

Middle East, central and western Australia and Indochina. Similarly, Sillman and Roeckner (2008) project significant increases in consecutive dry days in Mediterranean countries, California, north Mexico, Mauritania, South Africa and Australia, using another climate model. Both studies examined an SRES A1B scenario in the 2080s.

Planton et al. (2009) examined global outputs of six of the climate models used in IPCC AR4 and noted that the change in the maximum number of consecutive dry days is fairly consistent between models in the Mediterranean, whereas in other regions, such as the Sahel, the changes are inconsistent, even in direction. Recent advances in climate science point to the global oceans, specifically the warming of tropical oceans, as the cause of recent continental scale change in the climate of the African Sahel. However, it is still not known whether climate change will exacerbate this desertification or cause a re-greening.

Since the IPCC AR4, Costa and Soares (2009) have identified pronounced observed trends in indices of aridity in Southern Portugal between1955-1999 showing the area is vulnerable to drought and desertification. Studies have continued to project enhanced seasonal changes in precipitation across Europe, and increased frequency of long duration events (Blenkinsop and Fowler, 2007a, b; Beniston et al., 2007; Gao and Giorgi, 2008; Sheffield and Wood, 2008). A critical risk area for drought in south and south-eastern Europe has now been identified (Lehner et al., 2006; Weiss et al., 2007; Planton et al., 2008; Warren et al., 2010[1]). Under an A1B scenario in the 2070s, Lehner et al. (2006) project the rate of return of the 100-year drought to shrink to 40 years, or in extreme cases 10 years, over Portugal, the Mediterranean countries, Hungary, Bulgaria, Romania, Moldova, Ukraine, and south Russia. Weiss et al. (2009) similarly estimate 10-fold reductions in return rates of the100-year drought in the 2070s under an SRES A2 scenario. Frei et al. (2006) and Warren et al. (2010[1]) both identity a north-south divide in Europe with decreasing return periods of drought events seen in the Mediterranean region, mainly in the summer, and increased wetness in northern Europe particularly Scandinavia. These findings are generally consistent across studies which address meteorological drought or hydrological drought, which use various different drought indicators, or various

[1] This paper is under review at Climate Research as of November 2010.

different climate model outputs. Warren et al. (2010[1]) shows how the risks of Mediterranean drought are dramatically reduced by stringent mitigation action.

The Commonwealth Scientific and Research Organization (CSIRO) and Australian Bureau of Meteorology (BoM) (2007) project over 20% more drought months over most of Australia by 2030, and over 40% and 80% more droughts by 2030 and 2070 respectively in Eastern Australia and south-western Australia respectively, using two climate models and the SRES A2 scenario.

The picture in Asia appears highly variable and less clear. Kim and Byun (2009) projected reductions in drought frequency and duration by the end of the century in much of Asia using daily precipitation data from 15 climate models under the A1B scenario. However, in some areas the frequency of extreme drought events was projected to rise even though the total number of drought events is projected to decrease. However in north-west Asia increased drought frequency, intensity and duration were projected. Many studies emphasise the combined role of climate change and local human activity in desertification, especially in China. However, Wang et al. (2008) emphasises correlations between desertification and climatic change; whilst Yang (2009) identifies recent *reductions* in desertification in parts of China. Wang et al. (2009) project either decreased desertification in most of western China by 2039, but increased desertification thereafter, or continually increasing desertification depending on the climate model used. It is considered that this would lead to decreased livestock and grain yields possibly threatening China's food security.

7.4. Summary of new findings since the IPCC AR4

- The IPCC AR4 stated that 0.670-1.538 billion people might be affected by increased water scarcity due to climate change in a 2°C warmer world.
- New results suggest this range might be slightly wider at 0.570 – 1.960 billion people and recent studies do not suggest a major change in the risk of climate change on water resources, but they do represent a move towards a better representation of climate modelling uncertainty in water resources modelling (Preston and Jones, 2008; Gosling et al., 2010a; Hayashi et al., 2010).
- Furthermore, a novel approach to considering the role of climate modelling uncertainty is to use climate projections from perturbed

parameter ensembles, which work in progress at the Met Office Hadley Centre and Walker Institute, University of Reading is currently exploring.

- Preliminary results show that hydrological simulations forced by climate change patterns from 21 climate models included in the IPCC AR4 show substantial decreases of around 25% in average annual runoff for the Mediterranean and central South America for a global mean temperature rise of 2°C relative to present, and around 40% for a 4°C rise (Gosling et al., 2010a). Importantly, there is high agreement across the 21 climate change projections from different climate models regarding the simulated changes in runoff across the Mediterranean, but there is less agreement with the projected changes for South America.
- An important post-IPCC AR4 development, which has policy relevance, has been the exploration of the potential benefits of mitigation for global water resources stresses. Three studies suggest that mitigation could lower, but not eliminate, the impact of climate change on water resources (Fischer et al., 2007; Arnell et al., 2010a, b). A different study suggests the opposite (Hayashi et al., 2010), but this was based upon projections from a single climate model, whereas the other studies used projections from multiple climate models to account for climate modelling uncertainty.
- Observations and model projections continue to be consistent with the projections for increased drought that were presented in the IPCC AR4, but more detail is now available.
- New knowledge highlights a critical risk area for drought in south and south-eastern Europe under climate change. This risk can be greatly reduced by mitigation. Other areas at risk of drought include Australia, west Africa, north-west Asia, and parts of the Americas and Africa. Desertification is mentioned as a particular risk in the Mediterranean, Australia, and parts of Africa.

8. Agriculture and food security

8.1. Benefits of mitigation

The IPCC AR4 briefly highlighted the potential benefits that stabilisation of atmospheric CO_2 could have on regional and global crop production. For instance, Tubiello and Fischer (2007) showed that compared to the impacts of climate change on crop production by 2100 under business-as-usual scenarios, the impacts were significantly reduced (production losses cut by 70% to 100%) under a 550ppm stabilisation scenario. In the first decades of this century and possibly up to 2050, some regions may be worse off with mitigation than without, due to lower CO_2 levels and thus reduced stimulation of crop yields. Research into potential benefits of mitigation policy has expanded since the IPCC AR4. A new study has demonstrated the potential health benefits that might be accrued by limiting livestock production as a means of reducing global emissions. With use of the UK and Sao Paulo (Brazil) as case studies, Friel et al. (2009) considered potential strategies for the agricultural sector to meet the target recommended by the UK Committee on Climate Change (CCC) to reduce UK emissions in 2050 to 80% below 1990 levels, which could require a 50% reduction by 2030. Agricultural food production and land use contribute to greenhouse-gas emissions worldwide and around 80% of agricultural emissions arise from the livestock sector. Livestock products provide large amounts of saturated fat, which is a known risk factor for cardiovascular disease. The study identified that a combination of agricultural technological improvements and a 30% reduction in livestock production would be needed to meet the CCC target. Friel et al. (2009) modelled the potential benefits of reduced consumption of livestock products on the burden of ischaemic heart disease and showed that the disease burden would decrease by about 15% in the UK and 16% in Sao Paulo. Whilst the strategy posed likely health benefits, such a strategy will probably encounter cultural, political, and commercial resistance, and face technical challenges.

A useful insight into the potential benefits of emissions mitigation policy has been demonstrated through the AVOID programme; Arnell et al. (2010a[1]) applied climate change patterns from 5 climate models to the general large-area model for annual crops (GLAM) and showed that global wheat

[1] This paper has not yet been published but it uses an established crops model for the assessment and the climate change scenarios applied are currently undergoing preparation for peer-review.

production could decrease (in the absence of adaptation) by between 30 and 40% by 2050 under the A1B emissions scenario, with relatively little difference between climate models. The introduction of emission mitigation policies had little effect by 2050, but prevented production declining further through the 21st century. Soybean production was also projected to decrease, by a similar magnitude to wheat production, and mitigation reduced the effect of climate change and offset production loss by 10-30%. Importantly, in some regions such as Europe, the effect of mitigation was highly dependent on the climate model pattern. Arnell et al. (2010a) also explored the implications for undernourishment; simulations with the FEEDME (Food Estimation and Export for Diet and Malnutrition) model under the SRES A1B emissions scenario and a number of mitigation scenarios from the HadCM3 climate model showed that unmitigated climate change is projected to have very substantial effects on exposure to undernourishment during the 21st century in a sample of countries. Assuming some form of adaptation – reducing exports and reducing the diversion of crops to feedstock – reduced, but in most cases did not eliminate, the projected impacts of climate change. Policies aimed at limiting global-mean temperature rise to 2°C typically reduced exposure to undernourishment by 30-50%. In practice, food trade is likely to be used to adapt to climate change and therefore reduce undernourishment, and the results presented by Arnell et al. (2010a) can be interpreted as characterising the demand for adaptation. A new study by Falloon and Betts (2010) takes a unique perspective on the potential for adaptation of agriculture to climate change, by considering the interaction and feedbacks between climate, water resources and agriculture. They show that changes in future hydrology and water management practices will influence agricultural adaptation measures and alter the effectiveness of agricultural mitigation strategies. Adaptation in the water sector could potentially provide additional benefits to agricultural production such as reduced flood risk and increased drought resilience, for instance. Falloon and Betts (2010) conclude that since changes in climate, agricultural ecosystems and hydrometeorology depend on complex interactions between the atmosphere, biosphere and hydrological cycle there is a need for more integrated approaches to climate impacts assessments, which is an important avenue for future research.

8.2. Effects of enriched CO_2 concentrations on crop productivity

The IPCC AR4 highlights a key area for future research as the understanding of the effect of enriched CO_2 concentrations on crop productivity, particularly for non-cereal crops and understanding the combined effects of elevated CO_2

and climate change on pests, weeds and disease. It concludes (with medium confidence) that new Free-Air Carbon Dioxide Enrichment (FACE) results indicate that at 550 ppm atmospheric CO_2 concentrations, crop yields increase under unstressed conditions by 10-25% for C3 crops, and by 0-10% for C4 crops (Easterling et al., 2007). However, research published since the IPCC AR4 suggests that the effects of elevated CO_2 on crop yields may be less positive than initially suggested, and importantly, that there is a high degree of uncertainty associated with the relationship. The IPCC AR4 also concludes that the CO_2 effect may be relatively greater (compared to that for irrigated crops) for crops under moisture stress and this is supported by new studies.

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 IPCC AR4 assessment. This less positive tone is supported by new research published by Lobell et al. (2008), which takes a probabilistic approach using 20 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 IPCC AR4. Specifically, the results indicate South Asia and Southern Africa as two regions that, without sufficient adaptation measures, will likely suffer negative impacts on several crops that are important to large food-insecure human populations. However, the conclusion of the IPCC AR4 that the CO_2 effect may be relatively greater (compared to that for irrigated crops) for crops under moisture stress is confirmed by Tubiello et al. (2007) - under unstressed conditions, CO_2 enrichment tended to increase crop yields by 5-20% at 550 ppm CO_2.

Challinor and Wheeler (2008) cast doubt on the generality of the effect of CO_2 enrichment. Their study modelled the effect of CO_2 enrichment on groundnut productivity in India using GLAM under unstressed and water-stressed conditions. The increases in yield simulated by GLAM for doubled CO_2 were between 16 and 62% and the stimulation of groundnut productivity was more than offset by the projected increased frequency of high temperature extremes. The difference in mean percentage increase between well-watered and water-stressed simulations was 6.8, which does confirm the IPCC AR4 conclusion that the CO_2 effect may be relatively greater (compared to that for irrigated crops) for crops under moisture stress. However, the study concluded that current observational data were not sufficient to constrain the uncertainty in the estimated effects of enrichment, meaning that the statement that 'water-stressed crops show greater CO_2 stimulation than well-watered crops' cannot be held to be universally true. This conclusion is supported by Lobell and Field (2008), a study which applied an empirical approach and demonstrated that country-level estimates of crop CO_2 responses were highly uncertain. Furthermore, it is important to note that whilst the IPCC AR4 concluded that under unstressed conditions, CO_2 enrichment tends to increase crop yields, the impacts on crop yields will vary regionally. For instance Aggarwal (2008) estimates that crop production loss in India by 2100 could be 10-40% despite the beneficial effects of higher CO_2 on crop growth, with losses of 4-5 million tonnes of wheat for every rise of 1°C in temperature. Also, a series of studies (Reilly et al., 2007; Van Dingenen et al., 2009; 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.

In some cases, the impacts are severe; Van Dingenen et al. (2009) showed that by 2030 changes in ozone will result in a 2–6% wheat loss and 1-2% rice loss globally, with India accounting for 50% of these global increases in crop yield loss. Translating these assumed yield losses into total global economic damage for the four crops considered, using world market prices for the year 2000, Van Dingenen et al. (2009) estimate an economic loss in the range $14–$26 billion, with about 40% of this damage occurring in China and India. Ainsworth and McGrath (2010) present an interesting discussion on the role of FACE for crop productivity. They show that current best estimates for the response of the staple crops wheat, soybean and rice from FACE experiments are that grain yield will increase by 13% at 550 ppm CO_2, and for the C-4 species, sorghum and maize, grain yield is not expected to increase at elevated CO_2 if water supply is adequate, whilst grain quality is adversely affected by elevated CO_2. Ainsworth and McGrath (2010) show that protein content decreases by 10-14% on average in non-leguminous grain crops and concentrations of minerals, such as iron and zinc decrease by 15-30%. They conclude that the majority of FACE studies have been conducted in temperate regions, and do not account for possible interactions of rising CO_2 with other aspects of climate change, including increased temperature, drought stress and tropospheric ozone concentration. This highlights the high degree of uncertainty that surrounds the effects of enriched CO_2 concentrations on crop productivity and represents an important area for future research.

8.3. Moving towards a more complete treatment of uncertainty

New assessments are starting to provide a more comprehensive treatment of uncertainty, including, for instance, emissions uncertainty, climate modelling uncertainty and crop modelling uncertainties. Li et al. (2009) conducted a drought-risk assessment of world crop yield impacts under current and future climatic conditions using data from 20 climate models and 6 SRES emissions scenarios and a revised Palmer Drought Severity Index. By applying a probabilistic approach Li et al. (2009) simulated an overall enhanced drought risk in the future under climate change, relative to present. They showed that globally, the drought disaster-affected area will increase with rising global temperature, from around 15% in present to 44% by 2100. This was associated with the rates of yield reduction related to drought disaster for major crops increasing significantly with future climate change, by over 50% in 2050 and almost 90% in 2100. Modelling studies have shown that the impacts of extreme climate will vary regionally and by the methods of crop cultivation applied; for instance, Wang et al. (2009) showed that within China, climate change is likely to be harmful to rain-fed farms but beneficial to irrigated farms, with farms in the Southeast only mildly affected but farms in the Northeast and Northwest bearing the largest damages. Whilst the study notes it did not capture the indirect effects on farms of possible changes in water availability (which was assumed to remain at present day levels) and did not consider projections from all climate models included in the IPCC AR4, the study applied results of three climate models specifically chosen to represent the spread of multi-model variability in projections across the climate models included in the IPCC AR4. Therefore it would appear that post-IPCC AR4 studies support the conclusion that extreme events such as droughts will have a negative effect on crop production.

However, the evidence for impacts associated with changes in the mean climate is less straightforward. Many of the crops impacts estimates given in the IPCC AR4 are non-probabilistic. Recently, a comprehensive treatment of uncertainty in a climate change-crops impacts assessment study is provided by Tebaldi and Lobell (2008), which may be seen as a blueprint for future assessments. By applying a probabilistic approach, the study showed that projected changes in temperature and precipitation negatively affect global crops yields by causing a decrease in yield of about 9% (with 95% probability intervals of 1.7%–17%) for barley, by 13% (5%–25%) for maize and by 5% (1%–10%) for wheat. Including CO_2 fertilization reduced projected losses by an average of 7% for wheat and barley but did not change significantly the impact on maize, and had relatively small effects on overall uncertainty. Tebaldi and Lobell (2008) specifically demonstrate why their assessment is advantageous over the projections that are presented in the IPCC AR4. For example, they note how quantitative but non-probabilistic statements are included in the IPCC AR4, such as

> "550 ppm CO_2 (associated with approximately 2°C of warming) increases C3 crop yield by 17%; this increase is offset by temperature increase of 2°C assuming no adaptation and 3°C with adaptation" (Easterling et al., 2007, p. 276),

whereas Tebaldi and Lobell (2008) considered a shorter time frame of 2030 when CO_2 levels are expected to reach around 450 ppm and they estimated at most a 75% chance that CO_2 and climate effects will cancel by 2030 for wheat, at most a 30% chance for barley, and 0% for maize. Tebaldi and Lobell (2008) conclude that given these findings, the statement that global yields of C3 crops will be unaffected at 550ppm thus appears optimistic, although within their fairly wide uncertainty bounds. They adopt the IPCC nomenclature and suggest that the chance that global losses from climate change by 2030 will outweigh gains from CO_2 as unlikely for wheat (<33% chance), likely for barley (>66% chance) and virtually certain for maize (>99% chance). As such, the results of Tebaldi and Lobell (2008) suggest a less optimistic outlook for global crop production than what is suggested in the IPCC AR4. A similar approach was adopted by Tao et al. (2009) to simulated projected changes in maize production for China; they developed a new "super-ensemble" based probabilistic projection approach to account for the uncertainties from CO_2 emission scenarios, climate change scenarios, and biophysical processes, by using 10 climate scenarios consisting of the combinations of five climate models and two emission scenarios, the corresponding atmospheric CO_2 concentration range, and 60 sets of crop model parameters. Tao et al. (2009) presented expected yield changes of -9.7 (95% probability intervals of -29.4, +15.8), -15.7 (-45.7, +24.0), and -24.7% (-92.8, +20.3) relative to present across Henan province during the 2020s, 2050s, and 2080s respectively. Whilst the probabilistic approaches employed by Tao et al. (2009) and Tebaldi and Lobell (2008) yield negative changes in crop productivity with climate change relative to present, a non-probabilistic approach applied by Hayashi et al. (2010) yielded positive global changes in production potential. Based upon a single climate model and the SRES B2 emissions scenario, Hayashi et al. (2010) estimated that global wheat production potential relative to the 1990 level will increase approximately 20% in 2050, 20% in 2100, and only 8% in 2150. Rice production potential was estimated to increase approximately 40% in 2050, by 50% in 2100, and by 50% in 2150. The results of Hayashi et al. (2010) are more optimistic than those presented by Tao et al. (2009) and Tebaldi and Lobell (2008) and as such, are in more agreement with the conclusions of the IPCC AR4. However, Hayashi et al. (2010) overlook the issue of climate model uncertainty, so the probabilistic estimates of Tao et al. (2009) and Tebaldi and Lobell (2008) may be considered more robust. **Figure 11** displays probability density functions (PDFs) of maize yield changes for four of the areas Tao et al. (2010) investigated; the PDFs demonstrate that there is a probability of positive yield changes with climate change, which would support the findings of Hayashi et al. (2010), but the probabilities would be low, and this demonstrates the benefit of the probabilistic approach over the non-probabilistic approach.

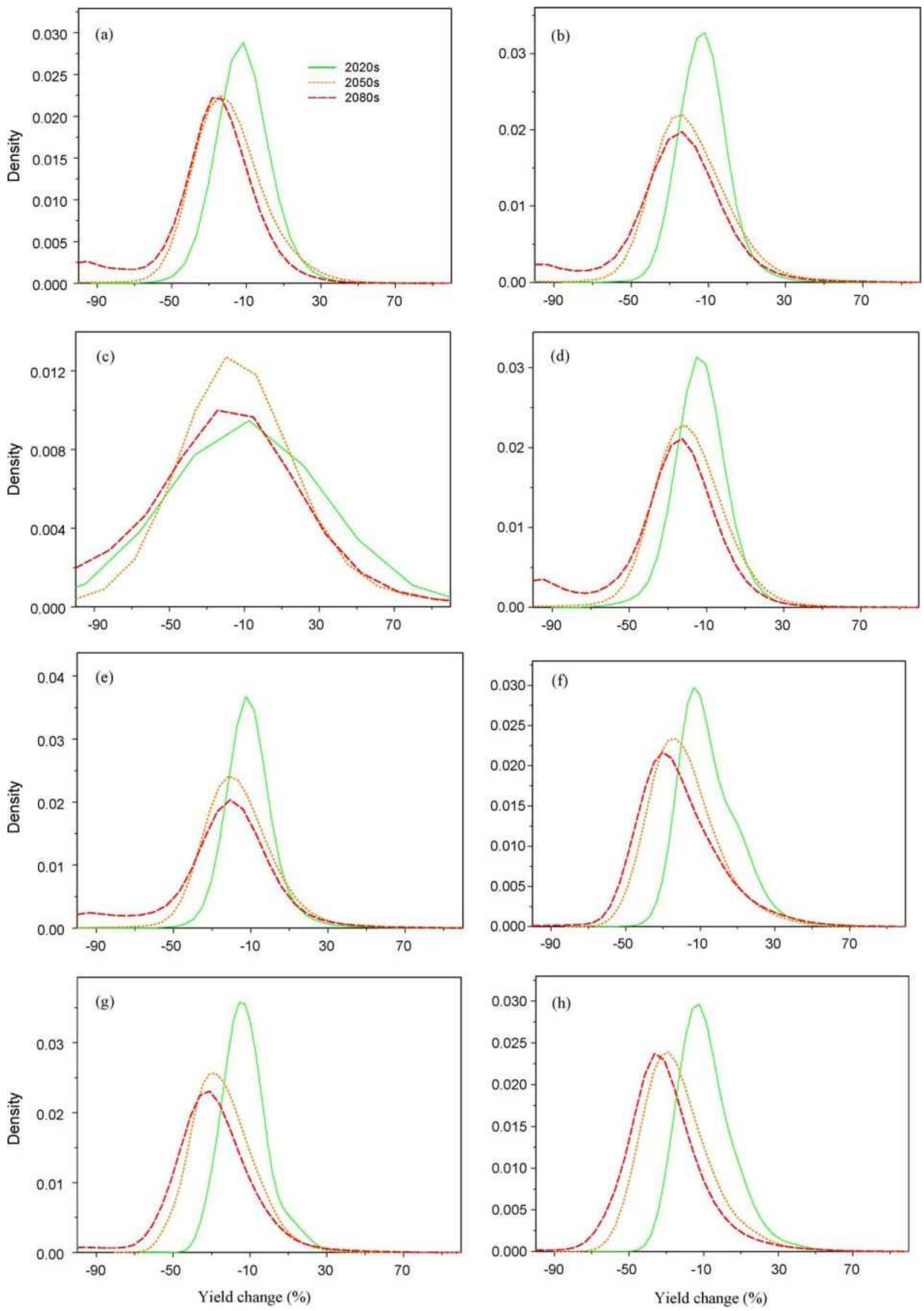

Figure 11: Probability density functions of maize yield changes during the 2020s, 2050s, and 2080s, relative to 1961–1990, at the grid of Luoyang (a), Pingdingshan (b), Luohe (c), Xinxiang (d), Jinan (e), Qingdao (f), Weifang (g), and Taian (h) in China. Source: Tao et al., (2010), p. 1271.

8.4. Summary of new findings since the IPCC AR4

- New studies have confirmed suggestions by the IPCC AR4 that substantial reductions in the magnitude of the impact of climate change on global crop production and nourishment could be realised by mitigation policy (Friel et al., 2009; Arnell et al., 2010a), e.g. policies aimed at limiting global-mean temperature rise to 2℃ could reduce exposure to undernourishment by 30-50% relative to a business as usual scenario, and crop production losses could be cut by 70-100%.
- New research has demonstrated the complex interactions between changes in climate, agricultural ecosystems and hydrometeorology, which highlights a need for more integrated approaches to climate impacts assessments (Falloon and Betts, 2010).
- There has been a rapid expansion of research into the potentially positive effect of CO_2 enrichment on crop productivity since the IPCC AR4 (Tubiello et al., 2007; Lobell et al., 2008; Ainsworth and McGrath, 2010; Aggarwal, 2008; Reilly et al., 2007; Van Dingenen et al., 2009; Booker et al., 2009). Generally, the results of these studies suggest a less optimistic conclusion can be formulated upon the response of crops to CO_2 enrichment because of the offsetting of yield increases by yield declines associated with increased ozone, temperature and prevalence of pests and weeds. High uncertainty is associated with the projections because the majority of FACE studies do not account for possible interactions of rising CO_2 with other aspects of climate change, including increased temperature, drought stress and tropospheric ozone concentration.
- New probabilistic impacts assessments generally suggest declines in crop productivity with climate change (Tao et al., 2009; Tebaldi and Lobell, 2008), which are less optimistic than those made in IPCC AR4, although within their fairly wide uncertainty bounds.

9. Human health

9.1. Extreme events

The IPCC AR4 concludes that overall, empirical research has further quantified the health effects of heatwaves since the IPCC Third Assessment Report (IPCC TAR) but that there has been little additional research on the health effects of other extreme weather events (Confalonieri et al., 2007). In this section we evaluate whether the post-IPCC AR4 literature suggests any new perspectives on the impacts of climate extremes on human health.

The European heat wave of 2003 and its impact on mortality is well-documented (e.g. Le Tertre et al., 2006; Conti et al., 2005; Gosling et al., 2009a) and the event has been suggested as being analogous for typical summers under climate change in the latter half of this century (Stott et al., 2004; Beniston, 2004). A recent study by Robine et al. (2008) has presented updated mortality estimates for the heat wave and suggests that more than 70,000 additional deaths occurred in Europe during the heat wave, which is larger than previous estimates. An important result concerns the number of deaths attributed to ‘mortality displacement’ (deaths among people who would have died soon after the heat wave event regardless of whether it had occurred or not because they we already close to death, e.g. due to a pre-existing illness) – Robine et al. (2008) demonstrated that mortality levels across 16 European countries after the heat wave were not lower than during the reference period, which suggests mortality displacement was not a factor. The implications of this are that the heat wave may have had a more serious impact on mortality than previously thought because it affected more of the ‘fit and healthy’ population. This in turn has implications for assessments of the impact of climate change on heat-related mortality.

Whilst recent post-IPCC AR4 empirical evidence points to the underestimation of the effects of climate on mortality during heat waves (e.g. Robine et al., 2008), modelling studies are now also highlighting that previous climate change impacts assessments might be underestimating (and in some cases overestimating) the number of heat-related deaths attributable to changes in the climate due to the methodological approaches they have applied. Past assessments typically apply the ‘delta’ method, which assumes only the mean temperature changes under climate change, with the variability remaining unchanged. However, this is unrealistic. For example, Ballester et al. (2010) have shown that both extreme warm and cold day events in Europe are expected to increase in intensity to a larger degree than central values with climate change. The implications that this has for projections of heat-related mortality under climate change scenarios has been demonstrated by Gosling et al. (2009b, 2009c) where heat-related mortality under climate change scenarios simulated by the HadCM3 climate model was estimated for six cities in situations where climate variability changed and remained at present-day variability respectively. Results showed that for some cities (e.g. London), the number of annual summer heat-related deaths attributable to climate change could be up to twice as large when climate variability is accounted for in the 2080s. However, because variability is projected to decrease from present levels for some locations, Gosling et al. (2009b) also demonstrates that for some cities, heat-related mortality could be lower than previous studies have suggested (e.g. Dallas). Both Ballester et al. (2010) and Gosling et al. (2009b) conclude that future impacts assessments should consider changes in temperature variability, as defined by the shape of the probability density function (PDF) with climate change.

The IPCC AR4 concludes that additional research is needed to understand how the balance of heat-related and cold-related mortality could change under different socio-economic scenarios and climate projections. Post-IPCC AR4 research is now addressing this and an emerging issue concerns the offsetting of increased summertime mortality associated with more frequent and intense summer heat waves by reduced wintertime mortality associated with milder winters. Bosello et al. (2006) – not cited in the IPCC AR4 chapter on human health – claimed that increased temperatures would *reduce* global 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. Indeed, Gosling et al. (2009b) 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. A more recent study presented by Hayashi et al. (2010) supports the findings of Bosello et al. (2006) – Hayashi et al. (2010) showed that for an approximately 2℃ warmer world than present in the year 2100, climate change would result in around 4 million extra heat-deaths and around 6 million less cold-related deaths relative to present - hence thermal stress reduces by around 2 million deaths by 2100 (see **Figure 12**). However, an important limitation is that the temperature-mortality models applied by Hayashi et al. (2010) are based upon the models presented by Tol (2002a, b), which are the same models Bosello et al. (2006) applied. Therefore the similarities in results are not surprising and as such are subject to the same criticisms discussed by Ackerman and Stanton (2008). Given this, the credibility of the suggestion that global temperature-related deaths may decrease with climate change is very much up to the degree to which the issues raised by Ackerman and Stanton (2008) are considered robust. Also, it is important to note that the aggregation of national mortality to the global scale hides important regional variations. Nevertheless, whilst the early work on cold versus heat-related mortality offsetting is proving controversial, it presents an important area that requires further research in order that we may better our understanding of the relationship.

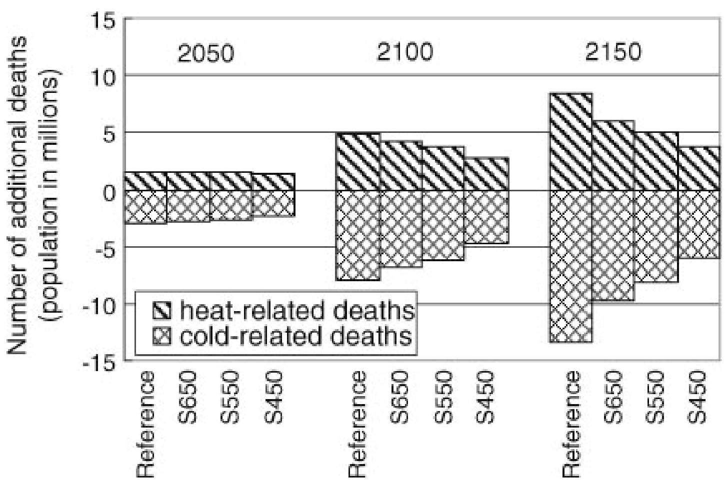

Figure 12: Number of global additional deaths caused by heat- and cold-related thermal stress due to climate change for a reference scenario (SRES B2) and three mitigation scenarios that stabilize atmospheric CO_2 concentrations at 650ppm, 550ppm and 450ppm respectively. Source: Hayashi et al. (2010), p. 97.

The IPCC AR4 concludes that heat-related mortality is likely to increase with climate change but does not give specific estimates of the possible impacts for different amounts of climate change. Two recent studies address this caveat. Gosling et al. (2009b) showed that even when changing temperature variability remains unaccounted for, annual summertime heat-related mortality could increase by more than threefold from present-day levels in an approximately 4°C warmer world for cities including Boston, Budapest, Dallas, Lisbon, London and Sydney. Hayashi et al. (2010) showed that for an approximately 2°C warmer world than present in the year 2100, climate change would result in around 4 million extra heat-deaths relative to present

Whilst we are able to report upon the aforementioned developments for the impacts of heat waves on human health, a review paper presented by Mills (2009) argues that there is a high degree of uncertainty associated with the impacts of other climatic extremes on human health, and as such does not suggest there is any new evidence post-IPCC AR4 to suggest a change in damage from extreme events under climate change scenarios. Mills (2009) conducted a literature review to address how climate change impacts on a group of extreme weather events could affect US public health and concluded that cumulative uncertainty in projecting climate change driven characteristics of extreme events and adaptation prevents confidently projecting future health impacts from hurricanes, wildfires, and extreme precipitation/floods attributable to climate change. Given that the IPCC AR4 acknowledges that there has been little additional research on the health effects of other extreme weather events since the IPCC TAR (Confalonieri et al., 2007), we highlight, along with others (e.g. Kovats and Akhtar, 2008) that there is a need to better describe the risks to health from extreme weather events, especially under climate change scenarios.

9.2. Vector-borne and other infectious diseases

The IPCC AR4 shows that climate change could alter the incidence and geographical range of malaria and notes that few models project the impact of climate change on malaria outside Africa – they note greater confidence in projected changes in the geographical range of vectors than in changes in disease incidence because of uncertainties about trends in factors other than climate that influence human cases and deaths, including the status of the public-health infrastructure (Confalonieri et al., 2007). For instance, no impacts studies reviewed in the IPCC AR4 incorporate economic scenarios. Importantly, the IPCC AR4 suggests that uncertainty in projections are large because malaria is a complex disease to model and all published models have limited parameterisation of some of the key factors that influence the geographical range and intensity of malaria transmission. The IPCC AR4 cites van Lieshout et al. (2004); a study that showed some central Asian areas are projected to be at increased risk of malaria, and areas in Central America and around the Amazon are projected to experience reductions in transmission due to decreases in precipitation. They also cite a study which estimated that for an approximately 2°C warmer world than present, 5-6 billion people would be at risk of dengue as a result of climate change (based upon projections from 4 climate models) and population increase, compared with 3.5 billion people in the absence of climate change (Hales et al., 2002) – no studies published since then have assessed the impact of climate change on dengue at the global level.

Recent research confirms the role of the climate in determining the range of malaria – Chaves and Koenraadt (2010) re-examined over 70 studies that investigated the association between climate change and the spread of malaria to highland areas in East Africa, South America and South Asia that has been observed over the past 40 years. Their study concludes that the evidence for the role of climate in these dynamics is robust but that other factors also play an important role, such as people migrating from lowlands that may be introducing the malaria parasite into highland regions, changes in farming practices and increased irrigational farming. An important part of the analysis conducted by Chaves and Koenraadt (2010) regards their disagreement with a study presented by Hay et al. (2002) and cited in the IPCC AR4 (Confalonieri et al., 2007). Hay et al. (2002) studied the Kericho highlands of western Kenya and found no warming trend in the area and suggested that malaria incidence has increased in the apparent absence of climate trends. However, when Chaves and Koenraadt (2010) ran the same temperature data from that study through three additional statistical tests, each test indicated a significant warming trend. They argue that similar statistical errors plague other comparable studies and they found that most studies concluding that climate change is indeed playing a role in highland malaria tend to be statistically strong. This is further supported by Wandiga et al. (2010) – analyses of temperature and precipitation data for 1961–2001 with socio-economic data for the East African highlands confirmed the link between climate variability and the incidence and severity of malaria epidemics and the relationship was showed to be influenced by the coping and adaptive capacities of individual communities, with poverty playing an important role. Importantly, Wandiga et al. (2010) also showed a clear rising trend in temperature for the Kericho highlands of western Kenya between 1978-2004 (see **Figure 13**).

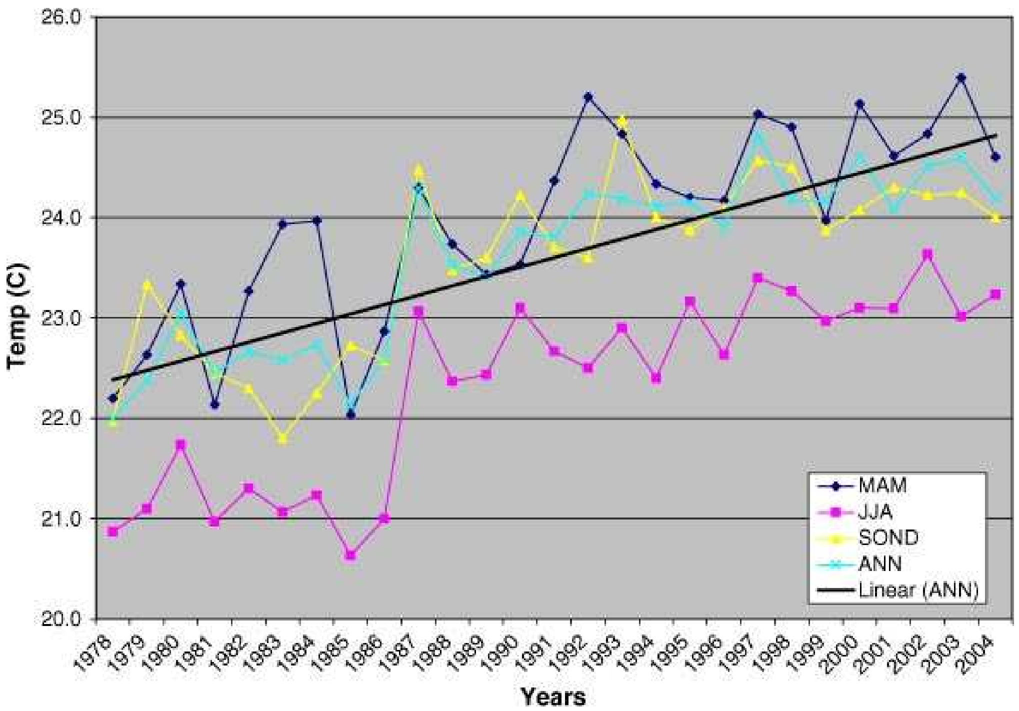

Figure 13: Three seasonal variations of maximum temperature for the Kericho highlands of western Kenya for 1978-2004. The annual data shows a clear increasing trend, which supports the findings of Chaves and Koenraadt (2010), and provides further evidence to counteract the conclusions of Hay et al. (2002) that malaria incidence has increased in the apparent absence of climate trends. Source: Wandiga et al. (2010), p. 481.

Recent modelling studies have highlighted the potential impact of climate change on malaria. Hayashi et al. (2010) simulated the number of deaths caused by malaria and dengue in sub-Saharan Africa under three different CO_2 stabilisation scenarios and the pattern of climate change from a single climate model. They estimated that climate change will cause around 85,000-100,000 extra deaths due to malaria and dengue in the region in 2050. Whilst the study presents a bold attempt to put a figure on the number of infectious deaths due to climate change, it is limited by applying models that are strongly dependent upon a country's GDP/capita, which means they estimate zero deaths from malaria and dengue attributable to climate change in the region in 2100. Also, Peterson (2009) has shown that *Anopheles gambiae* and *A.*

arabiensis, the two most important malaria vectors in Africa, are likely to see less suitable conditions for their populations across portions of West Africa due to large projected temperature increases, whilst both species are likely to see improving conditions in regions of southern Africa, in areas where annual mean temperatures are increasing sufficiently to permit these species to establish populations. Further supporting evidence of the impact of climate change on malaria is presented by van Vuuren et al. (2010[1]); a study which used the IMAGE integrated assessment model to simulate the global number of deaths due to malaria in 2025 and 2050 respectively under two scenarios, a business as usual scenario which leads to an increase of global mean temperature of 4 °C by 2100 compared to pre-industrial levels and an ambitious mitigation strategy which leads to 2 °C increase by 2100 compared to pre-industrial levels. van Vuuren et al. (2010) showed that in the absence of autonomous adaptation that increases with GDP, deaths due to malaria increase from around 1 million in 2000 to around 1.15 million in 2025 and 1.1million in 2050. The difference between the mitigation scenario and the business as usual case was small: mitigation reduced malaria health risks by about only 2%. However, when autonomous adaptation was considered, malaria deaths reduced by around 50% in 2050 relative to assuming no adaptive potential. This implied that adaptation contributes more to reducing mortality than mitigation.

Whilst post-IPCC AR4 studies suggest that the role of climate change on malaria may be grater than initially suspected (Hayashi et al., 2010; Chaves and Koenraadt, 2010; Wandiga et al., 2010), it is important to note that malaria incidence is affected by numerous factors other than average temperature, and post-IPCC AR4 research is highlighting this. Paaijmans et al. (2009) have demonstrated temperature fluctuation around means >21°C slows malaria parasite development compared with constant temperatures, whereas fluctuation around <21°C speeds development. Consequently, impacts models which ignore diurnal variation overestimate malaria risk in warmer environments and underestimate risk in cooler environments. This has important implications, considering that temperature-based malaria transmission models generally only use mean monthly temperatures. An interesting modelling study is presented by Linard et al. (2009); they used a multi-agent simulation to demonstrate that the risk of malaria re-emergence is low in the Camargue region of southern France.

[1] In press as of November 2010.

They showed that if the disease would re-emerge, it would be the result of a combination of unfavourable conditions including the introduction of a large population of infectious people or mosquitoes, combined with high levels of people-vector contacts resulting from significant changes in land use, tourism activities, agricultural policies, biological evolution of mosquitoes, and climate changes. Wandiga et al. (2010) have shown that community poverty is an important determinate of malaria risk in the Kericho highlands of western Kenya. A post-IPCC AR4 development has been the growth of climate-malaria studies outside of Africa for countries including Colombia (Mantilla et al., 2009), France (Linard et al., 2009), USA (Soverow et al., 2009), Taiwan (Wu et al., 2009), and Australia (Russell, 2009), but there have been relatively few global studies conducted (e.g. Chaves and Koenraadt, 2010; Hayashi et al., 2010).

9.3. Benefits of climate change mitigation

There is very little research reviewed in the IPCC AR4 chapter on human health (Confalonieri et al., 2007) that explores the potential benefits of mitigation for health impacts but this is now an expanding area. An international task force on climate change mitigation and public health has recently assessed the potential health benefits of various climate change mitigation measures (Haines et al., 2009). They assessed the benefits in terms of disability-adjusted life-years (DALYs) saved and demonstrated that certain mitigation options could have substantial benefits for public health. For instance, lower carbon and more active transport was shown to reduce the burden of disease by 7400 DALYs (per million of the population) for London, and 13,000 for Delhi. Other mitigation options considered included low carbon fuels/technologies (100 DALYs/million saved in the EU), housing related energy efficiency (850 DALYs/million saved in the UK), and adoption of clean-burning cookstoves (12,500 DALYs/million saved in India). Note that whilst this study does not necessarily show any specific change in damage to public health from climate change under a business as usual scenario, it is novel in that it demonstrates the potential benefits of mitigation practices, which are different from the mitigation policies considered under the AVOID programme (previously discussed, e.g. Arnell et al., 2010a; Bernie et al., 2010). The benefits of three different levels CO_2 stabilisation (650, 550 and 450ppm) for global deaths due to thermal stress are presented by Hayashi et al. (2010) – reduction in CO_2 emission levels were shown to mitigate the increase in the number of deaths due to heat-related thermal stress after the middle of the twenty-first century while simultaneously limiting the decrease in the number of deaths due to cold-related thermal stress. Hayashi et al. (2010) suggested that globally around 1 million heat-related deaths could be avoided by 2100 if CO_2 levels are stabilized at 450ppm relative to 650ppm (see **Figure 12**). However, it should be noted that these estimates are based solely upon climate change projection patterns from a single climate model and the methodology of estimating temperature-related has been criticized by Ackerman and Stanton (2008).

9.4. Summary of new findings since the IPCC AR4

- Previous assessments of heat-related mortality are likely underestimates because they do not consider the role of temperature variability with climate change and/or mortality displacement adequately (Robine et al., 2008; Ballester et al., 2010; Gosling et al., 2009b).
- New research shows that in a 2°C warmer world, globally there would be 4 million extra heat-related deaths and around 6 million less cold-related deaths relative to present - hence thermal stress reduces by around 2 million deaths due to warmer winters but the aggregation of regional mortality to the global level hides important regional variations.
- New research shows that in a 4°C warmer world annual summertime heat-related mortality could increase by more than threefold from present-day levels for cities including Boston, Budapest, Dallas, Lisbon, London and Sydney.
- The IPCC AR4 concluded that additional research is needed to understand how the balance of heat-related and cold-related mortality could change under different socio-economic scenarios and climate projections. Post-IPCC AR4 research is now addressing this but findings are proving controversial (e.g. Ackerman and Stanton, 2008) - initial suggestions are that the global total number of temperature-related deaths will decrease with climate change (Bosello et al., 2006; Hayashi et al., 2010). Nevertheless, the aggregation of regional deaths to the global scale hides important regional differences.
- Given that the IPCC AR4 acknowledges that there has been little additional research on the health effects of other extreme weather events since the IPCC TAR (Confalonieri et al., 2007), we highlight, along with others (e.g. Kovats and Akhtar, 2008) that there is a need to better describe the risks to health from extreme weather events, especially under climate change scenarios.

- The impact of climate change on malaria may be grater than initially suspected (Hayashi et al., 2010; Chaves and Koenraadt, 2010; Wandiga et al., 2010) but it is important to note that malaria incidence is affected by numerous factors other than average temperature, which new research is highlighting (Linard et al., 2009; Wandiga et al., 2010).
- New results show that in the absence of adaptation, global deaths due to malaria could increase from around 1 million in 2000 to around 1.1million in 2050 under a climate change scenario that results in a 4℃ warmer world in the year 2100 - limiting warming to 2℃ reduced malaria health risks by about only 2% and the impact reduces by around 50% if adaptation is considered (van Vuuren et al., 2010). In sub-Saharan Africa, climate change could cause 95,000 extra deaths from malaria in the year 2050 under a climate change scenario that results in a 2℃ warmer world in 2100 (Hayashi et al., 2010).

10. Conclusions of changes in climate impacts

We have presented an updated literature review of the impacts of climate change on six major sectors that were included in Working Group II of the IPCC AR4; coastal system impacts and adaptation, ocean acidification, ecosystems and biodiversity, water resources and desertification, agriculture and food security, and human health. **Table 2** summarises the magnitude of the impacts projected for each sector, for 2℃ and 4℃ warmer worlds than present respectively that this review has highlighted.

A number of important post-IPCC AR4 emerging themes can be drawn from the review.

Firstly, is the application of probabilistic methods of impacts assessment and/or the consideration of climate modelling uncertainty. This method of assessment is now becoming more common in, for example, crops modelling (Tebaldi and Lobell, 2008; Tao et al., 2009) and water resources modelling (Gosling et al., 2010a; Arnell et al., 2010a, b; Preston and Jones, 2008) but remains absent in health impacts modelling for instance, where most studies typically assess the impacts associated with climate projections from only a small number of climate models (e.g. Hayashi et al., 2010). Importantly, the conclusions that can be drawn from a probabilistic assessment can be different from those drawn from a non-probabilistic assessment. For example, Tebaldi and Lobell (2008) applied a probabilistic approach and showed that the global impact of climate change on crop production may be less optimistic than suggested by the non-probabilistic statements of the IPCC AR4. The uncertainties associated with projections across different climate models can be large (e.g. for precipitation; Meehl et al., 2007), so we recommend that future impact assessments adequately address this source of uncertainty, where possible. This will allow for a more informed policy- and decision-making process.

Secondly, a major IPCC AR4 development that this review has highlighted is a move towards assessing the potential benefits that could be accrued under different climate change mitigation scenarios, relative to a business as usual reference scenario (e.g. Haines et al., 2009; Arnell et al., 2010a, b; Hayashi et al., 2010; Bernie et al., 2010; Fischer et al., 2007). In many ways, this reflects a shift towards using climate change impacts science to inform policy- and decision-making. Across the impact sectors we considered here, such policies generally show that mitigation reduces the magnitude of the impacts relative to the reference scenario, but it does not eliminate the effects of climate change. In some cases the potential benefits may be large (e.g. undernourishment, Arnell et al., 2010a) and so this can be seen as a case for recommending mitigation measures in order to reduce some of the possible impacts of climate change. However, given that mitigation does not eliminate impacts, adaptation is still an important factor.

Thirdly, this review has shown that there are still several uncertainties associated with understanding the association between climate and natural or human systems. For instance, research into the impact of climate change on fish communities has grown since the IPCC AR4 (Checkley et al., 2009; Munday et al., 2009;) but this remains a relatively under-studied area. Other key uncertainties regard the role of CO_2 enrichment on crop productivity (Challinor and Wheeler, 2008), the role of extreme events (other than heat waves and cold snaps) on human health (Mills, 2009), the association between climate change and malaria (Paaijmans et al., 2009), and the response of calcifying organisms to ocean acidification (Ries et al., 2009; Hendriks et al., 2010).

Whether recent impact assessments show a changed risk of damage to human or natural systems since the publication of the IPCC AR4 depends upon the impact sector. For instance, recent water resources studies suggest no change in the magnitude of the impacts of climate change on global water resources stress (Preston and Jones, 2008; Gosling et al., 2010a; Hayashi et al., 2010; Arnell et al., 2010b). However, new assessments have shown that previous estimates of heat-related mortality may be underestimated (Robine et al., 2008; Ballester et al., 2010) and in some cases overestimated (Gosling et al., 2009b), and that the estimates made by the IPCC AR4 for crop productivity may be over-optimistic (Challinor and Wheeler, 2008; Tebaldi and Lobell, 2008). New research has also cast major doubt on the previously held assumption that malaria in the Kericho highlands of western Kenya had no association with rising temperatures (Chaves and Koenraadt, 2010; Wandiga et al., 2010). Furthermore, whilst recent findings support the IPCC AR4 that future changes in ocean acidification caused by emissions of CO_2 to the atmosphere are largely independent of the amounts of climate change (Cao et al., 2007; Matear, 2006; Orr et al., 2005) evidence suggests that climate change could potentially result in a mass extinction of worldwide coral species (Cao and Caldeira, 2008; Veron 2008; Veron et al., 2009). However, embedded within these projections there is always a degree of uncertainty associated with our understanding of the physical processes, the impacts models and the climate models applied to them. Some studies account for this explicitly through a probabilistic approach, whilst others do not. It is therefore important that future studies adequately acknowledge this in their projections so as to give an indication of the width of the uncertainty range surrounding their estimates. Furthermore, whilst we have shown that for some impact sectors there is a changed risk relative to the IPCC AR4, whether this change is *significant* or not should be left to expert judgment.

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Appendix A: Bibliographic search process

For Sections 2-3, our initial literature search was performed using the ISI Web of Science tool. For the section on large-scale climate change, key resources were the 2009 special issue of PNAS on climate tipping points (Kriegler et al., 2009), and the review by Fussel (2009). We also searched for literature which specifically cites Lenton et al. (2008). The number of citations for these sections are given in **Table A1**. The vast majority of papers cited were published prior to April 2010, with the exception of papers that we are aware were undergoing review at the time. The majority of these have been accepted and were in press by November 2010, and exceptions to this have been noted in footnotes in this report.

Table A1. Number of citations included for climate science and emissions research areas. Note that a small number of papers are cited in more than one section.

Sector	Citations
General and observed climate change	61
Statistical issues relating to choosing temperature and emissions targets	7
Changes in understanding of forcing	3
Climate response to given greenhouse gas concentration change	5
Biogeochemical feedbacks	12
Ice sheets	30
Sea ice	7
Sea level rise	13
Atlantic meridional overturning circulation	19
Tropical forests	11
Wetlands	10
Terrestrial permafrost	8
Ocean hydrates	8
Tropical climate system	2
Extremes – temperature, precipitation and windstorms	10
Interactions between potentially abrupt changes	1

The literature searches for the sections on climate impacts (4-10) were also conducted through the Thomson Reuters Web of Science online academic search engine, which provides access to several databases including the Science Citation Index (SCI), Social Sciences Citation Index (SSCI), and Conference Proceedings Citation Index: Science. Its databases cover over 10,000 journals from 256 categories and includes over 110,000 proceedings from the most significant conferences worldwide (WoS, 2010). Key-word searches were conducted for each impact sector using various combinations of the words included in **Table A2**.

Table A2. Words used for searches in Web of Science and number of citations included

Impact sector	**Key-words**	**Citations**
Coastal system impacts and adaptation.	Climate change; global warming; coast; coastal; flooding; sea level rise; SLR; impacts; adaptation; mitigation; global; tourism; ecosystem.	30
Ocean acidification.	Climate change; global warming; ocean acidification; impacts; mitigation; pH; ocean; acidity; ecosystem; global; calcification.	35
Ecosystems and biodiversity	Climate change; global warming; impacts; mitigation; ecosystem; biodiversity; plants; animals; forest; coral.	194
Water resources and desertification	Climate change; global warming; impacts; mitigation; water resources; runoff; hydrology; global; water stress; desertification; drought	32
Agriculture and food security.	Climate change; global warming; impacts; mitigation; global; agriculture; crops; food; food security; CO_2 enrichment.	18
Human health.	Climate change; global warming; impacts; mitigation; global; health; mortality; infectious disease; malaria; dengue; heat; cold; extreme.	35

Searches were limited to publications with a publication date in the range 2007-2010. Results presented by the Web of Science searches were supplemented by using the “Related Records®” feature, which enhances the power of cited reference searching by searching across disciplines for all the articles that have cited references in common. Searches with the same key-words presented in **Table A2** were applied using Google and Google Scholar because unpublished government and institutional reports may not show on the results from Web of Science. We aimed to include results from only peer-reviewed journals or conference proceedings in this review, and where results are reviewed from non-published reports, we acknowledge this.

Appendix B: Expert consultation

One of the main challenges in compiling this report lay in identifying the key papers which represent significant and relevant change in understanding, and interpreting them in a balanced fashion. Although the peer-review process offers some form of quality control, to some extent the real significance of major new papers can only be judged once time has been allowed for repetition, re-interpretation and follow-up work from other research groups. However, experts in specific fields generally have the most realistic view of the potential significance and inherent uncertainties in new studies (although there can be substantial disagreement even amongst experts in the same field). Therefore, the approach for sections 2-3 of the report was to be guided as far as possible by input from experts in the individual fields. We consulted experts from both within and external to the Met Office Hadley Centre. Our approach followed three stages. First, we performed our own initial literature review (as in Appendix A) and prepared a draft outline of the results. For each field, Met Office experts were then asked to comment on and revise this outline. The outlines were then expanded into paragraph form and sent to experts external to the Met Office for a further layer of review and revision.

In consulting the experts, as well as providing them with a brief background on the Committee on Climate Change, we attached the following questionnaire:

“Please could you tell me:

- if this needs changing to make it fit for purpose (see below). In particular, have I missed key literature, or is any of my interpretation incorrect?)

- the purpose of the document: to answer the question, "what are the key changes in the relevant literature since AR4 which might affect the setting of global emissions and temperature targets?"

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