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Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications

Papers of a Theme Issue compiled and edited by Mark G. New, Diana M. Liverman, Richard A. Betts, Kevin L. Anderson and Chris C. West

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Editorial

David Garner

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Editorial

I am honoured to be the new Editor of *Philosophical Transactions of the Royal Society A*, the oldest continuously published scientific journal. During its 345 years of existence, *Philosophical Transactions of the Royal Society A* has published many articles by great scientists describing major scientific advances in a range of fields of study. The quality, relevance and impact of these articles have ensured that, throughout its lifetime, *Philosophical Transactions of the Royal Society A* has maintained a prominent position in the world's scientific literature.

The nature of scientific publishing has changed a great deal during the past decade and is currently undergoing further changes. These changes have been focused primarily on the mechanisms of 'publication' and information access. What has not changed, and will not change, is the pressure experienced by all publishers of scientific information to maximize the quality of the articles they publish, to ensure that these articles are original, timely and influential and, therefore, of interest to a significant number of fellow scientists and other readers.

The major challenge that I face as an Editor of *Philosophical Transactions of the Royal Society A* is to ensure the production of 24 issues per annum, that cover the full spectrum of the physical sciences and are consistently of a high quality. In this and other respects, I have been greatly aided by the achievements and forward planning of my predecessor Professor Sir Michael Pepper. As the incoming Editor, I wish to continue the production of dedicated Theme Issues and the involvement of Guest Editors. Also, I will try and ensure that we continue to derive benefit from the Discussion Meetings held in the Royal Society's London and Kavli premises. I wish to continue to develop a community of readers and authors who interact constructively. Therefore, I invite suggestions for ways in which we can enhance the scientific quality and value of *Philosophical Transactions of the Royal Society A*.

With the assistance, expertise and support of the Editorial Board and the Royal Society staff, I am determined to ensure that *Philosophical Transactions of the Royal Society A* remains the journal of choice for high-quality contributions that make a significant contribution to the scholarship and philosophy of science. I look forward to my role as an Editor during the next 4 years. One highlight will be to plan the issues that will be published during the 350th anniversary year of *Philosophical Transactions of the Royal Society* in 2015.

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Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications

Mark New

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PREFACE

Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications

The idea of an international symposium focused on ‘Four degrees and beyond’ germinated in late 2008 after discussions with colleagues who were concerned that there was a large gap between the emerging policy target of keeping global warming below two degrees and some of the emissions-reduction scenarios that were being proposed in both the academic and policy literature. Many emissions-policy scenarios had (i) underestimated the rate of increase of emissions in the last decade and (ii) been unrealistically optimistic about when global emissions might peak, given the time it takes to transition out of carbon-based energy systems. A pessimistic, or some might say realistic, appraisal of the slow progress of the United Nations Framework Convention on Climate Change (UNFCCC) process, also suggested that avoiding two degrees would be highly unlikely, and that the chances of warming by four degrees in this century much less unlikely than previously thought. At the same time, the Oxford-based author Mark Lynas had just published his book ‘Six degrees: our future on a hotter planet’, and he had often commented on the scarcity of any scientific literature on the nature and impacts of climate changes larger than four degrees.

So, the Four degrees and beyond conference took place in September 2009, where we asked participants to specifically address the questions of (i) how probable a warming of four degrees or higher might be, (ii) what the consequences of such a warming might be for ecosystems and society, (iii) how to adapt to such large changes, and (iv) how to keep the risk of high-end climate change as low as possible.

The papers in this Theme Issue were written by participants in the Four degrees conference, at the invitation of the editors. In many cases, authors were asked to combine their separate conference contributions into a joint paper synthesizing multiple viewpoints and results. We appreciate their enthusiasm in taking on this challenge.

Now, as we go to press with the Theme Issue a year on from the conference, the results of the research presented in its papers seem even more relevant than a year ago. We have no comprehensive climate-change ‘deal’, and Yvo de Boer, in his final remarks as head of the UNFCCC before stepping down in 2010, said that it could take up to 10 years for negotiations to deliver a robust and effective agreement. Voluntary and non-nation state emissions-reduction

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commitments might give us some breathing space, but still take us closer to four degrees than is comfortable. The papers in this issue that look at impacts and adaptation challenges in a four degrees world are sobering: the possible impacts are large, in some cases, transformational, and the challenges in understanding and developing responses to these impacts considerable. Hopefully, this Theme Issue will stimulate much-needed further research that explores the implications of and solutions to high-end climate warming.

The Four degrees conference would not have been possible without financial support from the Tyndall Centre for Climate Change Research and Oxford University's Environmental Change Institute. Similarly, Maria Mansfield was invaluable, first as conference organizer, and then as editorial assistant for the Themed Issue. My co-editors Diana Liverman, Richard Betts, Kevin Anderson and Chris West valiantly shared the load in reviewing papers, chasing revisions and making final recommendations. Lastly, thanks are due to all those who contributed to the Four degrees conference, the Editor of Philosophical Transactions A for agreeing to the idea of this Themed Issue, and Suzanne Abbot, Publishing Editor, for her support and patience throughout.

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Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications

Mark New, Diana Liverman, Heike Schroder and Kevin Anderson

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INTRODUCTION

Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications

BY MARK NEW[1,*], DIANA LIVERMAN[2], HEIKE SCHRODER[3] AND KEVIN ANDERSON[4,5]

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The 1992 UN Framework Convention on Climate Change commits signatories to preventing ‘dangerous anthropogenic interference with the climate system’, leaving unspecified the level of global warming that is dangerous. In the late 1990s, a limit of 2°C global warming above preindustrial temperature was proposed as a ‘guard rail’ below which most of the dangerous climate impacts could be avoided. The 2009 Copenhagen Accord recognized the scientific view ‘that the increase in global temperature should be below 2 degrees Celsius’ despite growing views that this might be too high. At the same time, the continued rise in greenhouse gas emissions in the past decade and the delays in a comprehensive global emissions reduction agreement have made achieving this target extremely difficult, arguably impossible, raising the likelihood of global temperature rises of 3°C or 4°C within this century. Yet, there are few studies that assess the potential impacts and consequences of a warming of 4°C or greater in a systematic manner. Papers in this themed issue provide an initial picture of the challenges facing a world that warms by 4°C or more, and the difficulties ahead if warming is to be limited to 2°C with any reasonable certainty. Across many sectors—coastal cities, agriculture, water stress, ecosystems, migration—the impacts and adaptation challenges at 4°C will be larger than at 2°C. In some cases, such as farming in sub-Saharan Africa, a +4°C warming could result in the collapse of systems or require transformational adaptation out of systems, as we understand them today. The potential severity of impacts and the behavioural, institutional, societal and economic challenges involved in coping with these

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impacts argue for renewed efforts to reduce emissions, using all available mechanisms, to minimize the chances of high-end climate change. Yet at the same time, there is a need for accelerated and focused research that improves understanding of how the climate system might behave under a +4°C warming, what the impacts of such changes might be and how best to adapt to what would be unprecedented changes in the world we live in.

Keywords: climate change; global warming; impacts; adaptation; dangerous climate change; policy

1. Introduction

The 1992 UN Framework Convention on Climate Change (UNFCCC) commits signatories to achieving a 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system', leaving unspecified the level of global warming that is dangerous [1,2]. The succession of Intergovernmental Panel on Climate Change (IPCC) assessments has progressively improved the evidence base on the potential impacts of climate change, but large uncertainties remain. These uncertainties, combined with the geographical diversity of impacts, vulnerabilities and adaptive capacities, have made it difficult to arrive at a precise temperature target.

While the 2009 UNFCCC Conference of the Parties in Copenhagen failed to deliver any formal 'climate deal', the non-binding Copenhagen Accord recognized the scientific view 'that the increase in global temperature should be below 2 degrees Celsius' [3]. The adoption of this target occurred despite increasing evidence that for at least some nations and ecosystems, the risk of severe impacts is already significant at 2°C [4]; hence, the Accord includes an intent to consider a lower 1.5°C target in 2015.

The idea of a 2°C temperature target derives partly from a convergence of two themes in the IPCC assessments. First, an accumulation of potential impacts, with increasing certainty and severity, when moving from a 2°C warming to 3°C and 4°C, suggested that many of the more serious impacts could be avoided by keeping below 2°C (for example, the 'Burning Embers', fig. SPM-2 in the IPCC 3rd Assessment WG2 Report [5]). Second, a sequence of the IPCC mid-range emission scenarios projected global temperature increases of 2°C by the end of the twenty-first century.

As early as 1996, the European Union (EU) embraced 2°C above preindustrial levels as a target that 'should guide global limitation and reduction efforts' (Environment Council 1996, cited in Jordan & Rayner [6], p. 62). This was reaffirmed in various subsequent council meetings and by countries such as The Netherlands and the UK [7]. It also became the basis for the 15 per cent reduction target for all developed countries proposed by the EU for COP3 in 1997. Tol [7] argues that the policy justification for the target was based on a narrow and uncertain set of climate and economics studies and was somewhat arbitrary. It was certainly a pragmatic choice, being both potentially achievable, at least when first considered in the late 1990s, and a catchy number. The 2°C target 'became an enduring benchmark of danger and a metric that then constrained emission and concentration targets' [2].

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In the final plenary at a scientific conference on climate change in Copenhagen in March 2009, a discussion with the Prime Minister of Denmark, Anders Rasmussen, produced an interchange that demonstrates the tensions between evolving scientific knowledge and policy decisions. When told by a scientific panel that even a 2°C target might allow too much warming, with serious damages and possible tipping points occurring below 2°C, the Prime Minister expressed frustration: 'It was a hard battle to get agreement on two degrees, a real challenge, and now you tell me it's not enough and we need less than two!'.[1]

2. Feasibility of 2°C

At the same time that science was suggesting that 2°C might not be as safe a guardrail as previously thought, there was growing evidence suggesting that dramatic emission cuts were required to have any reasonable chance of staying below the 2°C target. For example, Rogelj *et al.* [8] argued that having a 50 : 50 chance of constraining warming to 2°C would require developed countries to cut emissions by up to 80 per cent below 1990 levels by 2050, but that even the best case commitments prior to Copenhagen only resulted in a 4 per cent cut by 2020 and a 63 per cent cut by 2050. They concluded that there was 'virtually no chance of limiting warming to 2°C above preindustrial temperatures'.

The challenges involved in keeping below 2°C have if anything increased since the 2009 Copenhagen meeting. While the introduction of the 2°C and 1.5°C targets in the Copenhagen Accord is significant, it has not been underpinned by adequate action. Parties were invited to communicate voluntary targets or actions for 2020 and their base year to the Secretariat by 31 January 2010. But this did not entice any stronger reduction pledges, bringing into question the feasibility and will of large emitters to seriously aim for the 2°C target, let alone 1.5°C. At the UNFCCC negotiations in Bonn in June 2010, the first formal negotiations after Copenhagen, expectations were expressed that a legally binding agreement would not be reached before 2012 at COP17 in South Africa. Yvo de Boer, in his final remarks as head of the UNFCCC before stepping down, said that it could take up to 10 years for negotiations to deliver a robust and effective agreement [9].

In this issue, Bowerman *et al.* [10] build on earlier work [11] to illustrate clearly the importance of cumulative carbon emissions budgets as a determinant of peak global temperature. They show that a total of 1 trillion tonnes of carbon (TtC) from 1750 to 2500 will produce a 'most likely' peak warming of 2°C. Importantly, the uncertainties in carbon cycling and climate system response to atmospheric CO_2 mean that there is considerable likelihood of exceeding the most likely figure of 2°C. Bowerman *et al.* [10] also demonstrate that the relationship between cumulative emissions and peak temperature is largely insensitive to the emissions pathway; therefore, a continued steep rise of emissions after 2010, with a high peak and steep post-peak decline, can produce the same peak temperature as a flatter emissions profile, provided they both keep to a 1 TtC cumulative total. Bowerman *et al.* [10] extend their earlier work by showing the likelihood range for peak temperatures under cumulative carbon budgets arising from less aggressive emissions reduction policies: 2 and 3 TtC result in most likely peak temperatures of 3°C and 4°C over preindustrial.

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[1] http://climatecongress.ku.dk.

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Defining the cumulative budgets and associated emissions pathways required to avoid 2°C with some likelihood begs the question of whether the emissions profiles that can deliver 1 TtC are technically, economically and politically feasible. This is addressed by Anderson & Bows [12] who explore how the approximately 0.5 TtC that can still be emitted while remaining within the 1 TtC total could be apportioned between Annex 1 and non-Annex 1 nations. Any reasonable assumptions about when non-Annex 1 emissions might peak and how steeply they will be able to decline chew up most of the remaining budget, requiring Annex 1 nations to immediately and radically reduce emissions at rates steeper than have been contemplated by most previous studies. Anderson & Bows [12] conclude that keeping below 2°C is virtually impossible; it follows that the proposed 1.5°C is simply unachievable.

Other post-Copenhagen analyses tend to support Anderson & Bows' view [13–15]. For example, Rogelj *et al.* [13] show that existing pledges by developed and developing countries offer a greater than 50 per cent probability of exceeding 3°C (95% CI 2.2–5.0°C), and that existing pledges, followed by successful achievement of a halving of current emissions by 2050, result in a 50 per cent chance of exceeding 2°C (95% CI 1.2–3.2°C). Importantly, even if 2020 pledges are successful, very high rates of reduction in emissions are required to get to the 2050 emissions target.

Bowerman *et al.*'s [10] paper also addresses the issue of 'emissions floors'—where, for example, current methods of food production generate greenhouse gases that are very difficult to reduce. They show that while these might be substantial—several GtC per year—their main effect is to reduce the rate at which temperatures decline from their peak. Getting emissions down to any realistic emissions floor is 95 per cent of the battle.

While the shape of any emissions profile leading to a particular cumulative budget is not a determinant of peak temperature, it does affect the rate of warming, which is strongly correlated with peak emissions [10]. If working towards a 1 GtC cumulative emissions budget; and associated 2°C peak temperature, emissions that peak at 20 GtC per year result in a peak warming rate of 0.3°C per decade; if emissions peak at 10 GtC per year, the peak warming rate is 0.18°C per decade. These different rates of warming have important implications, discussed in more detail below.

3. Implications of policy failure

Even with strong political will, the chances of shifting the global energy system fast enough to avoid 2°C are slim [12,16]. Trajectories that result in eventual temperature rises of 3°C or 4°C are much more likely, and the implications of these larger temperature changes require serious consideration. In this issue, Betts *et al.* [17] use a series of global climate model simulations, accounting for uncertainty in key atmospheric and coupled-carbon-cycle feedbacks on climate, to explore the timings of climate change under a high-end, roughly business-as-usual scenario, IPCC SRES A1FI, where emissions have reached 30 Gt of CO_2 (8 GtC) per year by 2100. All but two of the models reach 4°C before the end of the twenty-first century, with the most sensitive model reaching 4°C by 2061, a warming rate of 0.5°C per decade. All the models warm by 2°C between 2045 and 2060. This

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supports the message that an early peak and departure from a business-as-usual emissions pathway are essential if a maximum temperature below 4°C is to be avoided with any degree of certainty.

4. What might a 4°C world look like?

That there will be large variations in spatial patterns of climate change associated with any global temperature are well established and are well summarized in the IPCC 4th Assessment [18]. Land areas warm more than the oceans, so for almost all areas of human habitation, temperature increases will exceed, frequently by more than one-and-a-half times, the global average. Temperature changes at high latitudes are projected to be especially amplified, largely owing to snow and ice albedo feedbacks; boreal summer temperatures are at least twice the global average warming, and Arctic Ocean winter temperatures warm three times faster than average. While global average precipitation is projected to increase [19], most areas that are currently arid and semi-arid are projected to dry, while the moist tropics and mid-latitudes are projected to become wetter, a signal that appears to be emerging in recent precipitation trends [20].

An important question is whether this spatial pattern of change is similar in 2°C and 4°C worlds. Sanderson *et al.* [21] explore this by comparing global climate models that warm by at least 4°C by 2100 with those that warm less rapidly under the IPCC SRES A2 emissions scenario. They show that the pattern of warming relative to global mean temperature change is very similar between the two classes of climate model, apart from during boreal summers where warming is amplified in models that warm faster. In areas where precipitation decreases, temperature increases tend to be amplified, probably owing to reduced evaporative cooling of the land surface. The broadly constant ratio of local climate change to global temperature change implies that these local changes are amplified in a 4°C world; for example, a local change of 3°C in a +2°C world (1°C greater than the global average) becomes 7.5°C in a +4°C world (3.5°C above the global average).

One of the most certain outcomes of a warmer world is an increase in global sea level, although the actual amount of sea-level rise (SLR) is rather less certain. Nicholls *et al.* [22] review recent literature on SLR, and propose that in a world that warms by 4°C by 2100, global sea level will increase between 0.5 and 2 m by the end of the century, but with rises greater than 1 m being much less likely. A warming of 4°C will also commit the world to larger SLRs beyond 2100, as the ocean equilibrates thermally to atmospheric warming; these post-2100 increases could be large should irreversible melting of the Greenland ice sheet be triggered and some level of break-up of the West Antarctic ice sheet occur [22].

There are a range of other potential thresholds in the climate system and large ecosystems that might be crossed as the world warms from 2°C to 4°C and beyond [23]. These include permanent absence of summer sea ice in the Arctic [24], loss of the large proportion of reef-building tropical corals [25], melting of permafrost at rates that result in positive feedbacks to greenhouse gas warming through CH_4 and CO_2 releases [26,27] and die-back of the Amazon forest [28]. While the locations of these thresholds are not precisely defined, it is clear that

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the risk of these transitions occurring is much larger at 4°C—and so the nature of the changes in climate we experience may well start shifting from incremental to transformative.

5. Impacts and adaptation

Prior to the 2009 '4 Degrees' conference, very few studies of impacts had explored the implications of warming of 4°C and higher [29]. Five papers in this issue attempt to redress this, looking at specific sectors: coastal impacts, tropical forests, African agriculture, water resources and human migration.

Zelazowski *et al.* [30] examine the changes in potential climatic niche for humid tropical forests under 2°C and 4°C global warming scenarios. In South America, African and Asia, large fractions of current environmental niches are lost, but there are also gains, especially on the western margins of the Congo basin, in some cases resulting in a net increase in niche area. However, the authors note that much of the area that might become suitable is already under agriculture, so the chances of successful migration of forests into these areas are either slim or, at best, rather slow.

Nicholls *et al.* [22] evaluate the range of impacts from SLR should the world warm by 4°C by 2100. They consider a SLR range from 0.5 to 2.0 m by 2100, under scenarios of no protection (abandonment) and aggressive protection, including dyke building similar to that used in The Netherlands, and shoreline nourishment. Under both scenarios, large areas and many millions of people are at risk (table 1), particularly in South and Southeast Asia. If only sparsely populated coastal regions are abandoned, most people are protected, but at considerable cost, especially for a 2 m SLR: the annual cost of enhancing and maintaining sea defences that have kept up with rising sea levels through to 2100 is $270 billion. Many of the nations most at risk from SLR—such as Bangladesh and Vietnam—will find it difficult to meet the costs of full protection without contributions from richer nations, for example, through an adaptation fund. In reality, it is likely that protection will be patchy, falling somewhere between the two extremes examined by Nicholls *et al.* [22]. Further, the risk of continued SLR after global temperatures have peaked means that many more people could be at risk, particularly if areas that are protected up to 2100 are then forced to be abandoned.

Fung *et al.* [31] look at the interactions between climate change and population-driven demand for water in 2°C and 4°C worlds. As with previous studies [32,33], they show that patterns of precipitation change from different global climate models remain uncertain over large areas. However, at a global temperature of +4°C, the spatial extent of regions exhibiting consensus between models in both the sign and magnitude of precipitation change is much greater. Further, the regions of water resources decrease show even greater agreement, mainly because enhanced evaporation in a 4°C world reduces run-off in areas where there are no significant precipitation changes. Using some simple assumptions about the relationship between demand for water and population, Fung *et al.* [31] examine water stress at 2°C and 4°C under UN populations forecasts for 2030 and 2060, showing that for most river basins, stress is maximized when the higher populations expected in 2060 coincide

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Table 1. Impacts and costs of protection to range of SLR that might be expected in a world that warms by 4°C by 2100 [22].

	0.5 m SLR		2 m SLR	
	protection	no protection	protection	no protection
area lost (km^2)		870 000		1 789 000
population displaced	41 000	72 000 000	305 000	182 000 000
cost (billions $ per annum)[a]	25		270	

[a] Incremental costs of protection, at 2100, based on present-day coastal protection cost figures.

with higher degrees of climate change. Further, in some river basins, at 4°C, climate change starts to outweigh population growth as the primary driver of water stress.

Agriculture has long been highlighted as being at risk from climate change, especially in the seasonally dry sub-tropics and tropics, where even small increases in global temperature are projected to reduce crop yields owing to combined increases in heat and water stress [34]. Much of sub-Saharan Africa (SSA) is thought to be particularly vulnerable, owing to a combination of climate change and limited adaptive capacity of small farmers. A warming of 4°C or higher will exacerbate these stresses, but also raises the question of whether particular types of agriculture become unsustainable, for example because of either intolerable frequencies of crop failure or complete loss of suitable growing conditions [35]. Thornton *et al.* [36] evaluate the potential impacts of a 5°C global temperature increase on SSA agriculture. The ensemble mean response projects drying over most of the region, apart from a small precipitation increase over parts of East Africa, resulting in large decreases in growing season length, especially (greater than 20%) in the Sahel and over most of southern Africa. Simulations of key indicator crops also show decreases in yields over the region, and pasture yields decrease everywhere, except East Africa. Of particular concern is the increase in rain-fed crop failures; for example, in much of southern Africa such failures are projected to occur once every 2 years.

Within any sector—water, agriculture, coastal flooding or ecological function—impacts are clearly amplified in a +4°C world, in many instances to the extent that climate becomes the dominant driver of change. However, as Warren [37] explains in this issue, it is important to consider the interactions between these sectors, and also with efforts to mitigate emissions. While these interactions are difficult to assess, they may result in societal impacts that are greater than the sum of individual sectoral impacts; for example, shifts to biofuel production as an alternative fuel and programmes to prevent forest conversion to agriculture may place an additional stress on food and water security.

The larger impacts on society associated with a 4°C world clearly present greater challenges for adaptation, as discussed by Stafford-Smith *et al.* [38], in this issue. First, the continued failure of the parties to the UNFCCC to agree on emissions reductions means that those planning adaptation responses have to consider a wider range of possible futures, with a poorly defined upper bound. Second, responses that might be most appropriate for a 2°C world may be maladaptive in a +4°C world; this is, particularly, an issue for decisions with a

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long lifetime, which have to be made before there is greater clarity on the amount of climate change that will be experienced. For example, a reservoir built to help communities adapt to moderate temperature increases may become dry if they continue to increase, or coastal protection designed for 2°C may be overcome at 4°C. This will require systems that are flexible and robust to a range of possible futures. Third, for some of the more vulnerable regions, a +4°C world may require a complete transformation in many aspects of society, rather than adaptation of existing activities, for example, high crop failure frequency in southern Africa may require shifts to entirely new crops and farming methods, or SLR may require the relocation of cities. Stafford-Smith *et al.* [38] argue that a range of psychological, social and institutional barriers to adaptation is exacerbated by uncertainty and long time frames, with the danger of immobilizing decision-makers, and suggest ways in which some of these barriers might be overcome.

A 4°C world also raises the bar for the long-term financing of adaptation. Estimates prior to Copenhagen (most based on 2°C scenarios) ranged from about $40 billion to $170 billion a year. Agreement was reached in Copenhagen for fast-track funding for developing countries of $10 billion a year from 2010 to 2012 and a goal of $100 billion a year in 2020—but these funds are for both adaptation and mitigation [39,40]. It is still not clear where these funds will come from and the extent to which they will be additional to current overseas development assistance; clearly, however, the severity of impacts at 4°C will require much greater investments.

An interesting dynamic emerges between the potential impacts of climate change and the rate at which climate change occurs. First, many population scenarios project that world population will peak at about nine billion in the 2050s, with the largest increases between now and then concentrated in emerging economies. Demand for food and water will rise (and possibly peak) in parallel with this. If climate warms rapidly—as might occur with a steep rise in emissions, with a high peak emissions rate, perhaps exacerbated by a post-peak reduction that fails to keep to a 1 TtC budget—a temperature of anywhere between 2°C and 4°C might be reached by the 2050s or 2060s, precisely at the time when vulnerability as a result of population demands for food and water is highest. A slower rise in temperature, and associated regional climate change, would mean that maximum climate impacts would occur after demand for food and water begins to decline in line with a shrinking population. Second, early and rapid warming reduces the time available for adaptation, particularly if, as suggested by Stafford-Smith *et al.* [38], a 4°C world will require a transformative rather than incrementalist adaptive response. Faster and more serious impacts require more resources—financial, knowledge, technical, human—for adaptation over a shorter time, and there may simply be too little resource to go round, with the least well-resourced communities 'left behind'.

6. Mitigation options outside of the UN Framework Convention on Climate Change

The lack of agreement and binding commitment among nations in Copenhagen led some to pessimism regarding the likelihood of avoiding dangerous climate change. But it also led to a renewed focus on the role and potential of *non-nation-state*

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actors (NNSAs)—regional, city and local government, the private sector, non-profit organizations and individuals—in limiting emissions and helping the world adapt to warmer temperatures [41–45].

Because cities now host the majority of the world's population, and may produce somewhere between 30 and 75 per cent of global greenhouse gas emissions [46], they have the potential to make a substantial contribution to reducing the risks of climate change—both in terms of emission reductions and as key sites for adaptation to a warmer world. Researchers have noted the discursive and material actions of major cities such as London and Los Angeles that have committed to emission reductions of 60 per cent below 1990 baseline levels by 2025 and 35 per cent below 1990 baseline levels by 2030, respectively, and developed detailed adaptation plans [47]. They also highlight the importance of networks such as 'Cities for Climate Protection' and the C40 group of global cities that share best strategies and advocate for strong climate policies that support local action [48].

In countries such as the USA, Canada and Australia, state action has often moved out in advance of federal policy with California, for example, committing to an 80 per cent cut in emissions by 2050 and adopting standards for the carbon content of products that send ripples across the USA. Also in the USA, states have developed regional carbon markets such as the Regional Greenhouse Gas Initiative (RGGI) or Western Climate Initiative (WCI) that seek to provide flexible options for conforming to regional caps on emissions. In the USA, even though the federal government has not, as yet, passed comprehensive climate legislation, more than half the population lives within a jurisdiction with a greenhouse gas emissions reduction commitment, and new automobile standards and renewable obligations are also controlling emissions [49,50].

A growing number of major corporations are also taking steps to reduce their emissions—including firms from the energy, manufacturing, mining, cement and retail sectors. While some emission cuts are to comply with government policies or to take advantage of carbon trading opportunities, others reflect pledges on corporate social responsibility or the realization that there may be market savings in low-carbon pathways and market gains from being seen as a 'green brand' [51].

A wide range of commitments and actions by NNSAs has been described, but the aggregate sum of these actions in terms of emission reductions is hard to calculate. They are likely to be insufficient alone to avoid a 2°C or 3°C climate change, but they may help to reduce the rates of global emissions growth, the peak emissions and hence the feasibility of a delayed global agreement.

7. Geoengineering: the silver bullet?

Some scientists and policy makers are now looking beyond mitigation and adaptation to the possibility that the only effective solution to climate change will be *geoengineering*. Concerned that current efforts to limit emissions are inadequate, that the risks of rapid warming are unacceptable, they are now willing to consider various interventions to alter the climate. The serious impacts of a 4°C warming and the potential of reaching irreversible or discontinuous tipping points are sometimes used to make the case for geoengineering [52].

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A report on geoengineering by the Royal Society [53] reviews most of the technologies and discusses the technical, scientific, economic, ethical and governance challenges. They conclude that although geoengineering is technically possible, there are major uncertainties, and that geoengineering provides no justification to diminish efforts in mitigation and adaptation. They evaluate technologies for their effectiveness, affordability, timeliness and safety, finding, for example, that although stratospheric aerosols are effective, affordable and timely, they are potentially less safe than afforestation or carbon removal and storage. Afforestation is considered less effective and timely, and ocean fertilization is generally seen as less effective, affordable, timely and safe than other technologies. They propose that carbon dioxide removal may be preferable, partly because it deals with the ocean acidification problem, but that solar radiation management may be necessary to respond to rapid climate change or tipping points because it may be implemented faster. With solar radiation management, there are risks that any interruption could result in a sudden rise in temperature and thus a rapid return to higher temperatures associated with high greenhouse gas concentrations. Some of the less risky approaches are those with long implementation times—during which temperatures may continue to increase, whereas a failure to sustain the shorter term technologies of solar radiation management could bring a swift rise in the temperature. The debate is likely to continue over whether the risks of temperatures as high as 4°C are so great that geoengineering research and implementation should be accelerated.

8. Research agenda for a 4°C world

Most analysts would agree that the current state of the UNFCCC process and other efforts to reduce greenhouse gases make the chances of keeping below 2°C extremely slim, with 3°C much more likely, and a real possibility of 4°C, should more pessimistic analyses come to fruition. Despite a range of research over the past few decades that has informed our understanding of climate change, there are a range of issues and questions that are particular to high-end climate change.

— Many climate scientists caution that the broadly linear response seen in many components of the climate system—ENSO, monsoon rainfall, ocean circulation—under more moderate warming may break down in a +4°C world. So, there is a need for climate model simulations that persist for many decades at 4°C or higher to explore the potential behaviour and stability of these key climate process phenomena.

— At higher temperatures, our understanding of biogeochemical feedbacks, such as Arctic methane release, ocean CO_2 drawdown, ocean floor methane hydrates and forest carbon cycles, is poor. Yet, these feedbacks are critical to putting constraints on the upper end of climate change.

— There is a need for a concerted research effort that more fully explores the impacts of high-end climate change across scales and across sectors. The papers in this issue illustrate that the magnitude of impacts is large and not necessarily linear in a +4°C world. Improved understanding of these impacts, including the existence and location of thresholds such

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as permanent crop failure, is needed to enable the sort of new thinking about adaptation that is required and to estimate the costs and needed development investments to support such adaptation.

- Research into flexible, staged approaches to adaptation that are robust to significant uncertainties is needed. We need to start designing the institutional framework that allows for integrated adaptation strategies, as well as both incremental and transformative adaptation, across sectors and also across geographical scales.
- The modelling of future emissions pathways needs to work within a cumulative budget framework, rather than stabilization of concentrations in the atmosphere. This allows for incorporation of recent and concurrent emissions data, providing a realistic launch point for emissions profiles that fit the required budgets for a particular temperature target. Further, the cumulative budget approach allows for transparent discussion of how remaining emissions can be partitioned between nations.
- Further research is needed into the effectiveness and governance of geoengineering, with careful consideration of the relative risks, costs and benefits of alternative technologies as compared with the costs and benefits of mitigation and adaptation.
- Much of the work on impacts and adaptation looks at fixed ‘time slices’ in the future, either under a specific emissions scenario or, as with papers in this issue, at a fixed temperature threshold. However, different emissions pathways leading to the same peak temperature can result in quite different warming rates, and so further exploration of the sensitivity of systems to different rates of warming is required.
- A clearer understanding of the aggregate contributions of NNSAs towards mitigation and adaptation efforts is required, and how they can be promoted and fostered alongside international and domestic efforts.

Contemplating a world that is 4°C warmer can seem like an exercise in hopelessness: accepting that we will not reduce greenhouse gases enough or in time, and laying out a difficult future for many of the world’s people, ecosystems and regions. On the one hand, the papers in this issue add urgency to the need to swiftly curb emissions, and on the other, they suggest the importance of research and investment in adaptation, and even perhaps geoengineering, in case we cannot reduce emissions or must plan for at least an overshoot period of higher temperatures [54].

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Beyond ‘dangerous’ climate change: emission scenarios for a new world

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The Copenhagen Accord reiterates the international community’s commitment to ‘hold the increase in global temperature below 2 degrees Celsius’. Yet its preferred focus on global emission peak dates and longer-term reduction targets, without recourse to cumulative emission budgets, belies seriously the scale and scope of mitigation necessary to meet such a commitment. Moreover, the pivotal importance of emissions from non-Annex 1 nations in shaping available space for Annex 1 emission pathways received, and continues to receive, little attention. Building on previous studies, this paper uses a cumulative emissions framing, broken down to Annex 1 and non-Annex 1 nations, to understand the implications of rapid emission growth in nations such as China and India, for mitigation rates elsewhere. The analysis suggests that despite high-level statements to the contrary, there is now little to no chance of maintaining the global mean surface temperature at or below 2°C. Moreover, the impacts associated with 2°C have been revised upwards, sufficiently so that 2°C now more appropriately represents the threshold between ‘dangerous’ and ‘extremely dangerous’ climate change. Ultimately, the science of climate change allied with the emission scenarios for Annex 1 and non-Annex 1 nations suggests a radically different framing of the mitigation and adaptation challenge from that accompanying many other analyses, particularly those directly informing policy.

Keywords: emission scenarios; Annex 1; non-Annex 1; cumulative emissions; climate policy; emission pathways

1. Introduction

The 2009 Copenhagen Accord [1] has received widespread criticism for not including any binding emission targets. Nevertheless, it does reiterate the international community’s commitment to ‘hold the increase in global temperature below 2 degrees Celsius, and take action to meet this objective

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consistent with science and on the basis of equity' [1].[1] The Accord does not, however, quantify the degree of mitigation required to meet this commitment nor does it give an indication of whether it is still possible to do so. Moreover, and despite making reference to being guided by the 'science', the Accord makes no mention of cumulative emissions as providing the scientifically credible framing of mitigation; preferring instead to focus on the 'peaking of global and national emissions as soon as possible' and the need for 'Annex I Parties to implement ... quantified economy-wide emissions targets for 2020'. While the inclusion of nearer-term targets is certainly a welcome complement to targets for 2050, the Accord still falls short of acknowledging what the science makes absolutely clear—it is cumulative emissions that matter.

This paper takes both the Accord's commitment to 'hold the increase in global temperature below 2 degrees Celsius' along with its focus on the nearer term targets, and considers these in light of post-2000 and recession-adjusted emission trends. Building particularly on previous analyses by Anderson & Bows [2] and more recently by Macintosh [3], the paper translates earlier global assessments of cumulative emissions into emission pathways for Annex 1 and non-Annex 1 nations. The importance of the distinction between Annex 1 and non-Annex 1 is also noted in the Accord. Specifically, the Accord recognizes 'that the time frame for peaking will be longer in developing countries' and also, very significantly, that 'social and economic development and poverty eradication are the first and overriding priorities of developing countries'.

2. Analysis framing

The first decade of the new millennium has witnessed unprecedented increases in emissions reflecting ongoing high levels of energy usage for heat, electricity and transport within Annex 1 nations coupled with the very rapid industrialization of many non-Annex 1 nations, in particular China and India. Total cumulative emissions produced by nations that underwent industrialization in the nineteenth century and first half of the twentieth century will be eclipsed if the five billion people currently resident in non-Annex 1 nations remain or become locked into a fossil fuel economy. Although included in non-mitigation energy scenarios (e.g. [4,5]), this dramatic potential for emissions growth within non-Annex 1 nations is typically neglected in global and national mitigation scenarios. By considering global emission budgets alongside emission pathways for non-Annex 1 nations, this paper illustrates the increasing relevance of the latter for the mitigation policies of Annex 1 nations.

Recent years have seen the development of an increasing number of global emissions scenarios, each with a differing quantity of cumulative emission over the twenty-first century and hence with different temperature implications (e.g. [2,3,6–10]). Alongside these global analyses a growing range of ever more detailed national-level energy and emission scenarios are being developed (e.g. [11–13]). Clearly, integrating national and global analyses is a prerequisite of understanding the scale and rate of mitigation, impacts and adaptation associated with differing levels of climate change. However, as it stands, such integration is rare with

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[1] For the purpose of this paper, it is assumed that the '2 degrees Celsius' relates to the temperature rise above pre-industrial levels; though this is not made clear in the Accord.

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little more than perfunctory correlation between national and global emission pathways. By disaggregating selected global emission pathways into Annex 1 and non-Annex 1 nations, this paper provides an improved and more contextual understanding of the extent of the mitigation challenge specifically and the adaptation challenge more generally.[2] Such analysis cannot substitute for detailed national-level assessments, but does offer clear guidance as to the scale and rate of mitigation necessary to avoid particular rises in temperature above pre-industrial levels.[3]

The paper comprises three principal analyses. The first derives pathways for CO_2 emissions consistent with reasonable-to-low probabilities of exceeding 2°C. The second explores the implications of incorporating all greenhouse gases within the scenario pathways for a similar chance of exceeding 2°C. The third considers how a slower uptake of mitigation measures combined with later emissions peaking impact on cumulative emissions and, hence, temperature.

(*a*) *Determining the 'appropriate' probability for 2°C*

The framing of the Copenhagen Accord around the importance of 'hold[ing] to … below 2 degrees Celsius' reflects the clear and long-established stances of both the European Union (EU) Commission and the UK Government. The EU maintains it 'must adopt the necessary domestic measures … to *ensure* that global average temperature increases *do not* exceed preindustrial levels by more than 2°C' [15] (emphasis added). Within the UK, the language of many Government statements suggests, if not a zero probability of exceeding 2°C, at least a very low one [16]. For example, in July 2009, the UK Government published its *UK Low Carbon Transition Plan*, in which it stated explicitly that 'to avoid the most dangerous impacts of climate change, average global temperatures *must* rise no more than 2°C' [17, p. 5] (emphasis added). The previous Secretary of State for Energy and Climate Change, Ed Miliband, subsequently reiterated this commitment, stating 'we should limit climate change to a *maximum* of two degrees' [18] (emphasis added).

Although this language is qualitatively clear, the Accord, EU and the UK do not make explicit what quantitative 'risk' of exceeding 2°C is considered 'acceptable'. Without such quantification it is not possible to derive the accompanying range of twenty-first century cumulative emissions budgets from which emission pathways can be derived. In the absence of such quantification, probabilities may be inferred based on the approach developed for the Intergovernmental Panel on Climate Change's (IPCC's) reports, whereby a correlation is made between the language of likelihood and quantified probabilities [19, p. 23]. Following this approach, the Accord's, EU's and UK Government's

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[2] Similar but less-contextual analyses also illustrate the division of global emissions between Annex 1 and non-Annex 1 nations (e.g. [14]).

[3] It is important to note that within non-Annex 1 nations there will be significant differences in peaking years and emission reduction rates between the rapidly industrializing nations (e.g. China) and regions such as sub-Saharan Africa. However, whilst China's total emissions are now higher than those from any other nation, their *per capita* emissions are around one fifth of those for the USA, and given current trends and agreements, are unlikely to succeed those in the USA in the next two to three decades (see note 17 for a discussion on cumulative *per capita* emissions).

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statements all clearly imply very low probabilities of exceeding 2°C, and even a highly conservative judgement would suggest the statements represent no more than a 5–33% chance of exceeding 2°C.[4]

If government responses to climate change are to be evidence-based or at least informed significantly by science, the argument for low probabilities is reinforced still further. The characterization of 2°C[5] as the appropriate threshold between acceptable and 'dangerous' climate change is premised on an earlier assessment of the scope and scale of the accompanying impacts. However, these have since been re-evaluated with the latest assessments suggesting a significant increase in the severity of some impacts for a 2°C temperature rise (e.g. [20,21]). Consequently, it is reasonable to assume, *ceteris paribus*, that 2°C now represents a threshold, not between acceptable and dangerous climate change, but between dangerous and 'extremely dangerous' climate change; in which case the importance of low probabilities of exceeding 2°C increases substantially.

Although the language of many high-level statements on climate change supports unequivocally the importance of not exceeding 2°C, the accompanying policies or absence of policies demonstrate a pivotal disjuncture between high level aspirations and the policy reality.[6] In part this reflects the continued dominance of 'end point' targets[7] rather than scientifically credible cumulative emission budgets and their accompanying emission pathways. However, even within nations such as the UK, where the relevant policy community (and recent legislation) align themselves closely with the science of climate change, the disjuncture remains.

The first report of the UK's Committee for Climate Change (CCC) [8] heralded a significant departure from a focus on end-point and typically long-term targets. Complementing the UK's 2050 emission-reduction target with short-term budgets, the report proceeds to describe an emissions pathway out to 2050, acknowledging explicitly the need to re-align policy with cumulative emissions rather than simplistic targets. Nevertheless, although the UK Government's framing of its climate change legislation is the first to detail emission pathways, it is still far removed from its and others' high-level commitments to 'limit climate change to a *maximum* of two degrees' [18]. As it stands the carbon budget and emission pathway now enshrined in legislation are underpinned by analysis assuming a 63 per cent probability of exceeding 2°C [8, p. 21];[8] a position that cannot be reconciled with the probabilities implied repeatedly by Government statements (i.e. at their highest 5–33% of exceeding 2°C).

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[4] At the 'less likely' end of the spectrum, the IPCC categorizes a 33 per cent probability of missing or exceeding something as 'unlikely', 10 per cent as 'very unlikely', 5 per cent as 'extremely unlikely' and 1 per cent as 'exceptionally unlikely'.

[5] Or at least the rate of increase associated with a 2°C rise by 2100.

[6] Although this paper explicitly steers away from issues of governance, there are clearly major implications for all tiers of government, and wider public and private decision making in both bringing about the scale of mitigation accompanying 2°C and responding to the impacts and associated adaptation of a failure to significantly mitigate.

[7] Typically 2050 but also, more recently, 2020.

[8] The 63 per cent probability of exceeding 2°C is an outcome of the CCC's modelling approach and relates to its global cumulative emissions budget. Given the UK budget is premised on the CCC's choice of regime for apportioning global emissions between nations, it is reasonable to describe the UK's budget as correlating with a 63 per cent chance of exceeding 2°C, albeit with the important caveat that other nations, at least collectively, do not exceed their apportioned emissions budgets.

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While the climate specialists within the CCC are aware of the implications of their analysis and conclude explicitly that 'it is not now possible to ensure with high likelihood that a temperature rise of more than 2°C is avoided' [8, p. 16], the language of many policy statements suggests such implications are not either understood or accepted. In general there remains a common view that underperformance in relation to emissions now can be compensated with increased emission reductions in the future.[9] Although for some environmental concerns delaying action may be a legitimate policy response, in relation to climate change it suggests the scale of current emissions and their relationship to the cumulative nature of the issue is not adequately understood.

From a mitigation perspective, the gap between the scientific and policy understanding of the challenge needs urgently to be addressed. What is perhaps less evident is the implication of this gap for adaptation. As it stands and in keeping with the dominant policy discourse, the framing of much of the detailed research and practice around adaptation, if guided quantitatively at all, is informed primarily by the 2°C characterization of dangerous climate change. Yet, as the impacts of rising temperatures are unlikely to be linear and also given rising temperatures are increasingly likely to be accompanied by additional feedbacks and hence further temperature rises, adaptation must consider more extreme climate change futures than those associated with 2°C [22]. This is certainly important for the transition of Annex 1's existing built environment and infrastructures. However, it is appreciably more important for the development of new built environments, infrastructures, agricultural practices and water regimes etc. within the non-Annex 1 nations, where an opportunity still exists for societies to locate in areas geographically less vulnerable to the impacts of climate change.[10]

3. Scenario pathway assumptions

Scenario approaches are increasingly used within mitigation and adaptation research for visioning alternative futures, exploring consistency, assessing plausibility and providing policy guidance [23]. These approaches vary in terms of 'backcasting' and 'forecasting', and range from top-down and quantitative through to more bottom-up and qualitative assessments. The scenario pathways developed in this paper are explicitly 'backcasting' and quantitative. They are not vision-based, but rather are premised on a cumulative emissions framing of climate change for which richer and more qualitative scenarios could be developed in terms of mitigation, impacts and adaptation. With regard to exploring the consistency of scenarios, the relative simplicity of the analysis presented here permits the connection between temperature targets and emission reductions to be readily assessed. In that sense, the scenarios are internally consistent. This

[9] This is particularly evident in the continued recourse to the implementation of future and innovative low-carbon technologies (e.g. carbon capture and storage, nuclear power, marine-based biofuels, etc.) as the principal route by which emissions reductions will be achieved; a position that cannot be reconciled with the rate of reductions implied in high-level statements on 2°C.

[10] Such geographical vulnerability will need to be considered alongside other cultural, institutional and economic factors if resilience to the impacts of climate change is to be embedded in development.

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contrasts with most, if not all, bottom-up mitigation analyses where consistency is constrained to issues of mitigation with climate related impacts typically exogenous to the analyses.[11]

(*a*) *Cumulative emission budget*

The scenario pathways developed in this paper illustrate quantitatively the scale of mitigation implied in high-level policy statements on 2°C. Moreover, and with direct reference to Annex 1 and non-Annex 1 nations, the scenario pathways demonstrate the disjuncture between such high-level statements and the emission pathways proposed by many policy-advisers and academics. The scenario pathways are all premised on a cumulative emission budget approach, building particularly on the work of Macintosh [3] and Anderson & Bows [2,24] but also on a range of wider studies [7,25,26].

While Macintosh [3] focused on CO_2-only emissions in correlating twenty-first century budgets with global mean temperatures (denoted by the CO_2 plus regime), the budgets within Anderson & Bows' analysis were for the basket of six Kyoto gases. Given there are merits and drawbacks for each of the budgetary regimes, both are considered in this paper.

(i) *The CO_2-plus regime ($C+$) and twenty-first century budgets*

The budgetary regime used by Macintosh [3] separates CO_2 emissions from non-CO_2 greenhouse gases and aerosols by applying Meinshausen *et al.*'s [7] assumptions on the net radiative forcing of the non-CO_2 components. Consequently, for a given temperature and assuming other factors remain unchanged, the cumulative budget for CO_2-only is lower than would be the equivalent CO_2e greenhouse gas value. The advantage of this regime is that non-CO_2 emissions, including aerosols, are more robustly incorporated than is possible through the coarser regimes reliant on global warming potential. However, although offering significant scientific merit, the approach poorly represents the contextual framing of emission scenarios, for example, the link between aerosol emissions and assumptions about fossil fuel combustion and rates of deforestation.

The CO_2-only budgets considered in this paper are the same as the middle and lower estimates used by Macintosh [3]. Macintosh also analysed a higher budget of 2055 $GtCO_2$ (560 GtC) as an 'outer marker' of abatement necessary for avoiding a 2°C. However, given the analysis here illustrates pathways offering an 'unlikely to extremely unlikely'[4] chance of exceeding 2°C, Macintosh's high budget is excluded from the analysis.

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[11] For example, few if any energy scenarios addressing mitigation include reductions in efficiency of thermal power stations if the temperature of cooling water rises, the potential of culturally distinct migrants to embed alternative practices into established transport and housing energy use, how drought conditions may impact energy use for desalination and grey-water recycling or the impacts of changing precipitation and temperature on biomass yields. This is not a criticism of existing bottom-up analyses, but a recognition that the range of impacts associated with different levels of climate change and differential impacts on temperature and precipitation make bottom-up analysis much more challenging, if not impossible, with regard to achieving consistency.

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The two remaining budgets, 1578 $GtCO_2$ (430 GtC) and 1321 $GtCO_2$ (360 GtC), are taken directly from Macintosh [3]. The first is informed by the Garnaut Climate Change Review's 450 ppm CO_2e stabilization scenario [27][12] and according to Macintosh [3] provides an approximate 50 per cent chance of not exceeding 2°C. The latter, according to Macintosh reflects the 'risk that climate-carbon cycle feedbacks respond earlier and more strongly than previously believed' and corresponds with a higher probability of not exceeding 2°C.[13]

(ii) *The basket of six regime* (*B6*) *and twenty-first century budgets*

The B6 regime, used previously by Anderson & Bows [2], assumes the correlation between global mean temperature and cumulative emissions of the basket of six Kyoto gases as adequate for informing policy-makers of the scale of mitigation necessary. In relation to aerosols it assumes they are both short-lived and sufficiently highly correlated with fossil fuel combustion and deforestation as to have little net impact on temperatures associated with twenty-first century low-emission scenario pathways [10].[14] Moreover, it assumes the 'CO_2 equivalence' of Kyoto gases reasonably captures the warming implications of non-CO_2 emissions from producing food for an increasing and more affluent population. Evidently, the CO_2e regime is not as scientifically robust as the CO_2-only regime, but it more appropriately captures the contextual implications of alternative emission scenario pathways.

The two CO_2e budgets within this paper are those used within Anderson & Bows [2] and represent the low (1376 $GtCO_2e$) and high (2202 $GtCO_2e$) ends of the IPCC AR4 cumulative emission range for stabilization at 450 ppmv CO_2e [29]. Currently Meinshausen's *et al.*'s PRIMAP tool [28] does not permit a direct calculation of the probability of exceeding 2°C for emission pathways that maintain a substantial and long-term emission burden. However, a coarse-level but nevertheless adequate estimate is possible if the long lived gases within the 'emissions floor'[15] are added to the 2000–2050 cumulative values.

(*b*) *Empirical data*

The continued and high level of current emissions is consuming the twenty-first century emission budget at a rapid rate. Consequently, it is necessary to use up-to-date and complete emissions data to construct future emission pathways. Within this paper data are aggregated for the latest year available from a number of different sources.

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[12] For more details see Macintosh [3].

[13] Probabilities based on Meinshausen *et al.*'s [7] model assumptions can be calculated using the PRIMAP tool [28] if the 2000–2049 emissions are known.

[14] 'Twenty-first century low-emission' scenarios are premised on low fossil fuel combustion and low deforestation rates. The probabilities related to 2°C in the B6 regime do however take into account the radiative forcing of the different emissions including aerosols based on assumptions embedded in Meinshausen's *et al.*'s PRIMAP tool for estimating probabilities of exceeding 2°C [28].

[15] Refers to the lowest level of annual emissions considered viable in the scenario. These emissions are typically related to agriculture and food production.

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(i) *Energy and industrial process emissions*

For energy and process related CO_2 emissions from 2000 until 2008, data are taken for each Annex 1 and non-Annex 1 nation from the Global Carbon Project using the Carbon Dioxide Information Analysis Centre (CDIAC) [30] and aggregated to produce an Annex 1 and non-Annex 1 total. The nationally constructed data from this source exclude CO_2 emissions from international aviation and shipping. To include these additional emissions, data are not taken from CDIAC as their bunker fuel CO_2 emission data are not disaggregated between nations and global marine bunker emissions are based on sales records that currently underestimate significantly the global greenhouse gas emission burden [31]. Instead, international aviation CO_2 for Annex 1 nations is taken from the memo submissions to the United Nations Framework Convention on Climate Change (UNFCCC) [32]. Non-Annex 1 international aviation CO_2 data are taken from the International Energy Agency [33] as non-Annex 1 nations do not submit this information to the UNFCCC. For international marine bunkers, the data have previously been subject to high levels of uncertainty [34–36]. However, a recent study by the International Maritime Organisation [37] has produced a time series for greenhouse gas emissions associated with international shipping activity. These data provide a figure for the global aggregated CO_2 and other greenhouse gas emissions between 1990 and 2007. However, the data are not disaggregated into national statistics. To estimate the proportion of international shipping CO_2 emissions split between Annex 1 and non-Annex 1 nations, an assumption is taken that shipping activity is directly proportional to each nation's proportion of global GDP. This crude method of apportionment was used previously (e.g. [36]), and given difficulties in apportioning international shipping emissions to nations [38,39], is also used here as an adequate, though inevitably coarse-level, division of emissions between Annex 1 and non-Annex 1 nations.[16]

(ii) *Deforestation and land-use change*

For deforestation and land-use change (hereafter referred to as 'deforestation') data between 2000 and 2008 carbon emissions are again taken from the Global Carbon Project Carbon Budget Update 2009 [41]. Their figures are estimated based on deforestation statistics published by the United Nations Food and Agriculture Organization [42] and a bookkeeping method up until 2005. The 2006–2008 emissions are derived from estimates of fire emissions using satellite data from the Oak Ridge National Laboratory Distributed Active Archive Center Global Fire Emissions Database in combination with a biogeochemical model [43].

(iii) *Non-CO_2 greenhouse gas data*

The non-CO_2 greenhouse gas emission data for 2000–2005 are based on the US Environmental Protection Agency (EPA) estimates [44]. For 2006 and 2007, data are taken from an interpolation between the 2005 and 2010 EPA projections.

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[16] A hybrid approach for apportioning aviation emissions between regions may provide insights into potential apportionment regimes for shipping [40].

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This dataset is identical to the one used within Anderson & Bows [2] but in this case individual national statistics are aggregated to produce the Annex 1 and non-Annex 1 totals.

(*c*) *Economic downturn*

The economic downturn of 2007–2009 had a direct impact on greenhouse gas emission growth rates, particularly those associated with energy. Although the crisis is beginning to show within 2008 emissions inventories, data were not available for either 2008–2010 bunker fuel emissions or 2009–2010 domestic fossil fuel CO_2 emissions. In the absence of such data, estimates draw on the work of Macintosh [3] and the Global Carbon Project [41]. For Annex 1 nations, fossil fuel CO_2 (excluding bunkers) is assumed to decline by 6 per cent in 2009, stabilizing at 0 per cent in 2010. Non-Annex 1 nations are assumed to exhibit 0.5 per cent decline in emissions in 2009, but given China is already reporting high levels of growth for early 2010, the 2010 growth figure is assumed to be half the recent decade's average (i.e. 2.7%). Consequently, growth in global fossil fuel CO_2 (excluding bunkers) is assumed to be −3.0 per cent in 2009 rising to 1.5 per cent in 2010. For international aviation bunkers, it is estimated Annex 1 nations' emissions declined by 2 per cent in 2008, remaining static in 2009 and 2010. Non-Annex 1 nation aviation bunkers are assumed to be stable at 2007 levels until 2009, after which they grow at 2 per cent in 2010, again half the recent decade's average. Given the international marine bunker figures are based on proportions of global GDP, the same percentage growth rates for national emission trends are applied as for Annex 1 and non-Annex 1 domestic CO_2 emissions between 2008 and 2010.

For the emissions of non-CO_2 greenhouse gases, it is assumed that their growth is also impacted by the economic downturn. However, non-CO_2 greenhouse gas emission growth rates are typically lower than those for global fossil fuel CO_2 by approximately 1–2% per year. Given the absence of recent data from the EPA, Annex 1 and non-Annex 1 non-CO_2 greenhouse gas emissions are assumed to proportionally follow the percentage change in their CO_2 counterparts. In other words, if the rate of growth halves for Annex 1 CO_2 emissions, then the rate of growth for non-CO_2 greenhouse gas emissions is also assumed to halve.

4. Scenario pathway development

Following a brief explanation of how historical and deforestation emissions are accounted for, the construction of the scenario pathways involves the following steps.

- Decide on a global cumulative CO_2 and greenhouse gas emission budget associated with a range of probabilities of exceeding 2°C.
- Construct emission pathways for the *non-Annex 1* nations with varying peak dates.
- Construct emission pathways for the *Annex 1* nations for which the cumulative emissions, when added to non-Annex 1 and deforestation emissions, do not exceed the global '2°C' cumulative budget.

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- Construct emission pathways for the non-Annex 1 nations with a 2030 peak date and more ‘orthodox’ annual reduction rates following the peak.
- Construct emission pathways for the Annex 1 nations with a 2015 peak date and ‘orthodox’ annual emission-reduction rates following the peak.
- Assess the potential future climate impact of these more ‘politically acceptable’ and ‘economic feasible’ pathways.

(*a*) *Historical emissions*

In developing emission pathways for Annex 1 and non-Annex 1 regions it is necessary to make explicit which region is deemed responsible for which emissions. While the following analysis focuses specifically on the period 2000–2100, it is important to reflect briefly on the treatment of recent historical emissions. Given temperature correlates with cumulative emissions of greenhouse gases, a case could be made for considering the responsibility for twentieth century emissions in apportioning future twenty-first century emission-space between Annex 1 and non-Annex 1 regions. However, the highly constrained emission-space now remaining for a 2–3°C rise in global mean surface temperature leaves little option but to explicitly neglect the responsibility of historical emissions in developing pragmatic twenty-first century emission profiles.[17] Getting an appropriate balance of responsibilities is a matter of judgement that inevitably will not satisfy all stakeholders and certainly will be open to challenge. As it stands, the approach adopted for this paper in which historical (and deforestation) emissions are taken to be global overheads,[18] is a pragmatic decision that, if anything, errs in favour of the Annex 1 nations.[19]

(*b*) *Deforestation emissions*

To explore the constraints on emissions from Annex 1 nations of continued growth in emissions from non-Annex 1 nations, only data for fossil fuel combustion, industrial processes and agriculture are split between Annex 1 and non-Annex 1. Deforestation emissions are treated as a global overhead and thus removed from the available emission budgets prior to developing the pathways. Such an approach could be argued to unreasonably favour non-Annex 1 nations as deforestation emissions occur within their geographical boundaries. However, given most Annex 1 countries have already deforested (emitting CO_2) it could

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[17] Factoring *twentieth* century emissions from Annex 1 nations into calculations of the ‘fair’ emission space available for Annex 1 in the *twenty-first* century would leave Annex 1 nations already in ‘emission debt’. Whilst such an outcome may have some moral legitimacy, it evidently would not provide for a politically consensual framing of emission apportionment. However, the implications of including twentieth century emissions and the concept of emission debt may guide the scope and scale of climate-related financial transfers (arguably as reparation) between Annex 1 and non-Annex 1 nations.

[18] Emissions not attributable to any specific geographical location.

[19] It is worth noting that a recent paper [45] based on analysis undertaken at Tsinghua University in Beijing makes the case that ‘reasonable rights and interests should be strived for, based on the equity principle, reflected through cumulative emissions *per capita*’. Building on this *cumulative emissions per capita* approach, the authors demonstrate how China’s historical cumulative emissions are only one-tenth of the average in industrial countries and one-twentieth that of the USA.

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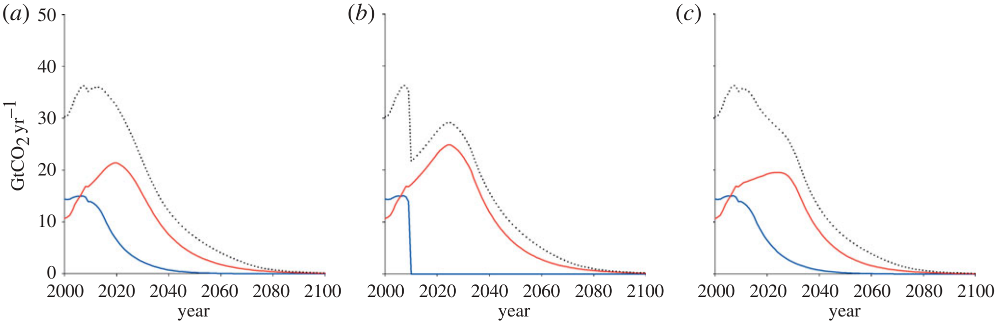

Figure 1. CO_2 scenarios for approximately 37% chance of not exceeding 2°C. All scenario pathways ((*a*) C+1, (*b*) C+2, (*c*) C+3) are for the same cumulative twenty-first century CO_2 budget of 1321 $GtCO_2$ (blue line, Annex 1; red line, non-Annex 1; dotted line, global including deforestation).

also be considered unreasonable to ascribe all of the non-Annex 1 deforestation emissions solely to non-Annex 1 nations. The global overhead approach applied here does not absolve non-Annex 1 nations of responsibility for deforestation emissions, as their available budget for energy-related emissions, along with the budget for Annex 1 nations' energy emissions, will be reduced as a consequence of the emissions from deforestation. The deforestation scenario used throughout the paper is taken as an average of the two scenarios used within Anderson & Bows [2], but updated to include the most recent emission estimates provided by the Global Carbon Project [41]. The original Anderson and Bows scenarios were optimistic compared with scenarios within the literature; the updated estimate used for this paper (266 $GtCO_2$ over the twenty-first century) continues in this optimistic vein.

(*c*) *CO_2 plus* (*C+*)

All C+ scenario pathways take the development of emissions within the non-Annex 1 nations as the starting point and then build a related Annex 1 emission pathway that holds CO_2 emissions within the chosen budget. While non-CO_2 greenhouse gases are not included in the C+ scenario pathway, CO_2 emissions associated with international bunkers and deforestation are included. The first three scenario pathways (C+ pathways 1–3 shown in figure 1) use the lowest CO_2 budget from Macintosh [3]. The second three (C+ pathways 4–6 in figure 2) use the mid-level CO_2 budget from the same paper.

C+1 assumes non-Annex 1 emission growth continues at lower than economic downturn rates from 2010 to 2015 (3% per year) and that emissions peak in 2020. For global emissions to remain within the budget, Annex 1 nations are assumed to reduce their emissions from 2011 onwards towards virtually complete decarbonization by 2050. Despite such significant reductions in Annex 1 nations (approx. 11% per year), non-Annex 1 nations' emissions still need to decline at 6 per cent per year following their peak in 2020 if global emissions are to remain within the cumulative budget. This scenario pathway results in a 56 per cent reduction from 1990 levels in emissions for Annex 1 nations by 2020, 98 per cent by 2050. Non-Annex 1 nations increase their emissions to 71 per cent higher than

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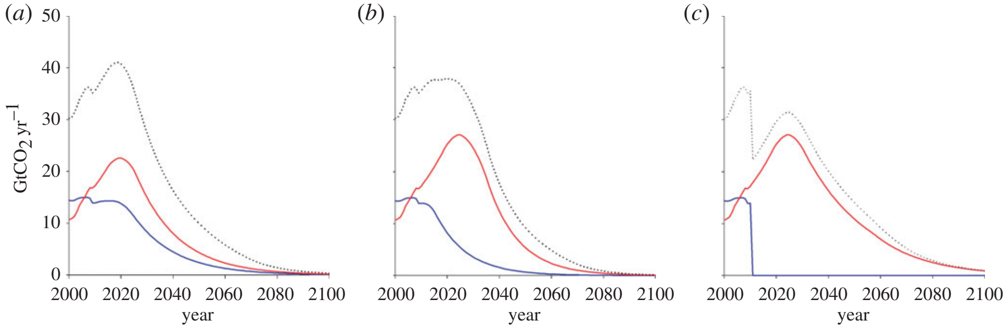

Figure 2. CO_2 scenarios for approximately 50% chance of not exceeding 2°C. All scenario pathways ((*a*) C+4, (*b*) C+5, (*c*) C+6) are for the same cumulative twenty-first century CO_2 budget of 1578 $GtCO_2$ (blue line, Annex 1; red line, non-Annex 1; dotted line, global including deforestation).

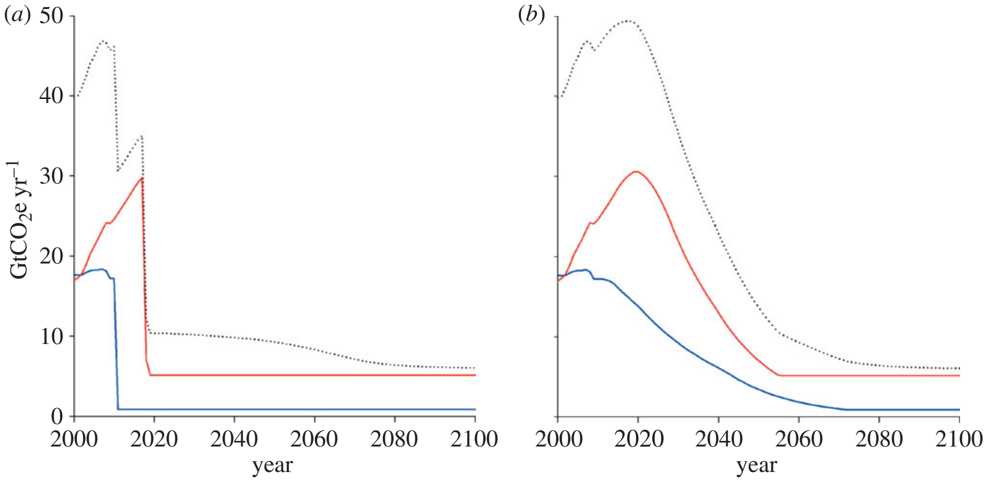

Figure 3. Kyoto gas scenarios for approximately 39–48% chance of not exceeding 2°C ((*a*) B6 1 not viable). For (*b*) B6 2, the cumulative twenty-first century CO_2e budget is 2202 $GtCO_2e$ (blue line, Annex 1; red line, non-Annex 1; dotted line, total including deforestation).

1990 levels by 2020 and then reduce them to 76 per cent below 1990 levels by 2050. Using the PRIMAP tool developed by Meinshausen *et al.* [7,28] this scenario pathway is estimated to have a 36 per cent[20] probability of exceeding 2°C.

Following the same approach, C+2 has non-Annex 1 emissions continuing to grow at a lower than pre-economic downturn rate until 2020 (3% per year), and peak in 2025. However, if this is the case, non-Annex 1 nations use the entire carbon budget and leave no emission budget for Annex 1 nations. Thus, this scenario pathway is not compatible with the lower of the cumulative carbon budgets.[21]

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[20] PRIMAP provides a range of probabilities and a 'best estimate' using cumulative emissions between 2000 and 2049. Here, 'best estimates' are presented; probabilities may vary slightly for the same twenty-first century budget, owing to differences in the 2000–2049 emissions.

[21] Given it is not possible to have an immediate cessation of emissions from all Annex 1 nations.

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To explore the potential of providing for more acceptable reduction rates while still offering a ‘reasonable’ chance of not exceeding 2°C, C+3 assumes non-Annex 1 nations’ emissions grow at a much reduced rate (1% per year) until 2025. Given this, and if Annex 1 emissions begin to reduce immediately (as in C+1), non-Annex 1 nations’ emissions must still reduce at 7–8% per year after the peak date in order for global emissions to remain within the cumulative budget. Following the dip in emissions owing to the economic downturn, and as a result of a step-change in emission growth from non-Annex 1 nations, global emissions peak in 2011 and Annex 1 nations’ future emissions do not grow any higher than current levels. This plausible but highly unlikely scenario has a 37 per cent chance of exceeding 2°C according to PRIMAP [28].

The next three scenario pathways (figure 2) use the higher budget of 1578 $GtCO_2$ within Macintosh [3]. C+4 assumes non-Annex 1 nation emissions grow at 4 per cent per year until 2015 peaking in 2020. The Annex 1 nations have more room to grow in early years than in C+1, but are assumed to reach a peak by 2015. Global emissions thus peak in 2019 with Annex 1 emissions 6 per cent below 1990 by 2020 and 84 per cent by 2050. Non-Annex 1 emissions are 186 per cent above 1990 levels in 2020 and 45 per cent below them by 2050. Global emissions are 67 per cent below 1990 by 2050. Both Annex 1 and non-Annex 1 emissions are assumed to decline post-peak at 5–6% per year. This scenario pathway has an estimated 50 per cent chance of exceeding 2°C according to PRIMAP [28].

C+5 again uses the higher budget within Macintosh [3] but assumes non-Annex 1 emissions to continue to grow at 4 per cent per year rates until 2020, and peak in 2025 with a rapid decline to a maximum of 7–8% per year. To remain within budget, Annex 1’s emissions peak by 2010 and decline at 7–8% per year. Within this scenario pathway, global emissions are broadly flat between 2014 and 2022, although emissions are highest in 2020. Thus the penalty for a five year delay in the non-Annex 1 peak date is an additional 2 per cent per year on top of the emission reduction rate for both Annex 1 and non-Annex nations, in addition to an immediate Annex 1 reduction. C+5 has a 52 per cent chance of exceeding 2°C. C+6 uses the same higher budget but illustrates that if reductions are lower, at 4–5% per year for non-Annex 1 nations following the peak date, no emission space is available for Annex 1 nations.

(*d*) *Basket of six scenario pathways* (*B6*)

In a similar approach to the C+ pathways, all B6 pathways (figures 3 and 4) take the development of emissions within the non-Annex 1 nations as the starting point and then build a related Annex 1 emission scenario pathway that must, in this case, keep total greenhouse gas emissions within the chosen budget. The significant difference between the B6 and the C+ pathways is that the given emission budget is assumed to apply to the full basket of 6 greenhouse gases mirroring the approach taken in Anderson & Bows [2]. In addition to considering the effect of non-CO_2 greenhouse gases contributing to the overall budget, an essential difference is the requirement for significant emissions space post-2050 to allow for greenhouse gas emissions (specifically N_2O and CH_4) associated with food production for an approximate 9.2 billion global population (based on UN

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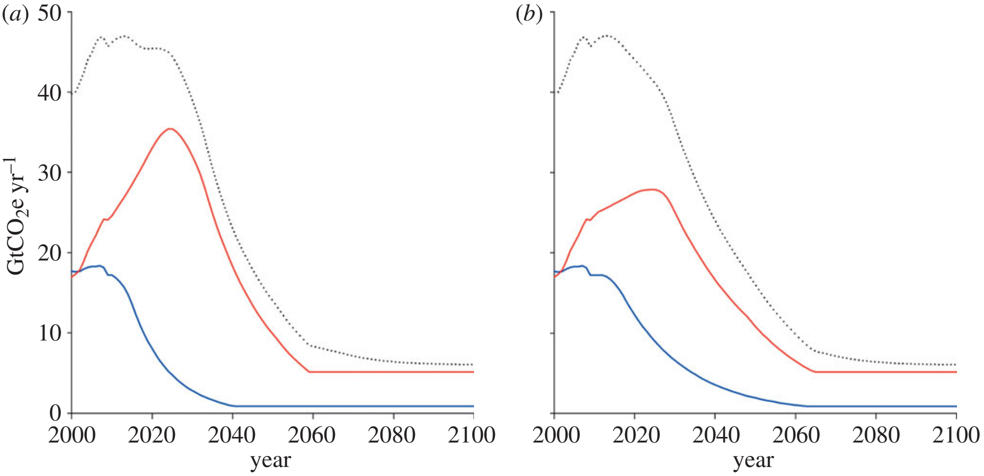

Figure 4. Kyoto gas scenarios for approximately 38–48% chance of not exceeding 2°C ((*a*) B6 3, (*b*) B6 4). The cumulative twenty-first century CO_2e budget is 2202 $GtCO_2e$. Blue line, Annex 1; red line, non-Annex 1; dotted line, total including deforestation.

median estimate for 2050 [46]). In an update to the previous Anderson & Bows [2] study, the assumed minimum level of greenhouse gas production related to food is more optimistic still at 6 $GtCO_2e$ per year as opposed to 7.5 $GtCO_2e$ per year. This is in line with the value chosen by the UK [8] and results in an estimated 0.67 tCO_2e per person from 2050 onwards for food-related non-CO_2 greenhouse gases compared with an approximate figure of 0.95 $GtCO_2e$ per person for 2010 [44,46]. Assuming by 2050 there are 7.9 billion people in non-Annex 1 nations, and 1.3 billion in Annex 1 nations [46], and assuming food consumption is more evenly balanced between Annex 1 and non-Annex 1 nations than currently, this would allow approximately 5.1 $GtCO_2e$ as a minimum annual greenhouse gas emission for non-Annex 1 nations and 0.86 $GtCO_2e$ per year for Annex 1 nations.

B6 1 uses the IPCC ‘low’ emission budget and assumes that between 2010 and 2015 non-Annex 1 emissions grow at slightly lower (3% per year) than pre-economic downturn rates and peak by 2020 (figure 3). Given the food-related non-CO_2 greenhouse gases post-2050, emissions from 2017 onwards for non-Annex 1 nations must tend immediately towards the emissions floor of 5.1 $GtCO_2e$. In other words, this scenario pathway is not viable.

B6 2 makes identical assumptions to B6 1 but for the ‘high’ IPCC emission budget (figure 3). The additional space allowed leads to a viable scenario pathway, where non-Annex 1 emissions peak in 2020, while Annex 1 nation emissions decline from 2010 onwards. Emission reductions for non-Annex 1 nations in this case are 6 per cent per year, while for Annex 1 they gradually build from around 3 per cent per year for 2015 to 2020 to 6 per cent later in the century. The PRIMAP tool to estimate the probability of exceeding the 2°C threshold assumes the vast majority of emissions are released pre-2050 (fig. 2 in [7]). Given that within the B6 scenario pathways there is a substantial cumulative emission total for the post-2050 emissions (with at least 300 $GtCO_2e$ from greenhouse gases associated with

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food production), inputting the 2000–2049 cumulative total for each B6 scenario into PRIMAP will result in an underestimate of the probability of exceeding 2°C. To account for this underestimate, an alternative probability is calculated assuming the following.

- The shorter-lived nature of methane compared with N_2O results in a negligible impact on post-2050 warming from methane.[22]
- N_2O and methane each account for approximately 50 per cent of the non-CO_2 greenhouse gases post-2050 (Smith, personal communication).
- The amount of non-CO_2 greenhouse gas emissions released per year possible post-2050 is 6 $GtCO_2e$ (in line with assumptions made by the UK CCC [8]) of which 3 $GtCO_2e$ per year is from N_2O.
- Thus 150 $GtCO_2e$ of cumulative emissions are added to the pre-2050 emissions to estimate an alternative probability.

If 150 $GtCO_2e$ is added to the cumulative emission total for each scenario, PRIMAP estimates an approximate ten percentage point increase in probability of exceeding 2°C (see table 1, figure is in brackets). For example, B6 2 has at least a 39 per cent chance of exceeding 2°C and is potentially as high as 48 per cent.

Both B6 3 and B6 4 take the IPCC's 'high' cumulative budget as a constraint. B6 3 assumes non-Annex 1 nation emissions peak in 2025 following a growth of 3 per cent per year between 2010 and 2020 (figure 4). With steep emission reductions for non-Annex 1 nations post-peak of 6 per cent per year, Annex 1 nations would need to reduce emissions from 2010 onwards at more than 10 per cent per year to remain within the high IPCC cumulative budget. More gradual reductions in emissions from non-Annex 1 nations would render this scenario pathway impossible. B6 3 has the same probability of exceeding 2°C as B6 2.

B6 4 mirrors the assumptions within C+3, with considerably slower growth of 1 per cent per year until a peak date in 2025 (figure 4). The emission reductions post-peak for non-Annex 1 nations are 4–5% per year, whereas for Annex 1 nations, following a levelling off of emissions until 2014, emissions decrease at 6 per cent per year. This scenario pathway has at least a 38 per cent probability of exceeding 2°C, and potentially as high as 47 per cent once post-2050 emissions are factored in.

(e) *Orthodox scenario pathways*

The final scenario pathways developed are unconstrained by a particular emission budget (figure 5). For both the C+ and B6 regimes, pathways are constructed that assume non-Annex 1 nations' emissions continue to develop along their current trajectory until 2025, peaking in 2030, then reducing at

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[22] This is an explicitly conservative assumption and results in slightly higher probabilities of not exceeding 2°C than would be the case if some allowance were to be made for post-2050 emissions of methane.

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Table 1. Summary of scenario pathway characteristics.

scenario pathway	global 21st century CO_2 or greenhouse gas budget in $GtCO_2$ or [$GtCO_2e$]	Annex 1 peak date/21st century cumulative emissions in $GtCO_2$ or [$GtCO_2e$]	non-Annex 1 peak date/21st century cumulative emissions in $GtCO_2$ or [$GtCO_2e$]	global peak date	Annex 1 % reduction on 1990 levels by 2020 (2050)	non-Annex 1 % reduction on 1990 levels by 2020 (2050)	post-peak Annex 1 rate of reduction	post-peak non-Annex 1 rate of reduction	post-peak global rate of reduction (includes deforestation)	approximate % of exceeding 2°C (based on 2000–2049 emissions using PRIMAP)
C+1	1321	2007 313	2020 742	2012	56% (98%)	+1714% (54%)	10–11%	6–7%	6–7%	36%
C+2[a]	1321	2007 139	2025 916	2007	100% (100%)	+193% (27%)	—	6–7%	6–7%	
C+3	1321	2007 313	2025 742	2007	56% (98%)	+143% (54%)	10–11%	7–8%	7–8%	37%
C+4	1578	2007 532	2020 780	2019	6% (84%)	+186% (45%)	5–6%[b]	5–6%	5–6%	50%
C+5	1578	2007 363	2025 949	2020	44% (95%)	+220% (32%)	8%	7–8%	7–8%	52%
C+6[a]	1578	2007 153	2025 1159	2024	100% (100%)	+220% (+38%)	—	4–5%	4–5%	—
B6 1[a,c]	[1376]	2007 [265]	2017 [841]	2017	95% (95%)	61% (61%)	—	—	—	—
B6[c] 2	[2202]	2010 [639]	2020 [1293]	2017	25% (82%)	+135% (46%)	4–6%	5–6%	3%	39% (48%)[d]
B6[c] 3	[2202]	2007 [429]	2025 [1503]	2013–2018	57% (95%)	+154% (24%)	8–10%	6–7%	4–5%	39% (48%)[d]
B6[c] 4	[2202]	2007 [552]	2025 [1380]	2013	34% (90%)	+111% (17%)	6%	4–5%	4–5%	38% (47%)[d]
orthodox C+	2741	2015 [729]	2030 1747	2027	2% (60%)	+223% (+163%)	3%	3%	3%	88%
orthodox B6	[3662]	2015 [891]	2030 [2501]	2028	5% (62%)	+180% (128%)	3%	3%	3%	88% (92%)[d]

[a] These scenario pathways are not viable as they could not remain within the carbon budget prescribed.

[b] This is the reduction rate following the period of relatively stable emissions until 2016.

[c] All B6 scenario pathways assume an ‘emission floor’ of $6GtCO_2e$ for food-related emissions for an approximate 9 billion population post-2050 until 2100. If a different ‘emission floor’ were to be used, emission reduction rates would be altered for the same cumulative values.

[d] The figure in brackets illustrates a higher probability to take into account the ongoing emissions associated with food production as opposed to greenhouse gas emissions tending to zero.

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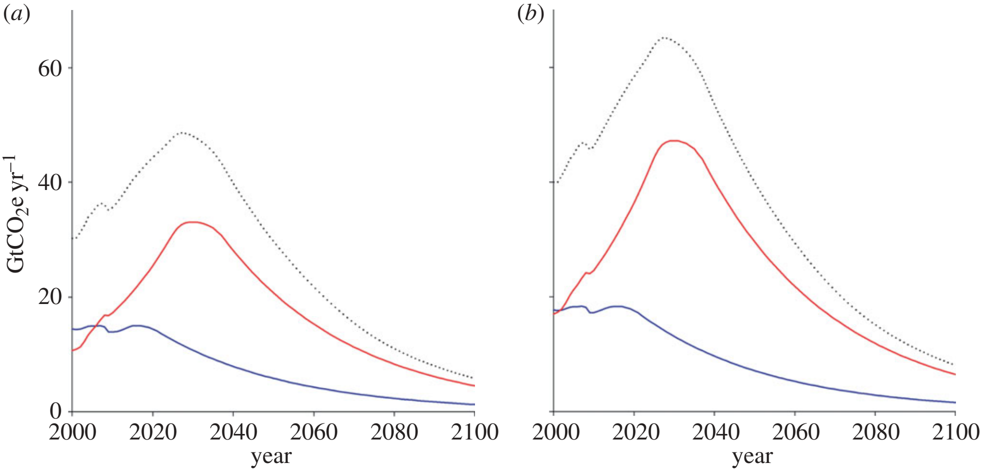

Figure 5. Emission scenarios for approximately 88–92% chance of not exceeding 2°C. Both plots illustrate 'orthodox' mitigation pathways with (*a*) C+ for CO_2 only (twenty-first century cumulative emissions: 2741 $GtCO_2$) and (*b*) B6 for Kyoto gases (twenty-first century cumulative emissions: 3662 $GtCO_2e$). Blue line, Annex 1; red line, non-Annex 1; dotted line, total including deforestation.

a rate considered politically and economically acceptable[23] (3% reduction per year). For the Annex 1 nations, emissions are assumed to be relatively stable with a peak in 2016 and subsequent emission reductions of 3 per cent per year. These scenario pathways both result in an 88 per cent chance of exceeding the 2°C threshold (potentially 92% for orthodox B6). Furthermore, their twenty-first century cumulative budgets suggest the future temperature increase compared with pre-industrial times is more likely to be of the order of 4°C rather than 2°C.

For orthodox C+, cumulative emissions of CO_2 alone are 2,741 $GtCO_2$. Cumulative emissions of approximately 2700 $GtCO_2$ are associated with stabilization of 550 ppmv CO_2. Figures in excess of 3500 $GtCO_2e$ can be assumed to be closer to the 750 ppmv range. Orthodox B6 has cumulative emissions of greenhouse gases of 3662 $GtCO_2e$, thus a reasonable probability of exceeding 4°C.

5. Discussion

(*a*) *CO_2 plus* (*C+*)

Although six C+ pathways were developed in the previous section, two were rejected for exceeding the constraints on cumulative CO_2 budgets related to the 2°C temperature threshold. One exceeded the lower of the two chosen

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[23] The pathway of the CCC's [8] most challenging scenario, '2016:4% low', has post-peak emissions reducing at 3.5 per cent per year from all sources. Stern [6] states 'there is likely to be a maximum practical rate at which global emissions can be reduced' pointing to 'examples of sustained emissions cuts of up to 1 per cent per year associated with structural change in energy systems' and that 'cuts in emissions greater than this (1%) have historically been associated only with economic recession or upheaval'. Stern concludes 'it is likely to be difficult to reduce emissions faster than around 3 per cent per year' [6, pp. 201–204]. The most stringent of the ADAM scenarios assumed emission reduction rates of approximately 3 per cent per year between a 2015 peak and 2050 [47 fig. 2, p. 32].

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budgets (approx. 37% of not exceeding 2°C) owing to non-Annex 1 emissions both continuing with recent growth rates out to 2020 and peaking in 2025. The other surpassed the higher of the two cumulative budgets (approx. 50% of not exceeding 2°C) because, in addition to the emissions growth and peak years, post-peak emission reductions of 4–5% per year were insufficient to stay within the cumulative budget. Those pathways remaining within the lower budget required an immediate and rapid decline in Annex 1 emissions and an early peak in non-Annex 1 emissions, unless the latter's emission growth was constrained to rates much lower than historical trends (i.e. to 1%, compared with current growth of 3–4% per year [48]). In all cases, Annex 1 emissions continue to decline following the current economic downturn at rates in excess of 5 per cent per year. Given these pathways explicitly exclude non-CO_2 greenhouse gas emissions, the rates of reduction for CO_2 presented in table 1 illustrate the change necessary within the energy system primarily. Furthermore, figures 1 and 2 illustrate the need for complete decarbonization of the Annex 1 energy system by around 2050. For the higher (approx. 50%) chance of not exceeding 2°C, figure 2 and table 1 illustrate that a 5 year delay in the peak year for non-Annex 1 nations (from 2020 to 2025) forces a 2 per cent increase in reduction rates globally in addition to an immediate emission reduction for Annex 1 nations.

(*b*) *Basket of six* (*B6*)

When developing the B6 pathways (figures 3 and 4), it became apparent immediately that the 'low' IPCC cumulative emission value was not viable if non-Annex 1 emissions peak as late as 2020. Consequently, the minimum probability of not exceeding the 2°C threshold achievable in this scenario pathway set is 38 per cent. Moreover, given a significant portion of emissions are attributable to food production post-2050, this probability is likely to be a significant underestimate, with a more probable figure closer to 48 per cent. This result is in line with the scenario pathway analysis within Anderson & Bows [2]. For the IPCC's 'high' end of the range, emission reductions of 6 per cent per year for both Annex 1 and non-Annex 1 nations are necessary if non-Annex 1 emissions continue at recent growth rates and peak in 2020. However, if these rates are sustained for a further five years (i.e. to 2025), and non-Annex 1 post-peak reductions are 6 per cent per year or less, no emissions space remains for Annex 1 nations. Even if non-Annex 1 emissions grow at much slower rates to a 2025 peak, post-peak emission reductions of 4–5 per cent per year are still needed from the aggregate of all nations. Therefore, under the IPCC's higher budget, all viable scenario pathways exhibit emission reduction rates well in excess of those typically considered to be politically and economically feasible.

(*c*) *Orthodox*

In light of the recent Copenhagen negotiations, there continues to be an absence of any meaningful global action to mitigate emissions or set binding targets. Even if Annex 1 nations agree on the scale of necessary emission reductions, it is more

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probable that non-Annex 1 nations will set targets based on levels of carbon or energy intensity improvements. Although these will go some way towards addressing future high-carbon lock-in, it is unlikely that emission growth rates will be significantly moderated during the coming decade. To explore the implications of this, the two orthodox scenario pathways paint a picture of ongoing non-Annex 1 emission growth, slow action to mitigate emissions on the part of Annex 1 nations, and then sustained emission reductions at rates considered politically and economically feasible. Resulting cumulative emissions, while still within the bounds of possibility of not exceeding the 2°C threshold (8–12% chance), are more closely aligned with much higher climate change futures associated with at least 3–4°C of warming.

(*d*) *Simple and complex scenarios*

The scenarios developed in this paper are relatively contextual[24] and as such complement the wealth of scenarios from more non-contextual integrated assessment models.[25] However, while it may be argued that the latter approach benefits from greater internal consistency and more theoretically coherent parameters, the outputs are typically removed from the political and empirical reality within which responses to climate change are developed. For example, recent overviews of scenarios generated by a range of different international integrated assessment modelling communities [10,14] illustrate the non-contextual framing that typifies much of this form of analysis. Of the principal 450 ppmv scenarios reviewed, the majority had a global emissions peak in 2010, this despite irrefutable evidence to the contrary [48].[26] Over a third factored in negative emissions through the inclusion of geo-engineering in the form of ‘biomass with carbon capture and storage’ (CCS) technologies. These bio-CCS scenarios all included wider CCS facilities, yet were without detailed analysis of potentially significant constraints on storage capacity.[27] At least half of the scenarios relied on significant levels of ‘overshoot’ (between 500 and 590 ppmv CO_2e)[28] and

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[24] Though constrained explicitly to consider top-down emissions only with coarse high-level divisions between food, deforestation, energy and industrial processes.

[25] Bottom-up and built on typically idealized inputs with only limited regard for ‘real-world’ constraints.

[26] While Köne & Büke’s [48] paper was published after many of the scenarios referred to, the overarching data and trend lines underpinning Köne and Büke’s analysis were available at the time many of the scenarios were developed.

[27] The inclusion of bio-CCS also demonstrates a degree of non-contextual engagement with technology. Aside from the considerable bio-energy debate surrounding the sustainability of biofuels, no CCS power plants have yet being built and consequently large-scale CCS remains a theoretical possibility with no operating experience of capture rates (though many of the component processes have undergone testing). Given the many unknowns around bio-CCS, it is perhaps surprising they are central to so many scenarios. This non-contextual approach to technology extends to nuclear power, included as a ‘key energy supply technology’ in all but one of the 450ppmv scenarios reviewed. Whilst sufficient uranium exists for moderate increases in conventionally fuelled reactors, significant ramping up of nuclear capacity is likely to require fast breeder reactors with major challenges associated with their widespread introduction; here too the integrated assessment modelling approach typically treats these wider concerns as exogenous and resolvable.

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several assumed fossil fuel CO_2 emissions from non-Annex 1 nations would exceed those from Annex 1 as late as 2013–2025 [14], despite the actual date being around 2006.[29]

The non-contextual framing of many complex modelling approaches (including integrated assessment modelling), allied with their inevitable opaqueness and often abstract and implicit assumptions, leaves space for the simpler, more transparent and contextual approach to scenarios presented in this paper. Making explicit the implications of particular assumptions (such as peak emission dates or very low probabilities of exceeding 2°C) provides insights that not only are intelligible to wider stakeholders and decision-makers, but can also provide ‘contextual’ parameters and constraints to more complex modelling approaches.

(*e*) *Development on the authors’ 2008 paper*

Two years on from earlier analysis by Anderson & Bows [2], only the global economic slump has had any significant impact in reversing the trend of rising emissions. However, with Annex 1 and non-Annex 1 nations returning rapidly to their earlier economic and emissions trajectories and with the failure of Copenhagen to achieve a binding agreement to reduce emissions in line with 2°C, the prospects for avoiding dangerous climate change, if they exist at all, are increasingly slim. Furthermore, disaggregating global into Annex 1 and non-Annex 1 emission pathways only serves to exacerbate the scale of this disjuncture between the rhetoric and reality of mitigation. In both these regards and with the continued high-level reluctance to face the real scale and urgency of the mitigation challenge, the conclusions arising from this paper are significantly bleaker than those of the authors’ 2008 paper.

6. Conclusions

Over the past five years a wealth of analyses have described very different responses to what, at first sight, appears to be the same question: *what emission-reduction profiles are compatible with avoiding ‘dangerous’ climate change?* However, on closer investigation, the difference in responses is related less to different interpretations of the science underpinning climate change and much more to differing assumptions related to five fundamental and contextual issues.

(1) What delineates dangerous from acceptable climate change?
(2) What risk of entering dangerous climate change is acceptable?
(3) When is it reasonable to assume global emissions will peak?
(4) What reduction rates in post-peak emissions is it reasonable to consider?
(5) Can the primacy of economic growth be questioned in attempts to avoid dangerous climate change?

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[28] Overshoot scenarios remain characterized by considerable uncertainty and are the subject of substantive ongoing research (e.g. [49,50]).

[29] Within the integrated assessment modelling scenarios referred to, the division related to Annex B regions. For all practical purposes aggregated emissions related to Annex 1 are the same as those for Annex B.

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While (1) and, to a lesser extent, (2) are issues for international consideration,[30] the latter three have pivotal regional dimensions that, at their most crude level, can be understood in relation to Annex 1 and non-Annex 1 emission profiles.

In relation to the first two issues, the Copenhagen Accord and many other high-level policy statements are unequivocal in both their recognition of 2°C as the appropriate delineator between acceptable and dangerous climate change and the need to remain at or below 2°C. Despite such clarity, those providing policy advice frequently take a much less categorical position, although the implications of their more nuanced analyses are rarely communicated adequately to policy makers. Moreover, given that it is a 'political' interpretation of the severity of impacts that informs where the threshold between acceptable and dangerous climate change resides, the recent reassessment of these impacts upwards suggests current analyses of mitigation significantly underestimate what is necessary to avoid dangerous climate change [20,21]. Nevertheless, and despite the evident logic for revising the 2°C threshold,[31] there is little political appetite and limited academic support for such a revision. In stark contrast, many academics and wider policy advisers undertake their analyses of mitigation with relatively high probabilities of exceeding 2°C and consequently risk entering a prolonged period of what can now reasonably be described as extremely dangerous climate change.[32] Put bluntly, while the rhetoric of policy is to reduce emissions in line with avoiding dangerous climate change, most policy advice is to accept a high probability of extremely dangerous climate change rather than propose radical and immediate emission reductions.[33]

This already demanding conclusion becomes even more challenging when assumptions about the rates of viable emission reductions are considered alongside an upgrading of the severity of impacts for 2°C. Within global emission scenarios, such as those developed by Stern [6], the CCC [8] and ADAM [47], annual rates of emission reduction beyond the peak years are constrained to levels thought to be compatible with economic growth—normally 3 per cent to 4 per cent per year. However, on closer examination these analyses suggest such reduction rates are no longer sufficient to avoid dangerous climate change. For example, in discussing arguments for and against carbon markets the CCC state 'rich developed economies need to start demonstrating that a low-carbon economy is possible and compatible with economic prosperity' [8, p. 160]. However, given the CCC acknowledge 'it is not now possible to ensure with high likelihood that a temperature rise of more than 2°C is avoided' and given the view that reductions in emissions in excess of 3–4% per year are not compatible with economic growth, the CCC are, in effect, conceding that avoiding dangerous (and even extremely dangerous) climate change is no longer compatible with economic prosperity.

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[30] Regions can evidently identify what may constitute dangerous within their geographical boundaries, but given many impacts (and the responsibility for them) extend well beyond such boundaries any regional assessment needs to be within the context of a more global perspective.

[31] If the impacts are to remain the principal determinant of what constitutes dangerous, then would it be more reasonable to characterize '1°C as the new 2°C'?

[32] Assuming the logic for the 2°C characterization of what constitutes dangerous still holds.

[33] With policies themselves lagging even further behind in terms of both actual reductions achieved or planned for.

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In prioritizing such economic prosperity over avoiding extremely dangerous climate change, the CCC, Stern, ADAM and similar analyses suggest they are guided by what is *feasible*.[34] However, while in terms of emission reduction rates their analyses favour the 'challenging though still feasible' end of orthodox assessments, the approach they adopt in relation to peaking dates is very different. All premise their principal analyses and economic assessments on the 'infeasible' assumption of global emissions peaking between 2010 and 2016; a profound departure from the more 'feasible' assumptions framing the majority of such reports. The scale of this departure is further emphasized when disaggregating global emissions into Annex 1 and non-Annex 1 nations, as the scenario pathways developed within this paper demonstrate.

Only if Annex 1 nations reduce emissions immediately[35] at rates far beyond those typically countenanced and only then if non-Annex 1 emissions peak between 2020 and 2025 before reducing at unprecedented rates, do global emissions peak by 2020. Consequently, the 2010 global peak central to many integrated assessment model scenarios as well as the 2015–2016 date enshrined in the CCC, Stern and ADAM analyses, do not reflect any orthodox 'feasibility'. By contrast, the logic of such studies suggests (extremely) dangerous climate change can only be avoided if economic growth is exchanged, at least temporarily, for a period of planned austerity within Annex 1 nations[36] and a rapid transition away from fossil-fuelled development within non-Annex 1 nations.

The analysis within this paper offers a stark and unremitting assessment of the climate change challenge facing the global community. There is now little to no chance of maintaining the rise in global mean surface temperature at below 2°C, despite repeated high-level statements to the contrary. Moreover, the impacts associated with 2°C have been revised upwards (e.g. [20,21]), sufficiently so that 2°C now more appropriately represents the threshold between dangerous and extremely dangerous climate change. Consequently, and with tentative signs of global emissions returning to their earlier levels of growth, 2010 represents a political tipping point. The science of climate change allied with emission pathways for Annex 1 and non-Annex 1 nations suggests a profound departure in the scale and scope of the mitigation and adaption challenge from that detailed in many other analyses, particularly those directly informing policy.

However, this paper is not intended as a message of futility, but rather a bare and perhaps brutal assessment of where our 'rose-tinted' and well intentioned (though ultimately ineffective) approach to climate change has brought us. Real hope and opportunity, if it is to arise at all, will do so from a raw

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[34] The reference to 'feasible' technologies typically extends to carbon capture and storage, which, in 2010, remains untried for a large scale power station. Moreover, it is often allied with biomass combustion to provide 'negative' emissions (§5*d*). Without such negative emissions, several of the major analyses (e.g. [9,10]) will have increased cumulative emissions and hence further increased probabilities of exceeding 2°C (see also footnote 27).

[35] With the only exception being C+4 where Annex 1 emissions are stable until 2016, reducing thereafter.

[36] In essence, a planned economic contraction to bring about the almost immediate and radical reductions necessary to avoid the 2°C characterization of dangerous climate change whilst allowing time for the almost complete penetration of all economic sectors with zero or very low carbon technologies.

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and dispassionate assessment of the scale of the challenge faced by the global community. This paper is intended as a small contribution to such a vision and future of hope.

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Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy

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A number of recent studies have found a strong link between peak human-induced global warming and cumulative carbon emissions from the start of the industrial revolution, while the link to emissions over shorter periods or in the years 2020 or 2050 is generally weaker. However, cumulative targets appear to conflict with the concept of a 'floor' in emissions caused by sectors such as food production. Here, we show that the introduction of emissions floors does not reduce the importance of cumulative emissions, but may make some warming targets unachievable. For pathways that give a most likely warming up to about 4°C, cumulative emissions from pre-industrial times to year 2200 correlate strongly with most likely resultant peak warming regardless of the shape of emissions floors used, providing a more natural long-term policy horizon than 2050 or 2100. The maximum rate of CO_2-induced warming, which will affect the feasibility and cost of adapting to climate change, is not determined by cumulative emissions but is tightly aligned with peak rates of emissions. Hence, cumulative carbon emissions to 2200 and peak emission rates could provide a clear and simple framework for CO_2 mitigation policy.

Keywords: cumulative emissions; emissions floors; rate of warming; climate change

1. Introduction

A substantial fraction of the carbon dioxide (CO_2) emitted into the atmosphere by human activity remains there, in effect, for centuries to millennia. Changes in ocean chemistry, which can be described through the Revelle buffer factor [1], limit oceanic removal of CO_2 [2], while the potential for terrestrial vegetation to take up CO_2 is also predicted by some models to fall as the climate warms [3],

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although the size of this feedback is uncertain [4]. Complete removal of these anthropogenic emissions may require long time scales [4], or assistance from large-scale air-capture technologies [5–7].

If the above properties of the carbon cycle are real and enduring, then it is likely that bringing future emissions to zero would not reduce temperatures except in the very long term. Rather, once temperatures have peaked, they would remain almost steady [8–10]. Several recent studies have sought to exploit this observation in order to provide a simple link between levels of cumulative emissions and future warming [11–14].

Allen *et al.* [11] considered the cumulative carbon emissions summed between pre-industrial times and 2500, linking them to peak warming. Meinshausen *et al.* [13] examined multi-gas pathways and used a cumulative emissions metric between years 2000 and 2050 to relate to the probability of exceeding a 2°C target, rather than the amount of warming. The German Advisory Council on Global Change [15] argued for a cumulative limit between 2010 and 2050, while Matthews *et al.* [12] argued that warming by a given date is proportional to cumulative emissions to that date.

These papers show how cumulative emissions provide a tractable, well-constrained and concise metric for use by policy-makers interested in avoiding some level of peak global warming. The recent Copenhagen Accord [16] contains an aim of limiting warming to no more than 2°C, and draws on earlier targets from the EU and G8 [17,18]. Though not specified in the Copenhagen Accord, this 2°C warming limit is usually presumed to be relative to pre-industrial levels [19]. Using the results in Allen *et al.* [11], a 2°C limit on the most likely peak CO_2-induced warming could be achieved by limiting cumulative emissions to one trillion tonnes of carbon (1 TtC).

Cumulative emission targets represent the sum of emissions over time, and therefore these cumulative emissions could be distributed over time in a number of ways. For example, an early peak in emissions could be followed by a relatively slow rate of post-peak decline, or a later peak could be followed by a much more rapid decline [20]. One real-world difference between the pathways is that it may not be technically or politically feasible, or economically desirable, to decrease emissions at rates much in excess of 3 or 4 per cent per year, so that peaking later may not be viable, assuming a 2°C warming target [21].

In this paper, we address the problem of CO_2-induced warming. This is a central but not exhaustive component of potentially dangerous anthropogenic interference with the climate system. Most multi-gas pathways of future radiative forcing currently in the literature describe a total anthropogenic warming that either approximately equals or exceeds CO_2-induced warming [22]. This is because of the warming effect of non-CO_2 greenhouse gases usually equalling or exceeding the cooling effect of aerosols. Hence, avoiding dangerous levels of CO_2-induced warming is a necessary, albeit not always sufficient, condition for avoiding potentially dangerous anthropogenic interference in the climate system.

Most of the largest non-CO_2 anthropogenic forcing agents are distinct from CO_2 in having much shorter effective lifetimes in the climate system. Hence, although warming induced by non-CO_2 forcing agents may affect CO_2 through temperature–carbon-cycle feedbacks, it is difficult to arrive at a comprehensive framework for treating the cumulative impact of all anthropogenic forcings in terms of a single CO_2-equivalent metric [23]. The exception is nitrous oxide (N_2O),

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which has an atmospheric lifetime comparable to, albeit different from, that of CO_2 and, crucially, longer than the response time of the physical climate system. Hence, it could be argued that nitrous oxide emissions should be considered in the same framework as CO_2, and, throughout this paper, CO_2 could be replaced by the combination of CO_2 and N_2O. Predicting long-term emissions of N_2O, given current rapid developments in agricultural technology, is even more difficult than predicting CO_2 emissions. Thus, for the sake of simplicity, we focus on CO_2 alone, and do not consider the issue of what fraction of these long-term emissions might be made up of N_2O, although we note that, in several other papers considering the impact of emissions over the very long term, this fraction is substantial.

In this paper, we explore how cumulative emission targets relate to more widely known policy targets, such as limiting emission rates in 2020 or 2050. First, we analyse the relative skill of different emission measures to predict the resultant future peak warming, comparing cumulative emissions over a range of periods and actual emission rates at years 2020 and 2050.

Second, we investigate whether the cumulative emissions metric still holds for a class of emission pathways that do not assume that all emissions can be mitigated over the coming centuries. It is often argued that it may not be technically, economically or politically feasible to eliminate emissions of all greenhouse gases while, for example, preserving global food security [24]. This limit has been referred to as an 'emissions floor' [25,26]. It is difficult to estimate a compelling emissions floor, either in terms of its size (in gigatonnes of carbon per year ($\mathrm{GtC\,yr^{-1}}$)), or in terms of the extent to which it can reduce over time as new technologies become available. Nevertheless, it makes sense to consider the possibility that it may prove prohibitively expensive to reduce emissions beyond some positive level, particularly when the impact of N_2O is also included. Thus, in this paper we examine the effects of emissions floors on the basic arguments behind cumulative emissions framings of climate change. We use the following conventions: if the emissions floor is constant, then we refer to it as a 'hard floor'. If, on the other hand, society is able to continue to reduce residual CO_2 emissions, eventually to the point where net emissions are zero, then we call this a 'decaying floor'.

Third, we recognize that mitigation alone will not avoid all potential impacts of climate change, even if global warming does remain below 2°C [27,28]. Since some adaptation will be required in the future, policy-makers also need information on the rates of future climate change. This will determine how quickly a response is needed. Neither the cumulative total metric nor 2°C warming targets provide information on short-term rates of change in global warming [29]. Here, we analyse correlations between rates of CO_2-induced warming and short-term emission rates, noting that warming rates are also strongly influenced by non-CO_2 climate-forcing agents.

2. Methods

Our method consists of deriving a range of idealized CO_2 emission pathways and using a simple coupled climate–carbon-cycle model to estimate the resulting climate change. As many parameters in the model are uncertain,

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a likelihood-based method is used to identify the values that give the best agreement with observations of the recent past or model studies with more complex coupled climate–carbon-cycle models [11].

For the majority of this paper, we run one simulation for each selected emission pathway, using the parameters that were previously found to give the best agreement with observations and more complex models. The model is run between the years 1751 and 2500. By running large ensembles containing hundreds of different emission pathways, we can begin to analyse trends across emission pathways. This method allows us to ask questions, such as: 'What is it about an emission pathway that controls the resulting peak rate of global mean temperature increase?'

(a) Emission pathways

We use emission pathways that follow the algorithm outlined by Allen *et al.* [11]. This gives the rate of change of future emissions according to the equations below:

$$E_a = \begin{cases} H(t) & \text{for } t < t_0, \\ a\mathrm{e}^{bt} & \text{for } t_0 \le t < t_1, \\ c\mathrm{e}^{dt^2+ft} & \text{for } t_1 \le t < t_2, \\ g\mathrm{e}^{ht} & \text{for } t \ge t_2, \end{cases}$$

where E_a is the carbon emissions in year t, $H(t)$ is historical emissions data, a, b, c, d, f, g and h are constants, and t_0 is the year at which historical data are replaced by emission pathways. The parameters b and h, representing the initial rate of exponential growth and final rate of exponential decline, depend on the specification of the emission pathways and are allowed to vary between emission pathways; t_1 and t_2 are the times of transitions, and also vary between emission pathways. The remaining constants are determined by the requirement that emissions are continuous everywhere, and that rates of change of emissions are continuous, where $t > t_0$.

Note that E_a is measured in tonnes of carbon, as opposed to tonnes of CO_2. To convert to tonnes of CO_2, one would simply multiply our emissions and cumulative emission values by a factor of 44/12.

To create the emission pathways, we select a number of values of parameters b, h, t_1 and t_2. Each combination of these parameters represents a different possible emission pathway. We select parameter options such that there are 12 750 possible emission pathways of the type outlined here. We choose the ranges of the parameters to give a range of emission pathways with cumulative emissions to 2200 between 0.7 and 3 TtC. We choose the parameters so that the majority of emission pathways have a maximum rate of emissions decline of less than 4 per cent per year, but we also consider a smaller number of pathways that decrease by up to 10 per cent per year.

We also develop a new set of pathways, extending those described above. These pathways have 'emissions floors' to represent the emissions that are potentially technologically, economically or politically unfeasible to mitigate. Although these are expressed in terms of CO_2 alone, they could also be assumed to include the impact of the other principal long-lived anthropogenic radiative forcing agent, N_2O. Including the impact of further non-CO_2 forcing agents is difficult. Because

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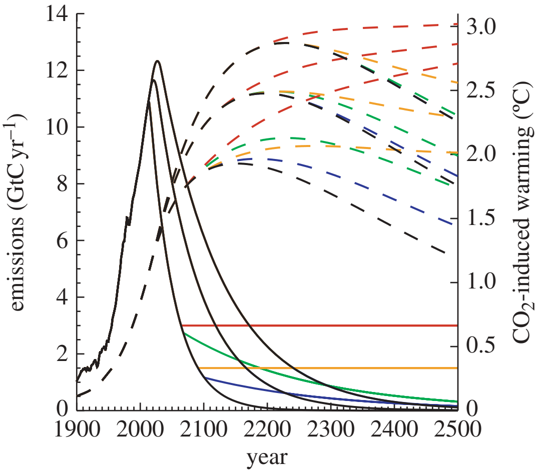

Figure 1. Fifteen emission pathways and their resulting temperature trajectories. The emission pathways are in solid lines, and can be read off the left axis, while the temperature trajectories are in dashed lines, and can be read off the right axis. The 15 emission trajectories are created by combining three possible pathways, shown here in black, with five possible emissions floors, shown here in coloured solid lines, as outlined in §2*a*. The upper, middle and lower plumes of overlapping coloured dashed temperature trajectories correspond to the black emission profiles that peak the highest, the second highest and the lowest, respectively. The three emission pathways in red solid line with the highest constant emissions floors have red dashed resultant temperature trajectories. The same correspondence applies for the other colours of emissions floors and their resultant temperature trajectories. The upper, middle and lower black curves have cumulative totals to 2500 of 2, 1.5 and 1 TtC, respectively.

of their very much shorter lifetimes, these emissions do not accumulate in the system, as does CO$_2$. We use two types of emissions floors: a hard floor, F_{H}, and a decaying floor, F_{D}. These two floors take the forms

$$F_{\mathrm{H}} \geq A$$

and

$$F_{\mathrm{D}} \geq B \exp\left(-\frac{t - t_{2050}}{\tau}\right),$$

where A and B are constants with units of gigatonnes of carbon per year (GtC yr^{-1}) and represent the size of the emissions floor in the year 2050 ($t = t_{2050}$), and τ is a time constant set to 200 years. Emissions floors are caps below which emissions are not able to fall, so for all t, where $t = t_0$, we take whichever is the larger of $E_a(t)$ and $F(t)$ to be our emissions pathway. If we take into account five alternative emissions floors, namely (i) no floor, (ii) low hard floor, (iii) high hard floor, (iv) low decaying floor and (v) high decaying floor, which could apply to each of the 12 750 possible pathways described above, we have 63 750 possible emission pathways. We do not use all of these possible pathways, but rather pick a random subset of a few thousand pathways to investigate with the simple coupled climate–carbon-cycle model. Fifteen of these pathways are plotted in figure 1, alongside their resulting warming trajectories as simulated by the simple model outlined below.

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(*b*) *Models*

Following Allen *et al.* [11], our analysis is based on a simple combined climate–carbon-cycle model with a time step of one year. The model uses a three-component atmosphere–ocean carbon cycle, in which we assume that the atmospheric CO_2, measured by a concentration C, can be split into three components, C_1, C_2 and C_3. Physically, C_1 can be thought of as representing the concentration of CO_2 in long-term stores such as the deep ocean; $C_1 + C_2$ as representing the CO_2 concentration in medium-term stores such as the thermocline and the long-term soil-carbon storage; and $C = C_1 + C_2 + C_3$ as the concentration of CO_2 in those sinks that are also in equilibrium with the atmosphere on time scales of a year or less, including the mixed layer, the atmosphere itself and rapid-response biospheric stores. Each of these components, C_1, C_2 and C_3, is then associated with some fraction of the emissions into the atmosphere, E, and a particular removal mechanism:

$$\frac{\mathrm{d}C_3}{\mathrm{d}t} = b_3 E,$$

$$\frac{\mathrm{d}C_2}{\mathrm{d}t} = b_1 E - b_0 C_2$$

and

$$\frac{\mathrm{d}C_1}{\mathrm{d}t} = b_4 E - b_2 \int_0^t \frac{\mathrm{d}C_1(t')}{\mathrm{d}t'} \frac{\mathrm{d}t'}{\sqrt{t-t'}},$$

where b_3 ($=0.1$) is a fixed constant representing the Revelle buffer factor, and b_1 is a fixed constant such that $b_1 + b_3 = 0.3$ [11]; b_1 represents the fraction of atmospheric CO_2 that would remain in the atmosphere following an injection of carbon in the absence of the equilibrium response and ocean advection; b_0 represents an adjustable time constant, the inverse of which is of order 200 years. The third equation in our simple carbon-cycle model, which relates to C_1, accounts for advection of CO_2 into the thermocline and land–biosphere; b_2 represents an adjustable diffusivity, while $b_1 + b_3 + b_4 = 0.85$ is the fraction of CO_2 that would remain in the atmosphere within a year of a pulse injection [11].

The surface temperature response, T, to a given change in atmospheric CO_2 is calculated from an energy balance equation for the surface, with heat removed either by a radiative damping term or by diffusion into the deep ocean. It is described by

$$a_1 \frac{\mathrm{d}T}{\mathrm{d}t} = a_3 \ln\left(\frac{C}{C_0}\right) - a_0 T - a_2 \int_0^t \frac{\mathrm{d}T(t')}{\mathrm{d}t'} \frac{\mathrm{d}t'}{\sqrt{t-t'}}.$$

Here, a_1 is a fixed heat capacity, which we approximate as the effective heat capacity per unit area of a 75 m ocean mixed layer; a_3 corresponds to a doubling of atmospheric CO_2 levels causing a forcing of $3.74\,\mathrm{W\,m^{-2}}$; and C_0 is the pre-industrial concentration of CO_2 [30]; a_0 and a_2 are both able to vary, and control the climate sensitivity, and rate of advection of heat through the thermocline, respectively. This is a simple energy balance equation, where the term on the left-hand side represents the thermal inertia of the system; the first term on the

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right-hand side (r.h.s.) is the atmospheric CO_2 forcing, the second term on the r.h.s. is a linearized temperature feedback, and the third term on the r.h.s. is a diffusive term representing the flux of heat into the deep ocean.

Finally, we represent the climate–carbon-cycle feedback by adding an extra, temperature-dependent component to the total anthropogenic emissions emitted each year (E_a):

$$E = E_a + b_5 T',$$

where T' is the temperature anomaly above an exponentially weighted running mean with a time constant of 100 years, and b_5 is the adjustable carbon-cycle feedback parameter. Since the industrial revolution, models showing this feedback have been largely linear; however, this linearization is unlikely to hold for temperatures greater than 3–4°C above pre-industrial temperatures. Further, the equation is unreliable for decreases in temperature, but these are not considered here.

Together, these equations make up the simple coupled climate–carbon-cycle model that we use throughout this paper. Figure 1 shows the temperature trajectories simulated by this model for 15 sample emission pathways.

(*c*) *Likelihoods*

For the majority of this paper, we use 'best-guess' parameters for each of the variables in the model; however, in §3*c*, we use a range of parameters to sample uncertainties. We varied five parameters in this coupled climate–carbon-cycle model in order to sample their uncertainties, while we kept the rest constant. The five parameters that we varied are a_0, a_2, b_0, b_2 and b_5. We did not vary the other parameters in the model because their fractional uncertainties are much smaller than those of the five parameters listed above.

We constrained these five parameters with five 'observations' (either direct, or based on more complex model simulations). These are (i) observed attributable CO_2-induced twentieth-century warming, (ii) global heat capacity, inferred from the combination of ocean warming and ocean heat uptake, (iii) historical record of atmospheric CO_2 concentrations, (iv) the rate of advection of CO_2 in the deep ocean, based on the C^4MIP family of climate–carbon-cycle general circulation models (GCMs) and models of intermediate complexity, and (v) the climate–carbon-cycle feedback parameter, again estimated from the C^4MIP family of models [11]. We require C^4MIP to help with some of these quantities in the absence of true observations of the carbon cycle. We assigned each of the constraints a log-normal distribution from estimates in the literature, as detailed by Allen *et al.* [11].

For each combination of the five model parameters, we operated the simple climate–carbon-cycle model, and calculated and then multiplied together the likelihoods for each of the constraints to create a single likelihood for each parameter combination. The parameter combinations that better reproduce the constraints are then more likely, and the parameter combination that best reproduces the constraints is considered to be our best guess, or the most likely [31].

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In most of this paper, we only use this best-guess parameter combination in the coupled climate–carbon-cycle model. In §3*c*, however, we use several thousand parameter combinations to create 'likelihood profiles'. Figure 1 shows 15 warming trajectories calculated using best-guess parameters.

3. Results

(*a*) *A comparison of different types of emission targets*

We compare the performance of a range of emissions and cumulative emission targets in estimating peak CO_2-induced warming. We do this comparison by constructing an initial set of 395 different emission pathways, each with a zero emissions floor, which have been randomly selected from the 12 750 possible pathways with no emissions floor outlined in §2*a*. Once we have randomly selected our 395 emission pathways, we use the simple coupled climate–carbon-cycle model described in §2*b* to estimate quantities such as the most likely peak warming for each pathway. We use these results to analyse the usefulness of each of six emission metrics of interest. We consider cumulative carbon emissions (i) from pre-industrial times to the time of peak warming and (ii) from year 2010 to year 2050. We also consider the actual emissions rates at (iii) year 2020 and (iv) year 2050. Additionally, we consider (v) the peak emissions rate and (vi) the year in which emissions peak.

The performance of each emission metric is shown in figure 2, where the emission metrics are plotted against the peak warming. The bars in the plot indicate the range for each metric in pathways with resultant values of peak warming at or very near to 2 and 3°C. Black bars consider only the pathways represented by black crosses with 'rate of emissions decline' less than 4 per cent. The grey bars include both black crosses and grey diamonds, corresponding to emission pathways with rates of decline as high as 10 per cent. For example, in figure 2*d*, pathways with a resultant warming of 2°C have emissions in year 2050 between 4.5 and 6.4 $\mathrm{GtC\,yr^{-1}}$, giving a range of 1.9 $\mathrm{GtC\,yr^{-1}}$.

Based on the metrics presented in figure 2, we conclude that, for cases with no emissions floor, the strongest correlation across all pathways occurs between peak warming and the cumulative emissions from pre-industrial times to the time of that peak warming, as shown in figure 2*a*. The correlation is almost as strong if cumulative emissions out to 2500 are considered (shown in black squares in figure 3*a*) because the vast majority of the emissions in these zero emissions floor pathways have occurred by the time of peak warming. Note that, because of the idealized nature of the climate model used here, it may not be quantitatively reliable above 3–4°C of warming.

An interesting feature of the tight correlation present in figure 2*a* is the curvature, which is due to the functional form of CO_2 forcing. Forcing due to CO_2 is proportional to the logarithm of the fractional change in atmospheric CO_2 since the pre-industrial era [30]. If the forcing were linear, the model used in this paper suggests that there would be a more linear relationship between cumulative emissions and peak warming [12].

For figure 2*b*–*f*, grey diamonds, representing emission pathways with a maximum rate of decline between 4 and 10 per cent, generally appear to the right and below the black crosses, representing emission pathways with peak

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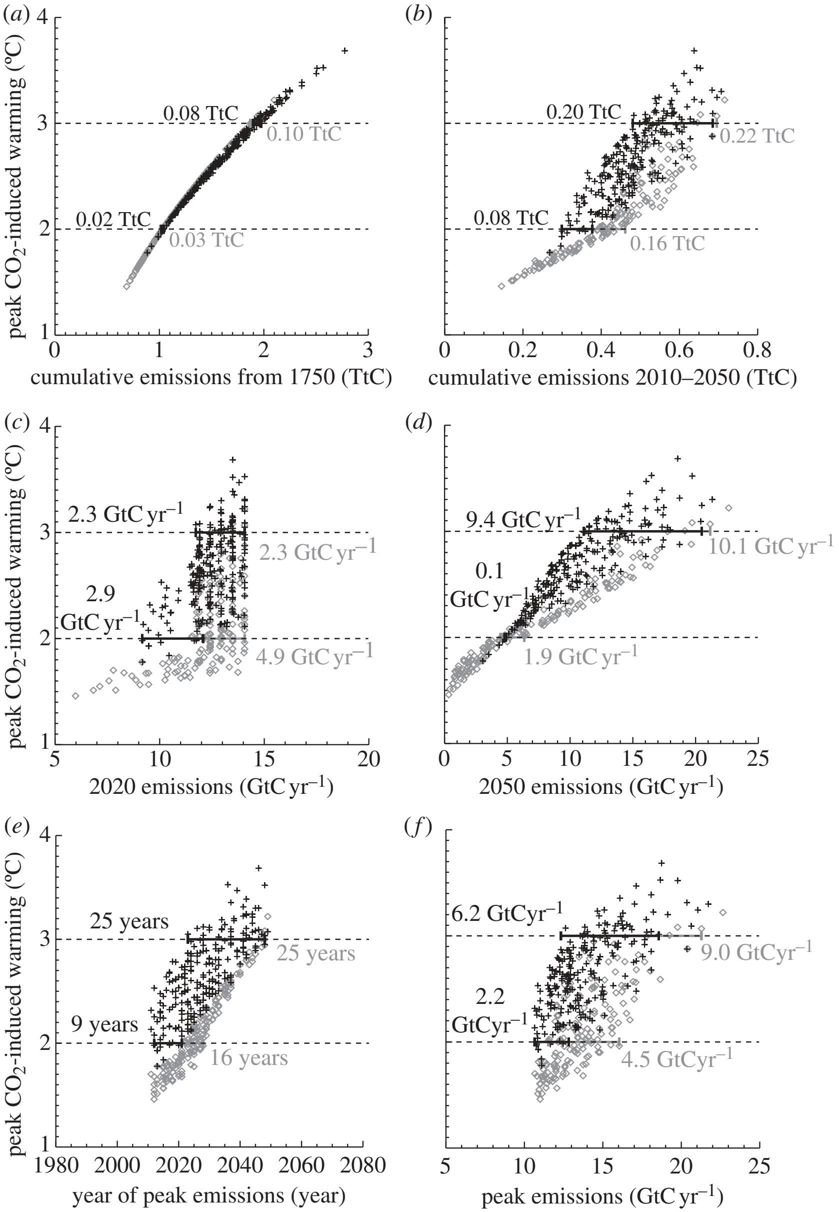

Figure 2. Scatter plots showing the relationship between most likely peak CO_2-induced warming and various global carbon emission metrics for 395 emission pathways. The x-axis for each panel shows: (*a*) emissions time-integrated between 1750 and 2500, (*b*) emissions time-integrated between 2010 and 2050, (*c*) emissions in the year 2020, (*d*) emissions in the year 2050, (*e*) the year in which emissions peak, and (*f*) the peak or maximum in emissions. Black crosses indicate emission pathways in which the maximum rate of emissions decline is less than 4% yr^{-1}; grey diamonds indicate the converse. The bars show the spreads of the metrics for pathways with a resultant peak warming of 2°C or 3°C. The black bars show the spread in pathways with peak rates of emissions decline less than 4%, while the grey bars show the spread in all emission pathways. We see that the strongest correlation is in (*a*), between peak warming and cumulative emissions between 1750 and 2500.

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rates of decline between 0 and 4 per cent. For a given peak warming, and so for a given cumulative total, pathways with a faster rate of emissions decline will have relatively more of their cumulative total emitted sooner than for pathways with slower rates of decline. As a result, these rapidly declining pathways will have higher cumulative emissions between 2010 and 2050, higher 2020 emissions, higher peak emissions and a later year of peak emissions. This effect also holds for 2050 emissions above 5 GtC yr^{-1}. For emission pathways with cumulative emissions less than 1 TtC, corresponding to a peak warming of 2°C, 2050 emissions occur once the pathway has been declining exponentially for a considerable period, and so rapidly declining pathways will have relatively lower emissions in 2050.

The correlation between peak warming and cumulative emissions between year 2010 and 2050, which is the emissions metric used by the German Advisory Council on Global Change [15], is plotted in figure 2*b*. We see that the correlation here is not as good as in figure 2*a*. Emissions before 2010 are not allowed to vary across emission pathways, so there can be no contribution to the spread in peak warming from this historical time period. The majority of the spread comes from the variation in post-2050 emissions, which will have a significant impact on peak temperatures, but which by definition are not included in 2010–2050 metrics. We see that, in cases where post-2050 emissions are small, the spread is much tighter, as shown by those pathways with cumulative emissions less than 0.3 TtC between 2010 and 2050. This is because the majority of future cumulative emissions in these pathways are emitted before 2050. This means that, up to roughly 1.8°C, the cumulative emissions between 2010 and 2050 has some skill in predicting peak CO_2-induced warming, but this skill is reduced for higher temperatures.

We also consider whether there is predictive skill in using the actual emission rates at a particular year; here we use year 2020 and year 2050. The former year is chosen because most of the Copenhagen Accord emission reduction pledges are quoted for this year [16]. The latter is chosen because several reduction targets for 2050 have also been presented [17,32]. Figure 2*c*,*d* shows 2020 and 2050 emissions against peak warming. As in Lowe *et al.* [33], we find that emissions in the year 2020 are not a good indicator of peak warming, because they are largely a function of current emissions, and are not a key determinant of cumulative emissions.

For figure 2*d*, year 2050 emissions do seem to be a good indicator at lower rates of emission, particularly at values that cause roughly 2°C of warming or less. However, we found 2050 emissions to be a less good indicator of peak resultant warming at higher rates of emission. This is in part a consequence of the choice of pathways, as we have considered only smooth pathways with a single maximum and exponential tails (see §2*a* for more detail on how the emission pathways are chosen). A wider range of functional forms to describe emission pathways would be expected to reduce the strength of the relationship between 2050 emissions and peak warming.

We also compare the peak emission rate and the year of peak emissions with the peak CO_2-induced warming. As shown in figure 2*e*,*f*, the spread is very large for both of these metrics, and there is little correlation, except for the rapidly declining emission pathways (grey diamonds) appearing to the right of the slowly declining pathways (black crosses), as explained earlier.

Under the assumption that society will work to avoid crossing a key temperature threshold, from figure 2*a*, the cumulative emission metric confirms that we have a choice of high emissions soon followed by rapid decarbonization, or

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more stringent emission cuts occurring soon with a lower rate of decarbonization in the future. As in Allen *et al.* [20], this actually forces the many potential emission pathways considered here, which have the same cumulative total, to cross around the middle of the twenty-first century. Lower cumulative totals, and thus pathways with these features that result in lower levels of warming, leave less flexibility, and thus all pathways must intersect in roughly the same place. At higher cumulative totals, there is more flexibility about when carbon is emitted, and therefore pathways do not cross in the same place, resulting in the wider spread of pathways at warmer peak temperatures. Thus, pathways with lower rates of emission in 2050 are likely to result in a similar amount of peak warming, while higher rates of emission in 2050 can lead to varying levels of peak warming, as seen in figure 2*d*.

(*b*) *The effect of emissions floors*

In figure 1, we calculated the warming trajectories not only for emission pathways with zero emissions floors, but also for pathways with non-zero floors. We show in figure 2 that cumulative emissions to the time of peak warming are tightly correlated with peak CO_2-induced warming for the case with no emissions floors, and here we investigate whether emissions floors affect this correlation. Figure 3 shows the impact of emissions floors on different cumulative emission metrics, and each of the panels has the same form as figure 2*a*.

We have plotted most likely peak temperatures as a function of four different cumulative emission metrics: year 1750–2500 (figure 3*a*), year 1750 to the time at which peak warming occurs (figure 3*b*), year 1750–2100 (figure 3*c*) and year 1750–2200 (figure 3*d*).

In figure 3*a*, we can see that pathways with larger emissions floors are shifted to higher cumulative totals. This occurs because the cumulative totals include contributions for portions of the emissions floor that are emitted after the time of peak warming, which can have no effect on peak warming, as illustrated by the green curves in figure 1.

We find that if a hard or non-varying emissions floor becomes too large, then the emissions cannot balance the natural processes that remove carbon from the atmosphere. At present, the precise value of the emissions when the floor becomes too large is uncertain, although we highlight that it may be model-specific. This is illustrated by the red curves in figure 1. Consequently, for large hard emissions floors, atmospheric levels of CO_2 continue to rise throughout our 750-year simulation, and are still increasing at the end of the experiment, along with associated levels of mean global warming. Extending this analysis to include pathways with cumulative emissions of more than 3 TtC, a resultant warming of more than 3–4°C, or cases in which temperatures fail to peak by 2500 would be possible in principle, but would take us outside the range of pathways for which such a simple model is appropriate. Hence, we have not plotted cases where temperatures do not peak by 2500 in figures 3 or 4, since we are unable to project when they would peak. All pathways with no floor, and all pathways with a decaying floor, have peaked by 2500; however, some pathways with a hard emissions floor have not.

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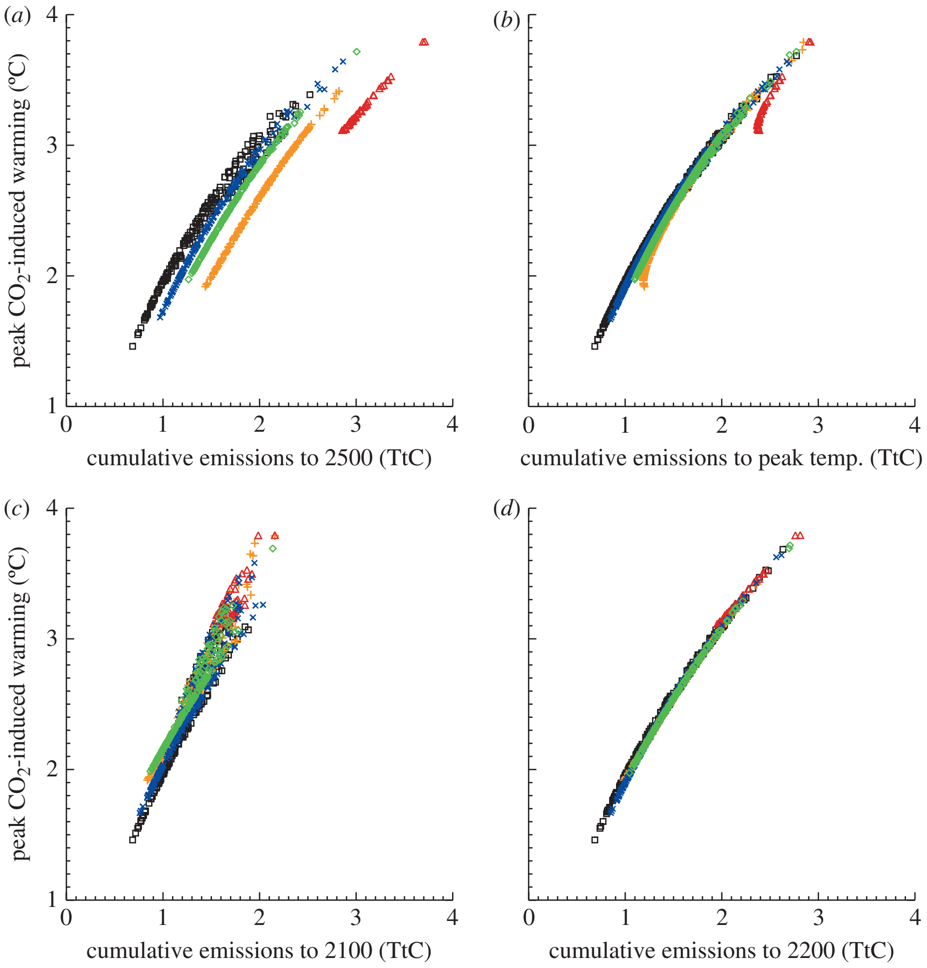

Figure 3. Most likely peak warming as a function of cumulative emissions for different emissions floors. The type of cumulative emission metric varies between the plots: cumulative emissions to (*a*) 2500, (*b*) the time of peak warming, (*c*) 2100, and (*d*) 2200. The panels in this figure are as figure 2*a*, but with different floors preventing emissions from dropping below certain values at certain times. The emissions floors used here are the same as those in figure 1, and use the same colour code. The black squares represent pathways in which no floor is present, so emissions are allowed to fall to zero. The yellow crosses and red diamonds indicate pathways in which a 'hard' floor is set at 1.5 or 3 GtC yr^{-1}; in these pathways, emissions are unable to fall below the floor and so remain at these values indefinitely. The blue crosses and green diamonds are pathways with an exponentially decreasing emissions floor, which has a decay time of 200 years. The blue crosses pass through 1.5 GtC yr^{-1} in the year 2050, while the green diamonds pass through 3 GtC yr^{-1} in that year. We observe the strongest correlation in (*d*), between peak warming and cumulative emissions to 2200.

The observational constraints are much more effective in constraining the short- and medium-term response of the climate–carbon-cycle system than they are at constraining the multi-century response. Hence, it is inherently hard to determine whether, after a significant injection of CO_2 into the atmosphere,

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certain emissions floors will cause temperatures to stabilize, decline or continue rising. Additionally, when considering an emissions floor, it could be argued that temperatures will be rising or falling so slowly that their trend could be reversed by actively intervening in the carbon cycle, or simply reducing or increasing emissions by an amount substantially smaller than has already been achieved in reaching that floor. The maximum rate of increase of CO_2 concentrations beyond 2200 associated with the emission pathways in figure 1 is 28 ppm by volume per century (ppmv per century). The rate of associated warming shown in figure 1 beyond 2200 is at most 0.27°C per century. In contrast, the associated maximum rates in 2100 are a concentration rise of 99 ppmv per century and a warming of 0.88°C per century. It could be argued that a society capable of achieving the kind of rates of emission reduction in the year 2100 that are assumed under these pathways would almost certainly be able to convert a static emissions floor into a decaying one if it were necessary to do so. Hence, it could be argued that the scenario of very rapid reductions followed by a completely stable ('hard') floor in CO_2 emissions is unlikely to occur, although the role of N_2O in very long-term emissions is potentially an issue here. Methane could also influence temperatures over the very long term, as could anthropogenic aerosols and other short-lived forcing agents. However, any agent with a lifetime shorter than the response time of the physical climate system must be treated in a very different way to CO_2, since such emissions do not effectively accumulate in the atmosphere over multi-decadal time scales.

Figure 1 shows that the size and types of emissions floors determine how temperatures will behave after they peak. Several studies have suggested that near-zero emissions are required to stabilize temperatures [10,14]. Our simple model's simulations suggest that temperatures will peak then fall slowly under near-zero emissions (figure 1), but this result is acutely sensitive to model structure. At present, there appears to be insufficient understanding and suitable observations of the carbon cycle to constrain behaviour during the regime when temperatures decline. In light of this lack of observational constraints, we do not feel confident in relying upon the simple model's simulations long after the time at which temperatures peak.

Figure 3*b* shows peak warming plotted against cumulative emissions integrated between the year 1750 and the time of peak warming. The correlation in this figure is much better than that in figure 3*a*. Figure 3*b* shows that a decaying emissions floor does not significantly alter the shape of the relationship between cumulative emissions and peak temperature, as the peak warming is still a function of the cumulative emissions. Emissions floors do, however, affect the lower ends of the curves with low values of cumulative emissions. Consider two emission pathways, both with a cumulative total of 1 TtC, but one with a decaying emissions floor, and one with no emissions floor: the pathway without an emissions floor will cause a temperature peak earlier than the pathway with the decaying floor, as the emissions floor causes emissions to be emitted over a longer time period. Consequently, in the case with an emissions floor, there will have been more time for carbon to be removed from the atmosphere, presumably resulting in slightly lower atmospheric concentrations at the end of our simulation period than in the no-floor case. As forcing is a function of atmospheric concentrations, the case with no emissions floor and higher CO_2 concentrations will result in a higher peak temperature.

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We can observe this phenomenon in figure 1 by comparing the lowest green and yellow emission pathways and temperature trajectories. The yellow emission pathway has a higher cumulative total than the green one, when integrated to the time when temperatures peak. Despite this higher cumulative total, the green curve has a higher peak warming than the yellow curve because its emissions are put into the atmosphere over a shorter time period. It is this phenomenon that causes the hard emissions floors to 'peel away' from the soft emissions floors in figure 3*b*.

In figure 3*b*, at the upper end of the curve, where cumulative totals are large, the existence of an emissions floor seems to make little difference to the peak temperature. This is because the fraction of the cumulative total that is part of the emissions curve is much larger than the fraction that is in the emissions floor. For the decaying emissions floor in particular, the floor will have decayed to near zero by the time that $E_a(t) = F_\mathrm{D}(t)$, as the pathway will reach the floor at a later time than it would have if it had a smaller cumulative total. In general, if the cumulative emissions over the duration of the emissions floor are small compared with the overall emissions, then the floor is not particularly important. If the cumulative emissions over the duration of the floor are a large fraction of the cumulative total, then the level of the floor is a crucial determinant of peak warming. This phenomenon is illustrated in figure 1 by considering the upper yellow and black emissions and temperature curves. The emission pathway is so large that the yellow emissions floor does not affect it until 2240, and as a result the yellow and black temperature trajectories are indistinguishable until after temperatures have peaked. This illustrates why emissions floors have less impact on peak warming for pathways with high cumulative totals.

In figure 3*c*, we see that the correlation between peak warming and cumulative emissions to 2100 is relatively weak. The points furthest to the right of the plot, however, are all black crosses, representing emission pathways with zero emissions floors. This is because, for pathways with zero emissions floors, more of the total cumulative emissions have been emitted by 2100 than for pathways with non-zero emissions floors. We see in figure 1 that all of the 15 temperature trajectories are still warming beyond 2100, and all emission pathways are still emitting beyond 2100. These emissions beyond 2100 are not accounted for in this metric, but will influence the peak warming, which accounts for most of the lack of correlation in figure 3*c*.

The best correlation of all the panels can be observed in figure 3*d*. This suggests that cumulative emissions, when calculated between 1750 and 2200, are a strong indicator of most likely peak CO_2-induced warming regardless of the type of emissions floor chosen. This is presumably because most of the warming trajectories peak within a few decades of 2200. Those trajectories considered here that do not peak near 2200 have all warmed to within a small fraction of their peak warming by this date, and therefore the emissions emitted in these pathways after 2200 only serve to maintain temperatures, and not to induce more warming. This phenomenon is illustrated by the lowest yellow curve, which peaks in 2273, but has warmed to 99 per cent of its peak warming by 2200. This example illustrates how emissions after 2200 have a very small influence on an emission pathway peak temperature, provided the emissions floor is not so high that it prevents temperatures from peaking until beyond 2500. We

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cannot be confident in the correlation between peak temperatures and cumulative emissions to 2200 for emission pathways that result in warming of more than 4°C, because peak temperatures will not necessarily occur near the year 2200 in these pathways.

One way this work can inform current policy targets is for policy-makers to view cumulative carbon emission budgets as spread over, say, four periods: (i) 2010–2020, (ii) 2020–2050, (iii) 2050–2100, and (iv) 2100–2200. Subject to the constraints and caveats outlined above, decision-makers have some flexibility in moving emissions from period to period; the important thing for a maximum temperature target is that the overall budget not be exceeded, since this is the primary determinant of peak warming. The inter-period flexibility regarding peak temperature targets ought to be of practical value to policy-makers, since it allows them to make informed trade-offs between near-term emissions and emissions in the longer term.

(*c*) *Likelihood profiles*

In §3*a*, we confirmed the very tight correlation between cumulative emissions and peak CO_2-induced warming, refined in §3*b* to consider the effect of non-zero emissions floors. We find that, even with non-zero emissions floors, cumulative emissions, particularly cumulative emissions to the year 2200, correlate well with the resultant peak warming below 4°C.

However, thus far, and in figures 2 and 3, our estimates have been of ‘best-guess’ or ‘most likely’ warming, as defined in §2*c*. In this section we estimate our level of confidence in these results.

We re-run our model but with perturbed parametrizations for each ensemble member. For each ensemble member, we can determine a relative likelihood through comparison against our knowledge of the historical record. As explained in §2*c*, models that better reproduced our constraints have higher relative likelihoods.

In figure 4, we do not plot the location of each ensemble member, but instead we plot the outline of the entire ensemble. This allows our likelihood profile to be independent of sampling strategy, provided that we have sufficiently explored parameter space.

For each emissions profile within 1 per cent of 1.0, 1.5 or 2.0 TtC cumulative emissions between 1750 and 2200, we calculate a likelihood profile, such that each panel in figure 4 actually contains dozens of likelihood profiles plotted on top of each other. All of these likelihood profiles are quite similar, which shows not only that the best-guess peak warming is independent of emission pathway for a given cumulative total, but also that the entire likelihood profile shares this property.

We repeat this process for each type of emissions floor so that we can compare likelihood profiles between types. By comparing the likelihood profiles for emission pathways with the same cumulative total but different emissions floors (e.g. the profiles in figure 4*d*–*f*), we find that the likelihood profile is unaffected by the type of emissions floor.

We note that figure 4*c* only contains three likelihood profiles, as we only consider three emission pathways with a hard emissions floor and a cumulative total to 2200 of within 1 per cent of 1 TtC. Cumulative emissions to 2000 are approximately 0.5 TtC, and a 1.5 $\mathrm{GtC\,yr^{-1}}$ emissions floor between 2000 and

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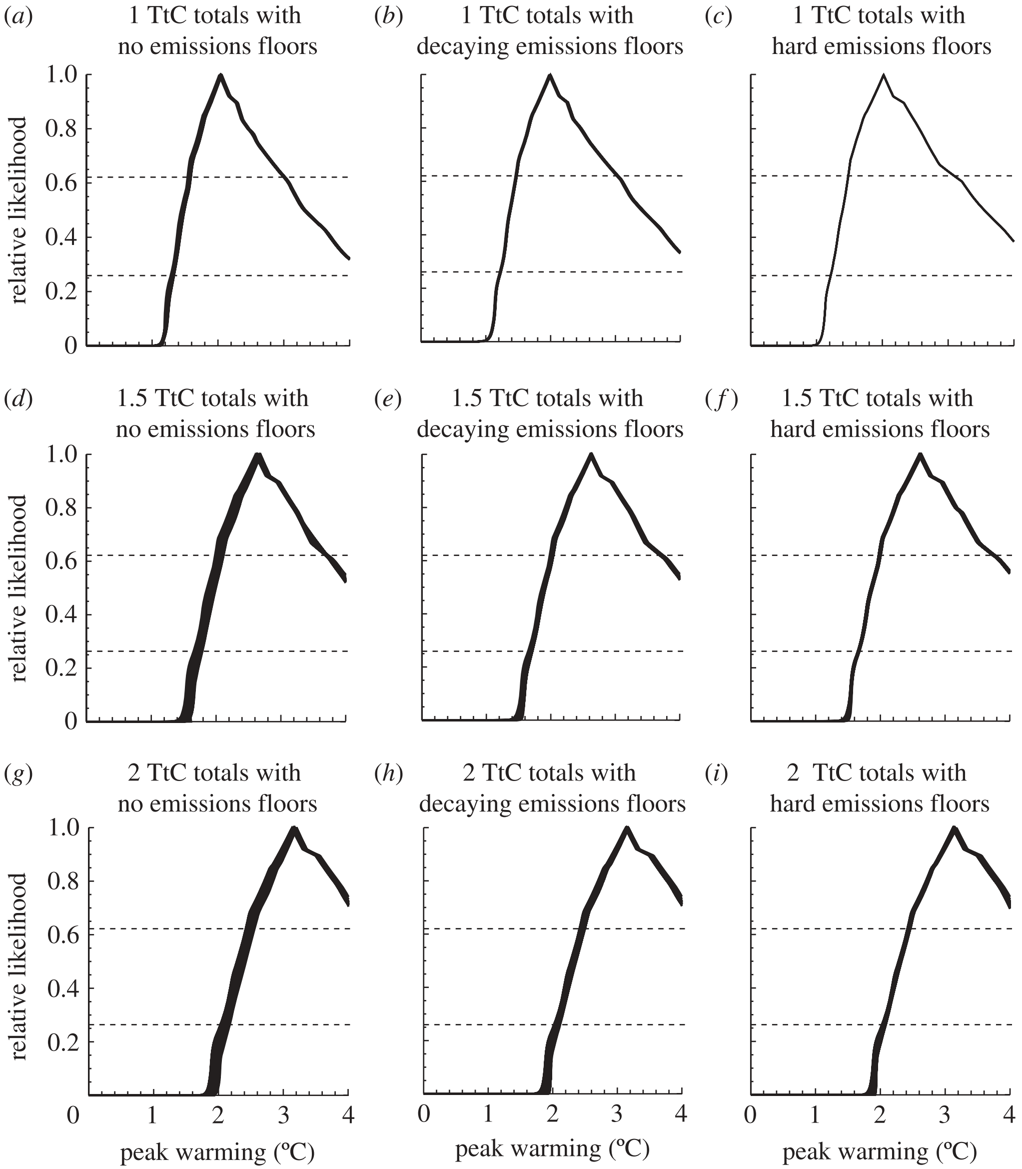

Figure 4. Peak warming for different cumulative totals and different emissions floors. These likelihood profiles are produced as outlined in §3*c* following Allen *et al.* [11]. Horizontal dotted lines show thresholds for the 17–83% and 5–95% confidence intervals [31]. Panels (*a*,*d*,*g*) have no emissions floor, so emissions are allowed to fall to zero. Panels (*b*,*e*,*h*) have a 'decaying' (i.e. exponentially decreasing with a 200-year lifetime, passing through 1.5 GtC yr^{-1} in 2050) emissions floor. Panels (*c*,*f*,*i*) have a 1.5 GtC yr^{-1} hard emissions floor. In each panel, we plot likelihood profiles over each other for every emission pathway with a cumulative total from 1750 to 2200 within 1% of the stated cumulative total. A sample emission pathway for each of the plots above is given in figure 1, alongside its resultant warming trajectory. The profiles with no emissions floors appear to be drawn thicker only because more emission profiles have been plotted upon one another. We see that the introduction of an emissions floor has little influence on the likelihood profile.

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2200 has a cumulative total of 0.3 TtC, which leaves only 0.2 TtC remaining if the pathways are to have a cumulative total of 1 TtC. This forces the emissions profile to have a high rate of decline, which could make these profiles socio-economically unfeasible [21].

(*d*) *Constraining the rates of warming*

Thus far, we have only considered constraints on peak levels of global warming. A key objection to using peak warming targets in isolation is that the feasibility and cost of adapting to future climate change will also depend strongly on the rate of change and not just on the magnitude of global warming. In order to determine which factors constrain the maximum rate of warming, we use the same model experiments as reported in figure 2. Thus, we use only best-guess or most likely ensemble members, and we only consider emissions profiles with zero emissions floors. We now plot the peak rate of CO_2-induced warming as a function of the emission metrics, as illustrated in figure 5.

In figure 5, we find a very different set of correlations from those presented in figure 2. The main result, across all the panels in figure 5, is that the tightest linkage is between the peak rate of warming and peak emission rate. We now explain these results in more detail.

Though cumulative carbon emissions have a tight correlation with peak warming, figure 5*a* shows that they share only a very weak correlation with the peak rate of warming. The maximum rate of warming is instead controlled by the peak rate of emission, as indicated in figure 5*f*. The gradient of the points in figure 5*f* suggests that, for each extra $\mathrm{GtC\,yr^{-1}}$ on the peak emission rate, the best-guess maximum rate of warming will increase by 0.016°C per decade.

It is known, however, that short-lived non-CO_2 greenhouse gases, such as methane, which we do not include in this paper, also influence atmospheric radiative forcing [34]. Although these gases have shorter lifetimes than CO_2 [34], they still have the potential to influence rates of warming beyond that induced purely by CO_2.

Figure 5*a* shows only a slight correlation, which occurs because the peak rate of emission and the cumulative emissions are not completely independent. Consider two emission pathways with different peak rates of emission and the same rate of emissions decline after the peak: the pathway with the higher peak will lead to a higher cumulative total, as shown in figure 5. As we cap the maximum rate of emissions decline to 10 per cent per year, higher peak emission rates will have a bias towards larger cumulative totals, which explains the correlation we observe in figure 5*a*.

The grey diamonds in figure 5 represent emission pathways that have a maximum rate of emissions decline of between 4 and 10 per cent per year, while the black crosses correspond to rates of decline between 0 and 4 per cent. For pathways with a cumulative total of less than 1 TtC and a rate of decline of less than 4 per cent per year, figure 5 shows only a limited range of possible rates of warming. This limited range of pathways all have a rate of warming less than 0.2°C per decade, which initially suggests that a cumulative emissions target could be used to constrain rates of warming, assuming that rates of decline are

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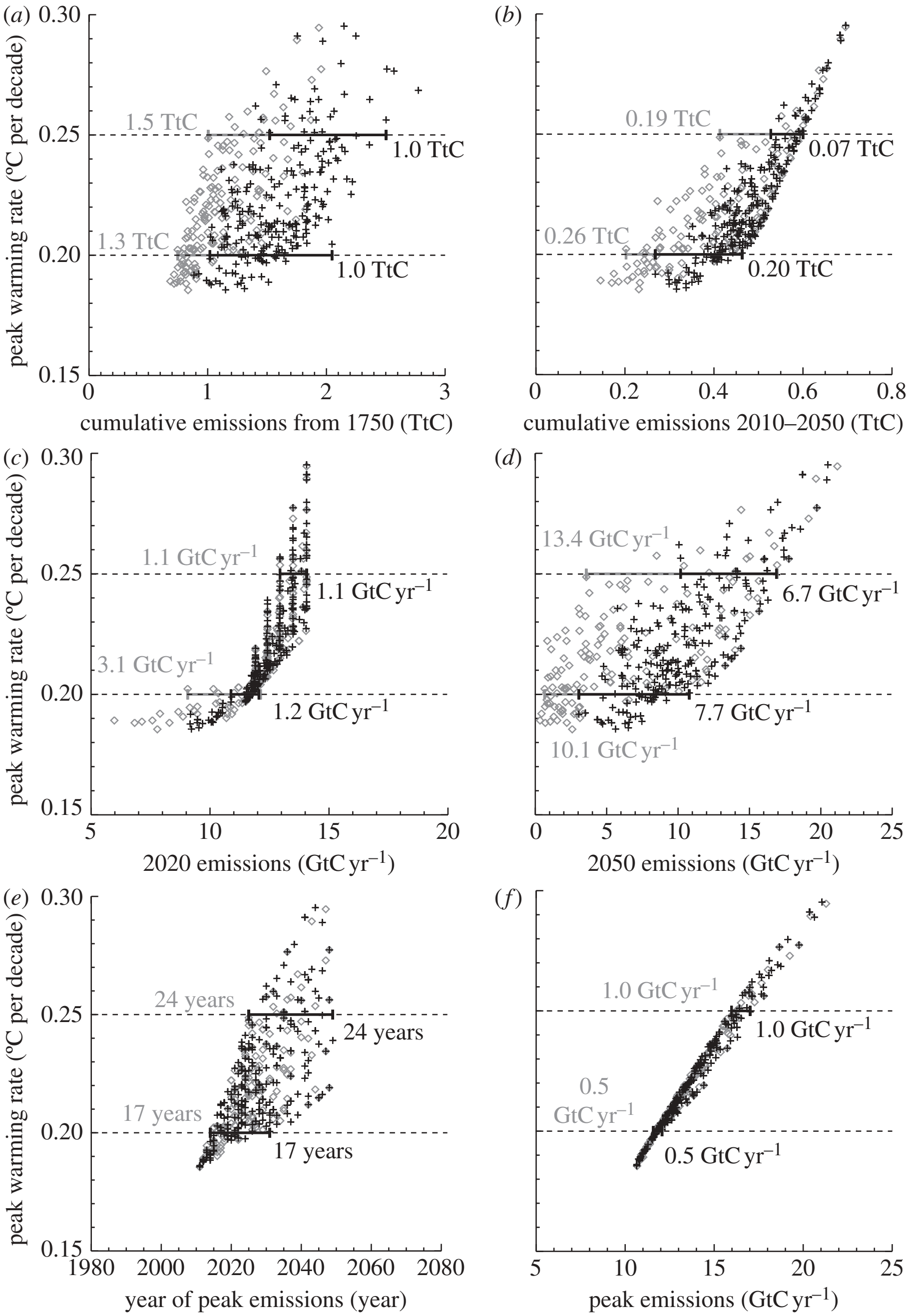

Figure 5. The correlation of emission metrics with most likely peak warming rate. This figure is like figure 2, but plotting against peak rate of warming instead of against peak warming. Again, black crosses indicate emission pathways in which the maximum rate of emissions decline is less than 4% yr^{-1}; grey diamonds indicate the converse. The bars show the spread of the metrics for pathways with a resultant peak rate of warming of 0.2°C or 0.25°C. The black bars show the spread in pathways with peak rates of emissions decline less than 4%, while the grey bars show the spread in all emission pathways. We see that the strongest correlation is in (*f*), between peak rate of warming and peak emission rate.

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kept at less than 4 per cent per year. However, these are CO_2-only pathways, and this range of warming rates would increase significantly if the possible range in non-CO_2 forcing pathways were included.

For a given peak rate of warming, and hence for a given peak emissions rate, pathways with a lower cumulative total or lower emissions in a given year must have a faster rate of decline after the peak. This phenomenon explains why all of the grey diamonds appear to the left of the black crosses in figure 5*a*–*d*. The grey diamonds are less visible in figure 5*e*,*f* because the black crosses have been plotted over the top of them.

In all of the emission pathways considered, emissions peaked between 2010 and 2050 by construction, and thus cumulative emissions between 2010 and 2050 are reasonably well correlated to peak emissions rate, particularly when we only consider pathways with rates of emissions decline between 0 and 4 per cent. This is indicated by figure 5*b*, where the black crosses are particularly well correlated.

The initially odd shape in figure 5*c* can be understood by considering the emission pathways of those points with peak rates of warming of 0.2°C per decade. We see that they have 2020 emissions of roughly 12 $\mathrm{GtC\,yr^{-1}}$. Figure 5*f* also shows that a peak emission rate of 11.5 $\mathrm{GtC\,yr^{-1}}$ produces a peak rate of warming of 0.2°C per decade, suggesting that the emission pathways in figure 5*c* with 2020 emissions of 11.5 GtC are peaking around the year 2020. Thus, the points with rates of warming of more than 0.2°C per decade have peak years of emissions later than 2020, and are less affected by the rate of emissions in 2020. Similarly, points to the left of 11.5 $\mathrm{GtC\,yr^{-1}}$ generally peak before 2020, and therefore their emission peaks are largely controlled by the rate of emissions today, and not the emissions in 2020.

Figure 5*d* shows that the 2050 emissions do not correlate well with the peak rate of warming, as 2050 emissions are not influenced much by the peak emissions rate. There is a slight correlation, however, which can be explained by considering the same mechanism that causes the small correlation in figure 5*a*.

Because an emissions peak in the next decade will be heavily constrained by the rate of emissions today, figure 5*e* appears to have some correlation near the present day, which gets worse as we move into the future. The black crosses and the grey diamonds lie in the same region of figure 5*e*, which suggests that the peak rate of warming is not heavily affected by the emissions after the emissions peak.

Figure 5*a*–*e* appear to correspond with our principal finding that peak emissions rate determines the peak warming rate, which is illustrated in figure 5*f*. This means that only two emission targets—the peak rate and cumulative carbon emissions—are needed to constrain two key indicators of CO_2-induced climate change (peak warming and peak warming rate), as evidenced by the maximum-likelihood estimation method used above. We suggest that these targets could provide a simple and natural framework for specifying climate mitigation policy, and comparing the effect of different policies. Inclusion of short-term forcing agents within a rate-of-change target is a natural extension of this approach, and could provide a framework for including both emissions rates, or ‘flows’, as well as cumulative emissions, or ‘stocks’, into a set of climate targets that are better informed by current climate science than emissions rates in a given year or long-term concentrations.

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4. Conclusions

A number of recent studies have considered the concept of cumulative carbon emissions and their relation to peak warming. Here, we consider how the concept of cumulative emissions interacts with other aspects of global change, such as emissions floors and rates of warming.

We consider other emission metrics, such as the emissions in year 2020 and 2050, and find that these cause a much wider range of magnitudes of resultant peak warming than metrics based on cumulative carbon emissions to the time of peak warming. For small cumulative totals, however, 2050 emissions can be a good indicator of peak warming; however, as soon as we consider 2050 emissions greater than around $5\,\mathrm{GtC\,yr^{-1}}$, this relationship breaks down. We also find that, for large cumulative totals in particular, cumulative metrics based on integrations over smaller time periods, such as 2010–2050, do not correlate with peak warming as well as cumulative emissions to a given date near the time of peak warming.

We extend the analysis of Allen *et al.* [11] of cumulative emissions to consider two types of emissions floors: 'hard' or constant floors, and exponentially decaying floors. In the situation that model temperatures peak before year 2500 and below 4°C, we find that cumulative emissions between pre-industrial times and year 2200 are highly correlated with that peak year, regardless of the type of emissions floor used. Floors do, however, provide a lower bound on cumulative totals at low values. We suggest that a natural geophysical time-frame for considering long-term climate policy is to the year 2200, instead of to the year 2100 as is often done today.

Cumulative emissions, however, say little about rates of global warming, which affect the cost and feasibility of societal and ecosystem adaptation in the short term. We show that maximum rates of CO_2-induced warming are much more closely correlated with peak emissions rates, and that, for each additional GtC per year on the peak emission rate, we will observe a best-guess increase of 0.016°C in the rate of warming per decade.

We also consider the short-term policy implications of our findings. The relationship between cumulative emissions and peak warming allows us to show how delaying mitigation in the short term creates the need for more rapid emission reductions later, in order to stay below a given cumulative emissions limit. Our findings relating to the rates of warming also show that only two emission targets (peak emission rate and cumulative carbon emissions to 2200) are needed to constrain two key indicators of CO_2-induced climate change: peak warming and maximum rate of warming. These targets could provide a simple and clear framework for specifying CO_2 mitigation policy over the next two centuries, and for comparing the effect of different policies.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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Review

When could global warming reach 4°C?

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The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) assessed a range of scenarios of future greenhouse-gas emissions without policies to specifically reduce emissions, and concluded that these would lead to an increase in global mean temperatures of between 1.6°C and 6.9°C by the end of the twenty-first century, relative to pre-industrial. While much political attention is focused on the potential for global warming of 2°C relative to pre-industrial, the AR4 projections clearly suggest that much greater levels of warming are possible by the end of the twenty-first century in the absence of mitigation. The centre of the range of AR4-projected global warming was approximately 4°C. The higher end of the projected warming was associated with the higher emissions scenarios and models, which included stronger carbon-cycle feedbacks. The highest emissions scenario considered in the AR4 (scenario A1FI) was not examined with complex general circulation models (GCMs) in the AR4, and similarly the uncertainties in climate–carbon-cycle feedbacks were not included in the main set of GCMs. Consequently, the projections of warming for A1FI and/or with different strengths of carbon-cycle feedbacks are often not included in a wider discussion of the AR4 conclusions. While it is still too early to say whether any particular scenario is being tracked by current emissions, A1FI is considered to be as plausible as other non-mitigation scenarios and cannot be ruled out. (A1FI is a part of the A1 family of scenarios, with 'FI' standing for 'fossil intensive'. This is sometimes erroneously written as A1F1, with number 1 instead of letter I.) This paper presents simulations of climate change with an ensemble of GCMs driven by the A1FI scenario, and also assesses the implications of carbon-cycle feedbacks for the climate-change projections. Using these GCM projections along with simple climate-model projections, including uncertainties in carbon-cycle feedbacks, and also comparing against other model projections from the IPCC, our best estimate is that the A1FI emissions scenario would lead to a warming of 4°C relative to pre-industrial during the 2070s. If carbon-cycle feedbacks are stronger, which appears less likely but still credible, then 4°C warming could be reached by the early 2060s in projections that are consistent with the IPCC's 'likely range'.

Keywords: climate modelling; climate-change projections; 4°C; global warming; dangerous climate change

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One contribution of 13 to a Theme Issue 'Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications'.

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1. Introduction

The Working Group I (WGI) volume of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; [1]) assessed the global climate change projected to result from six scenarios of greenhouse-gas aerosol emissions, taken from a larger set of scenarios from the IPCC Special Report on Emissions Scenarios (SRES; [2]). These six SRES 'marker scenarios' are identified as A1FI, A1B, A1T, A2, B1 and B2 and are discussed in more detail in §2. The scenarios represent the emissions that would be consistent with a range of plausible future trajectories of population, economic growth and technology change, without policies to specifically reduce emissions in order to address climate change. Even though the possibility of reducing emissions through climate policy was not included in these scenarios, they still project a very wide range of emissions (figure 1). Considering emissions over the entire twenty-first century, the lowest cumulative emissions are projected by the B1 scenario and the highest by A1FI. All six scenarios were considered by the IPCC to be equally sound; no scenario was considered to be more or less likely than any others [1].

The IPCC WGI assessed climate change under these scenarios from a large number of different climate models of varying levels of complexity, including ocean–atmosphere general circulation models (GCMs) and simple climate models (SCMs), with some models also including feedbacks between climate change and the carbon cycle. The IPCC used these model projections, along with observational constraints, to inform an expert assessment of the likely range of global warming that would arise from each scenario [4]. The conclusion was that under the six SRES marker scenarios, global mean temperatures are likely to increase by between 1.1°C and 6.4°C by the end of the twenty-first century, relative to the 1980–1999 average (figure 2). To present these changes relative to the usual policy-relevant baseline of pre-industrial rather than relative to 1980–1999, the IPCC recommended adding 0.5°C [5]. This implies that the likely range of global warming relative to pre-industrial under the SRES scenarios is 1.6°C and 6.9°C.

Although the six scenarios were all considered by the IPCC to be equally sound as representations of a world that does not implement policies specifically to mitigate climate change [1], not all the scenarios were examined to the same depth with climate models. Practical reasons, such as computational costs, meant that only a subset of the scenarios (A1B, A2 and B1) could be systematically examined with complex ocean–atmosphere GCMs from all the participating modelling groups.[1] SCMs were then used to estimate the warming that would have been projected by the complex models under the other scenarios (B2, A1T and A1FI). Consequently, in the AR4, the highest emissions scenario (A1FI) was examined only with SCMs and not directly with complex ocean–atmosphere GCMs [4].

The B1, A1B and A2 projections are shown in the main part of figure 2 (reproduced from the AR4) with multi-model means represented by the coloured lines and the model spread (5–95%) illustrated by the coloured plumes. The likely range of warming for these scenarios and that for the B2, A1T and A1FI projections are represented by the grey bars on the right-hand side. The best

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[1] A small number of groups had previously examined A1FI.

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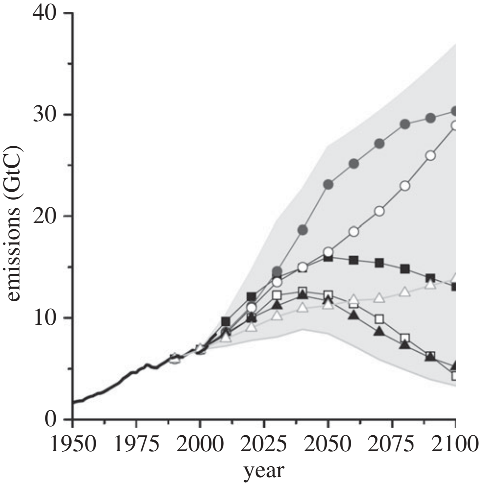

Figure 1. Emissions of CO_2 from fossil fuel in the six SRES marker scenarios (black curves) and the full range of SRES scenarios (grey plume). The SRES scenarios also include emissions of non-CO_2 greenhouse gases, aerosols and emissions from land-use change, which are not included in this figure. Filled circles, A1FI; open circles, A2; filled squares, A1B; open triangles, B2; filled triangles, B1; open squares, A1T. Reproduced with permission from van Vuuren & Riahi [3]. Copyright © Springer Science + Business Media B.V. 2008.

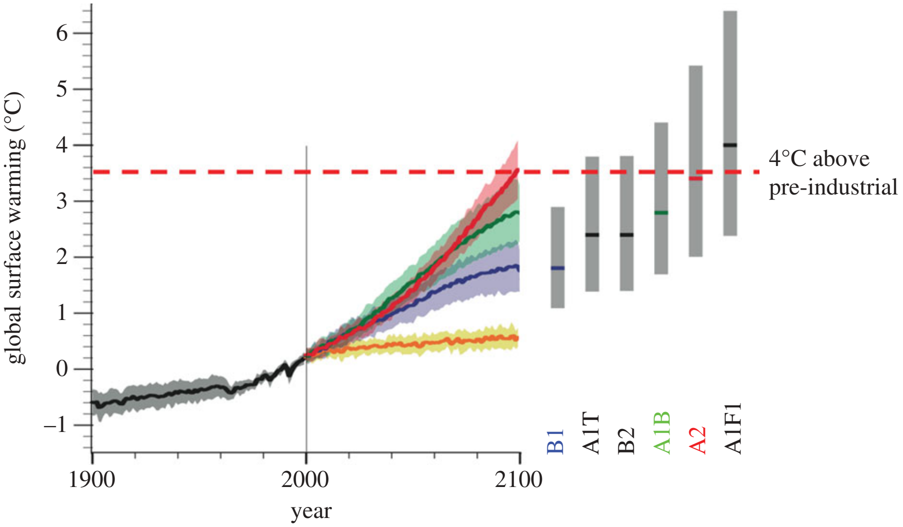

Figure 2. Past changes in global mean temperature (black curve), and projected future changes resulting from the IPCC SRES marker scenarios of greenhouse-gas and aerosol emissions (coloured curves and grey bars), relative to the 1980–1999 mean [4]. Climate changes under the A2, A1B and B1 scenarios were projected with GCMs (red, green and blue lines, with plumes showing 5–95% range of model projections without uncertainties in climate–carbon-cycle feedbacks). The full set of marker scenarios including a range of strengths of climate–carbon-cycle feedbacks were examined with SCMs. Grey bars show the likely range of warming at 2090–2099 for each scenario, from expert assessment based on all available evidence from GCMs, SCMs and observational constraints. The red dashed line marks warming of 3.5°C relative to 1980–1999, which represents 4°C relative to pre-industrial [5]. Red line, A2; green line, A1B; blue line, B1; orange line, year 2000 constant concentrations; black line, twentieth century. Copyright © IPCC, 2007.

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estimates for the B2, A1T and A1FI scenarios are shown as coloured lines within the grey bars, and match the GCM-based multi-model means or the simple-model estimates. It would appear that one consequence of this form of presentation has been that often only the GCM-based projections are presented when the AR4 figure is reproduced. This can give the impression that for unmitigated emissions, a global warming of 4°C is at the very upper end of the range, particularly since the baseline in this figure is 1980–2000. However, the 'likely range' of warming for the B1, A1B and A2 scenarios is actually 1.6–5.9°C relative to pre-industrial. Moreover, when the A1FI projection is considered, the likely range extends to 6.9°C relative to pre-industrial.

The impacts of climate change would depend not only on the level of climate change, but also on the speed with which this is reached. When assessing the warming of the full set of six SRES marker scenarios, Meehl *et al.* [4] focused largely on the magnitude of warming by the end of the twenty-first century. Discussion of the warming rates earlier in the century was centred more on the GCMs and on the B1, A1B and A2 scenarios. There was no specific assessment of the projected dates at which specific levels of global warming (such as 4°C) are projected to be reached.

With concern now increasing on the possibility of global mean temperatures rising to 4°C above pre-industrial or beyond if emissions are not reduced, this paper assesses the dates at which 4°C could be reached. We use a similar 'expert-assessment' approach to that used in the IPCC, drawing in evidence from a number of available sources. We assess whether any of the SRES marker scenarios can be identified as more likely than any other, discuss the methodology for quantifying uncertainties in deriving atmospheric CO_2 concentrations from emissions scenarios and discuss the implications of observed changes in the global carbon budget for future projections of climate–carbon-cycle feedbacks. We present an ensemble of GCM simulations driven by the A1FI scenario, and a new large ensemble of SCM projections exploring the combined uncertainty in climate sensitivity and climate–carbon-cycle feedbacks in simulations driven by the A1FI scenario. We compare all these lines of evidence to assess the consequences of the A1FI scenario for the projected magnitude of global warming by the end of the twenty-first century, and the times by which a global warming of 4°C is projected to be reached.

2. Special Report on Emissions Scenario marker scenarios and comparison with recent emissions

A key factor for future climate change will be the quantity of emissions of greenhouse gases and aerosols. These will depend on the global population, their lifestyle and the way this is supported by the production of energy and the use of the land. A large population whose lifestyle demands high energy consumption and the farming of large areas of land, in a world with its main energy source being fossil-fuel consumption, will inevitably produce more greenhouse-gas emissions than a smaller population requiring less land and energy and deriving the latter from non-fossil sources. These factors could vary in a multitude of ways; the international community is already examining how energy demand and production can be modified to cause lower emissions,

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but the implementation of this will depend on both the international political process and the actions of individuals. Even if no specific action is taken to reduce emissions, the future rates of emissions are uncertain since the future changes in population, technology and economic state are difficult if not impossible to forecast. Therefore, rather than make predictions of future emissions, climate science examines a range of plausible scenarios in order to examine the implications of each scenario and inform decisions on reducing emissions and/or dealing with their consequences.

The SRES scenarios [2] were grounded in plausible storylines of the human socio-economic future, with differences in economy, technology and population but no explicit inclusion of emissions reductions policies. A wide range of scenarios were developed using a number of integrated assessment models (IAMs), and six particular projections of emissions based on selected storylines were selected as ‘marker’ scenarios to illustrate the range of futures assessed. These scenarios extend out to 2100 and vary widely in their projected emissions by that time, although none of them includes a reduction in emissions through climate policy. The A1FI storyline describes a future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, with convergence among regions and decreasing global differences in *per capita* income. New technologies are introduced rapidly, but with a continued intensive use of fossil fuels. The B1 storyline describes the same pattern of population change as A1FI, but with much greater emphasis on clean and resource-efficient technologies, with global solutions to economic, social and environmental sustainability and improved equity. The A2 storyline describes a heterogeneous world with a continuously increasing population, regionally oriented economic development and fragmented *per capita* economic growth and technological change. The B2 storyline also features ongoing population growth but at a lower rate than A2, and with less rapid and more diverse technological change than A1FI and B1. As with B1, B2 is oriented towards environmental protection and social equity, but focuses on local and regional levels.

It is important to note that different IAMs project different emissions even for any single storyline, owing to different assumptions and methods within the IAMs. The SRES marker scenarios used different IAMs for different storylines, so each marker scenario is to some extent dependent on the IAM used as well as the underlying storyline of socio-economic change. A particular consequence of this is that the early stages of the emissions scenarios overlap considerably when all IAMs are taken into account; for example, considering the mean of all the IAM projections for each storyline, A1FI produces the highest emissions in early years just as in the long term. By contrast, when the marker scenarios based on individual IAMs are considered, A1B gives higher emissions than A1FI in the early years (figure 3). This illustrates the uncertainties in translating socio-economic factors into emissions.

Another important point is that all storylines (and hence emissions scenarios) are intended to represent long-term evolution of the driving forces of emissions as opposed to capturing short-term variations in the global economy. From 2000 to 2007, fossil-fuel CO_2 emissions grew by 3.6 per cent per year, driven largely by world gross domestic product (GDP; but growth in emissions slowed to 2% in 2008 in association with the global financial crisis) [6]. Global emissions fell by approximately 1 per cent in 2009—emissions from Organization for Economic

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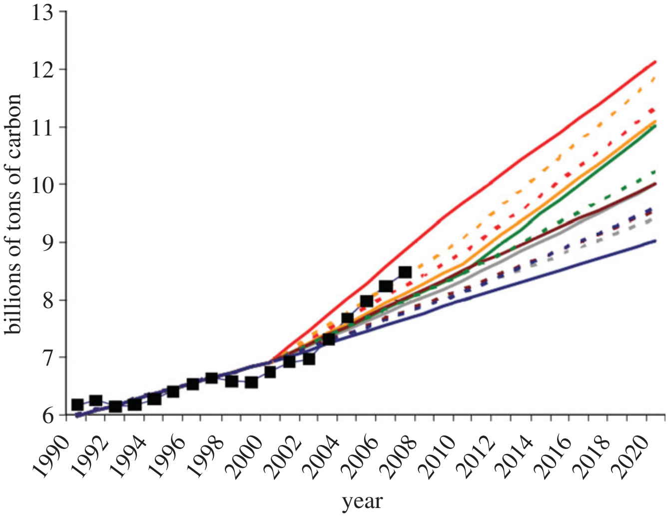

Figure 3. Comparison of actual fossil-fuel CO_2 emissions from 1990 to 2007 with SRES emissions scenarios. Dashed lines show mean emissions from all IAMs for each SRES storyline, and solid lines show the emissions from the SRES marker scenarios as used in the IPCC climate projections (figures 1 and 2). Observed emissions (published October 2008) are from Carbon Dioxide Information and Analysis Center, 'Latest Published Global Estimates' and '2006–2007 Global and National Estimates by Extrapolation' (http://cdiac.ornl.gov/trends/emis/meth_reg.html). Filled squares, actual; red line, A1B; orange line, A1FI; grey line, A1T; green line, A2; brown line, B1; blue line, B2; red dashed line, A1B*; orange dashed line, A1FI*; grey dashed line, A1T*; green dashed line, A2*; brown dashed line, B1*; blue dashed line, B2*. Adapted from Leggett & Logan [9].

Cooperation and Development (OECD) countries and Russia fell by 7 per cent owing to the economic situation, but this was almost balanced by an increase in emissions from China and India [7].

Suggestions that actual emissions have been above the upper limit of the IPCC SRES range are erroneous, and appear to be based on comparisons with the averages of different versions of the scenarios from different IAMs ([8]; dashed lines in figure 3) rather than with the individual scenarios that were actually used in climate models. Actual emissions have been within the range of the marker scenarios [3,6,9]. Given the uncertainties in the emissions scenarios themselves, and their aim of capturing long-term trends rather than short-term variations, it is still considered too early to reliably assess whether any particular SRES marker scenario is more plausible than any other [9].

3. Airborne fraction of CO_2 emissions: projections and recent observations

In the AR4, it was noted that projections of climate change should consider not only the uncertainties in the response of global temperature to a given change in CO_2 concentration ('climate sensitivity'[2]), but also the uncertainties

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[2] Climate sensitivity is the equilibrium response of global mean temperature to a doubling of atmospheric CO_2 concentration (or CO_2 equivalent of other greenhouse gases). In climate projections driven by time-dependent scenarios of greenhouse-gas concentrations, in which temperature change lags the change in forcing, a related measure is the temperature change at the time of CO_2 doubling ('transient climate response').

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in translating emissions scenarios into concentrations. The ratio between the rate of rise of atmospheric CO_2 concentrations and the rate of emissions is termed the future 'airborne fraction'. There is now a large body of evidence suggesting that the airborne fraction can be expected to be greater with climate change than without, particularly as land carbon sinks are projected to become weaker as a consequence of climate change [10–13]. The airborne fraction is currently approximately $40 \pm 14\%$ [14], and interpretations vary on whether the airborne fraction is already increasing significantly. Le Quéré *et al.* [6] suggest a trend of increasing airborne fraction of $0.3 \pm 0.2\%\,\mathrm{yr}^{-1}$ between 1959 and 2008, whereas Knorr [16] suggests an insignificant trend of $0.07 \pm 0.14\%\,\mathrm{yr}^{-1}$ since 1850. Uncertainties, particularly in CO_2 emissions from land-use change, make a precise determination of any trend difficult.

The Coupled Climate–Carbon Cycle Model Intercomparison Project (C4MIP; [12]) used a number of coupled climate–carbon-cycle models to examine uncertainties in the strength of feedbacks between climate change and the carbon cycle. The C4MIP included some models based on GCMs (including several that were closely aligned to those used for the main projections in the IPCC), and also Earth System Models of Intermediate Complexity (EMIC). The C4MIP models were driven by observed twentieth century emissions and the SRES A2 scenario of future emissions, and simulated the resulting carbon-cycle processes, including changes in land and ocean carbon sinks and in atmospheric CO_2 concentrations. The models were used in two modes: (i) changes in atmospheric CO_2 affecting the climate through changes in the greenhouse effect, to allow for climate change to affect the carbon cycle and (ii) 'switching off' the greenhouse contribution of additional CO_2, to isolate the behaviour of the carbon cycle in the absence of feedbacks from climate change. The different projections of atmospheric CO_2 concentration between (i) and (ii), therefore, showed the magnitude of the climate–carbon-cycle feedback.

The C4MIP models simulated airborne fractions of 38–56% in the absence of climate-change effects, and importantly, none of the models simulated a significant increase in the airborne fraction from 1960 to 2006, even when climate-change effects were included; indeed many of the models simulate a decrease in the airborne fraction (figure 4). The lack of increase in the airborne fraction over the twentieth century can be explained by the strong dependency on previous emissions [17]. Although the C4MIP models simulate a weaker land carbon sink over the twentieth century when climate-change effects are included, this does not translate into an increase in the airborne fraction at that time because previous emissions are still the dominant factor.

In the projections of twenty-first century CO_2 rise and climate change under the SRES A2 emissions scenario, all C4MIP models simulated a faster CO_2 rise and increasing airborne fraction when climate-change effects were included over the twenty-first century [12]. While there were shown to be large uncertainties in the strength of the climate–carbon-cycle feedback [18] and the consequent impact on the rate of rise in atmospheric CO_2 concentrations, there was unanimous agreement between the C4MIP models that this feedback is positive in sign and hence is expected to lead to an acceleration of the rise in CO_2 levels (figure 5). Recent simulations with coupled climate–carbon-cycle models now including

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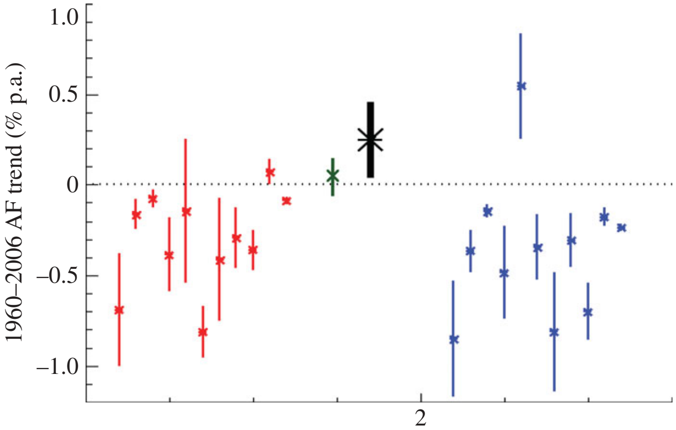

Figure 4. Trends in the airborne fraction (AF) of CO_2 emissions (fossil fuel and deforestation) from 1960 to 2006, estimated from observations by Canadell *et al.* [15] (black, with a similar estimate to Le Quéré *et al.* [6]) and Knorr [16] (green), compared with the airborne fraction trend simulated by the C4MIP models with climate–carbon-cycle feedbacks (red) and without climate–carbon-cycle feedbacks (blue).

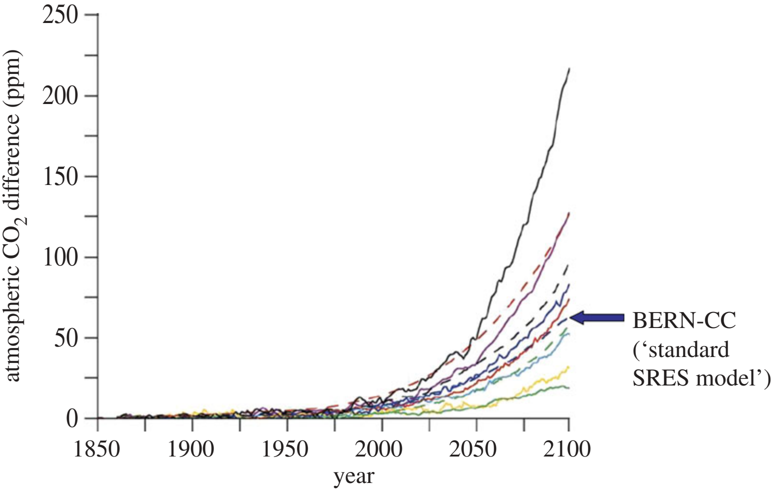

Figure 5. Effect of climate–carbon-cycle feedbacks on the rate of rise of atmospheric CO_2 from the A2 emissions scenario, from the C4MIP models. Each line shows, for each model, the difference in CO_2 projected with and without climate–carbon-cycle feedbacks. The model previously used to generate the CO_2 concentrations from the SRES scenarios as input to the GCMs used in the AR4 was the Bern climate–carbon-cycle model (BERN-CC) model; the projection of this model in the C4MIP study is highlighted here and labelled 'standard SRES model'. In this paper, we refer to the CO_2 concentrations generated by the BERN-CC model as the 'standard concentration scenario' for any given SRES scenario. Adapted from Friedlingstein *et al.* [12]. Copyright © American Meteorological Society, 2006.

nutrient cycles suggest that nitrogen limitation may reduce the climate–carbon-cycle feedback, but would still increase the airborne fraction through reduced CO_2 fertilization [19,20].

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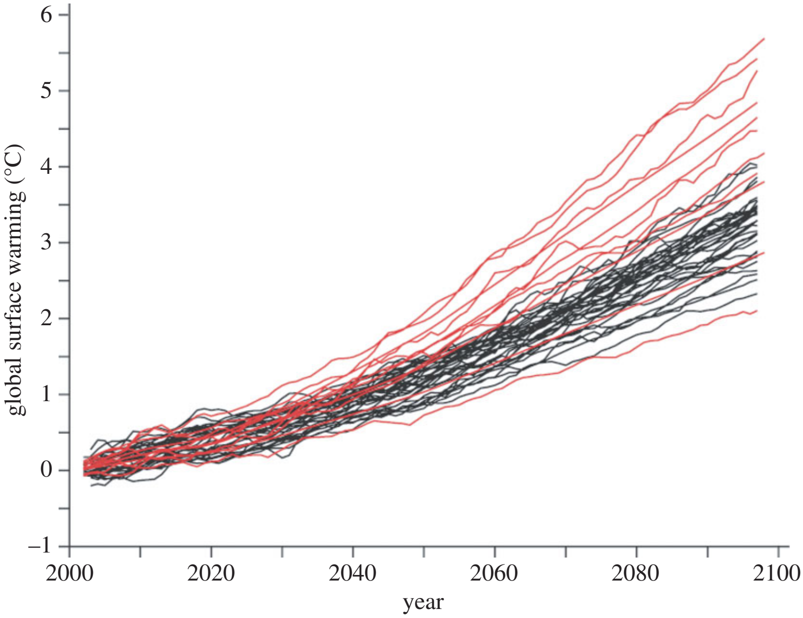

Figure 6. Projections of global mean temperature over the twenty-first century using the SRES A2 scenario, from the standard AR4 model ensemble driven by standard concentration scenarios (black lines) and the C4MIP ensemble of coupled climate–carbon-cycle models driven by CO_2 emissions (red lines). The C4MIP projections were driven by CO_2 alone [12], and for these purposes, were then scaled with a simple model to account for the radiative forcing of non-CO_2 greenhouse gases and aerosols. Adapted from Meehl *et al.* [4]. Copyright © IPCC, 2007.

The uncertainty in the strength of the climate–carbon-cycle feedback leads to increased uncertainty in the rate of global warming arising from a given emissions scenario (figure 6). Frank *et al.* [21] compare the strength of the climate–carbon-cycle feedback from temperature and CO_2 reconstructions of the Little Ice Age, but conclude that this constraint is unable to rule out any of the C4MIP models. The C4MIP study also showed that the climate–carbon-cycle feedback can increase nonlinearly in strength for greater levels of climate change, implying that the carbon-cycle feedback could be stronger under 4° of warming than previously observed during the Little Ice Age. This uncertainty mainly affects the upper end of the range of warming, owing to the model consensus that the feedback is positive. Therefore, the consideration of climate–carbon-cycle feedbacks raises the upper limit of the projected range of temperature responses, but does not significantly affect the lower limit (figure 6).

Although the IPCC assessed the feedbacks between climate change and the carbon cycle using a range of both simple and complex models, it was not possible to include this feedback mechanism in the GCMs used for the systematic projection of climate change because too few groups possessed operational carbon-cycle components of their GCMs at the time when the systematic climate-change projections were begun for the AR4. Following previous standard practice, the GCM simulations for the AR4 were instead driven by standard scenarios of CO_2 concentrations that were derived from the SRES emissions scenarios with an

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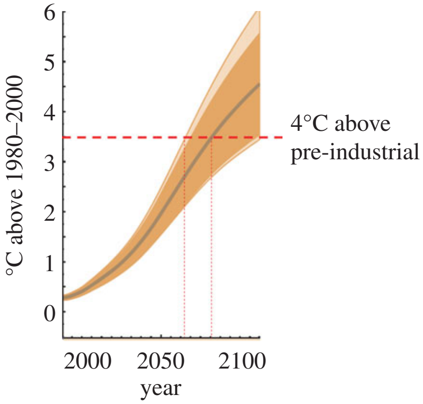

Figure 7. Projections of global warming relative to pre-industrial for the A1FI emissions scenario, using an ensemble of simulations with the MAGICC SCM tuned against the AR4 GCMs and C4MIP-coupled climate–carbon-cycle models. Dark shading shows the mean ±1 s.d. for the tunings to 19 AR4 GCMs, and the light shading shows the change in the uncertainty range when uncertainties in climate–carbon-cycle feedbacks from C4MIP are included. The horizontal red dashed line marks warming of 3.5°C relative to 1980–2000, which represents 4°C relative to pre-industrial [5]. Adapted from Meehl *et al.* [4]. Copyright © IPCC, 2007.

EMIC, in this case the Bern climate–carbon-cycle model (BERN-CC; [22]). In this model, the strength of climate–carbon-cycle feedbacks is below the average of the C4MIP ensemble ([12]; see also figure 5). In this paper, we follow Meehl *et al.* [4] in referring to these concentration scenarios as the standard SRES concentration scenarios, as distinct from the C4MIP-based ensemble projections of CO_2 concentrations, which explore uncertainty in climate–carbon-cycle feedbacks.

In order to assess the implications of the full set of six marker scenarios including climate–carbon-cycle feedbacks, the IPCC used SCMs designed to capture the global aspects of the more complex models with less computational expense and analytical complexity than GCMs and EMICs.[3] The SCM 'Model for the Assessment of Greenhouse-gas Induced Climate Change' (MAGICC) [23] was calibrated ('tuned') against the AR4 models to represent the range of atmospheric responses, and against the C4MIP models to represent the strengths of carbon-cycle feedbacks. The projections of climate change for the A1FI emissions scenario are shown in figure 7.

While this technique was used to estimate the likely range of warming for each scenario, including uncertainties in climate–carbon-cycle feedbacks, the 'best estimate' of warming from each scenario was based on projections using the standard SRES CO_2 concentrations, which is lower than the central estimate of CO_2 concentrations from C4MIP. The best estimate for B1, A1B and A2 used the mean of all GCM projections using the standard concentrations, and that for B2, A1T and A1FI used the MAGICC estimation of this GCM-based mean, again using the standard concentrations.

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[3] For further information on GCM-based Earth System Models, EMICs and SCMs, see Meehl *et al.* [4].

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4. New projections of climate change under the A1FI scenario

(*a*) *Overview of methodology*

The scenario with the highest emissions (A1FI) was not examined with GCMs in the AR4, but with global emissions generally continuing to increase, there is an increasing need to improve our understanding of the full range of potential consequences of ongoing emissions. In particular, with the impacts of high levels of climate changes expected to be severe, it is important to assess the likelihood of reaching such high levels of change and the timing of when this might be expected to occur. While these issues are subject to considerable uncertainty, a responsible risk assessment requires a range of plausible outcomes to be examined, including not only the most likely outcomes but also the less likely but potentially higher impact outcomes.

Section 4 aims to provide more complete information regarding the upper end of the range of global warming, focusing on the high-emissions scenario and a range of strengths of climate–carbon-cycle feedbacks. We assess a more comprehensive set of models, including both GCMs and SCMs, to estimate when the high-emissions scenario would give rise to a global warming of 4°C relative to pre-industrial. We provide expert-derived estimates of both a 'best guess' and 'plausible worst-case'[4] scenario. This expert-assessment approach is compatible with the approach used by the IPCC in assessing the magnitude of future climate change.

We used a perturbed physics ensemble of 17 simulations with variants of the HadCM3-coupled ocean–atmosphere GCM [24,25] to project possible climate changes over the twenty-first century following the A1FI scenario (which gives the highest emissions of the six SRES marker scenarios). We refer to this set of variants of HadCM3 as HadCM3-QUMP ('Quantifying Uncertainties in Model Projections'; [26]). The perturbed physics approach is designed to begin to quantify uncertainty in climate projections, and involves generating a number of variants of the model, which differ according to the settings of certain key parameters [25–27]. The parameter perturbations are designed to allow the ensemble to cover a wide range of behaviours of the model [28], although this is still limited by the number of simulations that can be carried out with available in-house computing resources. Here, the perturbed physics approach was used to explore a range of possible responses of the global atmospheric state to a given scenario of greenhouse-gas concentrations.

Since these simulations have been performed with variants of a single climate model, there may be an imprint of the underlying model structure. Therefore, we also compare the HadCM3-QUMP ensemble with the multi-model ensemble assessed in the IPCC AR4 (commonly referred to as the AR4 ensemble; [4]). This used 23 GCMs[5] from climate-modelling centres worldwide. The AR4 ensemble was not applied to the A1FI scenario; however, both the AR4 and HadCM3-QUMP ensembles were applied to the A1B scenario, so we use these sets of simulations to compare the climate projections from the two ensembles under a common emissions scenario.

[4] We consider the plausible worst case to be the most rapid projection of climate change within a reasonable range of uncertainty, discarding the outliers. A quantitative definition is given below.

[5] Twenty-four GCMs are shown in the AR4, but one was later withdrawn from the model-data archive.

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Table 1. Comparison of projections of global warming by the 2090s for the A1B scenario, projected by the HadCM3-QUMP and IPCC AR4 GCM ensembles.

ensemble	number of members	projected warming by 2090s relative to 1861–1890 (°C)			
		mean	median	minimum	maximum
HadCM3-QUMP	17	4.0	4.0	2.4	5.3
AR4 GCMs	23	3.2	3.2	1.9	4.9

A small number of uncalibrated ensemble members such as 17 or 23 are not considered sufficient to assign probabilities to different projections of climate change, and indeed there is a danger of outlying ensemble members being interpreted as representing relatively high probability outcomes. In order to estimate the relative likelihood of different projections and include estimates of uncertainties in climate–carbon-cycle feedbacks as well as uncertainties in atmospheric responses, we used the MAGICC model calibrated to represent the range of atmospheric responses of the HadCM3-QUMP ensemble and range of carbon-cycle feedback strengths in C4MIP. The ultimate aim of the QUMP project is to produce projections of global and regional climate change in the form of probability distribution functions (PDFs), conditioned on different emissions scenarios [29,30]. It has not been possible to produce such probabilistic estimates for this paper, including performing all the steps to test the robustness of such projections to methodological assumptions and compare the PDFs with other estimates. This we leave to future research.

(*b*) *Comparison of the HadCM3-QUMP and AR4 ensembles*

We compared the climate projections of the HadCM3-QUMP and AR4 ensembles driven by the standard A1B concentration scenario, i.e. with climate–carbon-cycle feedbacks specified using the BERN-CC model. Atmospheric CO_2 concentrations in the A1B scenario are projected to rise to 674 ppm by the 2090s. While the two ensembles project overlapping ranges[6] of global warming in response to this scenario, the mean, median and minimum of the HadCM3-QUMP ensemble projections were approximately 25 per cent higher than those projected by the AR4 ensemble, and the maximum was 8 per cent higher (table 1).

(*c*) *Climate change projected under the standard A1FI concentration scenario*

For this study, the HadCM3-QUMP ensemble is driven by the standard concentration scenario derived from the A1FI emissions in which CO_2 concentrations rise to 872 ppm by the 2080s. The ensemble mean warming by the 2090s is 5.1°C relative to 1861–1890, with the individual members projecting warming between 3.2°C and 6.7°C (figure 8 and table 2).

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[6] Considering changes projected by the 2090s relative to pre-industrial for the A1B scenario, 15 of the 17 HADCM3-QUMP simulations projected warming between the minimum and maximum projected by the full set of 23 AR4 simulations. Twenty-one of the 23 AR4 simulations projected warming between the minimum and maximum projected by the full set of 17 HadCM3-QUMP simulations.

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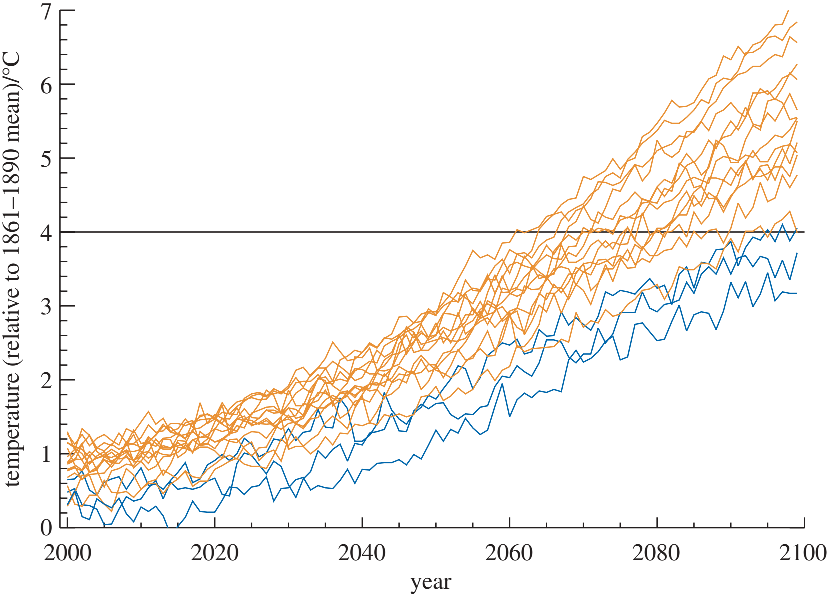

Figure 8. Projections of global mean temperature rise relative to 1861–1890 with the HadCM3-QUMP-perturbed physics GCM ensemble driven by the standard A1FI concentration scenario. Ensemble members that project a warming of 4°C or more by the 2090s are shown in orange, and the remainder are shown in blue.

Table 2. Global temperature rise by the 2090s relative to 1861–1890 projected by the 17 simulations in the HadCM3-QUMP-perturbed physics ensemble driven by the standard A1FI concentration scenario, and dates at which 4°C warming is projected to be reached. For any given simulation, the year of reaching 4°C warming is the first year in which the annual mean temperature of that year and all subsequent years is at least 4°C greater than the mean of 1861–1890.

HadCM3-QUMP A1FI			
year at 4°C	temperature 2090s (°C)	year at 4°C	temperature 2090s (°C)
2061	6.7	2076	5.1
2064	6.3	2077	5.4
2067	6.5	2079	4.9
2068	5.9	2081	4.8
2070	5.8	2085	4.5
2070	5.6	2092	4.0
2071	5.2	2095	3.9
2075	4.8	after 2100	3.6
		after 2100	3.2

Of the 17 members in the ensemble, 14 project warming above 4°C by the 2090s. The central members of the ensemble project 4°C to be reached in the 2070s, although the earliest date of reaching 4°C is 2061.

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Although GCMs were not used to project climate change under A1FI for the IPCC AR4, Meehl *et al.* [4] used an SCM to scale the results of the AR4 ensemble from other scenarios to estimate what the GCMs would have projected under A1FI. They estimated that the multi-model mean warming would have been approximately 4°C by the 2090s relative to 1980–1999, implying a warming of approximately 4.5°C relative to pre-industrial. As seen in §3 for the comparison of HadCM3-QUMP and AR4 ensembles under A1B, the estimated AR4-projected warming for A1FI is lower than that projected by HadCM3-QUMP.

It is unwise to rely on simulations that are outliers in the distribution—indeed the most extreme members of the ensemble simulated warming of 1°C or above by 2000, while warming observed between 1850–1899 and 2001–2005 was between 0.57°C and 0.95°C, with a best estimate of 0.76°C [1]. Hence, we caution against attaching too high a likelihood to the ensemble member that reaches 4°C by 2061 in response to the standard A1FI concentration scenario as represented here (in which no uncertainty in carbon-cycle feedbacks is taken into account). The extent to which this may need to be adjusted to account for carbon-cycle feedbacks is discussed in §4*d*.

(*d*) *Projected warming including uncertainties in atmospheric response and carbon-cycle feedbacks: an estimate using a simple climate model*

To estimate the climate changes that the HadCM3-perturbed physics ensemble would project with climate–carbon-cycle feedbacks included and driven by the A1FI emissions scenario, we followed the approach used in the IPCC AR4 by Meehl *et al.* [4], but with the climate sensitivity tuned against the HadCM3-QUMP GCM ensemble. Following Meehl *et al.* [4], we tuned MAGICC against the C4MIP models to represent the strengths of the carbon cycle. We carried out an ensemble of 729 simulations with MAGICC tuned in this way [31], and excluded the highest and lowest 10 per cent of projected rates of global warming from our judgement of ‘plausible’ climate changes (figure 9). Under A1FI, this ensemble projected a median warming of 5.6°C by 2100, with 4°C being reached at approximately 2070. The 10th and 90th percentiles encompassed a range of warming from 4.4°C to 7.3°C by the 2090s, with 4°C being reached between 2058 and 2088. This is broadly consistent with the results of Meehl *et al.* [4], with MAGICC tuned against the AR4 ensemble (table 3). The best estimate for reaching 4°C global warming relative to pre-industrial is approximately 5 years earlier in our ensemble, consistent with the HadCM3-QUMP ensemble exhibiting a systematically higher climate sensitivity than the AR4 ensemble as demonstrated with our comparison using the A1B scenario.

A key question is whether any statement of likelihood can be attached to our results. The IPCC AR4 [4] used a number of lines of modelling evidence and expert judgement to define a likely range of warming projections for the 2090s, with ‘likely’ being defined as a greater than 66 per cent probability of occurrence. The previous results from MAGICC tuned to the AR4 ensemble and C4MIP (figure 7) gave a warming of up to 6.5°C by the 2090s (below the upper limit of the IPCC’s likely range) and reached 4°C in the early 2060s in the upper uncertainty bound. Therefore, a projection of global warming of 4°C relative to pre-industrial by the early 2060s would appear to be consistent with the IPCC’s likely range for the A1FI scenario. More systematic probabilistic

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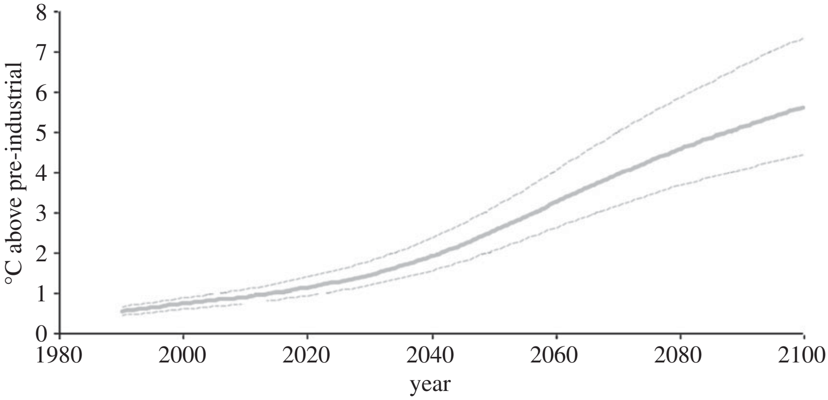

Figure 9. Global mean temperature change over the twenty-first century relative to pre-industrial, under the A1FI emissions scenario, projected with an ensemble of 729 simulations with the MAGICC SCM tuned against the HadCM3-QUMP and C4MIP ensembles. The central thick line shows the median projection, and the two dashed lines show the 10th and 90th percentiles of the frequency distribution of the 729 MAGICC experiments.

Table 3. Comparison of global warming projections by the 2090s for the A1FI scenario, from the HadCM3-QUMP ensemble, IPCC AR4 expert-assessment and MAGICC SCM ensembles tuned to AR4 + C4MIP and HadCM3-QUMP + C4MIP. The date of reaching 4°C is also given where this information is available. AR4 expert-assessment figures were originally given relative to 1980–1999. Here, we add 0.5°C warming to give warming relative to 1861–1990, as recommended in the IPCC AR4 synthesis report. (Note that the 'date of reaching 4°C' depends to some extent on inter-annual variability—for HadCM3-QUMP, we defined this date as the first year in which the annual mean temperature of that year and all subsequent years is at least 4°C greater than the mean of 1861–1890, but MAGICC does not represent inter-annual variability, so the date of reaching 4°C may be more representative of a long-term mean global temperature passing this threshold. Further details of AR4 simulations and expert assessment can be found in Meehl *et al.* [4].)

source	warming by 2090s (°C)	warming by 2090s (°C)	date reaching 4°C (best estimate)	date reaching 4°C (range)
MAGICC tuned to AR4 and C4MIP	4.9 (mean)	3.7–6.5 (±1 s.d.)	2075 (mean)	2065–2100 (±1 s.d.)
IPCC AR4 expert assessment	4.5 (scaled GCM mean)	2.9–6.9 (likely range)	not reported	not reported
HadCM3-QUMP	5.1 (median)	3.1–6.6 (full range)	2076 (median)	2061–after 2100 (full range)
MAGICC tuned to HadCM3 and C4MIP	5.5 (median)	4.3–7.2 (10th–90th%)	2070 (median)	2058–2088 (10th–90th%)

climate projections have previously been made for the UK using a complex, lengthy and systematic methodology bringing in as much of the available evidence as possible [30], but this methodology has not yet been applied to this specific problem. Our own MAGICC ensemble is designed to sample the uncertainty more

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completely than the HadCM3-QUMP ensemble, but nevertheless is still limited. The 90th percentile of our MAGICC ensemble projects a warming of 4°C by 2058. The IPCC [1] consider a probability of less than 10 per cent as 'very unlikely', so *if* our model results were interpreted as an indicator of probability, then this could be taken to indicate that it is very unlikely that 4°C would be reached before 2058 under the A1FI scenario. However, more complete sampling of uncertainty must be made before reliable estimates of likelihood can be made.

5. Conclusions

The A1FI emissions scenario is considered by the IPCC to be one of a number of equally plausible projections of future greenhouse-gas emissions from a global society that does not implement policies to limit anthropogenic influence on climate. Previously, this scenario has received less attention than other scenarios with generally lower rates of emissions. However, there is no evidence from actual emissions data to suggest that the A1FI scenario is implausible if action is not taken to reduce greenhouse gas emissions, and hence it deserves closer attention than has previously been given.

The evidence available from new simulations with the HadCM3 GCM and the MAGICC SCM, along with existing results presented in the IPCC AR4, suggests that the A1FI emissions scenario would lead to a rise in global mean temperature of between approximately 3°C and 7°C by the 2090s relative to pre-industrial, with best estimates being around 5°C. Our best estimate is that a temperature rise of 4°C would be reached in the 2070s, and if carbon-cycle feedbacks are strong, then 4°C could be reached in the early 2060s—this latter projection appears to be consistent with the upper end of the IPCC's likely range of warming for the A1FI scenario.

The above are estimates from our expert assessment and based on the current understanding of climate and carbon-cycle feedbacks derived from the model experiments described above. To that end, they are derived using an approach that is consistent with that used in assessment reports such as the IPCC AR4.

The natural next step that needs to be undertaken is to quantify the uncertainty and express climate projections in terms of PDFs. While we cannot comment in this paper on the ability to sample the PDF of possible human-induced emissions of greenhouse gases and other forcing agents, it is possible to explore modelling uncertainties in a systematic way. For example, Murphy *et al.* [30] describe an algorithm for sampling uncertainties in both physical and biological feedbacks using a single modelling structure with perturbations to key parameters. Model versions can be constrained by up-weighting those model versions that best reproduce observed aspects of climate and down-weight those that have the worst reproduction of the observations. Structural uncertainties may be further sampled using the international archive of climate-model output. The resulting PDFs can potentially be used to assess the degree of risk of dangerous climate change at both global and regional scales and for irreversible changes conditioned on different emissions pathways.

Such approaches use formal Bayesian statistical theories that are widely used in other prediction problems, but that are difficult to implement when using complex climate models. Climate model ensemble sizes are severely limited by

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available computing power, observational constraints are multi-variate and formal estimates of observational uncertainties are not readily available. There is a potential degree of subjectivity in implementing the Bayesian approach, which needs to be tested by sensitivity analysis. Nevertheless, this is an emerging area and we expect to see a number of probabilistic estimates of the risk of 4° warming (conditioned on emissions) and other dangerous climate change in the future, and these should be considered carefully in mitigation policy.

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Regional temperature and precipitation changes under high-end (≥4 °C) global warming

M. G. Sanderson, D. L. Hemming and R. A. Betts

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Regional temperature and precipitation changes under high-end (≥4°C) global warming

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Climate models vary widely in their projections of both global mean temperature rise and regional climate changes, but are there any systematic differences in regional changes associated with different levels of global climate sensitivity? This paper examines model projections of climate change over the twenty-first century from the Intergovernmental Panel on Climate Change Fourth Assessment Report which used the A2 scenario from the IPCC Special Report on Emissions Scenarios, assessing whether different regional responses can be seen in models categorized as 'high-end' (those projecting 4°C or more by the end of the twenty-first century relative to the preindustrial). It also identifies regions where the largest climate changes are projected under high-end warming. The mean spatial patterns of change, normalized against the global rate of warming, are generally similar in high-end and 'non-high-end' simulations. The exception is the higher latitudes, where land areas warm relatively faster in boreal summer in high-end models, but sea ice areas show varying differences in boreal winter. Many continental interiors warm approximately twice as fast as the global average, with this being particularly accentuated in boreal summer, and the winter-time Arctic Ocean temperatures rise more than three times faster than the global average. Large temperature increases and precipitation decreases are projected in some of the regions that currently experience water resource pressures, including Mediterranean fringe regions, indicating enhanced pressure on water resources in these areas.

Keywords: regional climate change; precipitation; temperature; global climate models

1. Introduction

Global emissions of greenhouse gases have continued to rise, with an increasing trend, throughout the twentieth century and the first decade of the twenty-first century. This has occurred against a backdrop of almost two decades of political efforts to limit greenhouse gas emissions since the Rio Earth Summit in 1992. The Copenhagen Accord, agreed in December 2009, has a stated aim of limiting global warming to 2°C above preindustrial temperatures. This target may be

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technically possible to achieve but will probably require substantial cuts in global greenhouse gas emissions in the very near future [1]. However, current national emissions-reduction pledges appear to be insufficient to keep global warming below 2°C [2].

Under scenarios of emissions in the absence of international climate policy, climate model projections assessed in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report ([3]; henceforth referred to as AR4) indicate a range of global mean warming between 1.1°C and 6.4°C for 2090–2099, relative to 1980–1999. Global temperatures rose by about 0.5°C between the preindustrial period and 1980–1999; hence, current climate projections encompass a range of 1.6–6.9°C for the end of the twenty-first century, relative to the preindustrial period. Such changes would be expected to exert major impacts and stresses on physical and human systems worldwide [4,5]. However, there are significant differences and uncertainties among the various climate models and their projections, and current knowledge on the potential for and implications of such extreme climate changes over the twenty-first century is limited.

One key issue is whether changes in global mean temperature are a useful guide to changes in a particular region. Observational data and models agree that the world is not warming at a uniform rate across the globe, and this geographical variation in the rate of warming is expected to continue. There have been previous analyses of regional climate change from global climate projections and identification of areas most strongly affected. Giorgi & Bi [6] analysed temperature and precipitation changes for 26 land regions using an ensemble of global climate projections that were forced by the Special Report on Emissions Scenarios (SRES) A1B scenario [7]. They found that, in the model simulations, temperatures increased in all regions during the twenty-first century, and precipitation decreased the most in Central America, southern South America, the Mediterranean and northern Africa, Central Asia, southern Africa and Australia. Precipitation increased over most other land areas, showing that, generally, rainfall decreased over dry areas but increased over wetter areas. Further analyses by Giorgi & Bi [8] identified when precipitation changes outside of the range of model projections and variability occur in various regions. Baettig *et al.* [9] developed climate change indices to identify regions where large changes in temperature and precipitation might occur. Using results from three global climate models, their results (for precipitation) were in agreement with those of Giorgi & Bi [6], except over the Amazon, southern South America and Central Asia.

Some models project a faster rate of global warming than others, but it is not yet clear whether this involves systematic differences at the regional scale. This is an important issue as it could indicate whether a faster rate of warming could be associated with particular regional changes. This paper begins to address this question by analysing atmosphere–ocean global climate model (AOGCM) projections from the AR4. The range of projected global warming of 1.6–6.9°C was from a wide set of emission scenarios examined with a number of different types of models, including AOGCMs, simple climate models and Earth system models (including both GCMs and simple models incorporating biogeochemical feedbacks). This paper focuses on a subset of these projections, specifically the AR4 AOGCM simulations driven by a single emissions scenario (the SRES A2 scenario; [7]).

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In §2, the methodology is described. Next, the magnitudes and patterns of climate change from high-end model simulations are examined and compared with the remaining projections, to see whether the behaviour of these two classes of model is very different. We then identify areas experiencing the greatest impacts of high-end climate change, which are those regions where the largest changes in temperature and precipitation occur.

2. Methodology

The AR4 ensemble of global climate model projections was forced with greenhouse gas concentrations inferred from several SRES emissions scenarios [7]. The emissions of greenhouse gases (and hence greenhouse gas concentrations in the atmosphere) are greatest in the A2 scenario. Gridded temperature and precipitation data from each model were obtained from the Programme for Climate Model Diagnosis and Intercomparison (PCMDI; http://www-pcmdi.llnl.gov). The models use many different horizontal grids; to facilitate comparison and analysis, all model results were transformed to the same horizontal resolution (1.875° longitude by 1.25° latitude) as the HadGEM1 model [10]. Here, we focused on the set of projections for the A2 scenario, to allow investigation of the variations in climate model responses to a single scenario of greenhouse gas concentrations. Of the 24 models discussed in the AR4, 19 were forced with the A2 scenario. Multiple simulations using the A2 scenario were available for some models (which differed only in the initial conditions used), in which case each simulation was treated independently. Overall, 40 simulations using the A2 scenario were available for our analysis. The models and simulations are listed in table 1.

Additionally, all models had been used to perform a preindustrial control experiment, where greenhouse gas concentrations were held at fixed levels throughout the simulation. We plotted time series of global annual mean temperatures calculated from the preindustrial simulations and examined them by eye. Any clear initial drift in the temperatures (resulting from the modelled climate adjusting from its initial state to that determined by the greenhouse gas concentrations) was identified, and that portion of the data was not included in the analysis. It was only necessary to exclude some of these data for a few of the models. Preindustrial mean temperatures were then calculated from the remaining years (which numbered between 180 and 940).

The increase in global mean temperatures between the preindustrial and the period 2090–2099 was calculated for all 40 simulations and rounded to one decimal point. In order to separate the simulations into those that warm faster and those that warm slower under a given forcing, we used an increase in global mean temperature of 4°C relative to preindustrial as an indicator. We classed those simulations that projected 4°C or more as ‘high-end’. There are too few results to assign probabilities to the changes; although appropriate methods to calculate probabilities are available (e.g. [11]), they are outside the scope of this paper. Internal variability in the models will not have a significant impact on the analysis, because simulated climate change by the 2090s will be dominated by the modelled response to the increasing greenhouse gas concentrations. These simulations suggest that a warming of 4°C could be reached from the 2080s [12].

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Table 1. AR4 models analysed. Only those models which were run using the SRES A2 scenario are listed. The columns headed 'run no.' contain the number of the simulation analysed. The change in annual mean temperature for each simulation between the preindustrial period and 2090–2099 is given in the columns headed 'ΔT(°C)'. Simulations classed as high-end (which are 4.0°C or greater) are shown in italics.

model	run no.	ΔT(°C)	model	run no.	ΔT(°C)
bccr_bcm_2	1	3.7	miub_echo_g	3	*4.0*
cccma_cgcm3_1	1	*4.5*	mpi_echam5	1	*4.0*
cccma_cgcm3_1	2	*4.5*	mpi_echam5	2	*4.0*
cccma_cgcm3_1	3	*4.5*	mpi_echam5	3	*4.0*
cccma_cgcm3_1	4	*4.4*	mri_cgcm2_3_2a	1	3.3
cccma_cgcm3_1	5	*4.4*	mri_cgcm2_3_2a	2	3.4
cnrm_cm3	1	*4.9*	mri_cgcm2_3_2a	3	3.3
csiro_mk3_0	1	3.4	mri_cgcm2_3_2a	4	3.4
csiro_mk3_5	1	*4.4*	mri_cgcm2_3_2a	5	3.4
gfdl_cm2_0	1	3.6	ncar_ccsm3_0	1	*4.3*
gfdl_cm2_1	1	3.6	ncar_ccsm3_0	2	*4.2*
giss_model_e_r	1	3.0	ncar_ccsm3_0	3	*4.2*
ingv_echam4	1	3.7	ncar_ccsm3_0	4	*4.2*
inmcm3_0	1	3.8	ncar_ccsm3_0	5	*4.2*
ipsl_cm4	1	*4.5*	ncar_pcm1	1	3.1
miroc3_2_medres	1	*4.0*	ncar_pcm1	2	3.0
miroc3_2_medres	2	3.9	ncar_pcm1	3	3.0
miroc3_2_medres	3	3.9	ncar_pcm1	4	3.1
miub_echo_g	1	3.8	ukmo_hadcm3	1	*4.0*
miub_echo_g	2	*4.0*	ukmo_hadgem1	1	*4.8*

3. Results

Overall, 21 projections using the A2 scenario were classed as high-end, and 19 as non-high-end. Temperature increases in several of the non-high-end projections reached 4°C or more during the 2090s in individual years. However, their decadal average temperature increases for the 2090s were less than 4°C, and so those models were not classed as high-end. Temperature increases from all simulations are given in table 1, where those from the high-end projections are in italics. In a similar analysis to that of Räisänen [13], the correlation between the temperature change and the modelled preindustrial mean temperature for all projections was calculated. Only the models that simulate the large areas of ice in the polar regions, which will have the coldest temperatures for the preindustrial period, can produce a large warming as the ice sheets recede. However, no correlation was observed, indicating that any relationship between modelled preindustrial ice sheet extent and temperature increases is complex and nonlinear.

Next, regional changes in temperature and precipitation in the high-end and non-high-end models are examined. To minimize any impacts of decadal variability, model results for 2070–2099 are analysed. The median changes in temperature and precipitation for December, January and February (DJF)

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and June, July and August (JJA), averaged over the period 2070–2099, were calculated from the high-end and non-high-end projections together with the maximum range from each group of models. Median values are used instead of the mean, because mean values are subject to bias from models that produce very large or very small changes that could be considered as outliers.

It is possible that the regional patterns of warming in the high-end and non-high-end models are similar, but are simply larger in magnitude in the high-end models. To focus on the regional responses, for each simulation, we normalized the local warming in each grid box by dividing by the global mean warming. This normalization was done separately for DJF and JJA. This approach assumes that the response of the models to global temperature change is linear, which has been shown to be a reasonable assumption [14]. The resulting patterns shown in figures 1 and 2 are the median regional temperature responses simulated by the models per degree of global mean temperature increase (colour-shaded contours) and the 5th–95th percentile range of temperature changes from each set of models (solid contours with labels).

The largest normalized regional temperature changes occur during DJF and are located over much of the Arctic for both high-end and non-high-end models (figure 1*a*,*b*) and have very similar magnitudes. These changes are much greater than those for JJA (figure 2*a*,*b*). The largest increases in DJF occur over Canada and the northern half of Asia and are about 4°C per 1°C of global warming. This large temperature increase at high northern latitudes is caused by the loss of ice and reduced winter snow coverage, exposing land and oceans which will absorb large amounts of incoming solar radiation (which will act to amplify the warming). Additionally, there will also be changes in the poleward energy transport, which is simulated to increase with rising temperature [15]. However, the range of temperature changes in the Arctic from the models is similar to or larger than the actual temperature change (figure 1*a*,*b*, solid contours with labels). Climate models are known to have large biases in their simulations of ice and snow cover over high northern latitudes. Models that simulate a large amount of snow and ice for the present-day climate are likely to simulate a large degree of warming in this region as the ice retreats. Models that simulate lower ice coverage in the Arctic will produce a smaller amount of warming [13]. The magnitude and inter-model range of simulated warming over high northern latitudes are very similar in the high-end and non-high-end models, which indicates that the biases among the models are larger than the climate change signal.

Figure 1*c* shows the difference between the normalized high-end and non-high-end temperature changes for DJF. A positive value indicates that the high-end models are warmer than the non-high-end models. The high-end models are colder by 0.5°C per 1°C global warming or more over the northeastern edge of Europe and the nearby Arctic regions, and around the northern parts of Japan. They simulate warmer temperatures around the coasts of Canada, Alaska, Greenland and the Arctic region of Asia. Warmer areas are also simulated by the high-end models over Central Asia, the northern coast of South America and northwestern Australia. Overall, the pattern-scaled temperature changes in the high-end and non-high-end models are similar over much of the globe, but there are some regional differences, indicating that the regional response of the high-end and non-high-end models to climate change is not completely identical.

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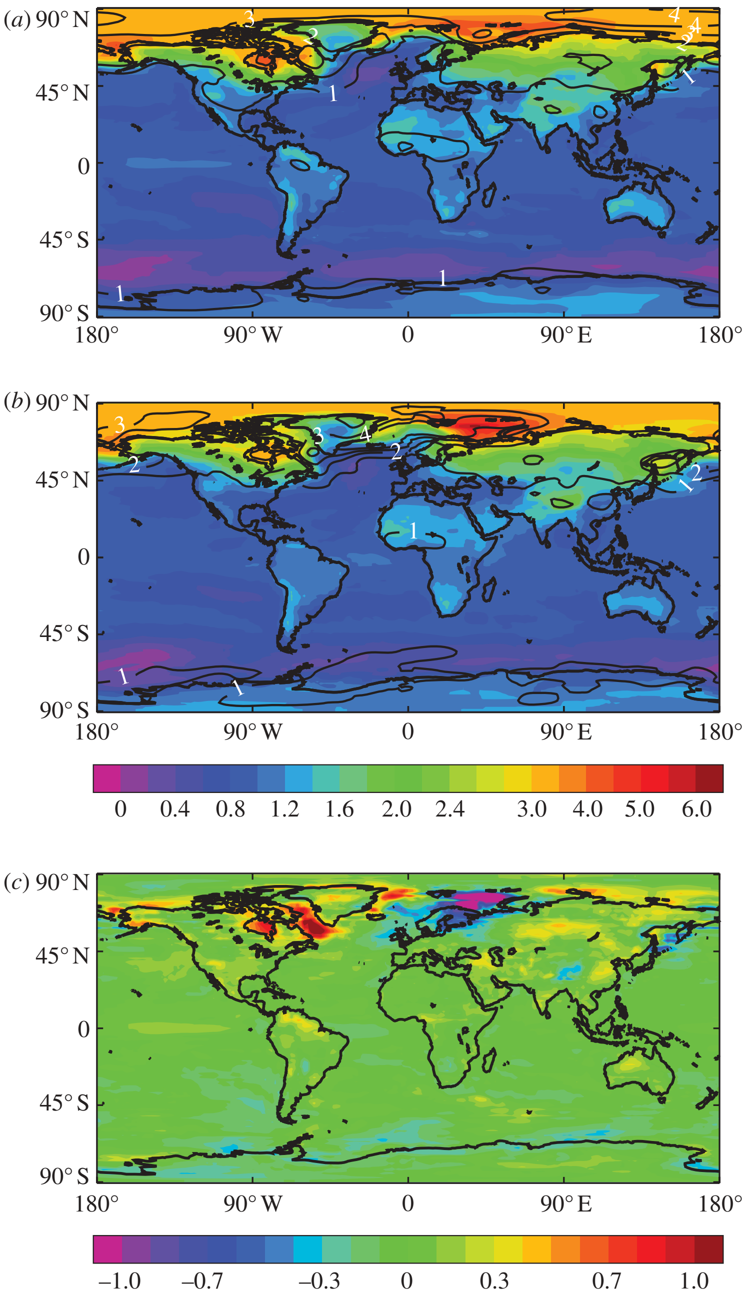

Figure 1. Median temperature responses simulated by the models per degree of global mean temperature increase for DJF. (*a*) Median temperature changes from the high-end members, shown by the colour-shaded contours. The solid contours with labels show the range of temperature changes across the high-end models (again scaled by the global mean temperature rise). Note that the temperature scale changes at 3°C. (*b*) As (*a*), but for the non-high-end members. (*c*) Difference between the medians of the high-end and non-high-end members. A positive value indicates that the scaled temperatures in the high-end models are warmer than the non-high-end models.

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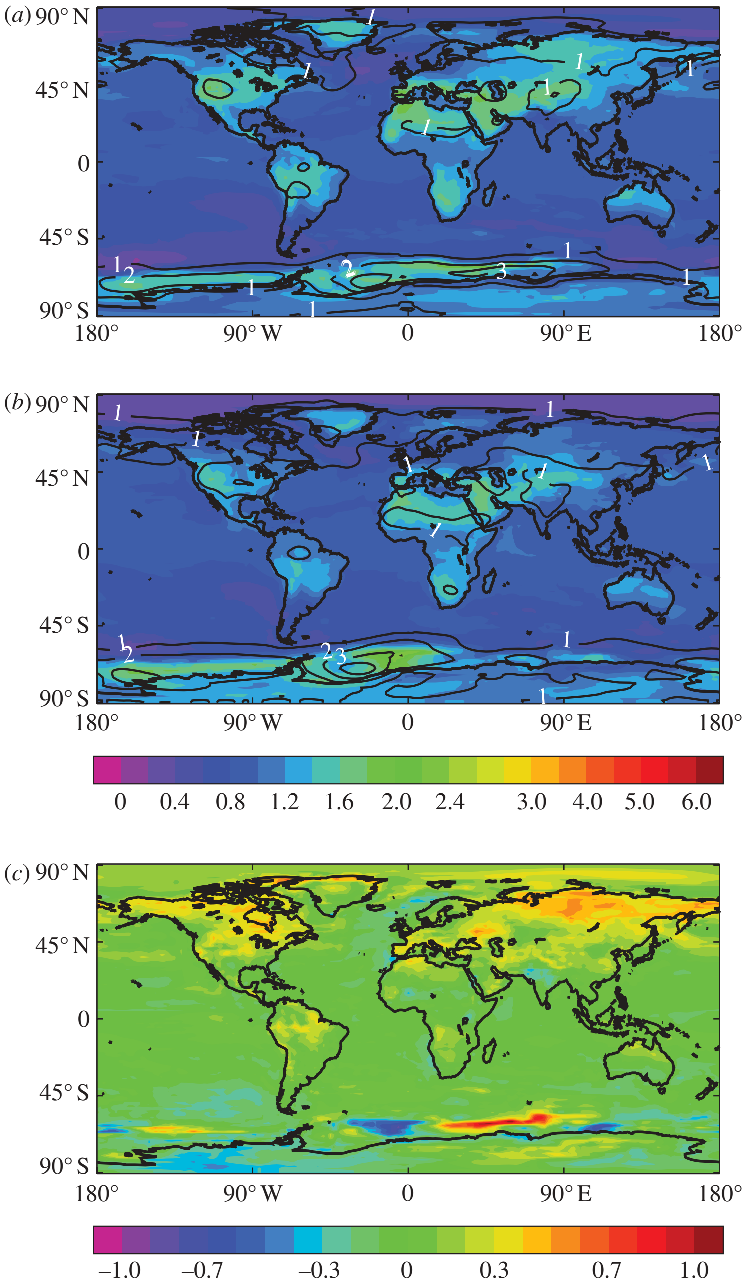

Figure 2. Median temperature responses simulated by the models per degree of global mean temperature increase for JJA. (*a*) Median temperature changes from the high-end members, shown by the colour-shaded contours. The solid contours with labels show the range of temperature changes across the high-end models (again scaled by the global mean temperature rise). Note that the temperature scale changes at 3°C. (*b*) As (*a*), but for the non-high-end members. (*c*) Difference between the (scaled) medians of the high-end and non-high-end members. A positive value indicates that the temperatures in the high-end models are warmer than the non-high-end models.

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An area of water where almost no warming occurs is projected to form in the northern North Atlantic, between the UK and Greenland, and this area is larger in the high-end models. This cooler water could be caused by a slowing of the North Atlantic thermohaline circulation [4]. None of the models analysed by the IPCC [4] simulates an increase in this circulation with a warming climate, and the modelled response varies between essentially no change and a 50 per cent reduction. There may also be increased deep vertical mixing in the high-end models, which acts to warm waters well below the surface but reduces the surface warming [13]. A similar area of water is also projected to form over much of the Southern Ocean. The spatial extent of this cooler water is larger in the high-end models than in the non-high-end models. The temperature range across the models in the Arctic and Antarctic regions is of a magnitude similar to or larger than the median change, indicating that biases resulting from differences in modelled ice and snow amounts are similar to or larger than the climate change response [16].

In JJA, the largest differences in normalized regional temperature changes between the high-end and non-high-end members occur over land and are mostly confined to smaller areas between 45° N and 45° S (figure 2*a*,*b*). The magnitude of these temperature changes is smaller than those seen for DJF. The land–ocean temperature contrast is also larger than in DJF. Enhanced warming is seen over much of the USA, parts of South America, the Mediterranean areas, northern and southern Africa, Central Asia and parts of northern Australia (colour-shaded contours). This normalized warming generally lies between 1.4°C and 2°C per 1°C global warming. The 5th–95th percentile temperature range across the models (shown by solid contours with labels) in these regions is smaller and has a different spatial pattern, suggesting that these simulated patterns of warming are not largely controlled by model biases. A small area with a high degree of warming is simulated around the coast of Antarctica, where the inter-model temperature range is also large. Again, this area of warming is likely to result from biases in modelled sea ice amounts [16]. The difference in scaled temperatures between the high-end and non-high-end models is shown in figure 2*c*. The high-end models project normalized regional warming, which is 0.2–0.6°C per 1°C global warming greater over much of the Northern Hemisphere land masses. Smaller areas of relatively faster regional warming are also seen over South America, southern Africa and Australia. This difference could be due to larger poleward energy transport in the high-end models, which is simulated to increase with warmer temperatures [15].

A small area of less warm water in the North Atlantic Ocean is simulated for JJA, and the warming is slightly greater than in DJF. Around Antarctica, both positive and negative differences in warming between the high-end and non-high-end models are seen. These differences are likely to be due to variations in the modelled responses of the sea ice.

Overall, the patterns of the response of regional climate to global climate change in the high-end and non-high-end models are similar during DJF and JJA. However, the regional response of the high-end models is larger, particularly during JJA. Much of the warming seen during DJF over high northern latitudes is strongly controlled by each model's simulation of ice and snow cover during the preindustrial period, and how they respond to a warming climate. Models are known to have large biases in snow and ice cover over high northern latitudes [16].

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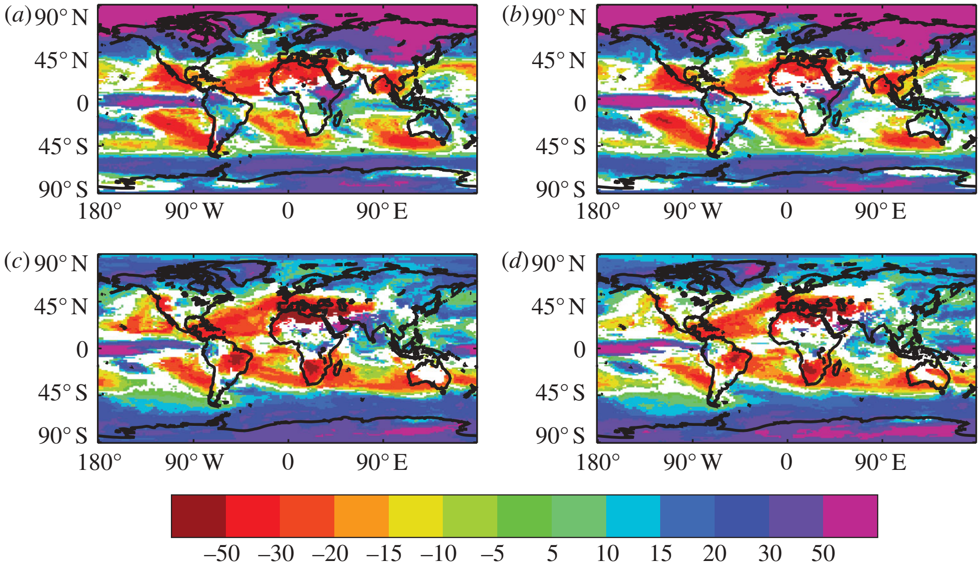

Figure 3. Precipitation changes (%) in (a,b) DJF and (c,d) JJA from the median of the A2 ensemble, after scaling to 4°C global mean warming in all cases. (a,c) Precipitation changes from the high-end members, and (b,d) changes from the non-high-end members. The data are only shown where 66% or more of the models agree on the sign of the change.

Maps illustrating the percentage changes in precipitation during DJF and JJA for the high-end and non-high-end members are shown in figure 3. It has been shown that the patterns of regional temperature response of the high-end and non-high-end models to climate change are similar, although the temperature response of the high-end models tended to be greater. The precipitation changes from each model were scaled to a global mean temperature rise of 4°C. Previous work [17] has shown that global precipitation in most models increases linearly with increasing temperature. By scaling the precipitation changes, the maps shown in figure 3 will illustrate any differences between the precipitation responses of the high-end and non-high-end models. The precipitation changes have only been plotted if 66 per cent or more of the models agree on the sign of the change. White areas in figure 3 are where fewer than 66 per cent of the models agree on the sign of the change, and thus represent locations where there is no reliable signal.

Areas experiencing large decreases in precipitation are evident in both DJF and JJA, in both the high-end and non-high-end members, and occur between 50° N and 50° S. The patterns in each season are very similar between the high-end and non-high-end models, but the precipitation decreases are larger in magnitude in some regions in the high-end models than in the non-high-end models. The total area (land and ocean) where precipitation decreases is also larger in the high-end models than in the non-high-end models, by 14 per cent in DJF and 7 per cent in JJA. In DJF, precipitation is projected to decrease over Central America, the Mediterranean, northern Africa, India and parts of Southeast Asia. Other regions experiencing a decrease in rainfall are the southernmost parts of

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South America and much of Chile. Precipitation is projected to increase over most of the remainder of South America, the Horn of Africa and much of Australia. Precipitation is projected to increase over almost all areas north of 45° N and south of 50° S.

During JJA, the area of Europe experiencing a precipitation decrease has extended northwards to cover most of the continent, except Scandinavia. Precipitation is still projected to decrease over Central America, and also to decrease over large parts of Brazil, southern Africa and Australia. Increases in JJA precipitation are projected over India and Southeast Asia. There is poor model agreement over much of the USA and Australia during JJA.

The differences in precipitation changes between the high-end and non-high-end models in DJF and JJA were also investigated (data not shown). The differences are very small over most regions (less than ±5%), except for a small area of the equatorial Pacific Ocean, where the non-high-end models project an increase in precipitation that is about 50 per cent greater than in the high-end models. There were also a few small areas over northern Africa, Alaska and the adjacent part of eastern Russia (Chukotka) where larger precipitation changes in the high-end models were projected, but these areas are small.

The increases in precipitation seen at higher latitudes are a result of increasing amounts of water vapour in the atmosphere. Warmer temperatures result in higher evaporation rates, and warmer air can hold more water vapour. There is also an increasing poleward transport of water vapour from lower latitudes. The subtropical regions (e.g. the Mediterranean, North Africa and Central America) experience a drying owing to increased transport of water vapour out of this area and an expansion of the subtropical high-pressure regions towards the poles [4]. In these regions, the air is very dry and the high pressures suppress precipitation.

Over Europe and the adjacent parts of central western Asia, the areas with enhanced warming in the high-end models are similar to the areas where the precipitation has decreased. This result suggests that the reduced precipitation has caused drier soils, which in turn have enhanced the warming owing to reduced cooling by evaporation. The areas with enhanced warming over the USA may also be caused by drier soils from reduced precipitation, although the poor model agreement in precipitation changes for this region means this conclusion is uncertain. The warming over southern Africa may also be a result of reduced precipitation. The JJA precipitation decreases by 20–50% in this region for a 4°C global warming, where enhanced warming is also seen.

The regions that could be most strongly affected by high-end climate change are now identified. These regions are defined as those where temperatures increase by at least 6°C and precipitation changes by at least 10 per cent, for 4°C global warming. These limits are arbitrary but are likely to have a large impact on ecosystems [5]. Temperature and precipitation changes from the high-end model simulations (21 runs) were scaled to a global mean warming of 4°C. Although there will be some nonlinearities in the modelled responses, they are unlikely to be large enough to affect the results [14].

The regions most strongly affected by high-end climate change are shown in figure 4. The colours indicate regions where both the temperature and precipitation changes are equal to or exceed the limits given in the previous

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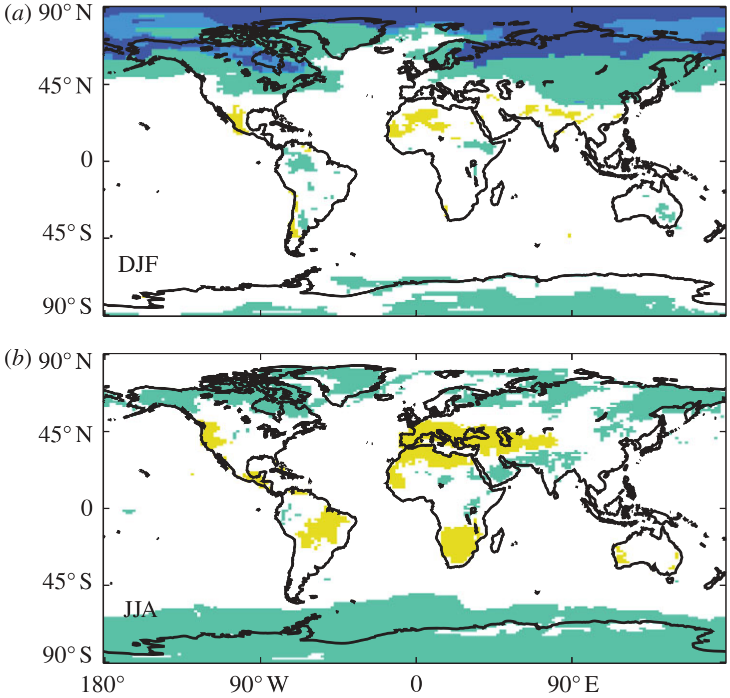

Figure 4. Areas most strongly affected by high-end climate change in (*a*) DJF and (*b*) JJA. The temperature and precipitation changes from the high-end models were scaled to a global mean warming of 4°C. The coloured areas indicate where precipitation changes by at least ±10% and temperature increases by at least 6°C for 4°C global warming. Yellow colour indicates areas where precipitation decreases, and at least 66% of the models agree on the sign of the change. Light green, light blue and dark blue colours show areas where precipitation increases by 10% or more for 4°C global warming. The light green colour areas show where one or more models project a temperature rise of at least 6°C, and at least 66% of the models project a precipitation increase. The blue colours indicate regions where all models project a temperature rise of at least 6°C, and 90% (light blue) or 100% (dark blue) of the models agree on the sign of the precipitation change.

paragraph. Light green, light blue and dark blue colours show areas where precipitation increases by 10 per cent or more for 4°C global warming. The light green areas show where one or more models project a temperature rise of at least 6°C, and at least 66 per cent of the models project a precipitation increase. The blue colours indicate regions where all models project a temperature rise of at least 6°C, and 90 per cent (light blue) or 100 per cent (dark blue) of the models agree on the sign of the precipitation change. The green and blue colours, therefore, represent the minimum (dark blue) and maximum (all green and blue colours) extent of regions projected to experience temperature and precipitation increases above the limits set earlier. The yellow areas in figure 4 indicate those regions where precipitation decreases by 10 per cent or more, at least 66 per cent of the models agree on the sign of the change and all models project a temperature rise of 6°C or more.

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For DJF (figure 4*a*), the spatial extent of the maximum and minimum areas projected to experience the highest climate changes under a global warming of 4°C is very different, highlighting the uncertainty that mostly originates from the different temperature changes projected by the models. There are smaller regions (Mexico, northern Africa and parts of Southeast Asia) shown in yellow where there is reasonable confidence that precipitation will decrease.

For JJA (figure 4*b*), Central America, parts of Brazil, southern Africa, and parts of Europe, northern Africa and the adjacent part of Central Asia are projected to suffer large rises in temperature and decreased precipitation. Small parts of the USA and Australia could be similarly affected. Much of the high northern latitude regions are projected to receive increases in precipitation together with large temperature rises. Other locations (the Arabian Peninsula, parts of northern India) may also change in the same way, but the areas are small. There are no regions during JJA where the temperature rises by 6°C, and 90 per cent or more of the models agree on the sign of the precipitation change (if that change is at least 10%). For JJA, the uncertainty in the projections mostly originates from differences in modelled precipitation changes.

4. Conclusions

Forty global climate model projections using the A2 scenario from the IPCC Fourth Assessment Report have been analysed, and a number of simulations that project a high-end warming of 4°C or more by the 2090s (relative to the preindustrial period) were found. About half of the simulations were classed as high-end. Under the high-end models, Northern Africa is projected to experience high (greater than 6°C) temperature increases and large precipitation decreases in both DJF and JJA, suggesting that this region is most at risk from high-end climate change. In addition, during JJA, Southern Europe and the adjacent part of Central Asia are projected to warm by 6–8°C, together with a decrease in precipitation of 10 per cent or more. This result suggests that drier soils, a consequence of the reduced precipitation, are the cause of the elevated temperatures, as the evaporative cooling effect will be smaller. The large-scale patterns of temperature and precipitation change in the high-end and non-high-end projections are similar, although the magnitudes of temperature change were larger in the high-end models, especially during JJA. The main difference in the regional temperature response of the high-end models from the non-high-end models occurs over much of the Northern Hemisphere land areas during JJA. The high-end models project enhanced warming over most of northern Asia, Canada and the USA. The patterns and magnitude of the precipitation changes (scaled to a global mean warming of 4°C) are similar in the high-end and non-high-end models, although the reductions in precipitation tend to be slightly greater in the high-end models.

The regions where the greatest climate changes occur under 4°C global warming were identified using results from the high-end models. These regions are defined as those where temperatures increase by at least 6°C and precipitation changes by at least 10 per cent. During DJF, high northern latitude land areas, Mexico and parts of northern Africa are identified. For JJA, the largest climate

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changes occur in northern and southern Africa, southern Europe and the adjacent part of Central Asia and parts of Brazil. The uncertainty in the regions affected by high-end climate change during DJF (the Arctic) is mostly due to differences in modelled temperature increases, which are caused by biases in simulated ice sheet extent and snow cover. However, for JJA, the uncertainty mostly originates from differences in modelled precipitation changes.

Much of the uncertainty in these results originates from the poor agreement in temperature and precipitation changes between the models in some areas. If agreement in these changes from the next generation of climate models, which will be used for the forthcoming IPCC Fifth Assessment Report, is greater, this work could be repeated to highlight other areas that could be strongly affected by high-end climate change. Further work could consider changes in extreme temperatures and precipitation.

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Water availability in +2°C and +4°C worlds

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While the parties to the UNFCCC agreed in the December 2009 Copenhagen Accord that a 2°C global warming over pre-industrial levels should be avoided, current commitments on greenhouse gas emissions reductions from these same parties will lead to a 50 : 50 chance of warming greater than 3.5°C. Here, we evaluate the differences in impacts and adaptation issues for water resources in worlds corresponding to the policy objective (+2°C) and possible reality (+4°C). We simulate the differences in impacts on surface run-off and water resource availability using a global hydrological model driven by ensembles of climate models with global temperature increases of 2°C and 4°C. We combine these with UN-based population growth scenarios to explore the relative importance of population change and climate change for water availability. We find that the projected changes in global surface run-off from the ensemble show an increase in spatial coherence and magnitude for a +4°C world compared with a +2°C one. In a +2°C world, population growth in most large river basins tends to override climate change as a driver of water stress, while in a +4°C world, climate change becomes more dominant, even compensating for population effects where climate change increases run-off. However, in some basins where climate change has positive effects, the seasonality of surface run-off becomes increasingly amplified in a +4°C climate.

Keywords: climate change impacts; global water resources; water resources stresses; macro-scale hydrological model; ensembles; uncertainty

1. Introduction

In December 2009, the Copenhagen Accord [1] reiterated the need to restrict global warming to no more than 2°C above pre-industrial levels. Since the accord, pledges for greenhouse gas emissions reductions put forward by nations (which include all major greenhouse gas emitters) lead to a 50 : 50 chance of a peak global warming of at least 3°C above pre-industrial levels [2], with some estimates of the 50 : 50 warming as large as 3.9°C [3]. These commitments are clearly far below what is required to keep below the 2°C target with any reasonable probability, and even more so for a limit of 1.5°C, a possible long-term goal of the Copenhagen

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Accord. Clearly, while 2°C remains an important policy target, larger warming is highly likely, and it is important to evaluate the difference in impact of warming between a world that meets its policy objective and one where there is significant overshoot of this target.

A large number of studies have assessed the impact of climate change on global water resources and have been reported in the series of assessment reports conducted by the Intergovernmental Panel on Climate Change (IPCC) [4] and in a number of other publications [5–11]. These analyses have typically used ensembles of global climate models (GCMs) developed by a number of modelling centres across the globe, the so-called ensembles of opportunity or multi-model ensembles (MMEs). These evaluations have assessed the time-evolving impacts under different emissions scenarios and the uncertainty that arises in future projections owing to different GCM structures [12,13], rather than the impacts that occur at particular global temperature change thresholds.

In this paper, we contrast water availability and water stress in a world where warming is limited to 2°C and one where policy fails and warming reaches 4°C. We make use of a new GCM dataset, from the ClimatePrediction.net (CPDN) experiment [14], in combination with data from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-GCM archive [15]. These provide us with a wide range of realizations of a world that warms by 4°C, enabling us to identify differences in climate, surface run-off and population that determine water stress in '+2°C' and '+4°C' worlds. We begin the paper by introducing the climate and hydrological models used, and how the data are processed to define the +2°C and +4°C worlds. This is followed by a description of the scenarios of future population growth we developed and how these are used to define water stress. We then present results showing differences in water availability and stress in +0°C (present day), +2°C and +4°C worlds. Finally, the implications for global and regional water resources are discussed.

2. Models and data

(a) The climate models

The CPDN perturbed-physics ensemble (PPE; available from www.climateprediction.net) comprises a large number of runs of a state-of-the-art GCM, HADCM3L. This is a version of the UK Met Office's (UKMO) Unified Model comprising a 3.75° longitude by 2.5° latitude resolution atmospheric model coupled to an ocean model with the same resolution; this is a lower spatial resolution than the ocean model (1.25° longitude by 1.25° latitude) used in the UKMO's standard version of this model, HadCM3. Each individual run uses a configuration of the GCM, with parameters representing various physical processes set to different values within their acceptable range, as defined by the experts in the relevant parametrization scheme [16,17]; see www.climateprediction.net for more details. For each combination of parameter values, an initial condition ensemble is used, enabling separation of internal and parameter variability. PPEs provide an approach for exploring a wide range of future climates, and this information can be used to assess potential impacts of climate change under that range of plausible futures.

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For this study, we have selected a subset of 1557 GCM runs from the CPDN experiment that provides global climate data from 1930 to 2079. This subset has been driven by the SRES A1B greenhouse gas emissions scenario, a 'middle of the road' scenario, representing a world in the twenty-first century with very rapid economic growth, rapid introduction of new and more efficient technologies and a world that does not rely too heavily on one particular energy source; total CO_2 emissions increase to just over 16 Gt carbon in the 2050s, and then decline slowly to 13.5 Gt by 2100 [18].

We also use an MME of 22 GCMs from the CMIP3 multi-model dataset [15] that have completed at least one model run forced by the SRES A1B scenario, and have archived precipitation and temperature for the period 1961–2079. This enables us to compare the hydrological response across different sources of uncertainty: parameter uncertainty in the case of the PPE, and combined parameter and structural uncertainty in the MME. The climate models used in this analysis include BCCR-BCM2.0, CGCM3.1, CNRM-CM3, CSIRO-MK3.5, CSIRO-MK3.0, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, GISS-EH, GISS-ER, FGOALS-g1.0, INGV-ECHAM4, INM-CM3.0, IPSL-CM4, MIROC3.2 (hires), ECHO-G, ECHAM5/MPI-OM, CCSM3, PCM, MRI-CGCM2.3.2, UKMO-HadCM3 and UKMO-HadGEM; see Randall *et al.* [19] for a full description of the climate models.

For both ensembles, each GCM is assumed to be an equally plausible projection and no model weighting or transformation of the ensemble outputs into a probability distribution has been applied.

A +4°C world is defined here as a one where a GCM's decadal global mean temperature is +4°C warmer than the 1961–1990 average in at least one season. This is different from the standard UNFCCC definitions for global warming, which are relative to pre-industrial temperatures; assuming a global warming of *ca* 0.7°C since 1850, our +4°C world is about 4.7°C warmer than pre-industrial. We select models that show an increase in global mean temperature of 2°C and 4°C at some point in the twenty-first century. For the CPDN simulations, this results in an ensemble of 1518 and 399 members for the +2°C and +4°C worlds, respectively. For the CMIP3 ensemble, all models exhibit a 2°C warming at some point in the twenty-first century, but only one model, namely MIROC3.2 (hires), warms by 4°C by 2100.

(*b*) *The climate variables*

The global hydrological model we use requires monthly inputs of precipitation and number of rain days, as well as several variables needed to determine potential evapotranspiration: temperature, vapour pressure, radiation and wind speed. These are available for the present day from the CRU TS2.1, 0.5° latitude/longitude observed climate dataset [20], where we use the time period 1961–1990 as our 'baseline' against which future changes are assessed, but regridded to 1° latitude/longitude, the resolution of the hydrological model.

As the CPDN experiment relies on distributed computing, where members of the public run a GCM on their personal computers [14], bandwidth limitations mean that only limited numbers of diagnostics are returned to the CPDN servers for archiving. Of the input variables needed for the

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hydrological model, only precipitation and temperature are available, as decadal seasonal means and at the model native resolution of 3.75° longitude by 2.5° latitude.

Climate models are well known to contain biases in their climatology; for precipitation especially, any large biases can force the hydrological model to operate outside the range of the parametrizations that are used to simulate surface run-off. To correct for these biases, we use the change factor method whereby absolute changes in temperature and percentage changes in precipitation fields from a GCM for a 30 year period (e.g. 2000–2029) are calculated relative to a 1961–1990 baseline. The seasonal change factors were then disaggregated linearly to produce monthly factors, and interpolated to a 1° latitude/longitude resolution, as required by the hydrological model. To calculate future climate, precipitation and temperature change factors are then applied to the CRU TS2.1 baseline climate; other climate variables required by the hydrological model, for which we do not have GCM data, were kept the same as observed climate. One of the main criticisms of this bias-correction method is that it only adjusts the long-term mean and does not take into account additional changes in climate variability [21]. However, given that only decadal seasonal means are available from CPDN, a more sophisticated method of downscaling would not be warranted. The CMIP3 GCMs were processed in an identical manner to allow direct comparisons in the analysis.

(*c*) *Water availability*

(i) *Global hydrological model*

We employ the MacPDM global hydrological model at a 1° spatial resolution. MacPDM is a semi-distributed daily water balance model that has been used in previous assessments of global water resources [7–9,22,23], and at its heart is a simplified version of the probability distribution model by Moore [24]. The model contains modules that simulate snowpack, lakes and wetlands but does not include a glacier component. As well as climate variables, other inputs include land cover, which has been derived from De Fries *et al.* [25], and soil textures, which have been taken from the FAO Digital Soil Map of the World. MacPDM internally disaggregates monthly precipitation to daily rates by using information on the number of rain days in each month and a random precipitation generator. The model is then run 10 times and the mean of the model outputs used. MacPDM outputs surface run-off at the monthly time step that, for this study, has been aggregated to mean seasonal values to reflect the temporal resolution of the CPDN climate model ensemble.

There are a large number of global hydrological models, including those currently involved in the WATCH project [26], some of which treat the hydrological system in a more sophisticated manner than MacPDM. However, MacPDM is used in this investigation owing to its relative simplicity and therefore amenability for running large ensembles. The spatial resolution used in this study is also not as fine as those used by others [5–11] but does compare well with recently published work [27–29]. Despite infrastructure and flow routing not being included in the model, the compromise in the spatial resolution should not hinder our analysis of impacts on a larger, more synoptic scale.

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(ii) *Water stress index*

Water stress or scarcity can be defined as the balance between water supply (potential or realized) and water demand. A large number of water stress indices have been devised, incorporating information on factors such as accessibility of water under low flow conditions (e.g. [30]), water demands with the inclusion of national water withdrawal information on various water users (e.g. [11,31]), economic and technological advancement (e.g. [6,27]) as well as access to water sources (e.g. [32]). On the whole, these methodologies require a large amount of input data, much of which can be very uncertain. Given that the main purpose of this paper is to look at the impacts of two global temperature regimes by using large climate model ensembles, we have chosen to analyse the water resources *per capita* calculated as the ratio of annual surface run-off to population, which we call here the water stress index (WSI). Although simple and rather limited in its reflection of true water stress [33], it provides a less complicated view rather than having to attempt to tease information out from a more sophisticated WSI.

The annual surface run-off required for the baseline WSI was obtained by driving MacPDM using the observed climate dataset for 1961–1990. The baseline population was obtained by using the Gridded Population of the World version 3 (GPWv3) dataset for 1990 [34] at a 1° resolution.

To calculate future WSI, we develop scenarios for future population growth for the 2030s and 2060s based on UN Population Division projections [35]. These projections are available at the national scale and provide estimates for urban and rural population growth up to 2050. As the GPWv3 is only available up to 2015, we have used a 30″ dataset that defines urban areas (also included in the GPWv3 [36]) to determine the spatial distribution of rural and urban populations. The UN rural and urban growth projections were applied to the baseline population according to country and whether they are rural or urban cells (a procedure similar to that of Gaffin *et al.* [37]). Finally, the populations were aggregated to a 1° spatial resolution. We have used the medium variant only for population growth and, as UN population growth rate projections are only available up to 2050, linear extrapolation was used to calculate the population for the 2060s for each country.

3. Results

(*a*) *Present-day water availability*

The baseline climatology of 1961–1990, representing the present-day climate, was used to drive MacPDM, producing monthly surface run-off values which were then aggregated to mean annual and seasonal values. The results of the baseline run are presented in figure 1*b*, representing the mean annual surface run-off (MAR) for the baseline time horizon. At this scale, a qualitative assessment of the spatial distribution of MAR reveals a similar pattern to that of mean annual precipitation (MAP; figure 1*a*), reflecting the strong control of precipitation on the water balance. Greenland has been excluded from this analysis as simple gridded hydrological models are notoriously bad at being able to capture the hydrology of the area. Further, from a water resource perspective, Greenland is not of particular significance.

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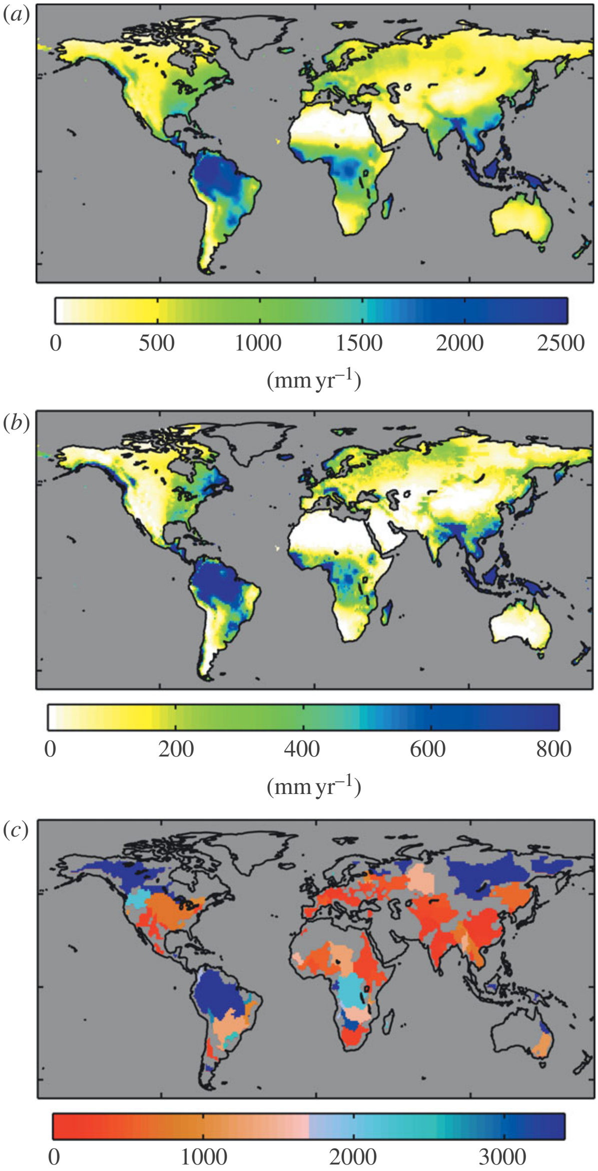

Figure 1. (*a*) Global mean annual precipitation, (*b*) mean annual surface run-off and (*c*) river basin WSI for the baseline period (1961–1990).

Total MAR and total population have been calculated and used to compute the WSI for 112 large river basins across the globe for the baseline period (figure 1*c*). The cells have been aggregated to the river basin level as a cell-by-cell analysis of the WSI would distort the results and represent a highly water-stressed world as transfers and reallocation of water by rivers, canals or pipelines from one part of a river basin to another would be ignored [9]. The WSI can be converted into the popular Falkenmark stress indicator where populations showing water availability

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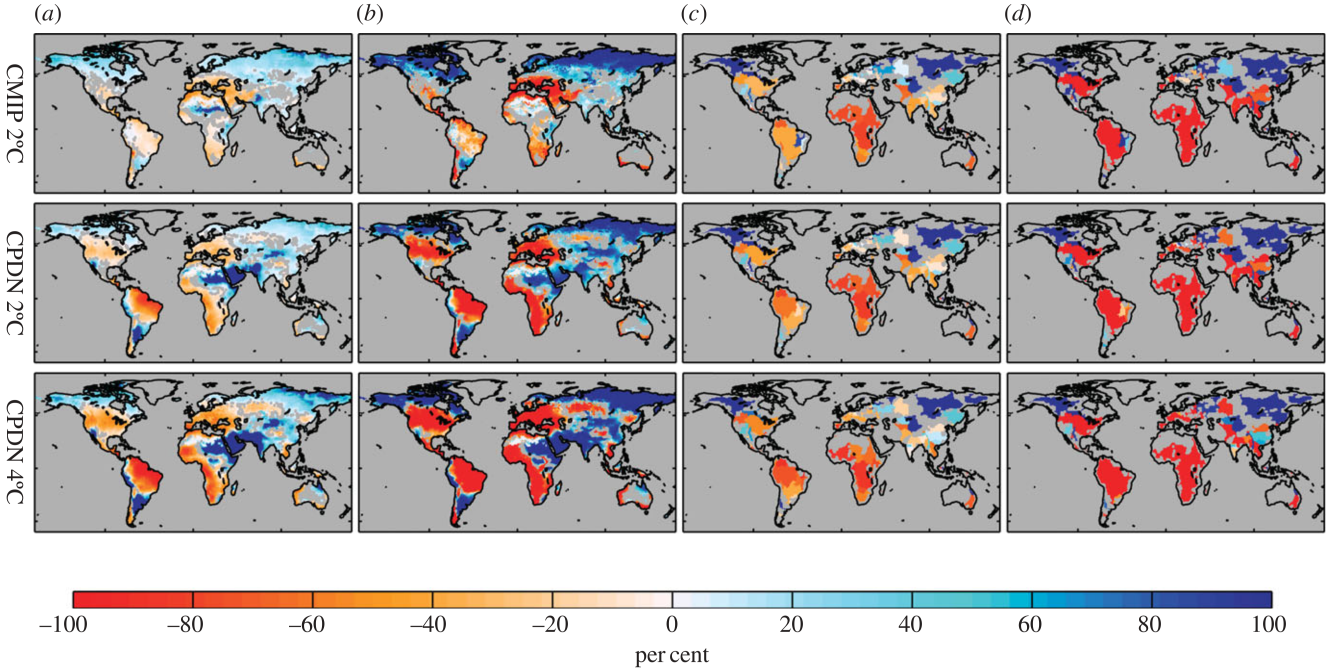

Figure 2. (*a*) Spatial pattern of ensemble-average changes in mean annual run-off (ΔMAR), (*b*) model consensus on direction of change in run-off, (*c*) ensemble-average change in water stress (ΔWSI) and (*d*) model consensus on the direction of change in water stress for a 2°C and 4°C rise in temperature and UNPOP60 population scenario compared with the baseline period. For the model consensus, red and therefore negative values represent the percentage of models showing a negative change in the respective parameter and for blue, positive values, represent the percentage of models showing a positive change. For ΔMAR and ΔWSI, colour classification spans from -100% to greater than 100% (this means that high positive values of ΔMAR and ΔWSI are effectively filtered out in these plots), whereas for consensus, colour classification spans from -100% to 100%. For plots of ΔMAR and consensus for the direction of change in run-off, grey land areas represent where ΔMAR is less than natural variability. For ΔWSI and consensus for direction of change in water stress, only 112 major river basins are plotted (Greenland has been excluded from the analysis).

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under 1700 m^3 *per capita* per year are classified as being water stressed [38] and the colour scale of figure 1*c* has been devised accordingly whereby any areas showing a value of WSI less than 1700 m^3 *per capita* per year are coloured from pink to red and those showing a greater value, i.e. no stress, from pale to dark blue. According to the Falkenmark stress indicator, the WSI shows that many of the world's large river basins are currently showing signs of extreme water stress, including those in South Asia, Southeast Asia, the Nile and eastern USA, i.e. in regions of the world where there are large populations.

(*b*) *Future water availability*

(i) *Global mean annual surface run-off and model consensus*

We now analyse the spatial distribution of the change in MAR (ΔMAR), change in WSI (ΔWSI) and the consensus among the MME and PPE ensembles for a +2°C and +4°C world. As the CMIP3 ensemble only contains one member that reaches a 4°C warming, we do not include an analysis of this ensemble at 4°C. For MAR, we only show the mean of ensemble members that show changes greater than natural variability: this has been defined as twice the standard deviation of the 30 year average annual run-off in the baseline period. If we compare the +2°C and +4°C worlds of the CPDN ensemble, it is clear that ΔMAR (figure 2*a*) becomes larger in the latter, as areas previously showing changes smaller than natural variability become more noticeable. We also evaluate consensus across the ensembles, defined as the percentage of models that show the same direction of change (figure 2*b*). The consensus is an indication of the uncertainty of the projected MAR where a smaller percentage value represents areas where there is little agreement on the direction of change in the ensemble and vice versa. Note that we only show areas of consensus where ΔMAR is larger than natural variability. In the +4°C world, there is stronger model consensus in many parts of the world and the spatial extent of these areas becomes larger. This result agrees partly with that of Milly *et al.* [5] who showed that regions experiencing a decrease in run-off are projected to grow in magnitude and spatial extent. For each ensemble member, we calculated the correlation between ΔMAR at corresponding gridpoints at +2°C and +4°C. Across the CPDN ensemble, there is a high correlation[1] between areas that get drier/wetter in the two temperature regimes, i.e. the pattern of changes in MAR at +2°C and +4°C is consistent in the direction of change, but amplified at +4°C. Thus, the ensemble shows linearity of hydrological response in relation to temperature: an assumption that underlies many of the pattern-scaling-based downscaling procedures for impact assessments [21].

A comparison of the CMIP3 and CPDN ensembles at +2°C shows that there is reasonable agreement in most parts of the world for the direction of ΔMAR apart from an area encompassing eastern Africa and the Middle East. For the CPDN ensemble, the positive direction of change in MAR in eastern Africa agrees with HadCM3, the GCM on which the CPDN is based (not shown). However, the positive changes in the Middle East, which are greater than that of natural variability, are not seen in HadCM3 where changes are either smaller than natural variability or negative. Figure 2 shows that there is much stronger consensus in

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[1] Ninety per cent of the ensemble members have a correlation between 0.87 and 0.97.

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many regions of the world for the CPDN ensemble compared with the CMIP3 ensemble, most likely owing to the fact that the CPDN ensemble is based only on one GCM, albeit with a wide range of physics parameter values.

We also explored the relative importance of changes in precipitation and evaporation on MAR, although completely disentangling the two effects is difficult without additional experiments. In our simulations, changes in potential evaporation (PE) are a function of temperature change only, as we assume other variables are unchanged in the future. Actual evaporation (AE) is dependent on both PE and soil water availability, so that in areas where there is soil water stress, increases in PE will not translate into equivalent changes in AE. For global land areas, the average ratio of MAR to MAP decreases in all simulations as one moves from the present day to +2°C and +4°C worlds (not shown), indicating that AE increases as a proportion of the overall water balance. However, this relative proportion also varies according to the direction and extent of precipitation change, with the ensemble members with the greatest reductions in precipitation showing the smallest decreases in MAR : MAP. This effect is amplified in a +4°C world, so that ensemble members that are particularly dry do not show as large a reduction in MAR : MAP going from +2°C to +4°C as they do going from the present to +2°C.

(ii) *Global water stress index and model consensus*

The mean percentage changes in WSI compared with the baseline WSI for the major river basins of the world across each of the climate model ensembles are also shown in figure 2, for the 2060s population scenario. Similar patterns to those found for ΔMAR emerge as one moves from the present day to +2°C and +4°C worlds, with 71 and 74 per cent of the basins showing an ensemble mean increase in stress (decrease in WSI) at +2°C and +4°C, respectively. For river basins that show an increase in stress, the stressed areas generally grow in spatial extent and magnitude as one moves from +2°C to +4°C, with 71 per cent of basins becoming *more* stressed.

A number of rivers show a different sign of change for WSI at +2°C and +4°C. The Godavari, Tapti and Yangtze basins show a decrease in WSI in a +2°C world and an increase in WSI in a +4°C world; the opposite trend occurs for Dniester, Garonne, Oder, Vistula, Rio Grande de Santiago, Sacramento and Chubut basins. The change in population and the directions of change in run-off in these basins for both temperature regimes are in fact the same: it is the magnitude of the changes in run-off and population that results in the opposite signs of change in WSI for the two temperature regimes. For the first set of basins, the changes in run-off are small and close to natural variability in a +2°C world. An increase in the population is observed for the 2060s, hence there is an increase in stress. However, in the +4°C world, the increase in run-off is much larger, thereby showing a decrease in stress. The reverse is observed for the second set of basins.

The CMIP3 and CPDN ensembles for the +2°C world are in general agreement that water stress will increase in all river basins in Africa, India, eastern USA and southern Europe; these areas are regions that are already indicated as experiencing some water stress for the baseline period according to the Falkenmark stress indicator (figure 1*c*).

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Consensus for WSI across each ensemble (figure 2*d*) is stronger than for MAR. This suggests that for the majority of river basins, the direction of change in WSI is very much dependent on the population in the basin, at least for the 2060s population scenario, i.e. depending on the basin, the population numbers are more important in determining the change in WSI than the spread of values across the climate ensembles. In fact, for 64 per cent of the river basins driven by the CPDN ensemble, there is greater than 99 per cent consensus in the direction of change in WSI for both temperature regimes. This also follows for the CMIP3 ensemble where 74 per cent of the ensemble shows consensus in the direction of change in WSI for the +2°C world. However, in a small number of river basins, there is little consensus at either +2°C or +4°C. For this subset of river basins (where consensus is less than 50%), we have compared ΔWSI for both the 2030s and 2060s population scenarios (not shown here). We find that there is no consistent signal in the change in consensus in WSI, for the two population scenarios, indicating that it is the uncertainty in the climate that dominates ΔWSI in these particular basins.

(iii) *River basins*

We next examine in more detail water resource response to climate model projections at +2°C and +4°C by focusing on six major river basins: the Amazon, Danube, Ganges, Mississippi, Murray Darling and Nile. In figure 3, we have plotted the frequency distributions for ΔMAR and ΔWSI for a 2°C and a 4°C warming for the CPDN ensemble for each basin. The response in the CMIP3 ensemble at +2°C has also been included, but because of the smaller size of this ensemble, we represent each ensemble member individually.

Once again, the ΔMAR frequency distributions for each of the river basins confirm the finding that ΔMAR in a +2°C world is amplified in a +4°C world. In particular, in a number of the basins, the entire frequency distribution for CPDN at +4°C becomes distinct from present-day MAR. However, the magnitude of these changes and differences between the CPDN and CMIP3 ensembles are dependent on the river basin analysed. For the Ganges, Amazon and Mississippi basins, the signal for ΔMAR for the CPDN ensemble in both the +2°C and +4°C worlds does not cover the range of ΔMAR values for the CMIP3 ensemble in a +2°C world. The Ganges and Amazon basins have already been identified here, and in the IPCC AR4, as areas where there is little consensus across the CMIP3 ensemble and great uncertainty exists in future projections of precipitation change. Thus, despite the stronger consensus shown by the CPDN ensemble for these regions, the ΔMAR values for the CMIP3 ensemble demonstrate the need to analyse an MME to capture the range of possible projections of ΔMAR.

An additional subset of climate models has also been plotted in figure 3, comprising those models that show a warming of 4°C, but at the point they warm to 2°C. While the range of this subset lies within that of the range for the full +2°C ensemble, the shapes of both frequency distributions are very similar. This suggests that the +4°C ensemble, although smaller in size, is representative of the responses that might be expected were the CPDN simulations long enough to allow all members to warm by 4°C. A spatial correlation analysis of the changes in run-off between all 1538 models showing a 2°C warming and all 339 models showing a 4°C warming run-off shows that over 50 per cent of the models have

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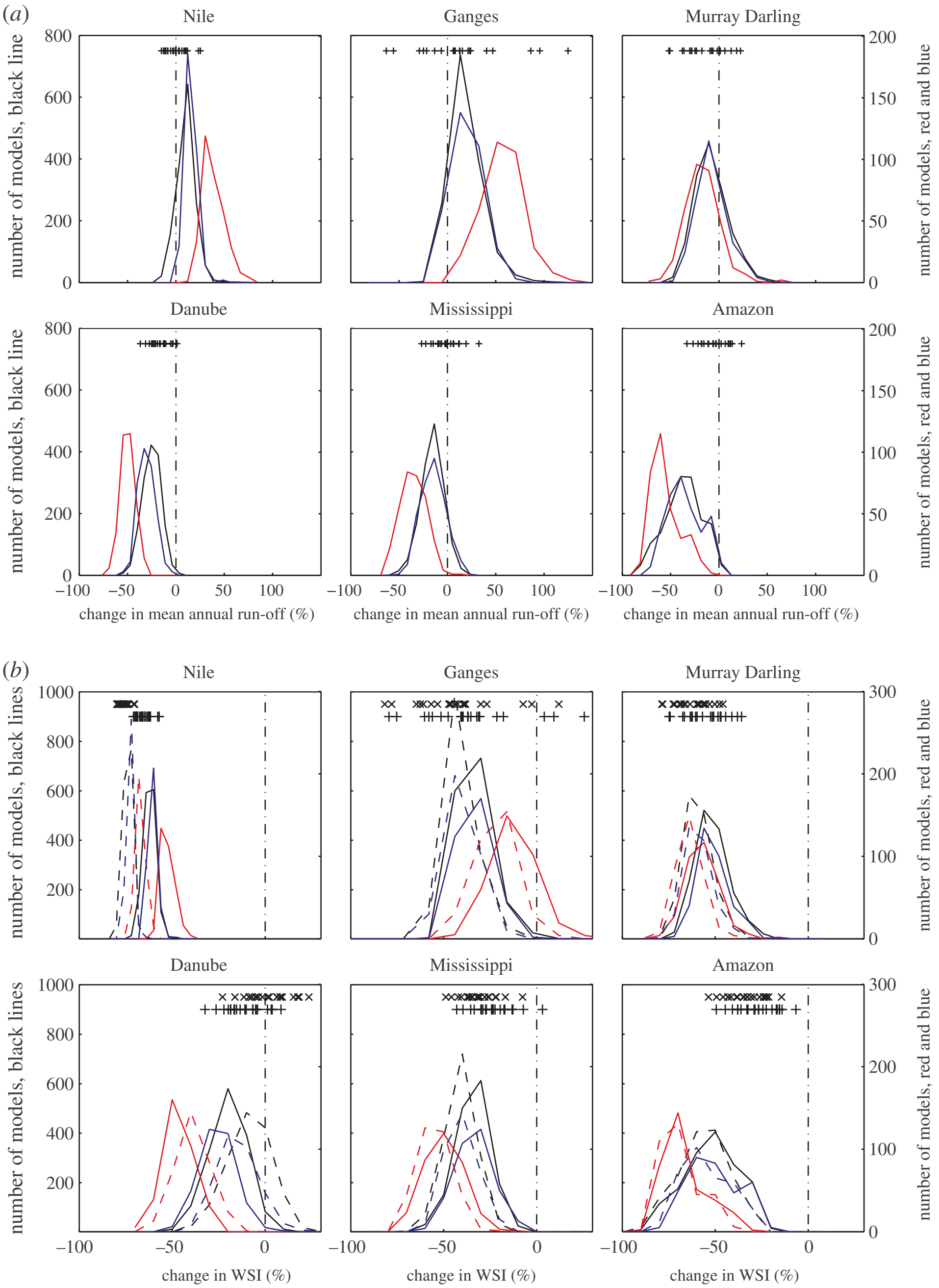

Figure 3. Changes in (*a*) MAR and (*b*) WSI for a +2°C and +4°C world for large river basins: Nile, Ganges, Murray Darling, Danube, Mississippi and Amazon, where frequency distributions are for CPDN models and pluses or crosses represent each CMIP model for a +2°C or +4°C world, respectively. Solid lines represent population scenario UNPOP2030 and dashed lines UNPOP2060. Black lines are for models that show a 2°C warming, red lines for a 4°C warming and blue lines for models in a +2°C world that show a +4°C warming at some point in the twenty-first century.

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a correlation coefficient of 0.90, i.e. for a large proportion of the world's land surface, there is a clear linear relationship between run-off and the two global temperature regimes. This should also be compared with the spatial correlation of the respective annual precipitation fields, where the correlation appears to be weaker where 50 per cent of the models have a correlation coefficient of at least 0.742.

We next turn to the WSI, and here we look at how stress varies under both the 2030s and 2060s population scenarios (figure 3*b*). In each basin, changes in demand produce a complex set of possible futures. For the Danube basin, population is projected to decrease and although most of the models for the two temperature regimes show increased stress for the 2030s, driven by run-off decreases, by the 2060s, some ensemble members produce decreased stress. Thus, the direction of change here is finely balanced between projected ΔMAR and population as we move between the different global temperature regimes and population scenarios. The Murray Darling experiences a large increase in stress, which may be a surprising result for a country such as Australia, where low growth projections would be expected. However, as the Murray Darling contains large urban centres and urbanization is projected to increase through the twenty-first century, there is a corresponding large projected increase in population in the Murray Darling. This leads to an amplification of stress related to reduced MAR, and more than offsets the effects in ensemble members where MAR is projected to increase.

Two of the selected basins show increases in ΔMAR, namely the Ganges and the Nile, but while the Nile experiences increases in water stress, for all climate and population scenarios, a large number of the CPDN ensemble shows decreases in water stress for a +4°C world under both population scenarios for the Ganges. Thus, as one moves from +2°C to +4°C, the effects of climate change become large enough to offset the large increases in demand expected in the Ganges basin.

For the Ganges basin, the CMIP3 ensemble shows not only a wider range of changes in MAR and WSI than the CPDN ensemble for a 2°C warming but also contains some members that are situated in the extreme wet end of the CPDN ensemble for a 4°C warming. For the Amazon basin, the CPDN ensemble is biased towards a drier future (consistent with the findings of Li *et al.* [39] for HadCM3) and the CMIP3 ensemble, while consistently dry, is not as extreme. It should be reiterated here that the two climate ensembles used here have different purposes: the PPE is used to explore parametric uncertainties in climate models, whereas the MME for structural uncertainties in climate models. The spread of ΔMAR and ΔWSI shown here highlights the necessity of using both ensembles to capture the range of climate futures.

(iv) *Seasonality of changes*

For some river basins where there is little in the form of natural or man-made water storage to smooth out the changes in run-off throughout the hydrological year, the seasonality of the water availability is of paramount importance. To look at this, the change in seasonal run-off has been assessed (figure 4). For all river basins, apart from the Amazon, the seasonality of run-off becomes stronger as one moves from a +2°C to a +4°C world, with wet seasons becoming wetter

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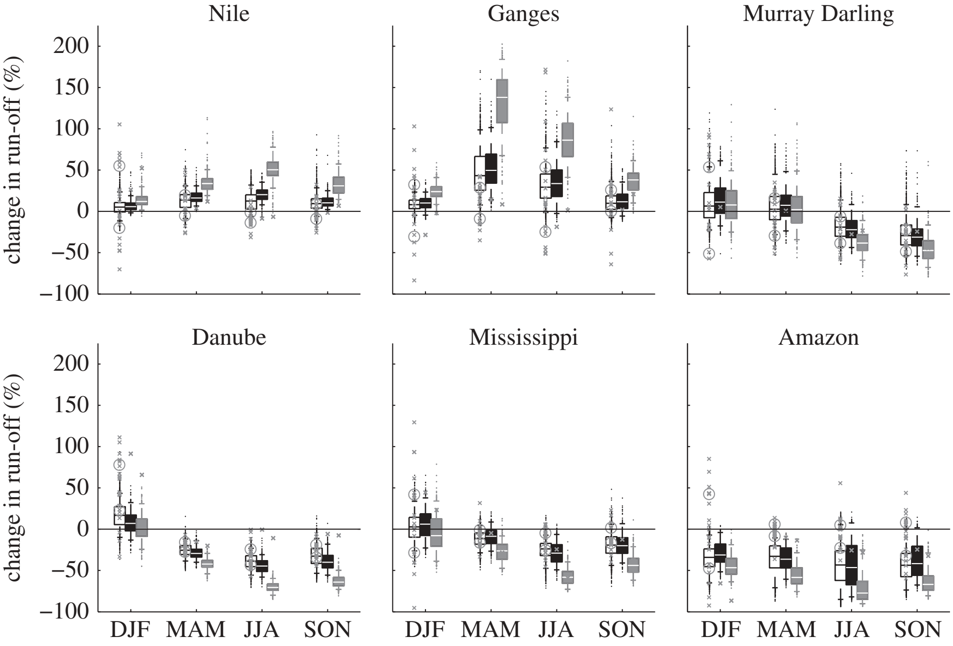

Figure 4. Seasonal changes in MAR for large river basins for CPDN ensemble, where top, middle and bottom of boxes represent 25th, 50th and 75th percentiles, respectively, whiskers extend to 5th and 95th percentiles and dots represent outliers: white boxes are for models that show a 2°C warming, black boxes are for a 4°C warming and grey boxes are for models in a +2°C world that show a 4°C warming at some point in the twenty-first century. Members of the CMIP3 ensemble are represented as crosses and the corresponding 25th and 75th percentiles marked with circles.

and dry seasons becoming drier. Given that the Amazon is largely tropical, and spans the seasonal migration of the inter-tropical convergence zone, there is little change in the seasonal regime for both +2°C and +4°C temperature regimes.

If changes in annual average stress are considered, as in figure 3, it would appear that stress in the Ganges and Nile will decrease as climate change progresses. However, figure 4 shows that the increase in surface run-off may be unevenly distributed across the year, and unless storage is available to smooth out the peaks in water availability throughout the year, the greater run-off volumes may present more difficulties, e.g. flooding, rather than alleviating water stress. However, it must be noted that GCMs find it notoriously difficult to model the Indian monsoon, so the results for the Ganges should be treated with particular caution [40]. Figure 4 also shows that the ensemble spread appears to be consistent for some basins as one moves from a +2°C world to a +4°C world, although the spread appears to be less for the Amazon and greater for the Ganges at +4°C.

4. Discussion

Through the use of a large PPE, we have shown that changes in mean annual run-off in a +2°C world are generally amplified in a +4°C world: drier areas dry further and wetter areas become wetter. Moreover, as these changes in MAR

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become amplified, both the consensus and spatial coherence of these changes strengthen. By investigating the changes in water stress in 112 of the world's major river basins, we have also found that the majority of these river basins are projected to suffer greater water stress in a +4°C world than in a +2°C world. However, as we move from a +2°C to a +4°C world, there are also a small but increasing number of basins that may experience less water stress, as they are located in regions where rainfall is projected to increase.

By using population growth scenarios for the 2030s and 2060s, we find that in a +2°C world, water stress is dominated by the change in population. However, as we move to +4°C world and the climate change signal becomes stronger, climate change can play a more dominant role in determining water stress in a river basin.

The timing of the global warming will be important in determining water stress across the world. Population growth is projected to increase through the twenty-first century, peaking in the middle of the century [41]. Should a rapid warming occur, with a plausible +4°C warming by the 2060s as shown by our CPDN ensemble and Betts *et al.* [42], the drier areas of the world may be affected by a combination of peak demand for water and larger decreases in run-off. However, if a more gradual warming is experienced and +4°C is reached in 2100 or beyond, when world population is projected to decline, water stress will be lower, and there will be more time to adapt to climate change.

We have also compared the PPE from the CPDN experiment and the MME from CMIP3 for a +2°C world and have shown that while there is considerable agreement between the two ensembles, there are significant regional differences as well. Thus, in order to capture the range of possible projections, both sets of climate model ensembles are required.

By examining a subset of the world's major river basins, we have shown that the picture for water stress in each river basin is dependent on the magnitude of the climate change and the nature of the population growth. For some river basins, the effects of climate change become large enough to offset the large increases in demand in a +4°C world, e.g. in the Ganges; in most basins, however, climate and population growth combine to increase stress or climate change is insufficient to offset increased demand.

We have also found that seasonality in run-off may be more pronounced in a +4°C world compared with a +2°C world; thus, even where annual average run-off increases, dry seasons can become more stressed. This could mean that more sophisticated infrastructure projects may be required in a +4°C world compared with a +2°C world in order to prevent flooding and droughts.

There are a number of caveats when interpreting our results. We have used an MME and a PPE (of one GCM) that, albeit covering a large range of climate projections, only represents a sample of the possible uncertainty range. The GCM ensembles have not been weighted or screened, recognizing that attempting to weight models is fraught with difficulty [12,13]. The bias-correction procedure used is also simplistic and does not include any information on climate variability, either inter-annual or intra-annual. Our results are therefore appropriate for assessing changes in mean run-off and stress, but not the possibility of changes in shorter term stress.

Some care must also be taken in the interpretation of the +2°C and +4°C worlds that have been used in our analysis, as the baseline used in our analysis is for the time period 1961–1990 rather than a 'pre-industrial' value or the time

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period of 1980–1999 used in IPCC [43]. Mean global temperatures for 1980–1999 are warmer than for 1961–1990 by 0.16°C and may mean larger changes in both run-off and water stress for some river basins. However, if a pre-industrialized value of 1861–1890 is used, the difference is about 0.31°C cooler, with changes in future run-off and water stress smaller in some river basins than those presented in our analysis.

MacPDM has been run offline and therefore any feedbacks into the climate system have not been included. It has also not been calibrated and its parametrizations have not been explored, although previous studies on small river catchments [44,45] find that climate model uncertainty is greater than hydrological modelling uncertainty. In fact, we have found that as we move from the PPE model data (temperature and precipitation) to MacPDM output (run-off), the spatial correlation appears to increase pointing to the importance of the model input parameters, such as soil type and land cover, in controlling the resulting run-off, which may themselves change in the future owing to direct impacts of climate change, adaptation responses and CO_2 effects on plant water-use efficiency.

The calculation of PE is included within MacPDM and is based on the Penman–Monteith equation; as shown in recent studies [46,47], this could be another source of uncertainty. This issue may need to be explored in future studies to determine the sensitivity of the CPDN ensemble to the PE calculations.

The population statistics are based on only one of the UN population growth scenarios (median variant) and exploration of the uncertainty in these projections has not been carried out. These population statistics have been calculated offline and therefore, once again, no feedback effects can be carried through to the climate and hydrological models, which may be important if the spatial distribution of populations depends on the availability of water.

The WSI used in this analysis is based solely on the annual surface run-off and river basin population. It does not incorporate many of the intricacies that may exist between water-use habits, water resources management, water infrastructure and adaptative responses, to name a few, that affect on-the-ground water stress. Although simple, the WSI used in this analysis has highlighted the need to look at river basins where there is great uncertainty in the direction of change in water stress as well as the areas that show an increase in water stress. However, to start unravelling the actual change in water stress in the region, a more detailed local assessment would be required. It must also be noted here that given the GCM data that are at best decadal seasonal means, a highly detailed assessment of water resources management options for water storage in reservoirs and groundwater replenishment is beyond the scope of this analysis.

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Agriculture and food systems in sub-Saharan Africa in a 4°C+ world

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Agricultural development in sub-Saharan Africa faces daunting challenges, which climate change and increasing climate variability will compound in vulnerable areas. The impacts of a changing climate on agricultural production in a world that warms by 4°C or more are likely to be severe in places. The livelihoods of many croppers and livestock keepers in Africa are associated with diversity of options. The changes in crop and livestock production that are likely to result in a 4°C+ world will diminish the options available to most smallholders. In such a world, current crop and livestock varieties and agricultural practices will often be inadequate, and food security will be more difficult to achieve because of commodity price increases and local production shortfalls. While adaptation strategies exist, considerable institutional and policy support will be needed to implement them successfully on the scale required. Even in the 2°C+ world that appears inevitable, planning for and implementing successful adaptation strategies are critical if agricultural growth in the region is to occur, food security be achieved and household livelihoods be enhanced. As part of this effort, better understanding of the critical thresholds in global and African food systems requires urgent research.

Keywords: food security; adaptation; climate change; livelihoods

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1. Introduction

Agricultural and food systems globally face considerable challenges in the coming decades. The demand for food continues to increase rapidly, as a result of various drivers. Current estimates of human population in 2050 range from 7.96 billion to 10.46 billion; the medium variant estimate is 9.19 billion [1]. Continued population growth could be a significant impediment to achieving improvements in food security in some countries, even as world population stabilizes sometime during the present century. Food demand is also strongly affected by urbanization. More people now live in urban settings than in rural areas. The next few decades will see unprecedented urban growth particularly in Africa and Asia. Urbanization has considerable impact on patterns of food consumption [2], but it is not necessarily associated with a reduction in food insecurity. Recent data from southern Africa indicate both chronic poverty and food insecurity in a survey of 11 cities [3]. A third key driver affecting food demand is income growth. Between 1950 and 2000, world *per capita* income grew at an annual rate of 2.1 per cent [4]. As income grows, patterns of food expenditure change, often to more meats, fats and sugar [5]. Projections of future economic growth vary considerably, but it is expected to continue. Fourth, the agricultural production sector is catering increasingly to globalized diets. Retailing through supermarkets is growing at 20 per cent per annum in some countries, and this growth is likely to continue over the next few decades as urban consumers demand more processed foods, shifting agricultural production systems from on-farm production towards agribusiness chains [6].

Several projections suggest that global cereal and livestock production may need to increase by between 60 and 100 per cent to 2050, depending on the scenario, because of the increasing demand and changing patterns of demand [7]. In sub-Saharan Africa (SSA), this will require considerable investments in agricultural research and technology and in infrastructural development [6]. Agricultural growth rates for SSA declined in the 2000s [8] and food insecurity is still a concern, as the prevalence of malnourishment has only dropped from 34 to 30 per cent in two decades [9]. Agriculture is still an economic mainstay of many SSA countries, employing about 60 per cent of the workforce and contributing an average of 30 per cent of gross domestic product [10]. Although the efforts of the agricultural research and development communities over the last 40 years have led to successes in improving yields, increasing incomes and contributing to food security, these successes have not been automatic and they have not occurred everywhere [11]. Rural communities and households continue to demonstrate tremendous adaptive capacity in the face of economic and social change, but this capacity needs appropriate social, institutional and political support [12].

Even more challenging, the necessary increases in food production will have to occur at the same time as the climate is changing and as climate variability increases. Potential impacts of climate change on agricultural production in SSA have been assessed in several modelling studies, using methods grounded in an understanding of both crop and climate science (see the review by Challinor *et al.* [13]). The inherent complexity of the climate–crop system, together with fundamental limits to climate predictability, mean that predicted ranges for major crops depend strongly on the methods and models used [14]. However, as in the current climate, these broad trends are likely to mask local differences caused

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by spatial variability in climate. The regional distribution of hungry people will change, with particularly large negative effects in SSA owing to the impact of declines in crop yields on both food availability and access [15].

The challenges for agricultural development are already considerable, and there is now general concern that climate change and increasing climate variability will compound these in vulnerable areas. The interactions of climate with other drivers of change in agricultural and food systems, and on broader development trends, are only incompletely understood, but the impacts on human health and nutrition and on water resources and other ecosystems goods and services may be locally severe. In this paper, we outline how the impacts of a changing climate in a world that warms by 4°C or more will diminish the options available for agricultural production and livelihoods in SSA. Many of the production trends and food security goals that SSA still needs to achieve will be compromised, as current crop and livestock varieties and agricultural practices will be inadequate. Food security will become more difficult to achieve as commodity prices increase and local production shortfalls become the norm. Although adaptation strategies for agricultural production and food security exist, and indeed rural communities have been adapting to climatic variability for centuries, the institutional and policy support needed to successfully implement such adaptation on the scale that SSA requires in a 4°C+ world would probably be very substantial [16]. We stress that planning for and implementing successful adaptation strategies with local communities and households are key to maintaining options for food security and agricultural growth in SSA, although exactly what constitutes a successful adaptation option is a key research question. Many issues pertaining to the role of livelihood diversification out of or in to different forms of agriculture need to be explored, and more attention needs to be given to empowering local communities so that they have greater control over their adaptation choices and livelihood pathways.

2. Impacts on agricultural production

(*a*) *Projected changes in growing season length and crop and pasture yields*

As noted above, several modelling studies have assessed the potential impacts of climate change on agricultural production in SSA, although the projected ranges of shifts in yields for the major crops vary widely [13,14]. Many of these studies have estimated yield impacts in response to the Special Report on Emissions Scenarios (SRES) greenhouse-gas emission scenarios [17]. The multi-model means of surface warming (relative to 1980–1999) for the SRES scenarios A2, A1B and B1 from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment show increases of about 1–2°C to the 2050s and about 1.5–3°C for the 2080s [18].

Multiple model simulations are needed in order to sample the inherent uncertainties in the projection of climate and agricultural production. Climate models are computationally expensive to run, and so choices must be made regarding the complexity, spatial resolution, simulation length and ensemble size of the simulations [19]. An emphasis on complexity allows simulation of coupled mechanisms such as the carbon cycle and feedbacks between agricultural land management and climate. In addition to improving skill, greater spatial resolution

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increases relevance to regional planning. Greater ensemble size improves the sampling of probabilities. Thus, assessments of a 4°C+ world are contingent on the choice of focus: studies that focus primarily on ensembles and uncertainty may fail to demonstrate consensus, while other studies may find a more clear consensus emerging.

Here, to examine some of the likely effects on agricultural production in SSA of warming of 4°C or more, we carried out some downscaling and simulation runs using climate projections from AR4 climate model runs assembled by New *et al.* available at www.geog.ox.ac.uk/∼clivar/ClimateAtlas/4deg.html. We used an ensemble mean of the three AR4 emissions scenarios (A2, A1B and B1) and the 14 general circulation models (GCMs) for which data were provided, and anomalies were scaled to a global temperature increase of +5°C. The climate differences were downloaded at a resolution of 1° latitude–longitude. There are several ways to increase the spatial resolution of climate model outputs, all of which have their own strengths and weaknesses, recently reviewed by Wilby *et al.* [20]. Here, we were also concerned to increase the temporal resolution of climate model outputs, from monthly means of key variables to characteristic daily data that could then be used to drive crop models. Accordingly, as in previous work, we used historical gridded climate data from WorldClim [21], aggregated to 10 arc-minutes to speed the analysis, which we took to be representative of current climatic conditions. We produced a grid file for Africa of climate normals for future conditions at 10 arc-minutes by interpolation using inverse square distance weighting, one of the methods that [20] refer to as 'unintelligent downscaling'. To increase the temporal resolution of the climate model outputs, we generated the daily data needed (maximum and minimum temperature, rainfall and solar radiation) for each grid cell using MarkSim, a third-order Markov rainfall generator [22] that we use as a GCM downscaler, as it uses elements of both stochastic downscaling and weather typing on top of basic difference interpolation. MarkSim generates daily rainfall records using a third-order Markov process to predict the occurrence of a rain day. It is able to simulate the observed variance of rainfall by way of stochastic resampling of the relevant Markov process parameters. MarkSim is fitted to a calibration dataset of over 10 000 weather stations worldwide, clustered into some 700 climate clusters, using monthly values of precipitation and maximum and minimum temperatures. All weather stations in the dataset have at least 12 years of daily data, and a few have 100 years or more. Some of the parameters of the MarkSim model are calculated by regression from the cluster most representative of the climate point to be simulated, whether that climate is historical or projected into the future. More details of the methods used are given in Jones *et al.* [23].

We carried out two sets of analyses. First, we estimated the average length of growing period (LGP) for each pixel in SSA. LGP is an indicator of the adequacy of conditions for crop growth, and is the period (or periods—some parts of SSA have more than one well-defined growing season per year) during the year when both moisture availability and temperature are conducive to crop growth. LGP was calculated on a daily basis using methods outlined in Jones [24], ignoring intervening drought periods, and is thus a proxy for the number of grazing days, but not necessarily of cropping success. Percentage changes in LGP between now and the 2090s are shown in figure 1*a*, for areas with at least 40 days LGP under current conditions. Much of the cropping and rangeland area of SSA is projected

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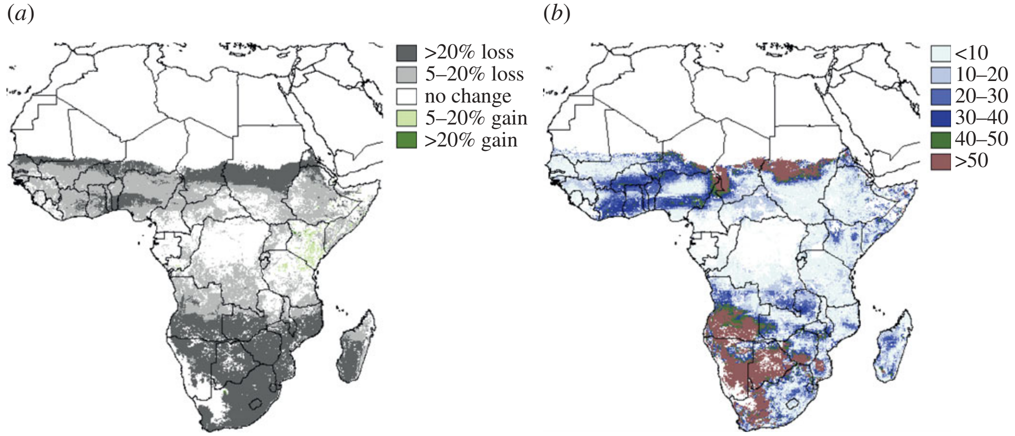

Figure 1. Length of growing period in the 2090s compared with the present. (*a*) Mean percentage change for an ensemble of 14 GCMs. (*b*) Coefficient of variation (%) of the change in length of growing period for an ensemble of 14 GCMs. See text for details.

to undergo some loss in growing season length, and most of Africa in southern latitudes may see losses of at least 20 per cent. Parts of East Africa may see moderate increases in growing period, on the other hand.

There are several sources of uncertainty attached to such estimates, including the uncertainties associated with the downscaling techniques used, and the uncertainties associated with the use of different combinations of GCM and emissions scenario. To assess the latter, we estimated the standard deviation of the mean estimate of change in LGP for each pixel from the 75th percentile of the ensemble distribution (14 climate models and three emissions scenarios). These are mapped as the coefficients of variation in figure 1*b*, and represent the variability of estimates of LGP primarily in relation to the different climate models (there are only limited differences between the three emissions scenarios in the first half of the current century). This variability among the climate models is relatively small for large areas of central and eastern SSA (20% or less), higher (to 40%) for the crop and agro-pastoral lands of West Africa and parts of southern Africa, and highest (greater than 50%) in arid and semi-arid rangelands in south-west Africa and the central desert margins in the north, where LGP is short and highly variable anyway. These results highlight both the reasonable consensus among the climate models for shifts in conditions in East Africa and the lack of consensus as to changes in agricultural conditions in some of the higher-rainfall areas of West Africa in particular.

We also calculated the primary season failure rate and reliable crop growing days per year; for methods see Jones & Thornton [25]. Results are not shown here, but season failure rates increase for all of SSA except for central Africa; in southern Africa they increase to the point where nearly all rain-fed agriculture below latitude 15°S is likely to fail one year in two. These trends are in accord with previous analyses [26], only here the effects are considerably greater.

In the second analysis, we ran crop simulations for conditions in this 5°C warmer world, for maize, *Phaseolus* bean, and an ‘indicator’ pasture species, *Brachiaria decumbens*, a cultivated forage grass widely used for feeding to cattle

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Table 1. Simulated yields (the pixel-weighted averages of 30 independent replications) in four regions of sub-Saharan Africa, for three crops grown on cropland and pastureland as defined by Ramankutty *et al.* [29], under current conditions and in the 2090s. Regions are defined as follows: Central: Cameroon, Central African Republic, Chad, DR of Congo, Congo, Equatorial Guinea, Gabon. East: Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania, Uganda. Southern: Angola, Botswana, Lesotho, Madagascar, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, Zimbabwe. West: Benin, Burkina Faso, Cote d'Ivoire, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo.

	2000s yield (kg ha^{-1})	2090s +5°C yield (kg ha^{-1})[a]	mean % change in production[a]	CV of change in production %[b]
maize				
central	744	612	−13	23
east	954	689	−19	7
southern	748	612	−16	22
west	764	536	−23	23
mean	806	612	−24	19
beans				
central	666	175	−69	58
east	685	263	−47	6
southern	716	220	−68	48
west	487	63	−87	47
mean	639	182	−71	34
B. decumbens				
central	1493	1311	−4	3
east	1745	1570	+9	7
southern	1384	1344	+11	18
west	1498	1437	−6	27
mean	1525	1422	−7	15

[a] Simulated from the ensemble mean climate of all applicable GCMs and the three AR4 SRES scenarios.

[b] Coefficient of variation ($100\sigma/\mu$) estimated from the simulated yields using the 75th percentile of the ensemble climate distribution for all GCMs and scenarios.

in the tropics and subtropics. Runs were done using the models in the decision support system for agrotechnology transfer (DSSAT; [27]) using similar methods as those described in Thornton *et al.* [28]. We ran 30-year replicated simulations for all pixels classified as cropland and pastureland in the dataset of Ramankutty *et al.* [29]. Average yields for the three crops are shown in table 1 on a regional basis for current conditions and for the 2090s with a 5°C temperature increase. These results show clearly that the increases in LGP projected for parts of East Africa will not translate into increased agricultural productivity; maize production is projected to decline by 19 per cent and bean production by 47 per cent, all other things (such as area sown) being equal, with little or no change for the pasture grass. These simulated changes take only limited account of shifts in weather variability; a substantial portion of this region that is currently cropped already experiences season failure rates of 25 per cent or more, and these areas will increase in size substantially in the future. Table 1 includes an estimate of the

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coefficient of variation in the change in production for these three crops, again calculated from the 75th percentile of the ensemble climate distribution for all climate models and scenarios. In general, this variability is high, indicating that yield changes are heavily dependent on choice of climate model and emissions scenario used, except for yield changes in East Africa (and pasture yields in central Africa), which appear to be remarkably robust.

(*b*) *Other impacts affecting food production*

Other studies indicate some of the additional impacts that may be experienced in a warmer world, which will increase challenges for food production and food security. Regarding water resources, by 2025 it is projected that 64 per cent of the world's population will live in water-stressed basins, compared with 38 per cent today [30]. Large increases in non-irrigation water demands will occur over the next 50 years, these increases being concentrated in developing countries. In a 4°C+ world, 15 per cent of the world's population (more than 1 billion people) may be exposed to increased water resources stress by 2080, and 50 per cent of flood-prone people may be exposed to increased flood hazard [31]. There are also likely to be substantial changes in land suitability for agriculture in a 4°C+ world: by the end of the century, 15 per cent of the land globally that is currently suitable for cultivation would become unsuitable, although this is more than balanced by an extra 20 per cent of land that is currently too cold to support cultivation becoming suitable [31]. But there is no balance in the situation for Africa: in East and southern Africa, Arnell [31] estimates that about 35 per cent of current cropland will become unsuitable for cultivation. These stresses will add to the difficulties of adopting new varieties or increasing agricultural productivity, as water and land availability are key limiting factors.

Over the long term, future disease trends are likely to be heavily modified by climate change, although there are no *a priori* reasons for expecting that disease risks will automatically increase in general, given that multiple interacting factors determine infection risk and exposure [32]. Nevertheless, climate change will increasingly make major public health risks more difficult to control, especially in developing countries [33]. Future trends in human, livestock and crop diseases will be affected by various drivers, including shifts in the spatial and temporal distribution of some disease vectors, such as ticks and mosquitoes, caused by changes in climate and climate variability, changes in human population distributions and age structures, and changes in the development and application of different technologies for combating infectious diseases. There is considerable heterogeneity in the disease issues associated with different regions, and the future outlook is complicated [34]. Hunger and conflict may be widespread in a 4°C+ world, and it is these processes and their consequences, rather than more direct impacts of climate change and changes in climate variability, that may become the dominant influences on health in the future [33].

Increasing frequency and severity of droughts and extreme weather events, sea-level rise and other impacts that are at least partially attributable to climate change, such as shifts in disease risks and the narrowing of livelihood options, are likely to bring about large-scale population movements during the current

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century. Many of the vulnerable regions are densely populated. It is not easy to disentangle the environmental drivers of migration from other drivers and thus to set apart 'climate migrants' from other migrants, but enormous migration pressures are likely to result in a 4°C+ world [35]. Wide-ranging policies would be needed to adapt to these greater migratory pressures, and in many cases, migration would need to be encouraged, not avoided, and the most vulnerable enabled to move [35].

3. Adaptation to maintain options for agricultural growth and food security

The impacts described above of a 4°C+ warming in SSA will require quite radical shifts in agriculture systems, rural livelihood strategies and food security strategies and policies. In this section, we discuss some of the potential for and constraints to adaptation in relation to crop varieties and species, livestock breeds, cropping patterns, changes in rural livelihood strategies and changes in food security interventions and policy. Our intent is a realistic evaluation of the steps needed for proactive adaptation to the additional stresses that climate change will bring to food systems in SSA. We acknowledge the many successes that local farmers have had in adapting to change [36–38] in modern times in spite of policies and economic trends that are not in their favour. We caution, however, that they also pay a price at times, as their capacity to manage multiple stresses is limited, and often economic pressures outweigh climatic stresses [39–41]. This is in many cases because of the lack of political and institutional power that vulnerable communities have throughout SSA. We also recognize the success stories in agricultural development, such as those highlighted in the recent book *Millions fed* [11], which demonstrates what can occur when institutional support is sufficient for innovation by farmers and researchers to succeed. However, proactive adaptation to a 4°C+ world will require much more concerted effort at all levels to manage quite radical shifts. In addition, when food security is considered as the outcome of food systems, which expand beyond agricultural production to include markets, trade and distribution networks, for example, the evaluation of successful adaptation becomes more difficult. Food security has not decreased much in SSA in the recent past, and over the last 3 years price shocks have combined with economic recession to increase the numbers of food-insecure [42]. The idea that there may well be limits to adaptation, beyond which action will not reduce vulnerability (or may even increase it for some), and/or that the necessary actions are not able to be implemented because of political or other constraints, becomes real in the case of agriculture and food security in SSA [43,44]. We return to this notion below.

For crops, changes in management practices and strengthening of seed systems are two key approaches to adapting agricultural systems in SSA [14]. While local seed systems can be resilient to climatic stresses [45], the challenge for the future is to improve access to the varieties that will be needed as climate changes and to adapt farming systems to new climatic, land and water constraints. As emphasized by experts on local adaptation, these new practices must build upon strategies and farming practices that local communities and farmers already use [39,40,46,47]. For livestock, there are several approaches, including movement

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of feed resources and/or of livestock over what may be large distances, where this is feasible, as mobility has been demonstrated as the key strategy that pastoralists rely on to maintain their herds during periods of drought [38]. A new approach is livestock insurance schemes that are weather-indexed, so that policy holders are paid in response to 'trigger events' such as abnormal rainfall or high local animal mortality rates. Index-based livestock insurance schemes based on satellite imagery are currently being piloted in several areas of drought-prone northern Kenya via novel public–private partnerships [48]. However, these schemes are themselves highly vulnerable to climate change, as increases in the frequency and severity of droughts could make them unviable. An approach that has been used by pastoralists in the past to deal with the vagaries of climate is to change the mix of livestock species and/or breeds, sometimes on a temporary basis [49,50], and indeed recent anecdotal information suggests that in parts of East Africa herders are switching from cattle and sheep to camels and goats. As for certain crops, some livestock species and breeds are better able to deal with dry and drought conditions than others, and there may be considerable potential in some areas for pastoralists and agropastoralists to adapt to a changing climate in this way.

(*a*) *Constraints to local adaptation*

Good practice in adaptation is constrained by a number of factors, and these will become much more critical in a 4°C+ world. First, there are inherent limits to the predictability of both climate and its impacts; and there is variability in the methods and assumptions used by any single study to assess probable impacts. Thus, not only is our knowledge of the future necessarily imprecise, but also the degree of precision claimed by different studies varies considerably, making such studies not directly comparable. Challinor *et al.* [14] discuss this in more detail, citing an example where the simulated responses of maize in Africa to a doubling of carbon dioxide can be as narrow as -14 to -12 per cent, or as broad as -98 to $+16$ per cent. Thus adaptation occurs in the context of uncertainty, and if that uncertainty is too great then it may be difficult to assess appropriate adaptation options. Uncertainty about the future can never be banished entirely, of course, and adaptation decisions will be taken in any case, but uncertainty may substantially raise the costs of being able to accommodate fully possible future events with different characteristics [51]. Experience with use of seasonal forecasts to make short-term crop choices or provide insurance to households and farmers suggests that uncertainty about even three months ahead can be difficult for decision makers to incorporate [52], although continued research on this is a promising way forward. Such research highlights the limits to scientific advances alone in fostering adaptation; any new technologies or information advances are only successful to the extent that they meet farmers' needs and contexts.

Second, adopting new varieties or different crop and livestock management techniques requires farmers to take on new risks and explore new markets, and also requires access to credit and technical support. The ability of many smallholder farmers in SSA to obtain access to such support mechanisms is already low [53,54]; the need to adapt to climate change may provide a stimulus to increase such support, but it can be achieved only with considerable institutional

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and political commitments [55,56]. Currently many farmers rely on a host of off-farm diversification strategies to support their own agricultural activities and ensure a household income [57]. If a changing climate increases the risks associated with agriculture, it is not clear how farmers will adjust the balance of on- and off-farm activities. As a 4°C+ warming will affect not only what can be grown but also where, as land suitability shifts, existing successful technological packages and systems may not be that useful. By 2050, temperature increases may result in about a quarter of African countries experiencing climatic conditions over substantial parts of their existing cropped areas for which there are no current analogues [58]. In places where no historical analogues exist, then pressures on farming systems, livelihoods, agricultural technology and supporting mechanisms may become intense, as smallholders become increasingly alienated from their realm of experience. In this case, the notable trend of economic diversification into non-farm activities would most probably increase even more, as rural residents made the logical choice to seek less climate-sensitive activities [59], although these choices may not lead to greater food security [60].

Many authors have argued for vulnerability-led approaches to adaptation, so as to contextualize how climate change affects livelihoods, and to explain that successful adaptation depends upon not only exposure and sensitivity to climate change, but also adaptive capacity and an enabling institutional and policy environment [61–63]. Emphasizing vulnerability as a social and political phenomenon also cautions against an over-reliance on research-led solutions alone. Although many studies in developing country contexts emphasize the importance of supporting local-level, grassroots adaptation, lessons from decades of agricultural development interventions have shown the need for higher-level institutional and policy support as well [59,64,65]; thus local adaptive capacity requires higher-level enabling support. For example, the recent collections of success stories in agricultural development and food security achievement compiled by the International Food Policy Research Institute (IFPRI) and the Food and Agriculture Organization (FAO) are explicit in describing the necessary enabling conditions, such as access to markets for new crops, national policy that prioritizes food security, agricultural extension and so on [11]. In a 4°C+ world, successful adaptation will require a huge investment in policy and technology.

The constraints described above can combine to produce particularly pronounced problems when it comes to any particular adaptation option. For example, the number of crop varieties cultivated by farmers has declined over time because of an increasing focus on high-yielding varieties, necessitated by the need for increased production and enabled by the globalization of trade, a phenomenon referred to as ‘genetic erosion’ (e.g. [66]). A changing climate will further constrain the number of varieties that can be used, since many may not be suited to the new environment. Thus, the options for adaptation through a change in cultivar diminish over time.

Increasing yields is, of course, not the only adaptation option. Expansion of cropped land can also be used to maintain production. However, climate change may heavily modify land suitability. In relatively large areas of SSA that are currently classified as mixed rain-fed arid–semiarid systems, cropping may become increasingly risky and marginal, perhaps leading to increased dependence on livestock keeping or increasing diversification into non-agricultural activities and migration to urban areas. Such areas may, to all intents and purposes,

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'flip' from a mixed system to a predominantly rangeland-based system: some 730 000 km^2 of SSA may be at risk of such flipping [25], of which about 16 per cent is located in areas within 3 h travel time of a population centre with more than 250 000 people (a proxy for 'good accessibility to markets'). We recalculated the size of the transition areas that may flip from mixed rain-fed arid–semiarid to rangeland-based arid–semiarid systems using the climate data outlined in §2*a* above. In a 5°C+ world, the transition zone increases in size to some 1.2 million km^2 (about 5% of the land area of SSA). Moreover, with such warming, the proportion of this transition zone that is in areas of high accessibility increases to about 50 per cent. Such conditions would mean considerable loss of cropland in SSA (cropping would become too risky in about 35% of the mixed rain-fed arid–semiarid systems); and increasing amounts of this land would be in the hinterlands of large urban areas with already high population densities.

Such changes in the agricultural landscape and crop geography will require significant adjustments in livelihood strategies and agricultural growth pathways. As already discussed, decades of work on agricultural development has shown that farmers need support to switch strategies, and the evidence suggests that there are no historical analogues for the growing conditions in a 4°C+ world in which globalization has changed the structure of food systems [8,67]. Although the recent increased investment by the World Bank, the Bill & Melinda Gates Foundation and other donors in the long-neglected agricultural sector are timely and welcome, the engagement of these groups with the reality of a changing climate is only just beginning, as evidenced by the 2010 World Development Report on 'Development and Climate Change' and the launch in 2010 of the new Challenge Programme on Climate Change, Agriculture and Food Security (www.ccafs.org).

(*b*) *The adaptive capacity of food systems*

As patterns of agricultural production will change profoundly in a 4°C+ world, the question of how food security will be affected, and whether food systems can adapt sufficiently to avoid increased food insecurity, raises a host of issues. Food security depends upon much more than just local agricultural production, as access to food is often the major reason why poor households suffer from hunger [42,68]. Access is a function of both income and price of food, as well as of the ability of markets and distribution networks to allocate food equitably (from the household to the international level; [69]). In Africa, progressive climate change will increase the probability of failed agricultural seasons owing not only to long-term shifts in temperature and precipitation but also to the probably increased frequency of droughts and floods [70]. Thus increases in transitory food insecurity episodes can be expected. The lessons gathered from 30 years of food security analyses and interventions demonstrate the following:

— Repeated droughts erode the assets of poor and marginal farmers, and relief interventions struggle to protect such households effectively from food insecurity and poverty [71,72]. Food aid as a long-term strategy is not wise [73]; both food- and cash-based transfer or safety net programmes are difficult to design and implement on a broad scale, particularly in response to seasonal shocks [74,75].

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— The responses of national governments to protect food security in the face of supply and price shocks are not always successful, particularly over the long term [76,77]. The domestic interventions of multiple national governments are partially blamed for exacerbating the impacts of the 2007–2008 food price increases.

As we saw in 2007–2008, crop failures in major exporting countries such as Australia, when occurring at the same time as other food system disruptions such as speculation, increased demand for agricultural commodities and low grain reserves, can lead to widespread, global food price increases [78]. As climate change is a global phenomenon, we can expect more price shocks in the future. The evidence about a country's 'adaptive capacity' in the face of the 2008 price shocks is sobering, as many reverted to domestic price controls, export bans or import tariffs, and globally food aid was in short supply. Food insecurity persists not only because of economic imbalances between rich and poor, but also due to power imbalances, between governments as well as between communities. This manifests itself not only in political negotiations such as the Doha Round of the World Trade Organization (WTO) but also in differential capacity of markets and national policies to accommodate food price shocks [79–81]. The lesson from this is that there is still much learning to do concerning how to implement risk management and agricultural growth strategies for SSA at the necessary scale. The IPCC's Fourth Assessment Report [15] assumes that regional shortfalls in SSA can be ameliorated with imports from global markets; the experience of 2008 underscores the difficulties that such an 'adaptation' strategy will face in reality.

(c) *Diminishing technical options for adaptation*

Constraints to adaptation at the local level (§3*a* above), together with the indications above that the adaptive capacity of food systems is also limited, lead to a reduction in the number of adaptation options as climate moves further from the current coping range. While, at first glance, globalization may appear to offer a mechanism for smoothing out geographical differences and thus stabilizing food supply, it is far from clear that this is the case. If options are reduced across the globe, then we cannot rely on redistribution of resources via trade as an adaptive mechanism. Simulation results for maize in the USA [82] are one indication that this may indeed be the case, with existing varieties showing an overall decreasing crop production under scenarios of climate change. Although there were some regional variations, the results of that study indicated that adaptation to climate change for maize yields would require either increased tolerance of maximum summer temperatures in existing maize varieties or a change in the maize varieties grown. Similar projections have been made for a range of crops across the globe. Spring wheat crop failures in China have been projected to increase with (both local and global) mean temperature, owing to an increasing occurrence of extremes of heat and drought [83]. This suggests that here too the options for adaptation are decreasing. Quantifying climate uncertainty is an important aspect of such assessments: using one regional climate scenario across India, and quantifying uncertainty in the response of crops to elevated CO_2, Challinor [83] found significant potential for adaptation of groundnut cultivation

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to climate change in India. However, a subsequent, fuller account of uncertainty in climate demonstrated that this potential will not necessarily maintain current yields [84].

Comprehensive analyses of adaptation options are difficult to make, partly owing to the complexity of any adaptive system. Even when only one option is considered, such as a change in crop variety, insufficient data may be available for analysis. Germplasm databanks provide an invaluable source of information for matching crops to future climates. Making use of one such dataset—the multi-location International Wheat Information System held at the International Maize and Wheat Improvement Center CIMMYT—we examined the response of 2711 varieties of spring wheat to increases in mean temperature. We used observed current crop durations with proscribed changes in mean temperature in order to calculate future crop durations. We chose the northern USA as the study region, since the current mean growing season temperature in this region is around 21°C, thus permitting the assumption that the optimum temperature for development is greater than any season-mean temperature and allowing us to use the methods of Challinor *et al.* [84, eqn (3)] to calculate duration. At +2°C of local warming, 87 per cent of the 2711 varieties examined, and all of the top five most common varieties, could be used to result in a crop duration similar to that of the current climate. This can be interpreted as a successful adaptation to mean warming. At +4°C, however, the proportion fell to 54 per cent of all varieties, and only two of the top five.

While the above analysis is relatively simple, assessing only crop response to mean temperature, it does illustrate the way in which adaptation options diminish as climate changes. Furthermore, we have seen that diminishing options in one region of the globe result in diminishing options elsewhere. Thus, the options available for adaptation to climate change for SSA, whether domestic or foreign, are likely to decrease. What is unclear is at what point those options become too few for successful adaptation across a region. This is a major question, given the many problems that continue to plague African food systems. It may be that critical thresholds are already being reached because of economic and policy failures. While understanding of physical thresholds in the Earth system is increasing [85], as yet we have little understanding of socio-economic and cultural thresholds. Understanding and quantifying the critical thresholds in global food systems and how these play out in SSA in particular is an urgent research issue.

4. Conclusions

The prognosis for agriculture and food security in SSA in a 4°C+ world is bleak. Already today, the number of people at risk from hunger has never been higher: it increased from 300 million in 1990 to 700 million in 2007, and it is estimated that it may exceed 1 billion in 2010 [42]. The cost of achieving the food security Millennium Development Goal in a +2°C world is around $40–60 billion per year, and without this investment, serious damage from climate change will not be avoided [86]. Currently, the prospects for such levels of sustained investment are not that bright. Croppers and livestock

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keepers in SSA have in the past shown themselves to be highly adaptable to short- and long-term variations in climate [14], but the kind of changes that would occur in a 4°C+ world would be way beyond anything experienced in recent times. There are many options that could be effective in helping farmers adapt even to medium levels of warming, given substantial investments in technologies, institution building and infrastructural development, for example, but it is not difficult to envisage a situation where the adaptive capacity and resilience of hundreds of millions of people in SSA could simply be overwhelmed by events.

At the moment, it seems unlikely that international climate policies will succeed in confining global warming to +2°C; even this will require unprecedented collective will and collective action [16]. What can realistically be done in relation to food security in SSA in the short to medium term? We highlight four things. First, we can assist the adaptation that is already inevitable by identifying, encouraging and helping to implement proactive adaptation to keep the number of options high for smallholders. Households' capacity to adapt in the face of increasing external stresses is largely governed by flexibility in livelihood options, and there is increasing evidence that generally it is the poorer households that can gain the most from implementing options for coping with and managing risk [87]. A wide variety of prospective options exist, from the effective use of climate information to paying smallholders for ecosystem goods and services to increase household income. Some of these options are likely to be robust, even given the uncertainties that exist concerning future patterns of climate change. But the lessons of the recent past teach us that the difficulty of implementing many of these options in SSA should not be underestimated: massive investment and increases in agricultural productivity will be necessary if economic development is to succeed in Africa in the coming decades [88].

Second, we need to go 'back to basics' in collecting data and information. Difficult though it may be for many people to accept in the second decade of the twenty-first century, the fact is that land-based observation and data collection systems in SSA have been in decline for decades. This affects the most basic data: weather data, land-use data, and crop and livestock distribution data, for example. For instance, estimates of the cropland extent in Africa range from about 1 to more than 6 million km^2, the value depending on choice of satellite-derived product [89]. The uncertainty in such basic information ('where are crops grown and how much of them is there?') adds considerable difficulty to the quantification and evaluation of impacts and adaptation options. There is much technology that is being brought to bear on data issues: remote sensing of weather information, validation of different land-use products using Wikis and Google Earth (see www.geo-wiki.org) and dissemination of market information using mobile phone technology in East Africa, to name just a few. But many of these things need to complement land-based observations, not substitute for them. A similar situation exists with respect to germplasm data. Specific information on the response of crops to weather and climate is often not collected, but it could be with relatively modest additional effort.

Third, concerted action is needed to maintain and exploit global stocks of crop germplasm and livestock genes. Preservation of genetic resources will have a key role to play in helping croppers and livestock keepers adapt to climate change

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and the shifts in disease prevalence and severity that may occur as a result. Genetic diversity is already being seriously affected by global change. Genetic erosion of crops has been mostly associated with the introduction of modern cultivars, and its continuing threat may be highest for crops for which there are currently no breeding programmes [90]. Breeding efforts for such crops could thus be critically important. For livestock, about 16 per cent of the nearly 4000 breeds recorded in the twentieth century had become extinct by 2000, and a fifth of reported breeds are now classified as at risk [91]. Using germplasm in SSA will need technical, economic and policy support. Revitalizing agricultural extension services, whether private or in the public sector, is key: no farmers will grow crops or raise livestock they do not know, are not able to sell, and are not used to eating.

Fourth, the social, economic and political processes that contribute to vulnerability and food insecurity must be addressed with even greater vigour. Food insecurity has received renewed policy attention since 2008, when several high-level meetings on food security were held in response to the food price crisis. Political reforms have been proposed, and countries have made commitments to better food system governance and increased investment in smallholder agriculture. In addition, the momentum for supporting community-based and local adaptation is building in communities of practice; however, this requires higher-level policy and institutional support to ensure that local-level adaptation is enabled and communities are empowered.

The agricultural landscape of SSA is likely to undergo considerable change in the coming decades as a result of several different drivers. Food systems will have to adapt to ensure food security for the extra billion people who will be populating the African continent by 2050, and this will require broad and integrated (yet locally context-specific) institutional and policy responses. It would not be wise to bank on limiting climate change to +2°C, and we should be prepared for more. Some places may see sustainable intensification of production, where this is possible, others may see shifts in crop and livestock production, and some of the drylands are likely to need sustainable extensification as cropping becomes ever riskier. Keeping smallholders' options open is key, and a substantial part of this will lie in much better understanding of the limits to adaptation and the thresholds beyond which much more radical action will be needed, if food security is to be achieved in SSA.

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Changes in the potential distribution of humid tropical forests on a warmer planet

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The future of tropical forests has become one of the iconic issues in climate-change science. A number of studies that have explored this subject have tended to focus on the output from one or a few climate models, which work at low spatial resolution, whereas society and conservation-relevant assessment of potential impacts requires a finer scale. This study focuses on the role of climate on the current and future distribution of humid tropical forests (HTFs). We first characterize their contemporary climatological niche using annual rainfall and maximum climatological water stress, which also adequately describe the current distribution of other biomes within the tropics. As a first-order approximation of the potential extent of HTFs in future climate regimes defined by global warming of 2°C and 4°C, we investigate changes in the niche through a combination of climate-change anomaly patterns and higher resolution (5 km) maps of current climatology. The climate anomalies are derived using data from 17 coupled Atmosphere–Ocean General Circulation Models (AOGCMs) used in the Fourth Assessment of the Intergovernmental Panel for Climate Change. Our results confirm some risk of forest retreat, especially in eastern Amazonia, Central America and parts of Africa, but also indicate a potential for expansion in other regions, for example around the Congo Basin. The finer spatial scale enabled the depiction of potential resilient and vulnerable zones with practically useful detail. We further refine these estimates by considering the impact of new environmental regimes on plant water demand using the UK Met Office land-surface scheme (of the HadCM3 AOGCM). The CO_2-related reduction in plant water demand lowers the risk of die-back and can lead to possible niche

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expansion in many regions. The analysis presented here focuses primarily on hydrological determinants of HTF extent. We conclude by discussing the role of other factors, notably the physiological effects of higher temperature.

Keywords: tropical forests; climate change; climate patterns; water stress; maximum climatological water deficit; carbon dioxide

1. Introduction

Tropical forests cover 10 per cent of all land area ($1.8 \times 10^7\,\mathrm{km}^2$; [1]), and represent about half of global species richness [2]. Clearing of these forests is estimated to account for 12 per cent of anthropogenic carbon emissions [3], which are partly offset by a forest carbon sink with enhanced forest productivity and biomass linked to elevated atmospheric CO_2 concentrations [4]. Over half of the tropical-forest area ($1.1 \times 10^7\,\mathrm{km}^2$) is represented by humid tropical forests (also called 'moist tropical forests', 'wet tropical forests', or 'tropical rainforests'; hereafter abbreviated to HTFs), characterized by high tree-species diversity and high biomass density [5–7].

Tropical-forest boundaries are often delineated by overlaying land-cover maps with maps of ecological zones defined by climate (e.g. [8,9]), as climate generally exerts the largest influence on the distribution of vegetation types at the global scale [10]. However, there is no commonly accepted delineation of tropical-forest types because, in reality, the transition between them tends to be gradual. Ecological zones concerning tropical forests are usually based on precipitation, and sometimes also temperature and humidity patterns. This study critically examines a number of approaches to describe climatic conditions that are optimal for HTFs, before proceeding with the study of climate impacts on this biome's potential distribution.

Lewis [11] characterized HTFs as having high annual rainfall (>1500 mm) and low seasonality defined by less than six months of dry season with monthly precipitation greater than $100\,\mathrm{mm\,month}^{-1}$. Malhi *et al.* [12] found the same value of annual rainfall (1500 mm) to be a reasonable threshold for viable broadleaf evergreen forests of Amazonia. A second boundary proposed in that study, related to the strength of the dry season, was the maximum climatological water deficit (MCWD; see §2) between −200 and −300 mm. The study, in some ways a precursor to the analysis presented here, used the key assumption that each month, the forest evapotranspires approximately 100 mm of water. Such an evapotranspiration rate for non-drought-stressed HTFs is widely used, and it reflects the findings from observational studies (e.g. Kumagai *et al.* [13]; Malhi *et al.* [14]), although recent estimates suggest that it may be somewhat higher [15].

Temperature may be used to refine the estimate of water stress; for example, Mayaux *et al.* [1] and Food and Agriculture Organization (FAO) [8] defined the HTF climatological niche as having a maximum of three dry months with monthly rainfall (in millimetres) lower than twice the mean temperature (in °C), although such an empirical combination of temperature and precipitation variables appears to have little mechanistic justification. Richards *et al.* [16] advised a broad classification of tropical climates in relation to vegetation based

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on annual rainfall, temperature and the perhumidity index (PI [17]) that attempts to summarize both the dry- and wet-season precipitation characteristics into a single index value. In this scheme, a low-temperature boundary is used to separate a group of tropical climates associated with biologically distinct *montane* forests, for which humidity, sunshine and cloudiness also play a role in defining the boundaries.

Climate change will manifest itself by changes in temperature and precipitation (see Betts *et al.* [18] for relevant analysis), as well as other aspects of the climate system, including humidity, radiation and wind. All of these changes may, to a varying degree, have consequences for the future distribution of conditions favoured by HTFs. Related to this problem is the concern about climate-induced 'die-back', which first received attention following Cox *et al.* [19]. A simple examination of the climate-related changes in the HTF climatological niche (defined in the current climate) provides insight into the future extent of this biome. However, potential shifts in the environmental optima, or thresholds, of biomes also need to be considered. For example, plant water-use efficiency (the amount of carbon assimilated per unit of water transpired) increases with atmospheric CO_2 concentration. Increasing temperature may have a positive or negative impact on photosynthesis and net carbon uptake [4,20,21]. Very high temperatures may also cause the closure of stomata. Hence, the impact of new climate regimes on plant physiology may be a key to determine the future distribution of HTFs. Although the issue is complex [20], and not yet fully understood, the ongoing ecological response of HTFs to climate change informs the debate, and the role of increased CO_2 emerges as an important factor to be considered [4].

Research concerned with climate-change impacts on tropical forests has tended to focus on Amazonia and address the possibility of climate-induced die-back [12,22–25]. Owing to teleconnections with other components of the climate system, this region has been recognized as one of the Earth system's potential tipping elements [26]. In reality, factors other than climate may also contribute to the major loss of Amazonian HTFs, such as anthropogenic deforestation and interactions between deforestation and fire spread. Die-back may be exacerbated by the interaction between these factors and imposed climate change [27]. The majority of literature devoted to the risk of forest die-back across the tropics has attempted to address this problem with Dynamic Global Vegetation Models (DGVMs) driven by future projections of climate change. The results depended largely on the assumed future climate pathway, and on the individual DGVM selected [28,29]. For example, early studies were based on the UK Hadley Centre model HadCM3, which predicts very dry and hot conditions over Amazonia, enhanced by feedback from forest die-back [19,24,30]. In that framework, the rising temperatures caused a strong decline in net primary production [31], which led to the loss of forest cover, as explicitly simulated by the Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) DGVM [32,33]. Subsequent studies attempted to account for uncertainty in future climate through either the use of conditions predicted by one Atmosphere–Ocean General Circulation Model (AOGCM) with various alternative parametrizations [25], or a number of AOGCMs (e.g. [34–37]). None of these studies reported any potential for new areas to be colonized by HTFs. It is possible that the low spatial resolution of the frameworks used (minimum of 60 km in the study

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by Cook & Vizy [38]) is inadequate to describe the broad distribution and variability of climatic factors and risks. Small-scale variation, notably linked to topography, may facilitate greater ecosystem resilience than what the models suggest [39,40].

In this study, we explore the possibility for retraction or expansion of HTFs under twenty-first century anthropogenic global warming. First, we take an empirical approach to defining the current climatological niche of HTFs. We then use projections from 17 coupled AOGCMs, downscaled using contemporary climatological data, to explore (i) the potential variation of this niche, assuming no impact of new climate regimes on plant water demand, and (ii) the consequences of potential change in plant water demand. Specifically, we ask the following questions:

- Which scalable climatological indices best define the current boundaries of the HTF biome, and what are the appropriate threshold values of these indices?
- What is the spatial pattern and magnitude of potential humid forest expansion and retraction considered over 17 different climate models?
- What does the consideration of higher resolution climatological patterns add to our understanding of potential risk regions and potential HTFs refugia that are resilient to climate change?
- How does the introduction of environmental controls on the plant physiology, which influence water demand, affect the likelihood and pattern of potential niche contraction or expansion?

The novel contributions in this work arise from a combination of (i) the empirical derivation of the hydrological threshold for tropical forests worldwide, (ii) consideration of multiple climate models, (iii) consideration of fine-scale variation in climate patterns, and (iv) inclusion of effects of new climate regimes on plant water-use efficiency. It is worth noting that this analysis focuses on ecosystem water demand and its potential variation, as inferred from the canopy conductance and photosynthesis model. It does not consider all ecophysiological influences of atmospheric change, for example high CO_2 altering the competitive balance between C3 photosynthesis-dominated forests and C4-dominated grasslands. Such ecophysiological considerations could be incorporated by employing a dynamic vegetation model, but are limited by a poor understanding of what the ecophysiological responses and thresholds are, and the extent to which plant processes can acclimate to higher temperatures. The merits and uncertainties of incorporating other ecophysiological processes are presented in §4.

2. Methods

(a) *Contemporary distribution of humid tropical forests and their niche*

Spatial distribution of tropical vegetation biomes was assessed based on the Global Land Cover 2000 dataset ([41]; figure 1) derived from satellite data. It employed the Land Cover Classification System of the FAO in which

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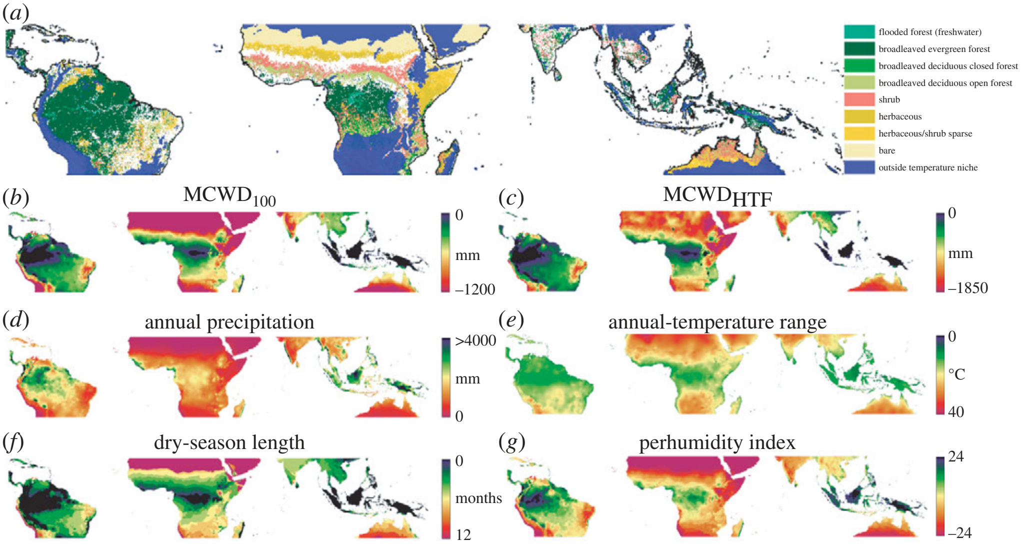

Figure 1. (*a*) Vegetation classes in the tropics. Areas too cold for lowland HTFs are shaded in blue. White areas within continents are covered by either anthropogenic or mixed land-cover types, and were not used in the analysis. (*b*–*g*) Key climate variables linked to the distribution of tropical biomes (see also table 1). Underlying data source: Global Land Cover 2000 and WorldClim datasets.

vegetation types are based on vegetation form (e.g. trees, shrubs), density, leaf type and phenology. HTFs were assumed to be represented by a class of evergreen broadleaved forests and forests flooded by freshwater, both within the tropics.

A number of variables related to surface precipitation and temperature were considered for the definition of climatological niche of the contemporary HTFs. The explanatory power of each variable in terms of the distribution of HTFs and other tropical vegetation types (non-evergreen forest types, dense non-forest vegetation and sparse non-forest vegetation) was assessed using multi-nomial logistic regression. Each variable's range, specific to a region within the tropics (Americas, Africa and south and insular Asia, referred to as 'Asia') was split into 44 equal bins (except for the dry-season length with only 12 bins), which were represented by a high number of vegetation-type counts (pixels). The assessment included three criteria: (i) deviance, which depicts the variable's overall capacity to predict the composition of vegetation types, (ii) the root mean-squared error (RMSE), calculated for HTFs, reflecting the difference between the predicted and actual contribution from HTFs across the variable's gradient, and (iii) the predictor's ability to capture both high and low probability of HTF occurrence, as inferred from the shape of the fitted curve. The considered climatic predictors included 19 variables of the Worldclim dataset [42], and 10 additional variables derived for this study, which included MCWD ([12]; equation (2.1)), PI [17], dry-season length (defined as in [1,8]; see §1), annual actual evapotranspiration (ET), and minimum and maximum mean monthly temperature (and the resulting annual-temperature range).

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The MCWD was derived in four ways, all of which conformed to the following general definition:

$$\left.\begin{aligned}&\mathrm{CWD}_n = \mathrm{CWD}_{n-1} + P_n - \mathrm{ET}_n; \quad \mathrm{Max}(\mathrm{CWD}_n) = 0;\\&\mathrm{CWD}_n = \mathrm{CWD}_{12}; \quad \mathrm{MCWD} = \mathrm{Min}(\mathrm{CWD}_1, \ldots, \mathrm{CWD}_{12})\end{aligned}\right\}. \tag{2.1}$$

Hence, the MCWD is the most negative mean monthly value of climatological water deficit (CWD) across the annual cycle, with each monthly step inferred from the difference between precipitation P and evapotranspiration ET.

The definition of monthly evapotranspiration ET varied depending on the approach taken. First (MCWD_{100}), the monthly ET was assumed to be constant (as in [12]). The second approach ($\mathrm{MCWD}_{\mathrm{ET}}$) used mean monthly ET estimates based on data from Fisher *et al.* [43], with a spatial resolution of 0.5°. As this second approach takes vegetation indices as input variables, it predefines to some extent the HTF niche. To bypass this issue, the third approach ($\mathrm{MCWD}_{\mathrm{HTF}}$) aimed at assessing the magnitude of ET in the hypothetical scenario, in which the whole extra-tropics are potentially covered by HTFs. The ET over this region was calculated based on the median value of the vegetation seasonality and density (described by spectral vegetation indices) inside the areas currently covered by HTFs, and the corresponding atmospheric moisture (described by water-vapour pressure). The simulation preserved the original values of net radiation and maximum air temperature, which meant that the primary drivers of potential evapotranspiration were unaffected.

The PI [17], another considered metric related to plant water stress, measures the degree of continuity of wetness (or perhumidity) of monthly precipitation series in a tropical climate. Each month is assigned a score, depending on the amount of rainfall in both that and the previous month. The sum of scores reflects both the dry- and wet-season characteristics of the climate.

Subsequent analysis of the future extent of the HTF climatological niche was based on the variables that were found to be the best predictors of its contemporary distribution. In addition, the low-temperature boundary (mean annual temperature below 20°C, and a coldest monthly mean below 18°C) based on Richards [16] was used to separate lowland rainforests from montane forests and other cooler forest biomes.

(*b*) *Climate-change patterns*

Climate-change patterns (or ‘pattern scaling’), as defined by Mitchell *et al.* [44] and Huntingford & Cox [45], are a method of providing monthly and regional estimates of variability in surface climate, and as a function of mean global warming. The underlying assumption is that attributes of surface climate vary approximately linearly with mean global warming over land, and the derived regression coefficients are referred to as ‘patterns’. The initial application of this approach was to allow rapid interpolation from the existing global climate model simulations to surface climate conditions associated with new pathways in atmospheric greenhouse-gas concentrations. The radiative forcing associated with such concentrations is calculated and used to drive a simple global thermal model (also called the Simple Climate Model; Wigley *et al.* [46]), leading to predictions of mean warming over land required to multiply the patterns. Although pattern scaling is an effective, and policy-relevant, way of generalizing climate data,

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it needs to be remembered that the patterns reflect only a portion of climate change which is scalable with warming over land or globe; thus they do not fully reflect the variability in scaled variables, including the highly variable precipitation [44,47].

This study focuses on climate regimes representing global warming of 2°C and 4°C (above pre-industrial levels; referred to as the '+2°C' and '+4°C' scenarios), simulated with coupled AOGCMs, which were employed in the Fourth Assessment (AR4) of the Intergovernmental Panel for Climate Change. Climate patterns were derived for 17 out of 24 AOGCMs (data available at the World Climate Research Programme's Coupled Model Intercomparison Project (WCRP CMIP3) portal; https://esg.llnl.gov:8443). The other seven AOGCM datasets were excluded as they lacked some of the required data. Key variables that were scaled for each AOGCM, and all of which are important to land-surface functioning, included: temperature, relative humidity, precipitation and radiation. The use of pattern scaling allowed emulation of the '+4°C' scenario, even if it was not present in the AOGCM data.

Spatial resolution of climate data varies between AOGCMs, although it is generally of the order of hundreds of kilometres. For this analysis, resolutions were homogenized as follows. First, all data were interpolated to a resolution of 1° with the Climate Data Operators package (www.mpimet.mpg.de/~cdo/). Subsequently, the data were re-mapped onto the HadCM3 model grid. The mapping procedure distinguished between land, ocean and mixed areas, and allowed for minor spatial shifts in grid boxes in order to preserve the land/ocean contrast in surface variables.

In order to circumvent the problem of known biases in the description of the current climate by some AOGCMs, which is especially important in the case of tropical rainfall, each AOGCM precipitation pattern (ΔP) was multiplied by the ratio of the observed precipitation ($P_{\mathrm{CRU\_XXc}}$) from the Climate Research Unit Time Series (CRU TS) 2.1dataset [48] and the one simulated by the AOGCM ($P_{\mathrm{AOGCM\_XXc}}$), as in Ines & Hansen [49] and Malhi *et al.* [12]:

$$\Delta P'(g,m,i) = \Delta P(g,m,i) \times \frac{P_{\mathrm{CRU\_XXc}}(i, m_{\mathrm{S}}, g_{\mathrm{S}})}{P_{\mathrm{AOGCM\_XXc}}(i, m_{\mathrm{S}}, g_{\mathrm{S}})}. \tag{2.2}$$

In this analysis, the adjustment was performed for each grid box g, month m and AOGCM i, after minimal smoothing in time and space (averaging over the grid box and its immediate neighbourhood: g_{S}, and across three months m_{S}), which significantly limited the number of artefacts caused by division by approximately 0. The remaining few cases of high divergence were capped at 5 and 0.2, based on the analysis of histograms of multiplication factors.

(*c*) *Downscaling of climate-change scenarios*

As a first-order approximation of the potential extent of HTFs in climate regimes defined by 2°C and 4°C of global warming (i.e. initial analysis; before accounting for changes in evapotranspiration), the current forest climatological niche was re-drawn based on high-resolution contemporary climate combined with projected climate-anomaly patterns. The patterns were scaled according to global and land warming in the high-emissions A2 scenario of the Special Report

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on Emission Scenarios (SRES) [50]. Whenever possible, the warming data were extracted from the available AOGCM data. Otherwise, they were generated with the above-mentioned simple global thermal model.

Climate patterns, all on the HadCM3 grid, were downscaled with the Worldclim dataset of observed monthly climate [42] on the grid with a high spatial resolution of 2.5′ (approx. 5 km). First, climate patterns representing coastal areas were expanded onto the nearest waters in order to make sure that the change is applied to all coastal areas in the high-resolution dataset. Second, the patterns were re-sampled to higher resolution using the nearest-neighbour method, and smoothed with an average filter. Finally, the resulting coverages with anomalies were added to the Worldclim climatology.

Downscaling is a topic of much debate within the climate modelling community (see [51,52]). The simple approach taken here assumes that the sub-grid patterns and relative magnitudes of rainfall and temperature are preserved under a climate-change pattern. This assumption breaks down if patterns of circulation or moisture transport shift substantially under the climate-change scenario (e.g. the position of orographic or coastal wet spots shifts as wind patterns change). Nevertheless, as a first approximation, such downscaling is useful and of practical importance as it highlights the existence of localized vulnerable or resilient regions in greater detail, something impossible from a low-resolution analysis alone.

(*d*) *Estimating the effect of climate change on ecosystem water use*

The effect of climate change on plant physiology, notably water use, was modelled explicitly using the Integrated Model of Global Effects of Climatic Anomalies (IMOGEN) framework [30,53], which comprises (i) the Met Office Surface Exchange Scheme (MOSES [33]) used in the HadCM3 AOGCM, (ii) the component to emulate the AOGCM simulation's climate pathway (including simple global thermal model), and (iii) the DGVM TRIFFID [33]. The latter component of IMOGEN was switched off; i.e. future changes in the carbon balance of vegetation did not affect the distribution of their functional types. In each run of the framework, the land-surface scheme was forced with atmospheric conditions generated from climate patterns specific to a given AOGCM, which were scaled with the simple climate model according to radiative forcing pathway of the SRES A2 scenario (derived from the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) model [54,55]) and applied to contemporary climate data CRU TS 2.1. The simple climate model was separately parametrized for each AOGCM, based on the available simulation data; however, the energy balance of the IAP-FGOALS-g1.0 AOGCM could not be reproduced.

The analysis of forest water use focused on 39 grid boxes of the HadCM3 grid that were within the tropics, and were parametrized as having at least 90 per cent cover of broadleaved forest. The combination of climatic drivers and plant physiological responses (the latter through the MOSES land-surface scheme) allowed for the assessment of the importance of each climate variable for evapotranspiration (ET). The results from this assessment were used to adjust the outline of the HTF climatological niche in warmer climate regimes (obtained in the initial assessment) by accounting for the influence of altered evaporative fluxes on plant water stress.

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3. Results

(*a*) *Current climatological niche of humid tropical forests*

The analysis of climate-related variables showed that the ones related to ecosystem water stress have the greatest explanatory power for the distribution of HTFs (as inferred from the RMSE), and to some extent, also other vegetation types (as inferred from the deviance). The first five predictors shown in table 1 (see also figure 1) are strongly linked to plant water stress. Annual precipitation, ranked sixth, is the second-best predictor among the Worldclim variables, below dry-season precipitation. Among the temperature-related variables, the strongest predictors were those describing annual-temperature range. However, it should be noted that the relationship between forest cover and low-temperature ranges is probably inverse, with high vegetation cover and transpiration tending to induce low diurnal and annual-temperature range through the surface-energy balance.

The usefulness of climatic variables for this analysis arises not only from their precision in identifying the probability of HTF occurrence in the climate space, as presented above, but also from their ability to distinguish regions of very high and very low probability of the HTF occurrence, which facilitates the creation of a robust map. In terms of such criteria, MCWD_{100}, $\mathrm{MCWD}_{\mathrm{HTF}}$, annual precipitation, PI and dry-season length, are the most robust predictors (see electronic supplementary material), although the last two have considerably lower resolution. Examination of these predictors revealed that the dataset over-predicts some HTF occurrence in high-stress environments, especially in the case of the Americas (probability of HTF occurrence does not reach zero), which is likely to reflect some inaccuracies in the climate and/or land-cover data.

Overall, these results suggest that the spatial distribution of HTFs is best described by their affinity towards high-precipitation regimes with rainfall evenly distributed throughout the year (i.e. low water stress), and they confirm the validity of the principal axes suggested by Malhi *et al.* [12].

Hence, in this study, the HTF niche is also defined through MCWD_{100} (preferred over the similarly robust $\mathrm{MCWD}_{\mathrm{HTF}}$ that is much more difficult to derive, and PI, which has a lower resolution) and annual precipitation. In addition, mean temperature of the coldest month and mean annual temperature were used to outline the boundary between lowland and montane forests and cool subtropical forests. We assume that change in the temperature range over the twenty-first century will not negatively affect the extent of HTFs, i.e. there is no significant temperature-induced tropical forest 'die-back', and that new areas may enter HTFs conditions as temperatures rise over the low-temperature threshold for HTFs.

Figure 2*a* plots biome dominance in the climatological space defined by MCWD_{100} and annual precipitation. HTFs quantitatively dominate other vegetation types at MCWD_{100} values between −450 and −350 mm. There are some cases where HTFs occupy areas with more negative MCWD_{100} values, but in most cases not as a dominant vegetation type. Along the annual precipitation axis, the vast majority of HTFs dominate at precipitation values above 1500 mm (as indicated by the density contours). In the Americas, there is some dominance of HTF at values below 1500 mm, but this is much less apparent in Africa or Asia.

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Table 1. Explanatory power of climate-related variables in terms of the distribution of four major vegetation types across the tropics: HTFs, other forests, dense shrubs and herbs and sparse shrubs and herbs. For each region, the first value is the RMSE of the actual versus predicted probability of HTFs across the variable gradient. The second value (s.d.) is deviance, and it concerns all four vegetation types (low value for dry-season length is because of its very low resolution). The presented ranking was done through averaging of regional RMSE-based ranks. See the electronic supplementary material for the actual and modelled probabilities of vegetation-type occurrence.

		performance as a driver for biome distribution					
		Americas		Africa		Asia	
no.	climate-related variable	RMSE	s.d.	RMSE	s.d.	RMSE	s.d.
1	$\mathrm{MCWD}_{\mathrm{HTF}}$	0.0769	2.73	0.0304	3.93	0.0448	7.38
2	perhumidity index	0.0784	4.47	0.0312	3.65	0.0433	8.07
3	MCWD_{100}	0.0763	5.09	0.0320	2.97	0.0495	7.98
4	precipitation of driest month	0.0533	1.70	0.0253	0.48	0.0886	3.30
5	dry-season length	0.0515	2.14	0.0391	2.74	0.0813	2.49
6	annual precipitation	0.0602	4.24	0.0562	3.72	0.0611	6.92
7	precipitation seasonality[a]	0.0474	2.12	0.0327	5.06	0.1047	7.44
8	annual-temperature range[b]	0.0851	4.51	0.0379	2.90	0.0459	5.38
9	precipitation of driest quarter	0.0590	1.91	0.0214	0.73	0.1060	3.19
10	annual monthly temperature range	0.0987	3.45	0.0566	7.24	0.0520	6.22
11	precipitation of wettest month	0.0485	4.45	0.0770	6.44	0.1350	7.39
12	isothermality[c]	0.0633	3.09	0.0394	8.30	0.1128	17.71
13	precipitation of wettest quarter	0.0503	4.54	0.0840	7.44	0.1556	8.81
14	maximum temperature of warmest month	0.0845	2.66	0.1003	8.81	0.0820	7.43
15	$\mathrm{MCWD}_{\mathrm{ET}}$	0.0572	3.83	0.0848	10.56	0.1665	9.52
16	mean diurnal temperature range[d]	0.0825	5.45	0.1198	5.30	0.0644	4.78
17	temperature seasonality[e]	0.1266	5.01	0.0578	5.45	0.0652	6.97
18	mean temperature of wettest quarter	0.0931	3.13	0.1039	11.58	0.0782	5.79
19	precipitation of warmest quarter	0.0648	3.16	0.1535	12.80	0.0856	4.31
20	mean temperature of warmest quarter	0.0870	2.88	0.1150	11.35	0.0930	4.20
21	minimum temperature of coldest month	0.0895	4.69	0.1020	6.40	0.1336	11.01
22	annual mean temperature	0.1171	4.94	0.1526	12.82	0.0643	4.67
23	maximum mean temperature of warmest month	0.1334	5.74	0.1082	10.88	0.0902	7.13
24	minimum mean temperature of coldest month	0.1024	4.45	0.1093	13.31	0.2311	17.55
25	annual evapotranspiration (as in $\mathrm{MCWD}_{\mathrm{HTF}}$)	0.1672	7.47	0.1196	12.47	0.0971	4.94
26	mean temperature of coldest quarter	0.1040	4.34	0.1149	12.20	0.2414	17.86
27	precipitation of coldest quarter	0.1354	5.45	0.2343	11.98	0.0937	3.92
28	mean temperature of driest quarter	0.1120	4.51	0.1230	8.55	0.1907	11.36
29	annual evapotranspiration (as in $\mathrm{MCWD}_{\mathrm{ET}}$)	0.1125	7.39	0.1513	20.05	0.2440	22.50

[a] Coefficient of variation.

[b] Maximum temperature of warmest month − minimum temperature of coldest month.

[c] (Mean diurnal range/annual-temperature range) × 100.

[d] Mean of monthly (maximum mean temperature of warmest month − minimum mean temperature of coldest month).

[e] Standard deviation of monthly temperature series × 100.

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The simple outline of the HTF niche (figure 2*b*), defined by one threshold of MCWD_{100} (−350 mm; about 50 mm lower than in Malhi *et al.* [12]) and one of annual precipitation (1500 mm), was found to be a good predictor for the majority of current HTFs distribution. It is apparent that both the MCWD_{100} and precipitation thresholds are useful (i.e. a logical AND combination of both thresholds). Consideration of the MCWD_{100} threshold alone would cause over-prediction of HTF extent in southern Brazil and West and Central Africa (regions with sufficiently weak dry seasons but insufficient recharge in the weak wet season: red zones in figure 2*b*), and consideration of the precipitation threshold alone would cause over-prediction in southeastern Amazonia and peninsular southeast Asia (regions with annual precipitation but very strong dry seasons: light blue zones in figure 2*b*). Therefore, the use of the overlap of the two index-based domains limits their individual shortfalls and makes the potential HTF niche more conservative. This contrasts with the analysis of Malhi *et al.* [12] for Amazonia, which used a logical OR combination of both the thresholds, with either threshold being sufficient for HTFs.

Nevertheless, there were a few regions where HTF extent is over-predicted (purple zones in figure 2*b*), in particular, northwest Amazonia (Colombia and Venezuela) with parts of southern Brazil, and the southwest Congo Basin. The South American mismatch zones partially correspond to seasonal wetlands (the Llanos) where poor surface drainage may prevent HTFs occurrence. The under-prediction in the southwest Congo Basin may be accounted for by radiation: this region has a very cloudy dry season, and hence water demand may be lower than our global analysis indicates—the cloud cover may allow HTFs to persist in drier rainfall regimes than otherwise possible. Deforestation may also be a factor in explaining discrepancies between predicted and observed extent, something very apparent in insular southeast Asia.

Overall, the MCWD_{100}- and annual precipitation-based definition appears to be an adequate descriptor of the current spatial extent of HTFs, and was used as a basis for the assessment of the future extent at global warming of 2°C and 4°C.

(*b*) *Changes in the climatological niche at global warming of 2°C and 4°C*

Global warming is expected to alter both the rainfall and temperature regimes, but prognoses for variables that appeared here as important are not equally robust. The predicted changes in precipitation vary between AOGCMs more than the changes in temperature, both in terms of the magnitude and direction of change (table 2), but also the spatial and seasonal distribution, which is of relevance to both annual precipitation and water stress.

Future decreases in precipitation over HTFs of tropical Americas are predicted by seven of the analysed models (approx. 41%), including the well-known extreme scenario from the HadCM3 model. In contrast, precipitation in the other two regions is consistently predicted to increase. The mean rainfall change for each contemporary HTF region at +2°C of global warming is −4, +42 and $+73\,\mathrm{mm\,yr^{-1}}$ for South America, Africa and Asia, respectively, and more than twice these amounts at +4°C (table 2). However, the mean change in water stress is greater in tropical Asia than in Africa, owing to differences in the spatial and seasonal distribution of rainfall change predicted by different AOGCMs.

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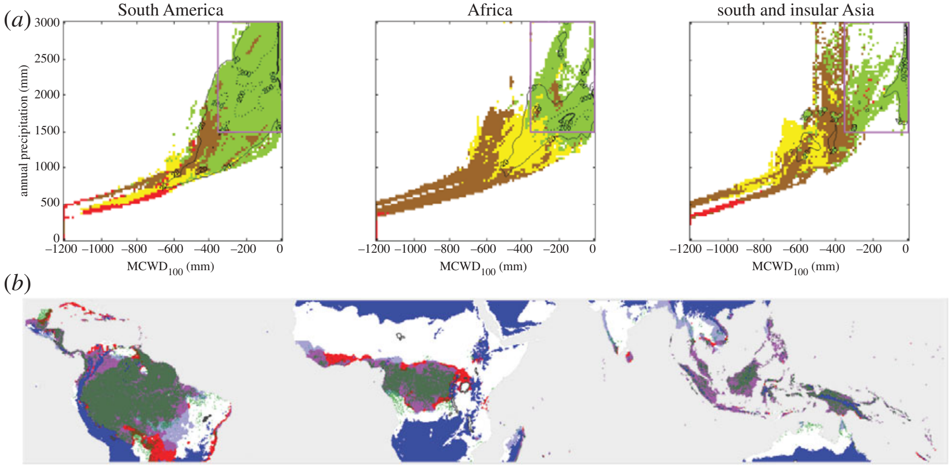

Figure 2. (*a*) Dominance of major tropical vegetation types in a two-dimensional space defined by MCWD_{100} and annual precipitation. Only the cases represented by more than 10 pixels (250 km^2) are plotted. Frequency of HTF pixels is marked with isoclines. The thresholds defining our simple HTF niche (annual precipitation greater than 1500 mm, and MCWD_{100} greater than −350 mm) are delineated by the purple square (green-shaded regions, HTFs; yellow-shaded regions, other forests; brown-shaded regions, dense shrubs and herbaceous; red-shaded regions, sparse shrubs and herbaceous). (*b*) Spatial extent of such HTF niches (in purple), and areas of annual precipitation (light blue) and MCWD_{100} (red) that fall above the proposed thresholds. The current HTF extent is marked in green. Areas too cold for HTFs are marked in dark blue. In mountainous areas adjacent to HTFs they define the boundary between lowland and montane HTFs (green-shaded regions, HTF; light blue-shaded regions, precipitation greater than 1500 mm; red-shaded regions, $\mathrm{MCWD}_{\mathrm{ET}=100}$ greater than −350 mm; purple-shaded regions, assumed HTF niche; dark blue-shaded regions, low-temperature boundary).

The patterns of future temperature change are much more consistent across AOGCMs than for precipitation, with the largest and smallest increases projected across tropical Americas and Asia, respectively (table 2).

These climate-change patterns imply changes in the extent of the HTF niche, which was re-drawn for each model, first with the assumption that the HTF water demand is not affected by climate change (figure 3). The presented frequencies of particular predictions reflect fractions of AOGCM output which predict that outcome; we do not translate this into a probability of that outcome occurring, as the AOGCM outputs are very unlikely to be distributed evenly across the uncertainty space. With this approach, insular Asia has the smallest risk of retreat of the HTF biome. In the +2°C scenario, the most threatened part of this region is the Indochinese peninsula; in the +4°C scenario, the risk concerning that region increases, and additionally expands to central Sumatra, Sulawesi, India and Philippines, with a maximum of approximately 30 per cent of total niche affected.

The risk for HTF retreat is much more substantial in the case of the tropical Americas, especially in southeastern Amazonia, and around the 'Santarem corridor' of eastern Amazonia. In fact, South America is the only region where models suggest more HTF niche contraction than expansion (see insets in figure 3). In the scenario of +4°C global warming, patterns from the HadCM3 and

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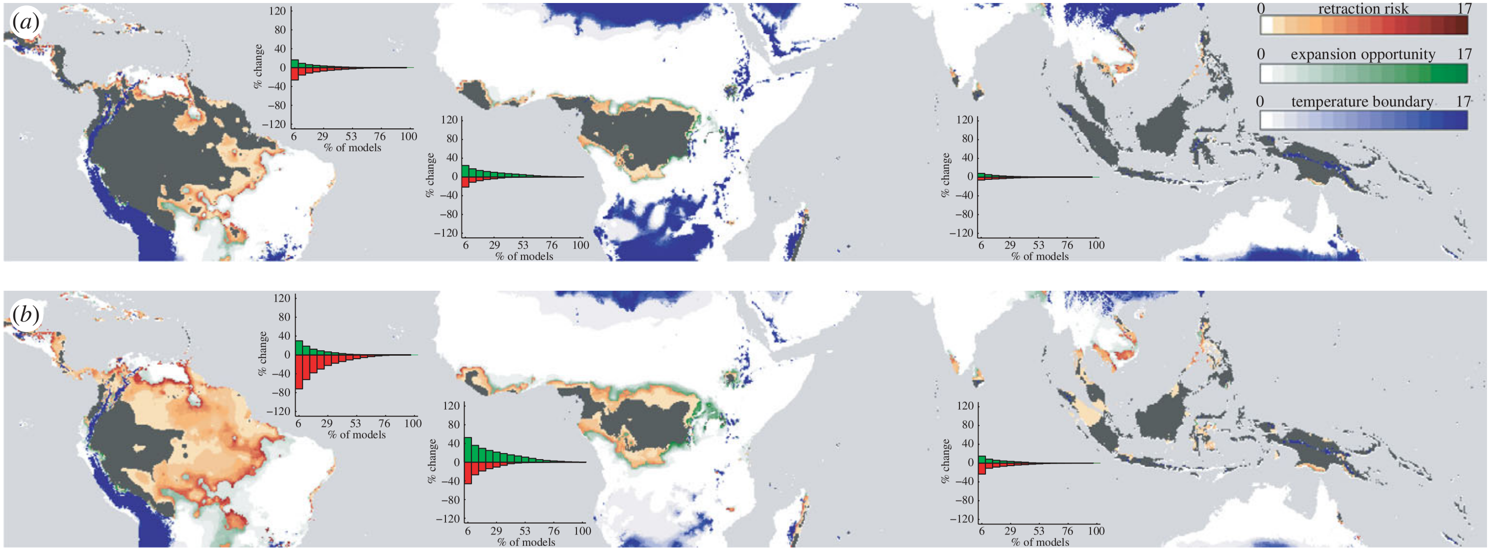

Figure 3. Change in the potential climatological niche of HTFs, as inferred from AOGCM data, assuming no change in ecosystem water demand. (*a*) HTF niche at 2°C and (*b*) 4°C global warming. Dark grey areas mark the niche derived from the current climatological conditions, and are predicted to remain by all AOGCMs. Shades of red and green mark the potential HTF niche contraction and expansion, respectively. Areas too cold for HTFs are marked in blue. In mountainous areas adjacent to HTFs, they define the boundary between lowland and montane tropical forests. Inset bar plots show the percentage of models that agree on a change up to the plotted level.

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Table 2. Annual mean temperature, annual precipitation and maximum climatological water stress (MCWD_{100}; with and without accounting for climate-change-induced changes in evapotranspiration, ET) in tropical regions inhabited by HTFs, and mean change in these variables at 2°C/4°C of global warming, as derived from AOGCM data. Values are given for regions spatially equivalent to HadCM3 grid boxes that currently support HTFs.

			temperature (2°C/4°C)			annual precipitation (2°C/4°C)			MCWD_{100} (2°C/4°C)			MCWD_{100} + ET change (2°C/4°C)		
no.	GCM	made in	Americas	Africa	Asia	Americas	Africa	Asia	Americas	Africa	Asia	Americas	Africa	Asia
	CRU (contemporary climate)[a]	UK	24.6	24.0	25.2	1952	1585	2021	−287	−322	−353	−287	−322	−353
	WorldClim (contemporary climate)	USA	24.8	24.0	24.8	1983	1553	1990	−208	−270	−283	−208	−270	−283
1	BCCR-BCM2.0[a]	Norway	1.6/3.3	1.6/3.3	1.5/3.2	78/163	71/150	60/127	−3/−24	21/34	7/8	77/102	100/150	86/131
2	CCCMA-CGCM3.1.T47	Canada	1.8/4.3	1.6/3.9	1.5/3.6	−42/−101	31/76	78/189	−23/−73	27/49	13/28	67/69	107/155	91/140
3	CSIRO-MK3.0[a]	Australia	1.9/5.4	1.7/4.6	1.6/4.6	−75/−208	103/287	155/434	−78/−290	2/-39	−26/−134	9/−143	88/89	56/−12
4	CSIRO-MK3.5[a]	Australia	1.9/4.7	1.7/4.2	1.4/3.4	−143/−347	36/88	96/232	−41/−176	−8/−50	−19/−87	49/−48	81/93	63/51
5	GFDL-CM2.0	USA	1.8/4.5	1.6/4.0	1.5/3.8	−50/−124	5/12	33/82	−24/−92	19/37	−1/−14	62/62	104/161	79/105
6	GFDL-CM2.1	USA	1.9/4.5	1.9/4.5	1.6/3.9	23/54	16/38	9/21	−23/−64	9/10	−16/−44	61/69	92/137	65/88
7	GISS-EH	USA	1.7/4.2	1.8/4.5	1.6/3.8	112/274	58/141	38/94	11/15	14/27	−12/−20	87/126	100/152	68/93
8	IAP-FGOALS-g1.0	China	1.9/4.5	2.0/4.8	1.7/4.1	10/24	24/58	82/202	−10/−37	24/42	−24/−89	73/82	108/141	57/30
9	INM-CM3.0[a]	Russia	1.5/3.6	1.6/3.9	1.5/3.5	165/401	37/91	34/82	−12/−64	34/36	−11/−66	71/68	115/153	67/68
10	IPSL-CM4	France	1.7/4.1	1.6/4.0	1.6/3.9	66/162	1/1	66/161	−3/−37	17/25	−5/−17	76/92	105/157	73/109
11	MIROC3.2 (hires)[a]	Japan	1.7/4.2	1.5/3.8	1.5/3.6	19/45	16/39	50/123	2/−20	18/33	10/12	81/105	103/153	88/129
12	MIROC3.2 (medres)[a]	Japan	1.9/4.5	1.5/3.5	1.4/3.3	28/69	85/206	71/172	−6/−30	54/92	8/15	75/100	131/184	86/131
13	MPI-ECHAM5	Germany	1.9/4.6	1.7/4.2	1.6/3.9	−16/−39	78/187	124/297	−23/−73	7/11	1/−1	62/72	95/142	81/120
14	NCAR-CCSM3.0	USA	1.5/3.6	1.2/2.9	1.3/3.2	69/169	78/189	84/203	−15/−50	46/93	13/29	69/88	123/194	90/141
15	NCAR-PCM1	USA	1.4/3.5	1.3/3.4	1.5/3.8	45/114	2/4	75/192	1/−20	7/−1	8/3	79/99	98/136	87/133
16	UKMO-HadCM3	UK	2.3/5.7	1.7/4.2	1.7/4.1	−234/−582	35/86	94/234	−86/−317	23/38	−18/−69	13/−133	106/149	64/73
17	UKMO-HadGEM1	UK	1.8/4.3	1.7/4.2	1.5/3.7	−125/−305	41/99	89/218	−33/−143	0/−8	5/6	57/10	89/134	84/132
	mean		1.8/4.3	1.6/4.0	1.5/3.7	−4/−14	42/103	73/180	−21/−88	19/25	−4/−26	63/48	103/146	76/98

[a] Data on minimum and maximum monthly temperature is available.

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CSIRO Mk 3.0 models imply a retreat of the majority of Amazonian HTFs (up to 80% of current HTF extent in the tropical American region), and patterns from seven models (41% of the dataset) predict at least a 10 per cent contraction of HTF extent. The northeastern coast of Amazonia is partly buffered from this risk because of the locally high rainfall at the oceanic boundary (at least at +2°C), a feature that is not apparent in lower resolution climate-model output. The forest zone of Central America and the Caribbean region (Yucatan, Guatemala, Honduras, Cuba) also shows high probability of forest retreat. The severity of the predicted HTF niche contraction, especially in the case of South America, depends on the adjustment procedure, which calibrates precipitation patterns according to each AOGCM's skill to reproduce the contemporary precipitation regime. Figures S2 and S3 in the electronic supplementary material present scenarios generated with precipitation patterns without adjustment, which lead to a somewhat smaller HTF niche contraction.

The scenario of forest expansion in some parts of Africa is the most robust among all regional projections (>80% of models predict some expansion). In the +2°C scenario, the HTF niche in the Congo Basin shows relatively little movement, with equally likely changes in both directions predicted mainly at the fringes. Data from one model predicts the possibility of substantial retreat of Congo Basin HTFs (up to approx. 20% of total area), but there also appears to be potential for eastward expansion of the humid forest niche north of Lake Victoria. The expansion scenario becomes very widespread in the +4°C scenario (up to approx. 50% of the current HTF area), whereas at the same time in the Congo Basin, the risk of forest retreat becomes substantial, with three models (approx. 18%) agreeing on up to 15 per cent contraction, almost leading to the split of the continuous block of forest cover into separate eastern and western parts. Three models suggest substantial contraction of west African HTF extent, leading to possible fragmentation of the upper Guinean forest zone.

Analysis of the temperature-related boundary of lowland HTFs shows that areas currently too cold to sustain HTFs in Africa and Asia may contract substantially, even in the +2°C scenario. In many cases, the current temperature boundary delineates the transition between the lowland and montane HTFs. Although the actual position of this boundary is very sensitive to downscaling of climate patterns, in some cases, the potential of lowland forests to encroach onto montane forests is manifested as large mountainous areas become warmer, for example in some parts of the eastern Andes.

(*c*) *The effect of decreased ecosystem water use*

The climate-induced change in ET, modelled with the land-surface scheme of the HadCM3 AOGCM, was approximated through the change in atmospheric CO_2, which was relatively well correlated with AET anomalies ($R^2 = 0.25$) of the pooled emulated 'SRES A2' AOGCM climate pathways. Across the simulations, the ET decreased steadily over time, reaching about 25 mm month^{-1} total decrease near year 2100 (figure 4*b*,*c*). On the other hand, the net primary production (NPP; figure 4*a*), reflecting the overall HTF functioning, was much more variable throughout the runs, and in general it first increased, and then started to decline at various points in time and with varying speed. The lowest NPP occurred at the highest temperatures, although the NPP drop below the

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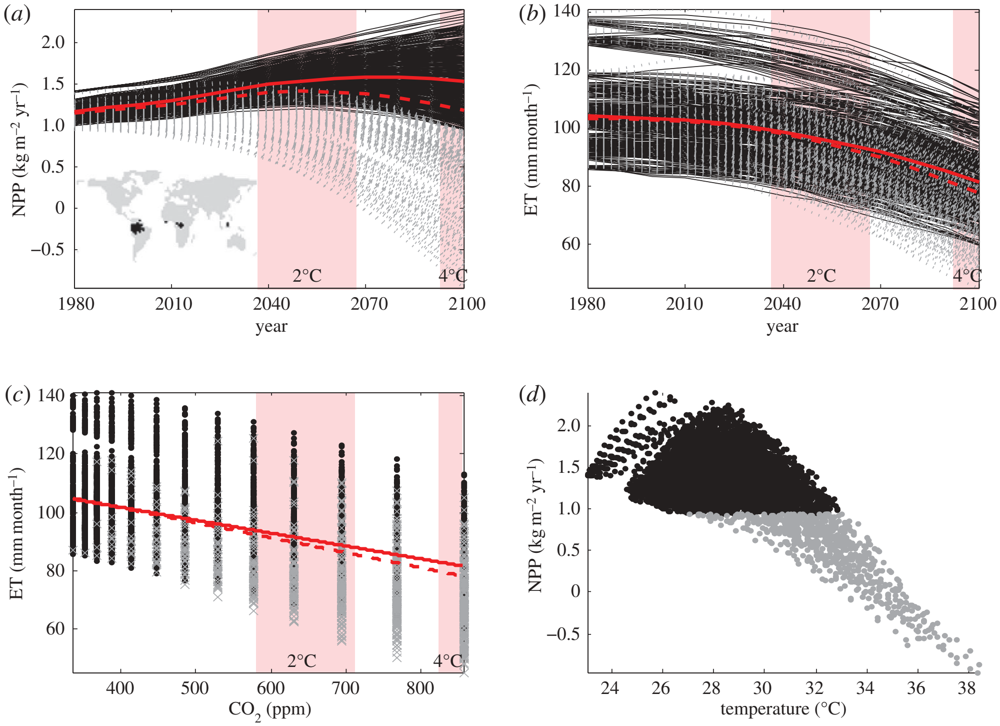

Figure 4. (*a*) Changes in the NPP of HTFs across SRES A2 scenario simulated with land-surface scheme and climate-change patterns from 16 AOGCM runs. The 39 considered grid boxes are situated within tropics (see inset map) and are covered by broadleaved forests in at least 90%. Red solid curve marks an average of pathways in which NPP does not drop below minimum contemporary levels (marked in solid black). The dashed red curve is an average of all cases (including the pathways reaching low NPP values, which are marked in grey). (*b*) Corresponding changes in evapotranspiration; red curves have the same role as in (*a*). (*c*) Relationship between the atmospheric CO$_2$ concentration and evapotranspiration, with regression lines marked in red. (*d*) NPP plotted against monthly mean temperature.

minimum contemporary levels occurred at varying temperatures, so any specific temperature threshold for HTF functioning could not be established (figure 4*c*). These results are generally consistent with the simple approach to delineate the HTF niche, and the appearance of some risk of die-back at the +2°C scenario, which in some areas becomes substantial at the +4°C scenario. In order to avoid confusing the ET decrease that reflects better plant water efficiency in the CO$_2$-enriched atmosphere, with the ET decrease induced by the declining NPP, all pathways with NPP that fell below the minimum contemporary levels were excluded from the analysis.

Taking into account the possible decrease in ecosystem water demand drastically changed the estimates of the HTF potential niche in the future (figure 5), overall shifting the scenarios towards potential forest expansion. At +2°C, the scenario of severe niche contraction in South America is offset by the potential niche expansion southeastwards. In Africa, the potential for expansion markedly prevails over the contraction. Finally, there is a small potential for niche expansion in continental south Asia (i.e. expansion of humid forest into monsoonal

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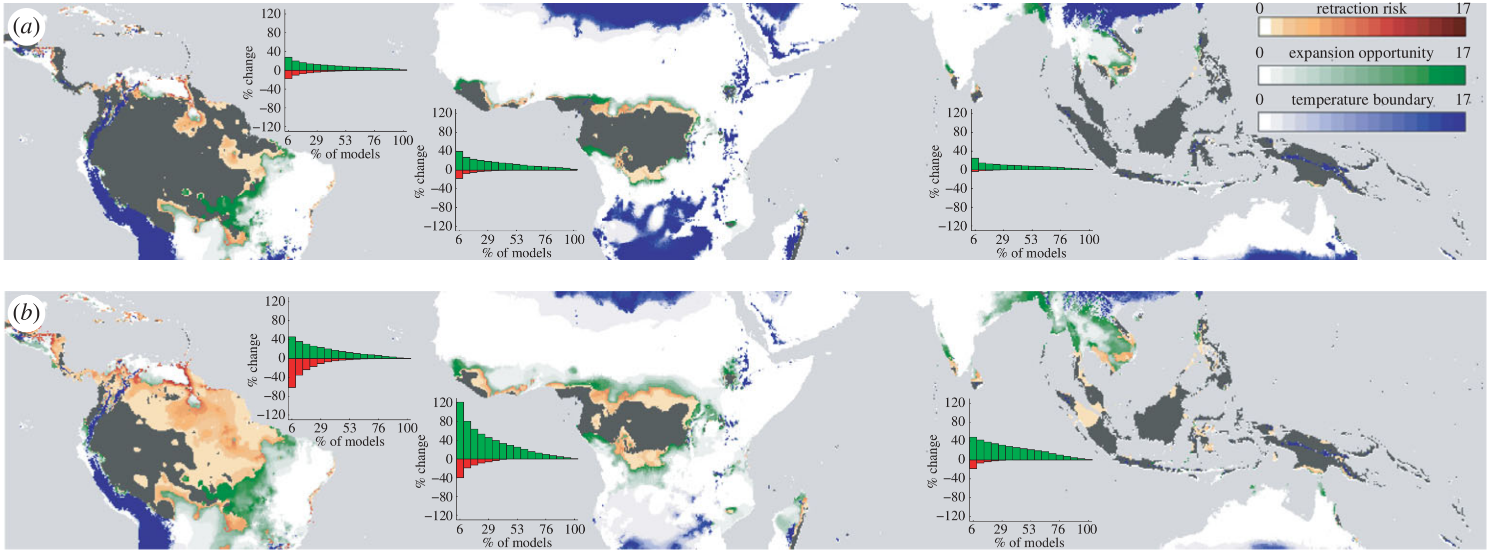

Figure 5. Change in the potential climatological niche of HTFs, as inferred from AOGCM data. (*a*) HTF niche at 2°C and (*b*) 4°C global warming. This scenario accounts for the decrease in ecosystem water demand in new climate regimes, modelled in the land-surface scheme (see also figure 4). Dark grey areas mark the niche derived from the current climatological conditions, and are predicted to remain by all AOGCMs. Shades of red and green mark the potential HTF niche contraction and expansion, respectively. Areas too cold for HTFs are marked in blue. In mountainous areas adjacent to HTFs, they define the boundary between lowland and montane tropical forests. Inset bar plots show the percentage of models that agree on a change up to the plotted level.

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forest zone). At +4°C, the risk of climate-induced deforestation in Amazonia is still apparent (four models, or 24% of the dataset), and in the most pessimistic scenario (HadCM3), it surpasses the potential for expansion. In addition, parts of Central America and the Caribbean still show a substantial risk of forest retreat. In Africa, the potential expansion of forest area around the Congo Basin increases, although the risk of niche contraction remains, mainly at the north and south. Moreover, large new areas in west Africa and Madagascar appear as potentially suitable for expansion. In Asia, the risk of forest die-back in the Philippines is reduced, but remains in central Sumatra (one model) and Sulawesi (two models). Moreover, there is an increased potential for expansion of the HTF niche into the seasonal (monsoonal) forest area of mainland southeast Asia and eastern India.

4. Discussion

The presented results show that the distribution of HTFs can be fairly well characterized by the rainfall regime, in particular the plant water deficit. This was reflected by the relative explanatory strength of tested climate-related variables. The findings were generally consistent across the three tropical regions; however, on average, the predictors of vegetation classes performed best across the African region, where all major vegetation classes are well represented and relatively well preserved, and strong wet–dry gradients lead to delineation of sharper boundaries of the HTFs biome. Confusion in classification of remotely sensed data, inaccuracies in interpolated climate data, and bias owing to pixel aggregation can also be expected to play a role. In fact, some of the findings seem to confirm the presence of some flaws in the dataset used; for example, the apparent presence of some HTFs in high water-stress environments.

Precipitation change is among the aspects of climate change that are the most difficult to predict [56]. This problem is reflected by large differences in the derived precipitation-change patterns, and by the varying skill of AOGCMs to reproduce contemporary precipitation regime, which in turn also has an impact on the magnitude of the predicted patterns of change. The latter is well exemplified by the discrepancy between the HTF extent estimated with precipitation patterns adjusted for the AOGCM bias (main results) and not adjusted (electronic supplementary material). Our analysis demonstrates the likely spatially complex pattern of the HTF response to climate change, which is not captured by low-resolution modelling frameworks, though the pattern's exact form is highly dependent on the quality of current climatological data, and on the downscaling method. At fine spatial scales, there is often greater potential for the persistence of HTFs in part of the landscape or region. The fine scale also enables better representation of spatially variable vulnerability to drought. In contrast, some aspects of the HTFs response to climate change are much more spatially uniform, such as the considered increase in water-use efficiency in the atmosphere richer in CO_2. Such factors make the pattern of the future HTFs occurrence more spatially consistent.

The climatological niche presented in this study is a simple, but scalable, model of the environmental space inhabited by HTFs. This model does not include non-climatic factors like soil fertility, soil hydrology and relief, which can play a role in both the contemporary and future distribution of HTFs. Moreover, the model is

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based on climatic means, which do not fully capture the frequency of occasional dry periods that have a strong effect on biome boundaries. Hence, the presented spatial patterns in the HTF niche extent should be interpreted as a visualization of basic mechanisms governing the change, rather than exact predictions of the actual forest cover. The results could also be interpreted in the context of the changing fire risk, as well as the uncertain plant physiological response to higher temperatures. These two aspects of future HTF distribution are discussed below, as they were not included in the construction of the presented maps.

The expansion of the potential HTF niche requires cautious interpretation. First, actual migration and colonization of non-HTF regions may well lag behind expansion of the potential niche, as processes of dispersion and competition play out. Second, in practice, the expansion often means migration of forest into areas already heavily deforested and cultivated, where heavy anthropogenic pressure will preclude it. Third, expansion of HTFs into dry forest, savanna or grassland is not without consequences for the retreating dry ecosystem, which can host high and unique biodiversity, and may be more threatened by anthropogenic pressures than the HTF biome (for example, the high biodiversity and highly threatened cerrado biome of Brazil or the savannas of east Africa). This study highlights regions where the interactions of climate change with land-use change may be strong (especially, east Amazonia and west Africa), and the nature of these interactions needs to be explored in greater detail for each sensitive region (e.g. [12]).

The simulations performed with the land-surface scheme have shown that high CO_2 may cause an increase in ecosystem water-use efficiency, and greater HTF resilience in drier rainfall regimes, which in turn decreases the risk of the potential niche contraction, and in some regions, translates to its significant expansion. It seems likely that if this analysis had also incorporated impacts on altered photosynthesis and respiration on plant competition, the CO_2-enriched environment would favour further forest expansion into C4 grasslands. On the other hand, increased temperatures could potentially favour retreat of HTF extent at the expense of grasslands, but this depends critically on how close tropical forests are to a high-temperature threshold. South American HTFs have the greatest risk of facing dangerous temperatures, as the rates of warming over this region are predicted to be the highest of any tropical region.

The vulnerability of tropical trees to future warming is uncertain and controversial [21,57]. The maximal temperatures may be important for the forest survival if they approach levels at which enzymes responsible for photosynthesis are denatured (around 45°C; [18,58]). Lloyd & Farquhar [21] argue that tropical forests will not exceed their optimal temperature ranges, whereas Clark *et al.* [57] suggest reduced photosynthesis or increased plant respiration in response to short-term warming. The temperature sensitivities of both photosynthesis and respiration can change, and there are ecophysiological arguments that plants can acclimate to a warming of a few degrees [59,60]. However, there are very few empirical data on the degree to which tropical trees respond and are able to acclimate to increased temperatures and drought [61–63]. Several contemporary dynamic vegetation models may be overly sensitive to temperature and not allowing for acclimation effects [31]. Other components of the ecosystem, however, such as insect pollinators, may be more vulnerable to a small warming (e.g. [64]), with knock-on effects for forest-plant communities.

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Moreover, warming increases the risk of fire [12,27]. In a complementary study, Le Page *et al.* [65] project the potential area under threat from future biomass burning. Whereas the physiological effects lead to reduced plant water use, through reductions in plant transpiration, fire danger is linked to dead fuel moisture and thus evaporation. Therefore, although plant physiology acts to mitigate the effects of warming on the potential forest extent, these forests may be more susceptible to future forest fire. If the effects of temperature on fire risk and photosynthesis were included in the presented analysis, it could be expected that the distribution of HTFs may be more constrained than that presented here, especially in areas exposed to anthropogenic fire ignition (South America, insular Asia).

Precipitation and temperature patterns appear as crucial factors determining plant functioning and the type of vegetation cover, as they are directly linked to the availability of (soil) water and (thermal) energy that influence photosynthesis and respiration. However, there may be other aspects of water and energy availability that are also relevant. In practice, these are often more complex and more difficult to map. For example, atmospheric humidity is an important ecological factor in tropical forest areas because of its effect on evapotranspiration, and hence photosynthetic rates of plants. The saturation deficit pattern of HTF areas contrasts with those of both seasonal and montane forest areas in the tropics [16]. Another potentially critical variable, net radiation, is the strongest predictor of the spatial pattern of evapotranspiration over the humid tropics [15,66], and is linked with the intensity of photosynthesis both directly (via photosynthetically active radiation; PAR) and indirectly (via thermal radiation). Changes in the ratio between diffuse and direct radiation, perhaps because of biomass burning haze, can alter canopy light penetration and overall canopy photosynthesis [21,67]. These, and other, variables may covary with precipitation and temperature, and their importance could become apparent in new climate regimes. The definition of the future climatological niche of the HTFs could be extended by incorporating some of the above factors, but such an extension is beyond the scope of this study.

Climate-change-driven shifts in the extent of tropical forests represent a risk for policies concerned with biodiversity loss and climate change, including the reduced emissions from deforestation and forest degradation (REDD [68]) discussed under the United Nations framework convention for climate change. The scheme is meant to exploit the potential to mitigate climate change through the protection of forests' carbon pool (and biodiversity—as a co-benefit [69]), but its success will depend on the long-term forest resilience. Direct deforestation and uncontrolled fire already undermine forest permanence [70]. In comparison, the risk of climate-induced die-back seems only hypothetical. However, this risk is potentially a critical one because its cause, once present, cannot be addressed on short time scales owing to the climate system's inertia.

In conclusion, water availability is the best determinant of the current distribution of HTFs, which can dominate over other vegetation types only in high-precipitation, low water-stress environments. Because climate models differ in their predictions of future precipitation regime, change in the extent of the HTF niche is uncertain. However, the risks and opportunities are not evenly distributed and some patterns emerge from the ensemble of models used. For example, Amazonian forests seem relatively more likely to experience some decrease in precipitation, and a few models suggest extensive possibility of retreat of the

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HTF niche, or 'die-back'. In contrast, the majority of HTFs in South and Insular Asia are not predicted to face climate-driven die-back. In Africa, there is potential for both HTF contraction and expansion. In all regions, the potential to expand is due to both the more favourable precipitation regime, and the retreat of the low-temperature threshold. If CO_2 has an effect on water balance as predicted, then the expansion of the HTF niche is more likely than the contraction. In practice, in many places with high agricultural pressure, it is more plausible for HTFs to be locally destroyed than naturally colonize new areas, although apparent forest expansion and woody encroachment has been reported in many areas of Africa. Future extent of HTFs may also be controlled by other factors, for example, critically high temperatures, which are not yet fully understood.

While this study has its limitations by not incorporating fully the (poorly understood) physiological responses to temperature (although some temperature effect is implicit in the CO_2 effect on water-use efficiency), it makes an important contribution in highlighting areas of potential risk and resilience to climate change, and incorporating multiple climate models and high-resolution climatology. The presented approach is a step towards a more biodiversity- and conservation-relevant interpretation of the climate modelling results. Future improvements to the approach could include higher resolution climate patterns, more complex HTF niches, more sophisticated downscaling, and sensitivity analysis to the critical temperatures and acclimation rates.

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Robert J. Nicholls, Natasha Marinova, Jason A. Lowe, Sally Brown, Pier Vellinga, Diogo de Gusmão, Jochen Hinkel and Richard S. J. Tol

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century

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The range of future climate-induced sea-level rise remains highly uncertain with continued concern that large increases in the twenty-first century cannot be ruled out. The biggest source of uncertainty is the response of the large ice sheets of Greenland and west Antarctica. Based on our analysis, a pragmatic estimate of sea-level rise by 2100, for a temperature rise of 4°C or more over the same time frame, is between 0.5 m and 2 m—the probability of rises at the high end is judged to be very low, but of unquantifiable probability. However, if realized, an indicative analysis shows that the impact potential is severe, with the real risk of the forced displacement of up to 187 million people over the century (up to 2.4% of global population). This is potentially avoidable by widespread upgrade of protection, albeit rather costly with up to 0.02 per cent of global domestic product needed, and much higher in certain nations. The likelihood of protection being successfully implemented varies between regions, and is lowest in small islands, Africa and parts of Asia, and hence these regions are the most likely to see coastal abandonment. To respond to these challenges, a multi-track approach is required, which would also be appropriate if a temperature rise of less than 4°C was

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expected. Firstly, we should monitor sea level to detect any significant accelerations in the rate of rise in a timely manner. Secondly, we need to improve our understanding of the climate-induced processes that could contribute to rapid sea-level rise, especially the role of the two major ice sheets, to produce better models that quantify the likely future rise more precisely. Finally, responses need to be carefully considered via a combination of climate mitigation to reduce the rise and adaptation for the residual rise in sea level. In particular, long-term strategic adaptation plans for the full range of possible sea-level rise (and other change) need to be widely developed.

Keywords: sea-level rise; impacts; adaptation; protection; retreat

1. Introduction

Since the emergence of concerns about human-induced global warming in the 1980s, sea-level rise and its impacts on the coastal areas have attracted considerable concern. The large and growing concentration of people and assets in coastal areas mean that the potential impacts are high. It is estimated that at least 600 million people live within 10 m of sea level today [1], and these populations are growing more rapidly than global trends. Populated deltaic areas and many coastal cities are highly threatened by small rises in sea level [2,3]. While in global terms relatively small in number, the very existence of small-island nation states makes them vulnerable to rises in sea level of the order of 1 m [4]. Hence, the magnitude of global sea-level rise during the twenty-first century (and beyond) is of great importance.

Since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) [5], the possible magnitude of sea-level rise has attracted renewed attention, and a number of authors have suggested that the widely reported numbers in the AR4 underestimate the range of potential sea-level rise during the twenty-first century (e.g. [6,7]). Renewed concerns about the stability of the Greenland and west Antarctic ice sheets reinforce these messages, and at the least, a low-probability, high-consequence rise of sea-level rise of more than 1 m cannot be ruled out during the twenty-first century. This has important and direct implications for coastal society, and more widespread indirect effects in terms of potential disruption and displacement of people, economic activities and economic flows. However, while the equilibrium sea-level rise may scale linearly with temperature, the relationship between temperature and sea level is likely to be nonlinear on century time scales, complicating the analysis of sea-level rise in a rapidly warming world. This is because of the different climate system response times for surface temperature and both heat input to the deep ocean and ice-sheet adjustment. These issues are noted in our analysis of sea-level rise, and our analysis examines sea-level rise and its impacts during the twenty-first century for a range of scenarios, including for a world with a no mitigation policy where the global mean near-surface temperature may reach 4°C by 2100.

Sea-level rise causes a range of impacts for coastal areas, including submergence/increased flooding, increased erosion, ecosystems changes and increased salinization. Based on the exposed population, a large rise in sea level by 2100 could have major impacts, including in the worst-case scenario, a

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forced displacement[1] of a large proportion of the coastal population and economy. However, humans also adapt proactively to these changes via a range of measures, which can be characterized as protection, accommodation or (planned) retreat [2,8]. Such adaptation can greatly reduce the possible impacts. Most analyses have contrasted the simplest case of protection versus retreat (or land abandonment). While protection has significant costs, the available analyses suggest that in densely populated coastal areas, protection costs are generally much less than the avoided impacts, and protection generally makes economic sense (e.g. [9,10]). However, this does not mean that protection will take place, and a question remains about its practicality—and proactive adaptation in general, especially in the world's poorest countries, such as most small-island states or sub-Saharan Africa [11]. Looking at the literature, two distinct views concerning protection emerge [12]. The pessimists assume that protection is unaffordable and/or largely fails, and that most potential impacts are realized with sea-level rise leading to large-scale forced displacements of population on an unprecedented scale. This leads to an argument for stringent and immediate climate mitigation and preparation for environmental refugees. The optimists assume that protection will be widespread and largely succeed, and residual impacts will only be a fraction of the potential impacts. Hence, the main consequence of sea-level rise is the diversion of investment into new and upgraded coastal defences and other forms of adaptation (e.g. flood-warning systems). As we consider larger rises in sea level, hence concern that protection and proactive adaptation, in general, may fail, increases, and the potential for the pessimist's view to be realized grows.

This paper explores these issues, with a focus of trying to provide indicative outcomes given a beyond 4°C world. In §2, the science of sea-level rise is reviewed, with special consideration of post-AR4 sea-level-rise scenarios. These are synthesized to develop a potential range of rise by 2100 that is broadly consistent with a beyond 4°C scenario. In §3, the paper develops indicative estimates of the impacts both with and without adaptation. It uses the framework of the Dynamic Interactive Vulnerability Assessment (DIVA) model [13] for this purpose and creates scenarios consistent with the pessimistic and optimistic views that have been defined above. In §4, these results are reviewed in the light of the new synthesis of sea-level rise. Particular attention is addressed to key issues such as vulnerable hotspots in small islands, deltas and coastal cities. Section 5 is a conclusion.

2. Sea-level-rise scenarios for the twenty-first century

(*a*) *What does the Intergovernmental Panel on Climate Change Fourth Assessment Report tell us?*

In the IPCC AR4, the global surface temperatures at the end of the twenty-first century (2090–2099) are projected to reach higher than 4°C relative to 1980–1999[2] in three of the Special Report on Emission Scenarios (SRES) emission scenarios:

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[1] Forced displacement is a (reactive) last-resort retreat response. However, more proactive approaches to adaptation would be preferred which would avoid the large costs and potential conflicts that such forced displacement would engender.

[2] This is a 4.5°C rise above pre-industrial temperatures.

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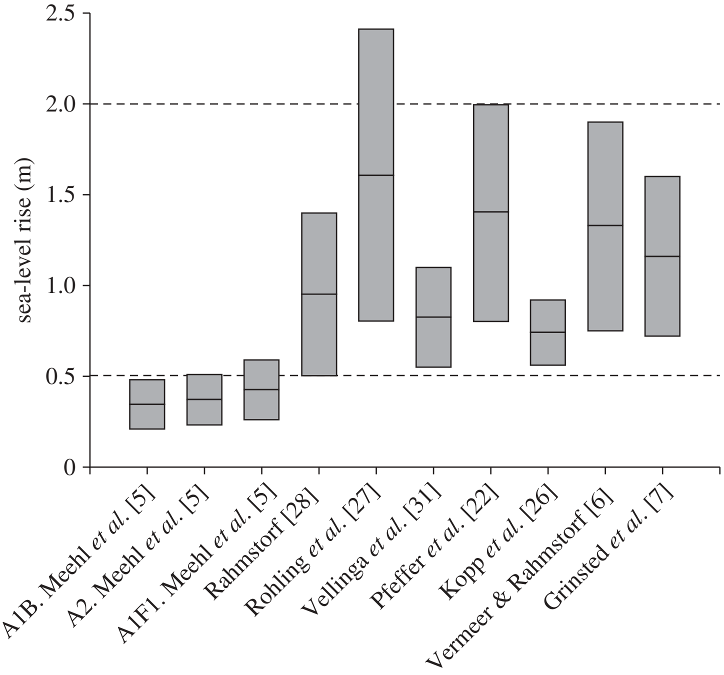

Figure 1. A graphical summary of the range of IPCC AR4 [5] sea-level-rise scenarios (for 2090–2099) and post-AR4 projections (see table 1) possible in a 4°C world. The dotted lines represent the minimum (0.5 m) and maximum (2.0 m) bounds considered in terms of impacts in this study.

A1B, A2 and A1FI [14]. The upper bounds of the temperature in these scenarios are within the range of 4.4°C (A1B scenario) to 6.4°C (A1FI scenario). The upper bounds of projected sea-level rise for these same emission scenarios ranged from 48 to 59 cm (figure 1).[3] In those models, a significant portion of this sea-level rise (around 66%) is attributable to thermal expansion, with the contribution from glaciers and small ice caps being the next biggest term. For the A1B scenario, the contribution of the Greenland ice sheet is estimated to be 8 cm, while the contribution from Antarctica is negative at −2 cm owing to the accumulation of extra precipitation on the ice sheet. Thus, the sea-level-rise contributions from ice sheets are considered to be small in these AR4 model projections.

However, prior to the publication of IPCC AR4, some rapid changes were observed on the Greenland and Antarctic continental ice sheets ([14], later published by Rignot *et al.* [15] and van de Wal *et al.* [16]), but in Greenland these high rates were not sustained from 2006 to 2008 [17]. In 2007, these observations of rapid change could not be reproduced by state-of-the-art ice sheet models, forced by outputs from climate models (temperature, precipitation), because there was limited understanding of some key processes and feedbacks between the local climate and the ice sheets. The response of the IPCC was to include an often-overlooked statement that the ‘understanding of some important effects driving sea level rise is too limited … [to] provide a best estimate or an upper bound for sea level rise’ during the twenty-first century ([18], p. 45). They also provided an illustrative scenario such that if the discharge term was to increase linearly with

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[3] This is based on the 95th percentile from table 10.7 in Meehl *et al.* [5].

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temperature, then it could add around 0.1–0.2 m to the projected upper bound for sea-level rise in 2100. This raised the projected upper bounds for the A1B scenario to 61 cm, and that for A1FI to 76 cm, and this has often been interpreted as an upper limit to sea-level rise during the twenty-first century, despite the IPCC statement on the undefined nature of this upper bound. This approach generated extended debates, mainly because the scaled-up values may not fully consider the feedbacks between ice-sheet melting/disintegration and sea level, and hence underestimate the ice-sheet contribution.

A further key question to ask of the IPCC AR4 analysis is how well do the methods reproduce the observed climate change? The observations for the period 1961–2003 are $1.8 \pm 0.5\,\mathrm{mm\,yr^{-1}}$, while for the period 1993–2003, they are $3.1 \pm 0.7\,\mathrm{mm\,yr^{-1}}$: the corresponding sums of the simulated sea-level components being 1.1 ± 0.5 and $2.8 \pm 0.7\,\mathrm{mm\,yr^{-1}}$, respectively, are below these observations [19]. The more satisfactory agreement for the more recent period, during which individual terms are better known and satellite altimetry is available, indicates improvement in understanding. It should also be noted that the observed sea-level rise is following a trajectory at the high end of the SRES projections made in the IPCC Third Assessment Report in 2001 [20,21].

Hence, while we cannot link sea-level rise and temperature rise in a simple manner, a pragmatic choice is to consider 48 cm (or in round terms, 50 cm) as a lower range for the twenty-first century sea-level rise in a beyond 4°C world. In §3, we consider additional evidence to develop an upper estimate of sea-level rise under such warming.

(*b*) *Why might global mean sea-level rise exceed the Intergovernmental Panel on Climate Change Fourth Assessment Report projection?*

The most often cited mechanism that could cause sea level to increase significantly beyond the IPCC AR4 projected range is the acceleration of ice-sheet discharge above the linear rate used in Meehl *et al.* [5]. Several recent studies have considered this possibility using alternative approaches.

Pfeffer *et al.* [22] explored the kinematic constraints on the contribution of ice-sheet outlet glaciers and ice streams to sea-level rise, comparing the rates required to give more than 2 m of sea-level rise with potential glacier rates. They concluded that an increase of up to 2 m for the twenty-first century cannot be excluded, but a rise of 0.8 m is more likely. Pfeffer *et al.* [22] use simple physical considerations and some extrapolation of the combinations of contributions from Greenland and Antarctica based on varying glacier velocities. Therefore, their estimates should be regarded not as projections, but only as an indication of the physical constraint to the upper bound of global average sea-level rise. For instance, the earlier acceleration of some of the southeast Greenland glaciers had reversed by 2006 [17]. This revived the debate as to whether the recent rates of mass loss are transient or not, and whether they should be extrapolated into the future.

An alternative approach is to examine sea-level rise from a previous epoch when the ice sheets had some similarity with present configurations, and temperatures were similar to those expected during the twenty-first century. One such epoch is the last interglacial period (the Eemian), which occurred between 130 000 and 116 000 years ago. Ice-core data suggest that during the Eemian, global

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mean temperature was 2–3°C higher than in the present, while the regional temperatures in Greenland and Antarctic were about 5°C higher [23]. Palaeo-evidence suggests that during the Eemian, the Greenland ice sheet was about 30 per cent smaller than today [24], but with sea levels several metres higher than at present. There is evidence that the Antarctica ice sheet also contributed to this sea-level rise (e.g. [25]). Kopp *et al.* [26] estimated higher Eemian sea levels at between 6 and 9 m above present, with both the Greenland ice sheet and the Antarctic ice sheets significantly smaller than today.

The information from the Eemian is more useful if ice sheet and sea-level estimates can be dated with sufficient accuracy. Based on their palaeo-studies, Kopp *et al.* [26] estimate that the present ice sheets could also contribute about 0.92 m to global sea-level rise per century (with the possibility of higher rates for shorter periods), and this rate could be sustained for centuries. A further estimate of Eemian sea-level rise was provided by Rohling *et al.* [27] using a proxy record from the Red Sea. This reconstruction suggests that sea level rose with rates of 1.6 ± 0.8 m per century providing a constraint on the maximum rate of rise.

(*c*) *The most recent twenty-first century projections*

The kinematic and palaeo-studies cited above do not provide projections for the sea-level behaviour in a ‘beyond 4°C’ world. Rather, they provide a guide to the potential maximum rate of sea-level rise under conditions that might be realized during the twenty-first century.

Since the completion of the IPCC AR4, a number of semi-empirical model projections of sea-level rise have been developed. These use present relationships between temperature and sea-level rise combined with climate-model projections of future warming to give an alternative set of future sea-level projections (e.g. [28]). Many of these studies suggest that the upper end of the range of sea-level-rise projections in 2100 could be significantly higher than the IPCC projections (figure 1). However, it must be kept in mind that the semi-empirical approaches assume that the observed relationship between temperature and sea level will continue in the future, given much more rapid warming, yet this may not be the case [29].

Using the correlation between observations of past changes in sea level with temperature changes since the pre-industrial era, Rahmstorf [28] projected a 0.5–1.4 m rise of sea level by 2100, relative to the 1990 level. Vermeer & Rahmstorf [6] refined the method, adding a rapid-response term, which gives an upper value of 1.90 m in 2100 (excluding the uncertainty of the statistical fit of ±7%). Other semi-empirical approaches are also available that use slightly different formulations and statistical methods, such as Grinsted *et al.* [7]. These authors also include palaeo-constraints from preceding centuries, and project a future increase in sea level of up to 1.6 m for the twenty-first century for the SRES A1FI emissions scenario.

Some studies have been undertaken to directly support long-term flood-management responses to sea-level rise. In The Netherlands, the Delta Commission [30] requested an international assessment to explore the upper boundaries of the possible rise and to develop low-probability/high-impact scenarios for the years 2050, 2100 and 2200. This used both modelling and expert-judgement approaches, and assumed a large temperature rise of 6°C by 2100 [31].

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Table 1. Range of global sea-level rise (metre per century) according to post-AR4 research.

sea-level rise (metre per century)	methodological approach	source
0.5–1.4	semi-empirical projection[b]	Rahmstorf [28]
0.8–2.4[a]	palaeo-climate analogue	Rohling *et al.* [27]
0.55–1.10	synthesis[b]	Vellinga *et al.* [31]
0.8–2.0	physical-constraint analysis[b]	Pfeffer *et al.* [22]
0.56–0.92[a]	palaeo-climate analogue	Kopp *et al.* [26]
0.75–1.90	semi-empirical projection[b]	Vermeer & Rahmstorf [6]
0.72–1.60[c]	semi-empirical projection[b]	Grinsted *et al.* [7]

[a] Higher rates are possible for shorter periods.

[b] For the twenty-first century.

[c] For the best palaeo-temperature record.

Expert judgement is a useful technique as it provides a mechanism to capture important, but poorly understood, processes such as the ice-sheet response (cf. [32]), although it often expands the uncertainties. As a starting point, Vellinga *et al.* [31] used recent observations which imply that higher contributions from the two ice sheets are possible and took the palaeo-reconstruction of Rohling *et al.* [27] as an upper constraint. They concluded that plausible global sea-level-rise scenarios were 0.55–1.10 m in 2100, and 1.5–3.5 m in 2200 (these estimates were then used as a base for developing local sea-level-rise scenarios for The Netherlands by taking into consideration other components such as geoidal changes, vertical land movement and storm surges).

The UK Met Office also developed a low-probability, high-impact range of sea-level rise scenarios, called the H++ scenario, to explore impacts and adaptation responses above the IPCC AR4 range. This was applied in the Thames Estuary 2100 Project (TE2100), which concerned the future flooding of London, and then adopted to national scenario guidance [33]. It used research from Rohling *et al.* [27] and Pfeffer *et al.* [22] as constraints, and accounted for the recent observed rapid changes in the two ice sheets. Overall, it adopted a maximum global rise of 2.5 m by 2100. (Allowing for geodal changes (the necessity of which is discussed by Mitrovica *et al.* [34]) resulted in a sea-level rise around the UK of between 0.93 and 1.9 m during the twenty-first century.) However, Lowe *et al.* [33] also concluded that there is evidence that such a large increase should be considered very unlikely to occur during the next 100 years (see also [29]).

Based on a selection of the recent studies we have considered, table 1 summarizes the range of estimates for century-scale sea-level rise from a range of methods. While such estimates are possible, this should not be interpreted as being likely. What is likely, however, is that higher rates of sea-level rise will result from warmer temperatures.

The possibility of reversibility of large changes in ice sheets, and their corresponding contribution to sea level, is also important. Gregory *et al.* [35] concluded that a local warming of above 2.7 ± 0.5°C (average annual temperature rise related to 1990) would cause irreversible loss of the Greenland ice sheet. The approximate magnitude for this threshold is supported by results from the last

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interglacial period when temperatures were a few degrees warmer than today, and the Greenland ice sheet was smaller (see §2*a*), although Hansen [36] suggests that a lower threshold should be used. A recent study by Ridley *et al.* [37] suggests that a higher warming could be sustained, but only for a short period of time. Because of the presence of large uncertainties, AR4 did not assign a temperature threshold for the irreversible melt of the vulnerable west Antarctic ice sheet. However, Lenton *et al.* [38] suggested that it would be in the range of 5–8°C local warming, corresponding to 3–5°C global warming, if evidence, such as the disintegration of ice shelves along the Antarctic Peninsula and the crevasse/meltwater hypothesis [39,40], were taken into consideration. Equally, marine ice-sheet instability may be triggered by (ocean) temperature rise, but once started, it may be rather insensitive to the actual atmospheric temperature rise that is achieved [41].

(*d*) *Summary*

Our review of high-end post-AR4 sea-level projections suggests that a credible upper bound of twenty-first century sea-level rise is of the order of 2 m. Combined with the earlier estimates of sea-level-rise scenarios from the AR4, this suggests a pragmatic range of 0.5–2 m for twenty-first century sea-level rise, assuming a 4°C or more rise in temperature. However, since it is not certain that recent observed increases in ice discharge from the ice sheets will continue to accelerate, we must also be clear that the upper part of this range is considered unlikely to be realized. As advocated by Solomon *et al.* [14] and Lowe & Gregory [29], among others, while such uncertainty remains, it is fundamental to continue monitoring sea level to detect any large or unexpected accelerations of rise. In parallel, developments of process-based models could improve the robustness of projections. We also note the conclusions of Rahmstorf *et al.* [20] and Pielke ([21], p. 206) that ‘Once published, projections should not be forgotten but should be rigorously compared with evolving observations’.

Finally, we have focused on the range of uncertainty in the recent rate of global mean sea-level rise. The IPCC AR4 analysis also highlighted the significant spread in projected spatial patterns of sea-level rise. While there is a growing understanding of what drives regional sea-level rise [42], there still remains a large spread in the deviations of regional sea-level rise from the global mean value [43]. The uncertainty in oceanic density changes could be up to several tens of centimetres from the global mean value, depending on the location. A further local contribution would be required in scenarios with larger ice melt owing to gravitational changes [34,44–46]. Finally, the non-climate component of sea-level rise owing to subsidence could also be substantial (e.g. due to water abstraction), most especially in susceptible deltas where human groundwater withdrawal and sediment starvation can be greatly enhanced [11,47,48], and this also needs to be considered.

3. Sea-level-rise impacts and adaptation responses

The previous section showed that a global rise in sea level of 0.5–2.0 m by 2100 is consistent with a beyond 4°C world. To explore the possible impacts with and without a protection response, the potential impacts of a 0.5 and 2 m global mean rise in sea level by 2100 are now assessed as bounding cases using the DIVA

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model framework. These sea-level-rise scenarios are downscaled using estimates of glacial isostatic adjustment from Peltier [49,50] and natural subsidence in deltas, assumed as $2\,\mathrm{mm\,yr^{-1}}$. It is recognized that using a global-mean scenario is an idealized assumption. However, it follows all previous published impact assessments, and hence is broadly comparable with these earlier results. Further, unpublished results, which have examined impacts under a range of realistic sea-level-rise patterns, indicate that while the uncertainty in the impacts rises when this factor is considered, there is little systematic change to the results (e.g. [51,52]). The results are most sensitive to deviations around south, southeast and east Asia, as this is the region where the largest coastal population occurs. Hence, the use of global-mean scenarios is an appropriate simplification for this exploratory analysis. In all cases, the sea-level-rise scenarios are combined with a temperature scenario exceeding a 4°C rise and with the A1B[4] socioeconomic scenario in all cases [53].

In the analysis, impacts and adaptation costs are both assessed for assumptions that are consistent with the pessimist's and optimist's perspectives, respectively. The 'pessimists' and the 'optimists' generally accept the high-impact potential of sea-level rise, although pessimists may stress larger rise scenarios. They disagree much more on adaptation, especially protection. Pessimists view protection as being infeasible and likely to fail. Hence, actual impacts are similar to the exposure, leading to high impacts, numerous disasters, and an unplanned and forced retreat. In contrast, optimists view protection as likely to be applied in developed areas and likely to be successful. Hence, actual impacts are much smaller than the potential impacts, but there are significant adaptation costs. Below, impacts without and with adaptation are compared to illustrate the pessimistic and optimistic views, respectively.

(*a*) *The Dynamic Interactive Vulnerability Assessment model*

The DIVA model is an integrated model of coastal systems that assesses biophysical and socioeconomic impacts driven by climate change and socioeconomic development[5] ([13,54]; http://diva-model.net). The climatic scenarios comprise temperature and most importantly, sea-level change, while the socioeconomic scenarios comprise coastal population, gross domestic product (GDP) and land-use change. In DIVA, there are an explicit range of adaptation options. Hence, unlike most published assessments of sea-level rise (e.g. [55]), impacts do not solely depend upon the selected climatic and socioeconomic scenarios, but also on the selected adaptation strategy, with a no upgrade/adaptation strategy being one option. Here, only the flooding/submergence and erosion aspects of DIVA are considered. These are

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[4] The A1T, A1B and A1FI population and GDP scenarios are essentially the same, with a major difference being assumptions about the main energy sources. The A1 population peaks in 2050 and declines thereafter. The B1 population scenario is the same as the A1 population. The B2 and especially the A2 socioeconomic scenarios have larger populations and hence would give a larger coastal population.

[5] Here, DIVA v. 2.0.4 is used combined with DIVA database v. 1.3, where elevation is derived from the GTOPO30 dataset.

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discussed in more detail by Tol *et al.* [56] and Hinkel *et al.* [57], respectively, while the underlying model database and spatial structure are explained by Vafeidis *et al.* [58].

Both direct and indirect coastal erosion are assessed. The direct effect of sea-level rise on coastal erosion is estimated using the Bruun rule (e.g. [59]). Sea-level rise also affects coastal erosion indirectly as tidal basins become sediment sinks under rising sea level, trapping sediments from the nearby open coast into tidal basins [60]. This indirect erosion is calculated using a simplified version of the aggregated scale morphological interaction between a tidal basin and the adjacent coast (ASMITA) model (e.g. [61]). About 200 of the largest tidal basins around the world are considered. DIVA considers beach/shore nourishment as the adaptation response to erosion. In beach nourishment, the sand is placed directly on the intertidal beach, while in shore nourishment, the sand is placed below low tide, where the sand is expected to progressively feed onshore owing to wave action, following the recent Dutch practice [62]. The way these options are applied is discussed further below.

The flooding and submergence of the coastal zone caused by mean sea-level rise and associated storm surges is assessed for both sea and river floods. Large parts of the coastal zone are already threatened by extreme sea levels produced during storms, such as shown by Hurricane Katrina (USA, 2005), Cyclone Nagris (Burma, 2008) and Storm Xynthia (France, 2010). These extreme events are produced by a combination of storm surges and astronomical tides, and the return period of extreme sea levels is reduced by higher mean sea levels. Sea-level rise also raises water levels in the coastal parts of rivers (via the backwater effect), increasing the probability of extreme water levels. DIVA considers both these flooding mechanisms. In the analysis, the present storm-surge characteristics are displaced upwards with the rising sea level, which implies no change to the intensity or frequency of coastal storms or interaction between sea level and tidal and surge characteristics. This assumption follows twentieth and early twenty-first century observations of mean and extreme sea level (e.g. [63–66]). Taking into account the effect of dikes, flood areas for different return periods are estimated. This is done by estimating the change in safety, assuming that a dike system is present (cf. [67,68]), and dike construction/upgrade is the adaptation option for flooding and submergence. There is no empirical data on the baseline level of safety at a global level, so a demand for safety function is used as explained below, and the safety is assumed to be provided by dikes. Based on dike height, land elevation and relative sea level, the frequency of flooding can be estimated over time. This is further converted into people flooded and economic flood damages based on population density and GDP (see below). River flooding is evaluated in a similar fashion along 115 major rivers.

DIVA also estimates the social and economic consequences of the physical impacts described above. For this paper, the *number of people displaced* by sea-level rise can be estimated owing to a combination of erosion and increased flooding. In the case of flooding, a threshold return level needs to be assumed to define abandonment. This has been set at a greater than a 1 in 1 year frequency of flooding. If a lower frequency of flooding (e.g. 1 in 10 year) was selected, the land area lost and the number of people displaced would be reduced.

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DIVA computes impacts both without and with adaptation. Without adaptation, DIVA computes potential impacts in a traditional impact-analysis manner. In this case, dike heights are maintained at 1995 levels, but not raised, so flood risk rises with time as relative sea level rises. Beaches and shores are not nourished. With adaptation, dikes are raised based on the demand function for safety [69], which is increasing in *per capita* income and population density, but decreasing in the costs of dike building [70]. Dikes are not applied where there is very low population density (less than 1 person km^{-2}), and above this population threshold, an increasing proportion of the demand for safety is applied. Half of the demand for safety is applied at a population density of 20 persons km^{-2} and 90 per cent at a population density of 200 persons km^{-2}.

With adaptation, beaches and shores are nourished according to a cost–benefit analysis that balances costs and benefits (in terms of avoided damages) of adaptation. Shore nourishment has lower costs than beach nourishment, but is not widely practised at present and has the disadvantage of not immediately enhancing the sub-aerial beach. Beach nourishment is therefore the preferred adaptation option, but only if the tourism revenue is sufficient to justify the extra costs. The number of tourists and their spending follows the Hamburg tourism model (HTM), an econometric model of tourism flows [71,72]. In the HTM, tourism numbers increase with population and income. Climate change pushes tourists towards the poles and up the mountains.

Adaptation costs are estimated for the two adaptation options considered: dike building and beach nourishment. Initially, unit dike costs are taken from the global vulnerability assessment carried out by Hoozemans *et al.* [67]. Given that sea-level rise is up to 2 m, the dike costs for this scenario are raised offline to take account of the larger cross section that is required: a dike required in response to a 2 m rise in sea level is assumed to be four times the cost of that required for a 1 m rise in sea level (it is assumed that dikes of up to 1 m in height have a similar cost; cf. [73]). DIVA only considers the capital cost of dike construction, but maintenance costs are approximately 1 per cent per annum, and as the capital stock grows, so the maintenance costs can become significant. Hence, maintenance costs are considered here as an offline calculation. The costs of beach nourishment were derived by expert consultation with Delatares (formerly Delft Hydraulics). Different cost classes are applied, depending on how far the sand for nourishment needs to be transported, as this is a significant determinant of such costs. It is assumed that sufficient sand resources are available for nourishment purposes throughout the twenty-first century.

It is important to note that the purpose of the adaptation strategies described above is not to compute an optimal adaptation policy, but to model how coastal managers could respond to sea level rise. The complementary adaptation strategies serve the same purpose as the climate and socioeconomic scenarios, i.e. to explore possible futures. DIVA's different adaptation strategies show how different assumptions made about the behaviour of coastal planners translate into differences in impacts and adaptation costs. This interpretation can be enriched using the results from the climate framework for uncertainty, negotiation and distribution (FUND) model [74], which employs a benefit–cost approach. FUND estimated that 25 per cent of the developed coastal zone is abandoned if the costs of protection increased fourfold [73], and this correction is applied for the 2 m rise scenario.

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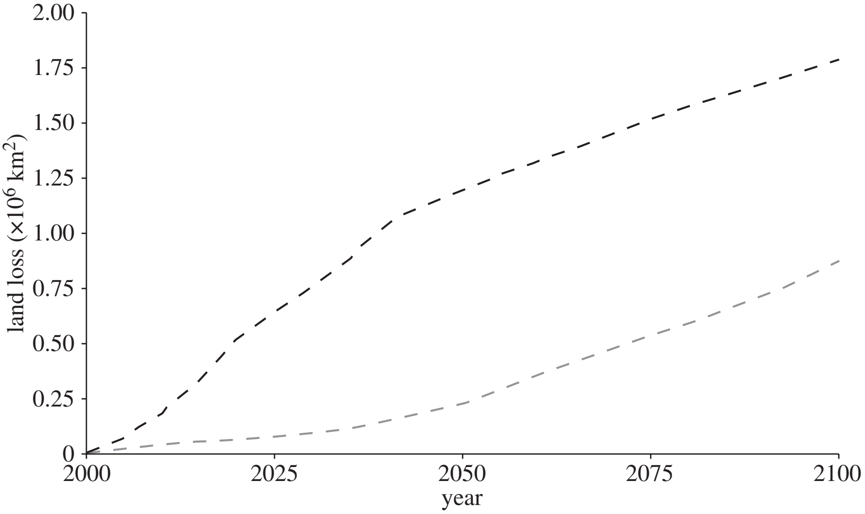

Figure 2. Global dryland losses according to the DIVA model assuming no adaptation for a 0.5 m (grey lines) and a 2.0 m (black lines) rise in sea level by 2100.

(*b*) *The pessimist's versus the optimist's view*

Results for a world where adaptation is not implemented/fails versus a world with successful adaptation are now contrasted for selected parameters.

Assuming no adaptation, of the two land-loss mechanisms considered in DIVA, submergence is a much larger contribution to the loss than erosion. Under these conditions, land loss amounts to a total of 877 000–1 789 000 km^2 for a 0.5 and 2.0 m rise in sea level, respectively (figure 2). This amounts to approximately 0.6–1.2% of the global land area. The net population displaced by this rise is more significant, being estimated at 72 and 187 million people over the century, respectively (roughly 0.9–2.4% of the global population). This reflects the high population density in coastal areas.[6] The results are consistent with the literature on environmental refugees (e.g. [75]), which forecasts large population displacements owing to sea-level rise. Most of the threatened people are concentrated in three regions in Asia: east, southeast and south Asia (figure 3). Given 0.5–2 m rise in sea level, a total of 53–125 million people are estimated to be displaced over the century from these three regions alone. In the three small-island regions (Caribbean, Indian Ocean and Pacific Ocean), 1.2–2.2 million people are displaced over the century, with all three regions contributing significantly. It is noteworthy that impacts in some regions such as north and west Europe and the North America Atlantic Coast, impacts are much greater for a 2.0 m scenario than for a 0.5 m scenario. This reflects that pre-existing defences provide benefits for a 0.5 m rise, but are overwhelmed by a 2.0 m rise.

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[6] Note that the socioeconomic scenarios used here assume no coastward migration: if coastward migration does continue in the coming decades, the impact potential would be amplified.

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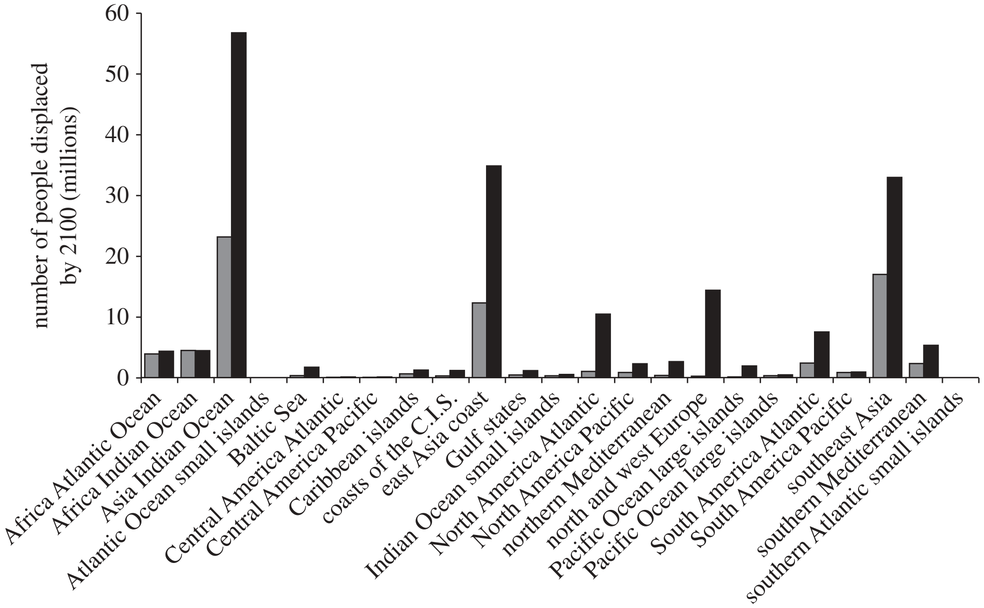

Figure 3. The distribution of net population displacement over the twenty-first century by region assuming no protection for a 0.5 m (grey bars) and a 2.0 m (black bars) rise in sea level. C.I.S., Commonwealth of Independent States.

If we assume protection with dikes and nourishment, the number of displaced people falls dramatically to comparatively minor levels of 41 000–305 000 people displaced over the twenty-first century. Hence, in contrast to the no-protection scenario, the problem of environmental refugees almost disappears.

The costs of protection are zero if we assume no protection. In contrast, the dike and nourishment responses have substantial costs. The incremental adaptation costs[7] are estimated at roughly between US $25 and $270 billion (1995 values) per annum for 0.5 and 2.0 m in 2100, respectively. Dike costs dominate these response costs, and dike maintenance becomes an increasing component of the costs over time. This illustrates an important long-term consequence of a widespread protection response to sea-level rise that will continue to grow beyond 2100. In 2100, the relative mix of nourishment, dike construction/upgrade and dike maintenance costs is 36, 39 and 25 per cent; and 13, 51 and 37 per cent for the 0.5 and 2.0 m rise in sea level, respectively. The regional spread of these costs is quite variable with east Asia, North America Atlantic, North America Pacific, north and west Europe and South America Atlantic being the five regions with the highest costs (figure 4). In terms of avoided human displacement as a function of protection investment, not surprisingly, the benefits are highest in the regions with most threatened people: east Asia, south Asia and southeast Asia. It directly affects those on the coast, but also has knock-on effects further inland.

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[7] Hence, these results assume an existing adaptation infrastructure that can be upgraded. If this is not the case, this is termed an ‘adaptation deficit’, which will require further investment to address [76,77].

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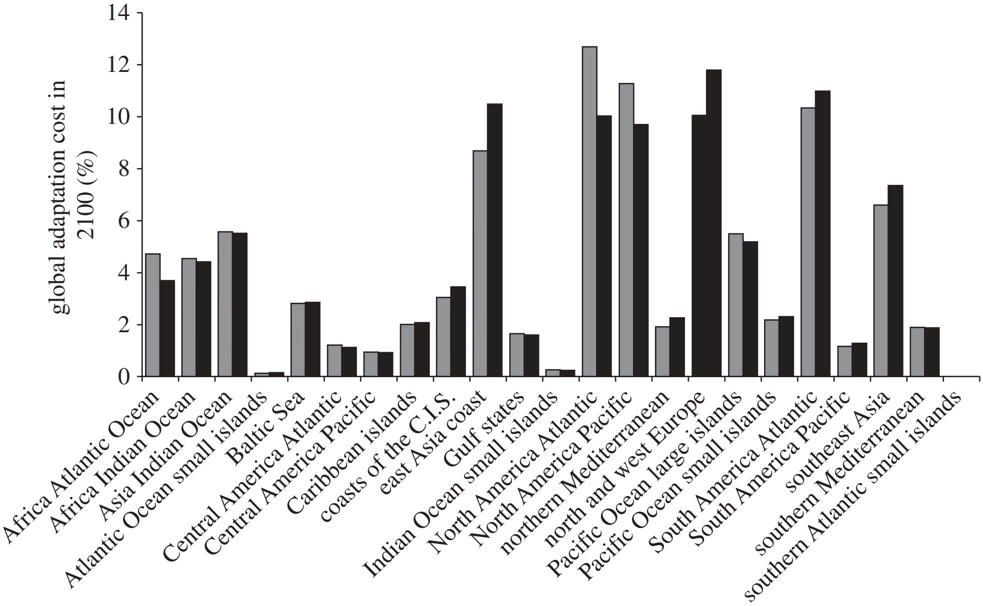

Figure 4. The annual protection cost by coastal region in 2100, as a percentage of global protection investment for a 0.5 m (grey bars) and a 2.0 m (black bars) rise in sea level by 2100.

4. Discussion

Section 2 showed that a sea-level rise of between 0.5 and 2.0 m is not an implausible range of climate-induced global rise in sea level in a 4°C world. Owing to our poor understanding of the underlying processes driving climate-induced sea-level rise, we cannot associate any likelihood with this range, and we conclude that rises above 0.5 m and especially 1 m by 2100 are possible, rather than inevitable. However, it is important to consider what would happen and what responses are available if such large changes did occur: in effect, there is a poorly understood potential for a high-consequence rise in global sea-level rise that is of significant interest to those concerned about coastal impacts and adaptation.

The results presented in §3 investigate the issue of impacts and adaptation assuming a rise in sea level between 0.5 and 2.0 m with or without upgraded protection by 2100. The results are indicative and are designed to provide an overview of their implications: they bracket the range of impacts and adaptation costs that might occur with intermediate sea-level-rise scenarios and partial-protection scenarios. They show that in addition to the uncertainty about sea-level rise, the outcome is very sensitive to our assumptions about protection. Without further upgrade to protection (no adaptation), sea-level rise will erode and more particularly flood and submerge extensive low-lying coastal areas displacing tens to millions of people or more by 2100. This would be a highly undesirable future world with many millions of forced environmental refugees owing to sea-level rise alone. In contrast, assuming a protection response, the impact of sea-level rise is mainly felt in terms of increasing protection costs. Hence, in developed coastal areas, a higher rise in sea level translates into a

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larger protection cost. While the residual impacts would also rise, this is minor in magnitude when compared with a no-protection scenario (cf. [10]), and this is not evaluated here. So in conclusion, there is great uncertainty about the magnitude and sources of impacts and costs under high sea-level-rise scenarios.

Climate mitigation remains a viable strategy to avoid the 4°C world considered in this paper [78]. Reducing temperature rise reduces the magnitude of sea-level rise, although importantly, stabilizing global temperatures does not stabilize sea level. Rather, it stabilizes the rate of sea-level rise, a process that has been termed the ‘commitment to sea-level rise’ [5]. Hence, a need to adapt to sea-level rise would remain even under mitigation, and mitigation and adaptation policies are more effective when combined in coastal areas: mitigation reduces the rate of sea-level rise to a manageable level and adaptation is required for the remaining rise [2]. At present, the appropriate mix of mitigation and adaptation is not well understood, partly because scenarios of sea-level rise under different stabilization trajectories are poorly developed as already discussed, and partly because of uncertainty about adaptation. Combined with the uncertainties in sea level already discussed in §2, this is an important area for further research.

Without mitigation, the fundamentally different outcomes come down to how successful adaptation, and protection in particular, might be. While there is extensive literature in both the camps, which this paper has termed the ‘pessimists’ and the ‘optimists’, respectively, there has been little attempt to reconcile these two perspectives and really understand coastal adaptation as a systematic process [10,12]. The ‘pessimists’ seem to take it as read that adaptation will either fail or people will not even try to adapt. In contrast, the ‘optimists’ appear overly confident that benefit–cost approaches describe human behaviour in response to threats such as sea-level rise [3,10]. Both views can find empirical evidence to support them. In particular, the response to relative sea-level rise in subsiding coastal cities support the optimist’s perspective as they have all been protected, rather than fully or even partially abandoned. This includes cities in developing countries such as Bangkok in Thailand. However, adaptation failure cannot be ruled out, and major disasters such as Hurricane Katrina in 2005 and its impact on New Orleans certainly suggest caution. New Orleans’ defences are now largely rebuilt and upgraded to a much higher standard than before Katrina at a cost of US $15 billion [79], but it is too early to assess the long-term effect of Katrina on the city (cf. [80]). In more general terms, it is certainly plausible that extreme events can trigger a cycle of decline and ultimately coastal abandonment [81]. Much more research on adaptation in coastal areas, including protection, is required. Historical analogue studies could be especially valuable.

Vulnerability to sea-level rise is not uniform and small islands, Africa and south, southeast and east Asia are recognized as the most vulnerable regions [11]. This reflects their high and growing exposure and low adaptive capacity. These regions are the areas where protection is most likely to not occur or fail, and they collectively contain a significant proportion of potential environmental refugees, especially the Asian regions (figure 3). Many of the people in Asia live in deltas, which are extensive and often subsiding coastal lowlands, amplifying global changes and making them more challenging environments for adaptation [47,48,82]. Small islands have relatively small population and given that implementing protection could also present significant problems, forced abandonment seems a feasible outcome for small changes in sea level (e.g. [83]).

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Hence, the threats to these vulnerable regions provide some of the strongest arguments for mitigation to avoid a 4°C world. In addition, adaptive capacity needs to be enhanced in these vulnerable regions, regardless of the magnitude of sea-level rise. Realistic assessments of responses are required across the spectrum of adaptation: at the extreme, planned retreat is to be preferred to forced abandonment.

To date, there are only two strategic attempts to plan long-term adaptation to sea-level rise and these are both in the developed world: (i) the Thames Estuary 2100 (TE2100) Project [33], which considers flood management in London and its environs, and (ii) the Delta Commission [30], which considers the future of The Netherlands under sea-level rise. As already noted, both studies were prepared to consider quite large rises in sea level—much larger rises than quantified in the IPCC AR4. In both cases, the problem was constructed as one where high uncertainty is inherent, and it is fundamental to evaluate the low-probability high-consequence scenarios. In TE2100, a scenario-neutral analysis was followed, where the flood-management system was tested against sea-level-rise scenarios of up to 5 m, without worrying about the timing of this rise. Hence, a progressive sequence of adaptation measures could be identified that would manage the range of sea-level rise. Issues of the timing of adaptation have been analysed subsequently. The Delta Commission took a slightly different approach and looked to 2200 and estimated that sea levels might be up to 3.5 m higher than today [31]. However, both studies came to the conclusion that improved/upgraded protection was the best approach in their study sites, although both projects aspire to work with, and mimic nature as much as possible within this goal. The principles illustrated here should be applied much more widely—coastal cities with a large exposure to flooding are widespread, especially in Asia and North America [73]. More generic analyses of adaptation are also useful such as the World Bank [77] assessment of the economics of adaptation to climate change. Broad-scale studies could also be more developed, including responding to large rises in sea level as considered in this paper.

5. Conclusions

Climate-induced rise of relative sea level during the twenty-first century could be larger than the widely reported absolute numbers published by the IPCC AR4 [5,18], and a rise of up to 2 m is not implausible but of unquantifiable probability. In essence, there is a low-probability/high-consequence tail to the sea-level scenarios, although we have no basis to evaluate what that probability might be. While the IPCC AR4 report also acknowledges this fact, the presentation failed to communicate this important point effectively, and most readers of the IPCC assessments failed to notice this caveat concerning the published scenarios. From the perspective of those interested in impact and adaptation assessments, this is an important failure that we hope the next IPCC assessment will explicitly address.

Linking sea-level rise to temperature rise is difficult and there is not a simple relationship between the two factors. Hence, the sea-level-rise scenarios for a 4°C rise in temperature is uncertain, and a 0.5–2.0 m global rise in sea level has been selected as a pragmatic range to associate with such a temperature rise.

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The human exposure is very large, reflecting the high population density in the coastal zone. Assuming no or failed adaptation, this exposure translates into catastrophic impacts with tens of millions or even more people being turned into environmental refugees owing to sea-level rise. In contrast, a protection response suggests that most of the threatened population would be protected, and the main consequence of a large rise in sea level is a larger investment in protection infrastructure. This analysis shows that it is incorrect to automatically assume a global-scale population displacement owing to a large rise in sea level, and coastal populations may have more choices than widely assumed. However, the more vulnerable locations such as small islands and populated deltas will be severely challenged by large rises in sea level, and the most appropriate adaptation responses, including protection, require more analysis.

Nicholls *et al.* [2] argued that the response to sea-level rise required a combination of adaptation for the inevitable rise, and mitigation to limit the inevitable rise of sea level to manageable magnitudes. This reflects the large inertia of sea-level rise, which means stabilizing global temperature in order to stabilize the rate of rise. Even so, rising sea levels will continue for centuries into the future. This analysis supports this view, as adaptation is more likely to succeed for smaller rises in sea level consistent with stringent mitigation. Better quantification of future sea levels and their links to temperature rise, including the role of the large ice sheets, is clearly important. Coastal adaptation requires more planning and there will be a debate about what allowances should be made for sea-level rise. The long-term vision of the Thames Estuary 2100 project [33] and the Delta Commission [30] are to be commended. These schemes are establishing a flexible approach to management where there is some upgrading of defences and a logical sequence of additional measures to reduce risk. This will be combined with monitoring of sea level so that the timing of further upgrades can be optimized. This type of adaptation planning needs to be applied much more widely in terms of developing a coherent strategy to deal with an uncertain rise in sea level over the next 100–200 years.

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Climate-induced population displacements in a 4°C+ world

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Massive population displacements are now regularly presented as one of the most dramatic possible consequences of climate change. Current forecasts and projections show that regions that would be affected by such population movements are low-lying islands, coastal and deltaic regions, as well as sub-Saharan Africa. Such estimates, however, are usually based on a 2°C temperature rise. In the event of a 4°C+ warming, not only is it likely that climate-induced population movements will be more considerable, but also their patterns could be significantly different, as people might react differently to temperature changes that would represent a threat to their very survival. This paper puts forward the hypothesis that a greater temperature change would affect not only the magnitude of the associated population movements, but also—and above all—the characteristics of these movements, and therefore the policy responses that can address them. The paper outlines the policy evolutions that climate-induced displacements in a 4°C+ world would require.

Keywords: migration; displacement; climate change; mobility; adaptation

1. Introduction

Massive population displacements are regularly forecast as one of the most dramatic possible consequences of climate change. In recent years, the concept of climate-induced migration has gained considerable currency, and 'climate refugees' are now a common feature in discourses on the human impact of climate change [1,2]. Works on this topic are usually rooted in an essentialist perspective, which assumes that migration is a logical by-product of climate change. Most forecasts and estimations adopt a deterministic approach based on the number of people living in regions that will be affected by sea-level rise, and conclude that about 150–200 million people could be displaced by 2050 as a result of climate change [3–5]. Such forecasts, however, have triggered wide controversy among the scholarly community, and have often been criticized for being too environmentally deterministic and not sufficiently rooted in empirical evidence [6,7]. Indeed, such forecasts took little account of vulnerability patterns and demographic trends, and did not factor in the implementation of possible adaptation strategies.

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This paper contends that the nature and extent of migration flows associated with the impacts of climate change depend not only on these impacts, but also on a wide range of other factors, such as cultural, economic or political conditions. It argues that the policy responses that will be implemented to deal with these flows will be particularly important in that regard. Migration policies, so far, have poorly accounted for environmental drivers of migration. The policy debate on adaptation, however, is increasingly considering that migration could be a way for populations to cope with environmental degradation, rather than a failure to adapt [8–10]. The planning of future adaptation policies that would address migration, however, is contingent upon predictions of future population movements. Current forecasts and projections show that the regions that would be most affected by such population movements are low-lying islands, coastal and deltaic regions, as well as sub-Saharan Africa [5,11]. Such estimates, however, are usually based on a 2°C temperature rise. In the event of a 4°C+ average temperature rise, this paper argues that the very nature of these migrations, rather than just their magnitude, would change and would therefore call for different policy responses. It puts forward the hypothesis that a greater temperature change would affect not only the magnitude of associated population movements, but also—and more importantly—the characteristics of these movements, and therefore the policy responses that can address them.

Section 2 reviews the different impacts of climate change that could trigger population displacements. Such impacts typically include sea-level rise, droughts and land degradation, as well as extreme weather events. Predictions and forecasts of population displacements related to these impacts, however, are marred by a double uncertainty, which concerns both the local impacts of climate change and the way people will respond to these changes. Despite these uncertainties, §3 attempts to examine how a temperature rise of 4°C+ could affect population displacements. Using past empirical evidence, the section suggests that people might migrate very differently in a 4°C+ world than in a 2°C world. Three expected changes in particular are highlighted, in a way that rebuts the deterministic perspective that dominates discourse on 'environmental migration'. Finally, §§4 and 5 outline the policy implications of this rebuttal and elaborate on some proposals for policy developments that could address the changing nature of climate-induced displacements in a 4°C+ world.

2. The impacts of climate change on migration

Climate change will affect societies through an extensive range of impacts. The prediction of such impacts, however, remains marred by uncertainties, especially at the regional and local levels [12,13]. Uncertainties are even greater when one needs to factor in the wide range of possible human reactions to these impacts. Empirical studies remain scarce [6], and experimentation is impossible, as is often the case in social sciences. Thus an assessment of the impacts of climate change on migration is, by its nature, a daunting task. It nevertheless appears possible to identify three types of impacts that seem most likely to have an effect on migration patterns, although these effects are not certain [11,14].

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(*a*) *Extreme weather events*

Extreme weather events include heat waves, tropical cyclones, droughts and flooding. The latest Intergovernmental Panel on Climate Change (IPCC) report predicts, by the end of this century, a '*very likely* increase in hot extremes, heat waves and heavy precipitation', a '*likely* increase in tropical cyclone activity', with 'less confidence in the decrease of tropical cyclone numbers', as well as '*very likely* precipitation increases in high latitudes and *likely* decreases in most subtropical land regions' [15]. In addition, it is expected that annual run-off and precipitation will increase in high latitudes, whereas water resources will decrease in mid-latitudes and in the tropics, as well as in arid regions. The IPCC notes that the increases in both droughts and tropical cyclone activity present a potential for population migration [16].

The latter claim, however, can be disputed, as the impacts of extreme weather events on migration flows are diverse and sometimes controversial. Disasters can indeed result in highly diverse patterns of displacement. For example, it is widely thought that disasters are more likely to induce temporary displacement, allowing people to return home once the danger is gone. As a result of this assumption, people forced to flee to another country because of a disaster have often been granted temporary protection status: for example, temporary protection status in the USA was granted to the people of Montserrat displaced by the volcanic eruption in 1997, and to the people of Honduras and Nicaragua displaced by Hurricane Mitch in 1998. The experience of Hurricane Katrina, however, showed that people displaced by natural disasters were not always able to go home, as a significant proportion of the population of New Orleans has still not returned, and seems unlikely to do so in the future [17]. It is now increasingly acknowledged that disasters result in both temporary and permanent displacement, as well as in both proactive and reactive displacement.

It is likely that an increase in extreme weather events will result in an increase in the number of natural disasters [18]. This would reinforce the upward trend in the occurrence of disasters, identified since the start of their systematic recording in the early twentieth century [19]. Until now, this upward trend has been primarily explained by the increased vulnerability of the affected populations. A disaster occurs when natural risk meets vulnerability [20]: if the number of natural risks increases with a temperature rise, the number of disasters will consequently increase unless the vulnerability of populations can be reduced. Unless robust adaptation strategies are implemented, there is no sign that vulnerability might decrease in the near future. In a 4°C+ world, however, the main driver of natural disasters might shift from an increase in vulnerability to an increase in the number and severity of natural events. In addition, the characteristics of these events themselves might change, as different hazards could combine with each other in an unprecedented setting. This could affect both the location of disasters and the design and implementation of disaster-reduction policies.

(*b*) *Sea-level rise*

The most obvious consequence of climate change with regard to environmental migration is probably sea-level rise. Though sea-level rise will not be uniform across the globe, some studies suggest that the rise could be about 1 m by the end of the century [21,22]. The IPCC notes that [23]:

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> Many millions more people are projected to be flooded every year due to sea-level rise by the 2080s. Those densely-populated and low-lying areas where adaptive capacity is relatively low, and which already face other challenges such as tropical storms or local coastal subsidence, are especially at risk. The numbers affected will be largest in the mega-deltas of Asia and Africa while small islands are especially vulnerable.

Unlike extreme weather events, sea-level rise is more predictable in the longer term, and populations at risk can be more easily identified, which facilitates the implementation of adaptation plans. Given that coastal and deltaic areas are usually very densely populated, the potential for large numbers of migrants is particularly high [24,25].

The projection of sea-level rise is usually based on a 2°C average temperature increase. In a world with a 4°C+ temperature increase, sea-level rise would be higher, especially with the increased probability of the deglaciation of the Greenland and West Antarctic ice sheets [26]. Sea-level rise would also induce greater coastal erosion, as well as bigger storm surges. The El Niño–Southern Oscillation could also be affected, magnifying the differences in local sea-level rises. It is especially important to understand and forecast local sea-level rises, as the associated migration potential depends on the local sea-level rise rather than the average one. In that regard, a 4°C+ temperature increase would increase not only the average sea-level rise, but also—and probably more importantly—the uncertainties associated with the migration potential.

(*c*) *Water stress*

Water stress will be caused by a series of cumulative factors: droughts, salt water intrusion due to sea-level rise, and also the melting of mountain glaciers in the long run. The IPCC forecasts that ‘freshwater availability in Central, South, East and Southeast Asia, particularly in large river basins, is projected to decrease due to climate change which, along with population growth and increasing demand arising from higher standards of living, could adversely affect more than a billion people by the 2050s’ [23]. The water supplies stored in glaciers and snow cover are also expected to decline, reducing freshwater availability in regions supplied by melt-water from mountain ranges. The situation is expected to be most difficult in Africa, where an estimated 75 million to 250 million people will be at risk of water stress due to climate change by 2020. Given that this water stress will be associated with higher demand, especially in big cities, water-related problems are very likely to be exacerbated [27].

The effects of water stress on migration patterns remain heavily contested: some authors argue that droughts and desertification are a major push factor for migration [28,29],[1] while others contend that people affected by droughts

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[1] Hammer [28] argues that one million people were displaced as a result of the 1985 drought in Niger, and that ‘hundreds of thousands of people from rural Sahel regions are displaced every year as a consequence of environmental change and desertification’. Leighton [29] makes a similar case for Northeast Brazil.

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have a choice between different coping strategies, including migration, and note that international migration actually decreases during these periods [6]. In a recent review of empirical case studies conducted in Africa, Jonsson asserts that 'environmental stressors such as droughts do not necessarily lead to migration' [30]. In any case, the nexus between drought and migration is not straightforward and depends on a wide range of factors [31]. Findings from the EACH-FOR project,[2] for example, confirm that water stress can affect migration patterns in different directions: Van der Geest [32] found that contemporary north–south migration in Ghana was environmentally motivated, but decreased during the worst droughts; Afifi [33] also identified droughts as an important push factor that influences both internal and international migration in Niger.

Here again, a larger temperature increase towards 4°C would further exacerbate problems of water stress, and would also increase uncertainties: the impact of aggravated water stress on human mobility remains unclear and poorly documented. According to the case and the wider context, it could result in different mobility patterns, with an increase in some regions and a decrease in others. In the Sahel, Jonsson observes that 'whether and how people migrate in response to environmental change depends largely upon the role that mobility already plays in their lives and livelihoods' [30].

The impacts of climate change in a 4°C+ world are difficult to translate into migration forecasts: increased temperatures might have different effects on migration flows, and it is impossible to conduct experimentation in this field to adjust the forecasts.

Historically, migration models have done a very poor job of accounting for environmental factors in the migration decision [34], and it is only recently that migration research has started to consider environmental changes as possible migration drivers. Hence, it is not possible to refer to explanatory models in order to predict the nature and the extent of the migratory movements that could be associated with climate change impacts.

We are thus faced with a double level of uncertainty: the first level deals with uncertainties related to climate impacts on local and regional scales; whereas the second level concerns the way humans will react to environmental changes. Such uncertainties are even greater in the event where the average global temperature would rise by 4°C and beyond. The first level of uncertainty can be reduced with more precise climate models, but the second level cannot yet be reduced, as current migration models do not account for environmental drivers. Thus the only tool we have at our disposal is to look at how environmental changes have affected migration behaviours in the past. This does not imply that humans will react in the same way to future environmental changes: these changes will be accompanied by other social, cultural and economic changes and transformations that will also influence migration behaviours. Past empirical evidence is not especially helpful in predicting future migration flows, but can nevertheless be used to show some trends that are likely to occur under a 4°C+ global warming.

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[2] EACH-FOR stands for Environmental Change and Forced Migration Scenarios, an empirical research project funded by the European Commission between 2007 and 2009. See http://www.each-for.eu for more details.

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3. Implications for a 4°C+ world

Given the uncertainties associated with a 2°C temperature rise, an assessment of climate-induced displacements in a 4°C+ world is a very tricky task. Though empirical evidence cannot predict future population displacements, it suggests that, in a 4°C+ world, people might move in a very different way than in a 2°C world: the very nature of the displacements might be affected more than just their magnitude. Three changes in particular can be expected.

As shown in §2, a 4°C+ world could result in increased environmental pressure on migration. Empirical research shows that mobility is often one possible option among different coping strategies to deal with environmental disruption. Over the years, people have developed traditional mobility patterns that allow them to cope with environmental changes, especially when these changes affect agricultural yields or livestock herds. For some people, mobility is an integral part of their livelihood, which allows them to increase, diversify or secure their incomes. Such traditional coping strategies are jeopardized by increased environmental pressure due to climate change [35,36]. As environmental disruptions would be exacerbated with a 4°C+ temperature increase, mobility might become a less-viable coping strategy.

For example, Van der Geest [36] observes that traditional nomadic patterns, which were used by pastoralists to cope with droughts, have been modified due to rapidly changing environmental and socio-economic conditions. A similar phenomenon is observed in Bangladesh, where the traditional movement of people from *char* to *char*[3] is disrupted by flash floods that are more violent and frequent than they used to be [37]. Thus, it appears that, if the impacts of climate change become more severe, they could disrupt traditional patterns of mobility and people might need to leave their usual place of residence. Migration options would become more limited. In that case, it is expected that the movement would most likely be a long-term or permanent migration instead of a temporary displacement—a trend that has been observed by the EACH-FOR project in different countries of Southeast Asia and sub-Saharan Africa (most notably Ghana, Vietnam and Bangladesh). In Vietnam, for example, rice farmers usually undertake seasonal labour migration to urban centres during the flooding season, in order to increase and diversify their incomes. Successive floods, however, leading to the destruction of crops, have prompted farmers to migrate permanently in search of a new livelihood [38,39].

Permanent dislocation affects the ability of migrants to cope and adapt in the destination region, but might also affect the rights and protection to which they are entitled, especially in the case of forced migration abroad, as no international protection regime exists for those displaced by environmental changes. Though the distinction between forced and voluntary migration is increasingly blurred [40], and probably no longer fit to describe the realities of contemporary migration, it remains a defining element of migration policies and law.

Climate change is expected to further blur this distinction, as environmental changes threaten not only the lives of people, but also their livelihoods [41]. Hence, people moving as a result of climate change impacts might do so both

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[3] A *char* is a temporary sandy island that forms in the bed of a river.

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because their lives are at risk and because they can no longer sustain their household. In a 4°C+ world, where environmental pressure to migrate could be higher, traditional patterns of mobility might be deeply affected: an increasing number of people could be deprived of the choice to leave or to stay, and feel *forced to move*.

However, not everyone moves when confronted with environmental changes. Another consequence of a temperature rise of 4°C+ might be, paradoxically and in some cases, a decrease in the number of people on the move. Numerous studies show that migration flows tend to decrease when environmental crises peak. This is especially true in the case of droughts, as people tend to allocate their income primarily to meet their household's basic needs rather than to moving [6,36]. People will move only if they have the resources that allow them to do so: this includes financial resources—moving is a costly process—but also access to social networks facilitating mobility. Furthermore, empirical evidence shows that the most vulnerable are often unable to move when faced with an environmental crisis. For example, prior to Hurricane Katrina, about 60 000 people were unable to leave the city of New Orleans: evacuation required money for food, gas and lodging, and many poor families were unable to afford the expense. Furthermore, the hurricane struck at the end of the month: many of the poorest residents were awaiting pay cheques, leaving even fewer resources available for their evacuation [42].

If vulnerability and poverty increase in some regions, as has been the case in recent decades,[4] one might expect that the number of people who would find themselves unable to move in the event of an environmental crisis would also be on the rise. An increasing number of people might thus find themselves *forced to stay*.

Finally, climate change-induced migration in a 4°C+ world is not expected to become more international, as often assumed. Apart from some specific cases of migration from small island states, discussed in §4, movements are expected to remain confined within the borders of states affected by the impacts of climate change, unless significant policy changes occur. No empirical evidence suggests that the distance of migration increases in relation to the magnitude of environmental disruption. Empirical findings from the EACH-FOR project reveal that the overwhelming majority of migration flows observed in relation to environmental changes are internal movements, often over very short distances [38].

Furthermore, international migration requires considerable financial resources for the migrants: unless significant financial transfers are made or developing countries undergo rapid economic development, these resources are unlikely to be available. In addition, policy developments with regard to international migration since the late 1970s point towards a restriction of international mobility, rather than an opening of borders. This trend is observed in both the North and the South, as exemplified by the recent building of a security barrier at the border between India and Bangladesh [37]. The barrier is supposed to protect India against intrusion by Islamist militants from Bangladesh, as well as smuggling

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[4] Research dealing with the increase in natural disasters over the past few decades suggests that the key driving force behind this rise is the increased vulnerability of populations, rather than a higher number of natural hazards [24].

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and illegal immigration. Bangladesh also ranks among the countries that are the most vulnerable to climate change impacts. In the event of climate-induced displacements from Bangladesh, the barrier would also, most likely, serve as a deterrent to prevent these migrants from entering India.

In a nutshell, the effects of a 4°C+ temperature rise on migration flows remain difficult to assess. The linkages between environmental changes and mobility cannot be explained through a linear, deterministic relationship, though many discourses on this issue remain rooted in an essentialist perspective. Empirical research has shown that responses to environmental changes vary according to a wide set of factors and are context-specific: this makes it difficult—if not impossible—to design a general predictive model of climate-induced displacement. Furthermore, a global warming of 4°C+ will bring unprecedented changes, which will make them difficult to compare with changes experienced by populations in the past. These changes will also, most likely, be accompanied by other changes and transformations of societies. These economic, cultural, technological or political changes might translate into opportunities or constraints for migration, and are in any case expected to affect mobility patterns. We should not assume, however, that climate change impacts will simply act as 'push' factors of migration. Migration theories have widely rebutted the 'push and pull' model as unfit to account for contemporary migration, and have shown the complex and nonlinear processes governing migration dynamics [43–45]. Climate change will most probably be an increasingly important element of these migration dynamics, but should not be considered independently of other changes and variables, as is too often the case in deterministic arguments linking climate change and migration in a direct, causal relationship.

So far, no migration theory has properly accounted for the effects of climate change, let alone a 4°C+ warming. Yet, some likely trends can be identified through a comparative assessment of empirical evidence. Traditional patterns of mobility could be disrupted, and an increasing number of migrants might feel deprived of a choice in their migration decision. At the same time, some people, especially the most vulnerable, might find themselves unable to move, lacking the resources to do so. Population movements associated with climate change impacts are expected to take place mostly at the internal level, over short distances, and eventually on a permanent basis. Overall, it appears that the most significant impact of a 4°C+ warming on migration would be to reduce populations' ability to move on their own terms, as many people would no longer have the choice to stay or to leave when confronted with environmental changes. This ability, or 'right to choose', however, will be highly dependent upon the policy responses that will be designed to address climate-induced displacements.

4. Policy implications

Historically, migration policies have often neglected environmental factors as drivers of migration. Environmental policies, on the other hand, have usually considered migration as a humanitarian issue resulting from natural disasters or other environmental disruptions [46]. Current debates on future policy developments tend to rely on the deterministic assumptions outlined in §2:

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migration is considered as a dramatic and unavoidable consequence of climate change impacts, with little account of people's agency and ability to respond. As a result, most policy discussions revolve around issues of protection and security rather than of governance and mobility.

As no international regime exists to assist those displaced by climate change, many policy proposals have recommended that a new convention or treaty be drafted to fill this gap in international law [47,48]. Most of the debates have focused on the international status that could be granted to the displaced, with many authors lamenting that the 1951 Geneva Convention Relating to the Status of Refugees does not apply to those displaced by environmental events [47,49]. An international status, however, would be inapplicable in most cases of climate-induced displacements, as these are primarily internal movements, beyond the reach of an international status. Despite this fact, various legislative proposals have been made in different parliaments, including those of Australia and Belgium, with the aim of establishing an international status for 'climate change refugees'. Overall, the issue remains framed in either a security agenda or a humanitarian one.

As described earlier, in a 4°C+ world, the adaptive capacities of many regions are likely to be overwhelmed by the impacts of climate change. Policy responses would therefore be crucial to enhance the migration options of those affected by the impacts. Yet, it appears that the current policy directions and development proposals remain rooted in a deterministic perspective, and take little account of empirical evidence. These policies would therefore be inadequate in the face of the greater and different migratory pressures in a 4°C+ world. In particular, this paper contends that policies should be more focused on assisting migration, both internal and cross-border, rather than limiting it. In order to achieve this goal, different policy agendas are needed.

(*a*) *Fostering the right to mobility*

As adaptation strategies will be a key element of the fight against climate change in a 4°C+ world, policy responses would need, in particular, to promote the right to mobility. Migration can indeed be an efficient adaptation strategy and traditional patterns of mobility in relation to environmental changes will most probably be deeply disrupted. Migration, in many cases, would need to be encouraged rather than avoided. Migration would have to become a core element of the affected populations' adaptive capacity, rather than a symptom of adaptation failure. This would also imply that the current security agenda be replaced by an adaptation agenda with regard to mobility. From a policy viewpoint, fostering the right to mobility with regard to climate change impacts means two things. First, barriers to migration remain considerable in many parts of the world, including at the internal level. These barriers would need to be lifted for migration to unleash its full potential as an adaptation strategy. Second, the most vulnerable often lack the resources to migrate. As environmental crises will become more frequent and more severe, it is likely that households' resources will not be available for migration, but would be used instead to meet the households' primary needs. Transfers of resources will therefore be needed in order to foster the right to mobility for the most vulnerable. The financial burden of migration could be met through adaptation

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funding, provided this funding includes a provision for migration. In a 4°C+ world, if the most vulnerable are not enabled to move to safer places, they will find themselves directly at risk of climate change impacts with tragic humanitarian implications.

In that regard, the issue of proactive displacements is not an easy one. Some governments, such as those of China and Mozambique, have started displacing their populations in anticipation of environmental changes. These populations need to be provided with adequate compensation, and human rights, including the right to choose one's destination, should be a policy priority. In any case, people should not be displaced against their will, and education and information about climate change impacts need to be improved.

(*b*) *Adaptation in the destination regions*

Adaptation remains largely envisioned as a way to prevent displacement in the regions of origin. Adaptation will also be needed, however, in the regions of destination. These regions will be faced with additional influxes of population. They will therefore need to adapt to both climate change impacts and higher demographic pressures, especially if they are already highly populated. If adaptation policies are not also directed to destination regions, these regions might find themselves unable to meet the needs of their populations. Emergency humanitarian aid will be insufficient to meet these requirements, as migrants will also need to be provided with jobs, housing, schools, etc. After Hurricane Katrina, the city of Houston welcomed an estimated 150 000–200 000 displaced residents from Louisiana. They were provided with emergency supplies and housing, as the authorities of Houston expected them to return home within a couple of weeks. It took several months, however, before residents could return to New Orleans, and many decided to resettle in Houston and in the region. The city of Houston, however, experienced a surge in crime, drug use and racism as a result of its inability to provide many of the displaced with jobs and long-term housing.

The humanitarian agenda will therefore need to shift towards a development agenda, as population movements are expected to become increasingly long-term and permanent movements. Migrants should not be considered as resourceless victims, but should be empowered in order to develop their adaptive capacities once in the destination region. The current deterministic perspective, however, continues to envision them as ‘refugees’, a label that could hinder their resilience and resourcefulness, ultimately impeding their resettlement in the destination region.

(*c*) *Protection and assistance*

As noted earlier, those displaced by climate change are not entitled to any kind of international protection or assistance. No international organization or United Nations (UN) agency has a mandate to deal with environmental displacement, though both the Office of the United Nations High Commissioner for Refugees (UNHCR) and the International Organization for Migration (IOM) now intervene regularly in situations of natural disasters to provide humanitarian assistance to the displaced. As forced migration worldwide would most probably increase as a result of a 4°C+ temperature increase, adequate mechanisms of protection and

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assistance will be needed to assist those forcibly displaced. Such mechanisms are already required today—the need for them would only be further reinforced in a 4°C+ world—as discussed by other authors [47,50].

(*d*) *Statelessness*

Statelessness, defined by the UNHCR as the condition of a person not considered as a national by any state under the operation of its law, could also become an important policy issue in a 4°C+ world. It is understood that low-lying small island states are especially vulnerable to the effects of climate change, and to sea-level rise and extreme weather events in particular. The sea-level rise that will be induced by a 4°C+ temperature change is expected to make some island states uninhabitable, and their governments might then have no other option than to organize the resettlement of their population abroad [51]. There are currently 38 small island states that have acquired full independence. Among them, the existence of at least six states, representing about one million people, would be directly at risk in the case of a temperature rise of 4°C+: Bahamas, Kiribati, Maldives, Marshall Islands, Nauru and Tuvalu. These island states are all of very low elevation, with a highest point situated below 100 m above sea level.[5] Though adaptation strategies in low-lying island states are usually limited and costly, they are not necessarily doomed to fail and one should not jump too quickly to describing islanders as stateless citizens in the making. Indeed, such rhetoric might just jeopardize the adaptation efforts of these countries [52].

In the event of a 4°C+ world, the resettlement of the whole population might in some cases become the only viable option. It should be carefully planned and organized, with the interests of the migrants as paramount, at both the individual and collective levels. In particular, their political rights, citizenship and collective identity should be preserved. Some authors have pointed out that the migrants would in this case fall under the 1961 Convention for the Reduction of Statelessness, and could avail themselves of the Convention's protection. An alternative view is that these migrants should not be considered as stateless citizens, and that these states continue to exist, even uninhabited. The continued existence of these states is a guarantee that the citizenship and political rights of their people be maintained—if they were to disappear as independent states, the irony would be that the very states that disappear into the sea because of climate change would also lose their seat at the UN table of negotiations. Furthermore, even in the case where the islands disappear, territorial waters would continue to exist and could provide an anchor for these states' political existence. This would probably also imply reconceptualizing the notion of citizenship.

5. Conclusion

As Danish physicist Niels Bohr famously put it, 'prediction is very difficult, especially about the future'. A 4°C+ world would bring unprecedented changes to the environment, likely to affect human mobility in different ways. How human societies could respond to these changes is highly uncertain, and will depend on a

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[5] Maldives, 2 m above sea level; Tuvalu, 5 m; Marshall Islands, 10 m; Bahamas, 63 m; Nauru, 71 m and Kiribati, 81 m.

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wide set of factors, with many of them not relating to environmental conditions. Despite the lack of explanatory theoretical models, or possibly because of it, the assessment of how a 4°C+ world would affect migration patterns remains dominated by an essentialist, deterministic perspective. This view sees climate-induced displacement conceptualized as a failure of adaptation, a humanitarian catastrophe in the making. In this paper, I have showed how and why such deterministic assumptions do not match current empirical evidence, and how policies may be out of touch with the reality of future migration movements. The relationship between environmental changes and migration is highly complex and depends upon many variables and specific contexts. It cannot be reduced to a direct causal relationship. Thus, the impacts associated with a 4°C+ warming might affect not only the magnitude of the induced population movements, but also, and above all, their very nature.

Among the factors that will also influence the nature and magnitude of migration flows, policy is especially important. For now, discussions on future policy developments in this regard remain rooted in a deterministic perspective, unlikely to provide an adequate policy framework to address climate-induced displacements in a warmer world. Both migration and adaptation policies would need to evolve significantly, and move away from the security and humanitarian agendas in which they are currently framed. Climate-induced migration should be addressed not only within the framework of climate change, but also within the discussions on the global governance of migration. In many cases, migration does not have to be envisioned as a humanitarian catastrophe, but can also be a solution to environmental disruption, which would allow people to relocate into safer areas and to cope better with climate change impacts.

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Rethinking adaptation for a 4°C world

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With weakening prospects of prompt mitigation, it is increasingly likely that the world will experience 4°C and more of global warming. In such a world, adaptation decisions that have long lead times or that have implications playing out over many decades become more uncertain and complex. Adapting to global warming of 4°C cannot be seen as a mere extrapolation of adaptation to 2°C; it will be a more substantial, continuous and transformative process. However, a variety of psychological, social and institutional barriers to adaptation are exacerbated by uncertainty and long timeframes, with the danger of immobilizing decision-makers. In this paper, we show how complexity and uncertainty can be reduced by a systematic approach to categorizing the interactions between decision lifetime, the type of uncertainty in the relevant drivers of change and the nature of adaptation response options. We synthesize a number of issues previously raised in the literature to link the categories of interactions to a variety of risk-management strategies and tactics. Such application could help to break down some barriers to adaptation and both simplify and better target adaptation decision-making. The approach needs to be tested and adopted rapidly.

Keywords: adaptation; uncertainty; decision-making; risk management; complexity; climate change

1. Introduction

The 4° and Beyond conference in Oxford (2009) presented pressing evidence that more global warming may occur much sooner than previously thought likely [1]. The 15th Conference of the Parties meeting in Copenhagen that occurred shortly afterwards provided little encouragement that these large changes can be prevented through politically negotiated emissions reductions [2]. Potential impacts associated with an increase of more than 4°C in global average temperatures are severe, particularly as even higher levels of change may be experienced locally (e.g. [3–5]). There is no doubt, therefore, that the subject

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of adaptation in a '4°C world' (here, we use this shorthand to refer to the world with a serious prospect of average global warming of 4°C or more) will become an increasingly urgent concern.

A stronger prospect of more climate change occurring sooner places a greater priority on considering substantial and continuing adaptation activities, and in particular on considering adaptation decisions with long *lifetimes*. Here, we define *decision lifetime* as the sum of *lead time* (the time from first consideration to execution) and *consequence time* (the time period over which the consequences of the decision emerge). Although a variety of issues regarding these decisions have been raised in the academic literature, these have not been absorbed by practitioners. Pittock & Jones ([6], pp. 9 and 15) made the critical point that 'Climate change in the foreseeable future will not be some new stable 'equilibrium' climate, but rather an ongoing 'transient' process', requiring 'an on-going adaptation process'. However, we explore some psychological and institutional barriers to acting on adaptation, showing that many of these are exacerbated for the more difficult, transformational and long-lifetime decisions.

The core purpose of this paper is to advance understanding of these adaptation decisions with a long lifetime, and to contrast them with other, simpler, adaptation decisions. We present an initial classification of decision types that is aimed at helping decision-makers to arrive at better adaptation solutions. The perspective of this paper reflects the experience of the authors working with practitioners: we write with the developed world in mind, based on our experience in planned adaptation occurring in Australia and the UK. The classification of decisions is universal, but we recognize that the context of adaptation decisions in developing countries may often differ.

Two recent papers provide a springboard for our analysis. Adger & Barnett [7] voice four concerns about adaptation to climate change, which we paraphrase as: the task is unexpectedly urgent and hard; adaptive capacity will not necessarily translate into action; there is widespread existing maladaptation; and the measurement of adaptation success is profoundly complex. Hallegatte [8] makes the same first point, which indeed underlies this entire Theme Issue: the speed and the magnitude of potential change creates major adaptation challenges, as does the ongoing nature of uncertainty about the future, a point which we elaborate further below. He goes on to emphasize the need for decision-makers today to adjust their practices and decision-making frameworks to account for these realities, and proposes five approaches to reducing the riskiness of their management in the face of uncertainty. These are '(i) selecting 'no-regret' strategies that yield benefits even in absence of climate change; (ii) favouring reversible and flexible options; (iii) buying 'safety margins' in new investments; (iv) promoting soft adaptation strategies, including (a) long-term (perspective); and (v) reducing decision time horizons' ([8], p. 240).

We concur with Hallegatte [8] that, while it is a challenge to include climate change in decision-making frameworks, there are many existing tools that may be used. However, his five approaches need to be framed within a broader classification of decision types. In §2, we consider how adaptation is currently viewed, identifying issues that are not yet embedded in practitioner thinking, but which are important in facing the challenges of a 4°C world. In §3, we explore some key barriers to acting on adaptation, noting how these particularly affect decisions with longer term implications. Section 4 then sets out an initial classification of

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the different types of adaptation decisions and responses which may be needed in a 4°C world, and presents some examples. We conclude by considering how this approach might be further developed.

2. Uncertainty and current issues in adaptation

Both Hallegatte [8] and Adger & Barnett [7] emphasize uncertainty about the future arising from climate change. In a broad sense this arises both from the *social uncertainty* about whether and when mitigation efforts will be agreed and achieved, as well as from the *scientific uncertainty* about how the many feedbacks in the Earth system operate, arising from imperfect climate modelling, the role of tipping points [9] and other limits to our understanding of the system. Hallegatte [8] notes that these sources of uncertainty will not go away in the foreseeable future: social uncertainties will play out over decades, and recent experiences of improving scientific understanding have often led to more uncertainty about the future rather than less [10], as the implications of unappreciated processes such as ice-sheet dynamics become clearer.

Set against these challenges, though, are two inescapable facts. Many areas of human endeavour proceed in the face of great uncertainty. Hallegatte [8] cites managing exchange rate risk, energy cost uncertainty and research and development outcomes among others. Thus, the issue is actually one of deploying the correct decision-making frameworks rather than being unable to make decisions under uncertainty, as has been often noted in the past decade [6,10–12].

In addition, not all aspects of uncertainty are equally problematic, and those that are genuinely difficult must not be allowed to inhibit decisions involving the simpler aspects. Notwithstanding the uncertainties, several aspects of climate change are straightforwardly monotonic, leading to only modest levels of uncertainty for many types of decision. The increasing concentration of carbon dioxide in the atmosphere, increasing global average temperatures, sea-level rise (and the general consequences for coastal inundation) and declining ocean pHs are all monotonic changes, with magnitudes that are reasonably certain for the next few decades. Even on longer time frames, it is possible to put high confidence on minimum changes. By contrast, projections of changes of some other elements (such as precipitation or storminess) remain subject to much uncertainty in climate models.

The sense of uncertainty that pervades thinking about adaptation is compounded by the daunting diversity of decisions that could be affected by climate change. However, just as not all uncertainties are equally problematic, nor are all decisions. The growing academic literature on adaptation has canvassed a number of relevant issues, but we contend that these have not yet been synthesized in terms of their implications for practitioners, nor generally embedded in practitioner behaviour.

First, decisions can be mapped with respect to their *lifetime*. Decisions may have a short lead time and short consequence period, such as the choice of which existing wheat cultivar to plant, a decision that can be adjusted every year. Alternatively, they may have a short lead time and long consequences, as with building individual houses, or a long lead time but short consequences, as with

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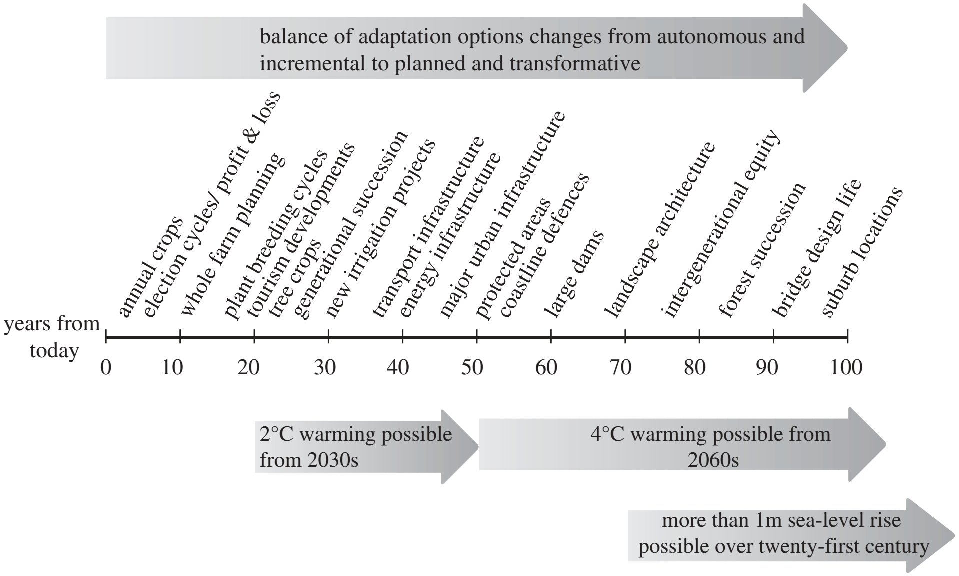

Figure 1. Timeline illustrating the lifetimes (sum of lead time and consequence time) of different types of decisions, compared with the time scales for some global environmental changes, and the changing implications for adaptation. Adapted from Jones & McInnes ([13], fig. 1.4), including items from Hallegatte ([8], table 1). Indicative global temperature rise since pre-industrial times from Betts *et al.* [1]. Indicative sea-level rise over the twenty-first century from Nicholls *et al.* [5].

developing a new cultivar of wheat for planting. Finally, they may have a long lead time *and* long consequences, as with the location of suburbs, which are very hard to move once developed [8,13]. In relation to climate change adaptation, the key issue is the total decision lifetime, as illustrated in figure 1. In general, decisions with a short lifetime need not take account of climate change until it is experienced, whereas decisions with a long lifetime need to consider climate change risks now, regardless of whether the long lifetime is a result of lead time or consequence time or both. Critically, the decision lifetime interacts with the nature of the climate change elements to which the decision is sensitive, as to whether these are changing rapidly or slowly, and with certainty or not.

Second, there has also been a growing understanding of the difference between *incremental* and *transformational* decisions in adaptation [14], building from the 'resilience' literature [15]. Transformational change is formally defined as a change in the set of variables that control a system's functioning [16]. In the present context, incremental adaptation generally implies that adjustments are aimed at enabling the decision-maker to continue to meet current objectives under changed conditions (e.g. changing cultivars to continue farming); whereas transformative adaptation addresses fundamental change in those objectives (e.g. changing out of farming to another land use, or moving an industry to another region). Transformation generally has a long lead time, needed for the players to come to terms with the scale of change. Horrocks & Harvey [17] argue that the ongoing and prospectively greater nature of change in a 4°C world implies

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greater attention to a process of what they termed 'continuous transformation'—ongoing adaptive cycles of incremental and transformational adaptation within a long-term pathway plan. Here, we refer to this as an 'adaptive pathway'.

Third, adaptation is multi-scaled [18], in that adaptation at household and community levels is embedded within the context set by provincial, national and international governments and industry organizations. Yet, the options open at those higher levels are also conditioned by the state of preparedness at lower scales. The issue of scale is also linked up with the nature of transformation, as intervention is often required from a higher scale to help with the envisioning and implementation of transformative change. Indeed achieving resilience at one scale is often only possible in a time of change by promoting transformation at other scales (e.g. a resilient agricultural sector may require radical changes in the operations of individual farms, just as the resilience of coastal communities may depend on changes in where households live).

Fourth, for more than a decade, a few commentators have been urging a greater focus on risk management and robust decision-making [10,12,19–22]. Yet, the emphasis in climate science continues to be on greater precision rather than on better characterization of uncertainty [10]. Either causing this emphasis or in response to it, many decision-makers perceive the need to know more exactly what is going to happen in the future. The likely persistence of uncertainty requires a change in decision-making style for some classes of decisions—primarily those with longer lifetimes—and possibly a reframing of the problem away from being driven by climate science at all. Robust decision-making approaches, as outlined in Dessai *et al.* [10], identify decisions that are robust across the range of future possibilities, even if they are not precisely optimal for any and as a consequence may be more costly to implement [23]. Scenario-based visioning of the future can encompass drivers of future sustainability, which are far more diverse than climate alone, such as those used in the Millennium Assessment [24].

Fifth, there is a small but genuinely difficult class of decisions where risk-hedging is necessary. For example, Steffen *et al.* ([25], box 9) argue that this is the case in post-fire management in the Victorian alpine forests. Here, the trees that will provide nesting hollows and microclimates for many other species in 120 years' time need to be established now; yet in 120 years different tree species are likely to be successful under different futures. In this case, the only option is to consider risk-hedging by promoting the establishment of different species in different parts of the same landscape, in the certain knowledge that some of them will turn out to be the wrong choices. The fact that some adaptation decisions may be so awkward needs recognizing, particularly as the likelihood of a 4°C world increases. However, this category of decisions should not be allowed to obscure the fact that the majority of decisions is less awkward.

Most of these observations have been recognized in the academic literature for at least a decade, but have not yet been integrated in a form that resonates with and informs practical decision-making on adaptation. On the contrary, in our experience of interacting with practitioners, much of the language used about adaptation emphasizes once-off, small adjustments to existing practice in which objectives are unchanged but pursued with climate change taken into account. In this mental model, adaptation is the means to ensure that we can

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continue what we are currently doing into the future, and the possibility that transformation might be needed is largely unaddressed. Strategies usually target building capacity, taking incremental steps and ‘mainstreaming’. The emerging prospect that the world will face at least 4°C global warming, as soon as the 2070s under some projections [1], demands that this approach be reassessed. If a 4°C world eventuates this century, many current actions are failing to meet the challenge. Adger & Barnett’s [7] concern about maladaptation will be realized if we invest in activities that prove, at best, costly and pointless if a 4°C future materializes, and at worst may have prevented more transformative measures.

3. Barriers to adaptation for a 4°C world

The prospect of 4°C global warming within the lifetimes of people born today is confronting, not least because there are many barriers to successful adaptation [7]. Although urgently needed, a comprehensive assessment of these is beyond this paper. However, we can consider those barriers that interact particularly significantly with the issues raised in §2, in order to unlock decision-making in the face of the 4°C challenge.

(*a*) *Psychological and social barriers*

Humanity’s ability to adapt physically to a 4°C world will depend in part on how well people adapt psychologically. Governments, other organizations and individuals will not undertake adaptation activities until they accept the need to do so. Most adaptation literature assumes that accepting the need to act follows from demonstrating the damage that will flow from failing to act. This makes the unwarranted assumption that humans respond to threats with adaptive coping strategies rather than with psychologically maladaptive ones or forms of denial [26].

There is a wide range of cognitive strategies that individuals (and groups) may employ to avoid fully or partially accepting the possibility of unpleasant futures and the need to act now. They are briefly described in table 1. Many of these are promoted by the sense that future climate changes are uncertain, distant or overwhelming, all characteristics of the current narrative around adaptation. Individuals and perhaps cultures have to pass through the stages of denial, notional acceptance but failure to accept any personal responsibility for acting, to finally acting on such issues, although this passage is by no means necessarily a smooth one [26,27].

The way individuals cope with a 4°C world will be influenced by how societies and their institutions respond to the new environment. If only a minority are pursing adaptive coping strategies while others are engaged in denial or maladaptive strategies, the former may feel isolated and disempowered, and governments and other institutions will be under less pressure to undertake adaptation measures, particularly those with long lifetimes. Thus, facilitating the majority to take at least small steps on an adaptation pathway may overcome this paralysis. Crompton & Kasser [28] propose two types of response to encourage governments, non-government institutions and professional organizations to

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Table 1. An analysis of psychological strategies for responding to the prospects of severe climate change (after [26]).

types	strategies	brief description
denial strategies	active denial	resolves cognitive dissonance by actively rejecting scientific claims
	casual denial	avoiding exposure to and dismissing uncomfortable facts with the assistance of narratives about scientific uncertainty or errors
maladaptive coping strategies	reinterpreting the threat	by making its scale seem smaller or its timeframe distant, people 'de-problematize' the threat
	diversionary strategies	appropriate thoughts and actions are displaced by positive but trivial actions (such as installing low-energy light bulbs) or by pleasure-seeking
	blame-shifting	responsibility is disavowed by blaming others for the problem. For example, China has become a popular scapegoat for global warming
	indifference strategies	deliberate apathy can reduce short-term pressures but may exact a heavy psychological toll
	unrealistic optimism/wishful thinking	'benign fictions' lead us to predict what we would prefer to see. Such unrealistic optimism becomes maladaptive when healthy illusions refuse to respond to external evidence and become delusions
adaptive coping strategies	expressing and controlling emotions	feelings of anger, despair and hopelessness are natural in the circumstances. Emotion-focused coping requires that we express these feelings but do not become 'stuck' in them
	problem-solving	finding out more about a threat may alleviate anxiety. If knowledge leads to action, working with others helps establish a sense of control
	new value orientation	considered reflection on death has been shown to promote life goals that are less materialistic and more pro-social

promote adaptive coping strategies: simply publicizing and encouraging adaptive strategies while gently pointing out maladaptive ones; and, promoting value shifts in society towards those that are more sympathetic to cooperation and recognition of intrinsic, rather than materialistic, values. Naturally, these are only two of many necessary contributions.

(*b*) *Cognitive responses to uncertainty*

A specific aspect of psychological barriers arises from our cognitive capabilities. Research demonstrates that individuals and organizations struggle to deal effectively with uncertainty. This is a well-recognized barrier to better decision-making in relation to climate change, even though there are many risk-management tools and techniques (see review in [29]) available to help policy-making under such conditions. As the analysis of climate adaptation becomes

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more sophisticated, there is a move towards a more explicit treatment of uncertainty through, for example, probabilistic scenarios. However, even when the outcomes and probabilities of an event are known ('risk'), this does not mean that decision-making is any easier or any more 'accurate' or that a risk-based approach to decision-making will necessarily lead to the effective management of uncertainty.

As individuals, we have a tendency to make judgements about future events based on our experience of past events, particularly those that evoke strong feelings or have occurred recently. Although a more 'deliberative' approach to processing information for decisions can be learned, this generally requires a high degree of conscious effort. The affective system of decision-making tends to prevail when there is uncertainty or disagreement over a decision. We tend to map 'uncertain and adverse aspects of the environment into affective responses' based on our past experience and feelings ([30], p. 105). Events in the future are considered abstract, so that people resist scientific conclusions if the findings are considered 'unnatural' or unintuitive [31]. When people are making decisions based on their 'affective' mechanism, a disjunction between measures of risk is likely, and this will play an important role in defining the scope for action [30–32]. A clear framework for making decisions in the face of uncertainty could reduce the level of cognitive processing required to tackle the problem, and at least make the processing of uncertainty more explicit and transparent. Indeed, experience from communicating uncertainty in weather forecasts, for example, suggests that it is necessary to communicate why information is uncertain, what in particular is uncertain and why it is important [33]. The framework presented in §4 is a starting point for such an approach.

The cognitive limitations of individuals often extend to organizations and institutions, even though these have the potential to act far more effectively than individuals. The process of organizational decision-making generally has little to do with 'intentional, future orientated choice' but is more a consequence of less formal influences that can spread through an organization like 'measles' ([34], pp. 97–106). Decision-making is tied closely to issues of power, political behaviour [34,35] and 'positioned practices' within organizations [36]. Research within larger organizations has found considerable evidence that decision-making cannot be easily influenced through tools and frameworks or the provision of information. Langley ([37], p. 600) found evidence that formal analysis (defined as 'written documents reporting the results of some systematic study of a specific issue') generally played little role in informing decision-making, and was conducted partly to provide information but also for symbolic purposes. For example, instead of leading to a change in strategy or direction, managerial tools may be used to legitimize or enhance the organization's reputation with legislators [36], and uncertainty can become an unwitting tool in these sorts of responses.

A clear categorization of types of decisions will not in itself remove institutional constraints but can provide a foundation for those seeking better outcomes within the institution—'facilitate the infection of measles' as far as the kinds of decision that need to be considered when facing a 4°C world. However, organizational fads are not enough—the role of the government is still crucial in influencing risk-management uptake and practice (e.g. [38–40]), as we now explore.

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(*c*) *Governance structures and institutions*

In addition to psychological and cognitive constraints, structural aspects of institutions lead to other barriers to effective adaptation. Often these can only be resolved by decision-makers at higher levels of governance (e.g. national governments may only become willing to act on handling refugees within their country once a global agreement is decided) or by a significant change in what is asked of the institutions by decision-makers at a grassroots level (e.g. voters changing their aspirations sufficiently that a Western democratic system has to follow them). In the absence of these drivers for action, the national scale can fall into what has been termed the 'climate change governance trap' ([41], p. 683): because of the scale of the climate change 'problem' it is perceived to be the responsibility of national politicians and policy-makers, who in turn are unwilling to impose potentially necessary, but unpopular, measures because of the electoral cycle.

This problem is significant since it is usually government that is responsible for long-lifetime decisions, such as major infrastructure and urban planning. While we are seeing the proliferation of policies, guidelines, committees and partnerships established to address adaptation, it is still unclear how these various governance structures will interact across scales to enable adaptation. To date there is limited research in this area, although recent evidence of progress in the UK [40] is encouraging. Other case studies have found that existing policies may have a negative impact on adaptation at lower levels of governance [42], and a mismatch may exist between local responsibilities and resources needed for implementation [43].

One political and institutional barrier to adaptation to high-end warming scenarios is peculiar to the climate change issue. This is the sense that it is not acceptable to consider adaptation to more than 2°C of global warming, because it is seen to weaken the negotiating position on emission reductions (e.g. [44]). Given the current failure of negotiations on emissions reduction, this attitude needs to be challenged as a matter of precaution.

(*d*) *Removing the barriers*

These situational factors highlight the difficulty of promoting adaptation action. They also help explain why there is so much focus on framing adaptation as capacity building, incrementalism and mainstreaming; it is difficult to make a case for adaptation among all the other signals competing for limited resources.

Despite these constraints, there are examples of institutions starting to look at the implications of more than 2°C of global warming in sensitive sectors that have long-term planning perspectives. Recently, the Institute of Mechanical Engineers [45], the Royal Institute for British Architects and the Institute of Civil Engineers [46] in separate policy-oriented reports have considered the possible future of adaptation in the UK especially in light of sea-level rise; studies in Australia have explored the implications for natural ecosystem management [25] and coastlines [47]. While the reports differ in focus and scope, the recommendations converge: countries must be prepared to consider and plan for radical changes to people's way of life, including considering the long-term viability of 'many settlements, transport routes and infrastructure sites, planning for either their defence or ordered abandonment' [45].

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These rare examples contrast with the entrenched tendency to make incremental adjustments. Simply presenting people with the prospect of a 4°C world is unhelpful and disempowering unless the complexity of dealing with the thousands of decisions that might be affected by climate change can be simplified. In response, therefore, we argue that a systematic approach is required to reduce the complexity of the adaptation decision-making environment at just the time when that complexity seems to be growing with the increasing expected rates of change. Such a systematization needs to show that the future is less uncertain than often supposed. It also needs to show how decisions are not all equal: complex decision-making can be structured into manageable and actionable steps for which there are well-trodden analytical pathways, even in the face of uncertainty. We now turn to the beginnings of such an approach.

4. Responses under diverging climate futures

Global climate models, driven by a range of emissions scenarios, are used to define the envelope of uncertainty surrounding future climate change (e.g. [1]). This envelope increases over time (figure 2), resulting in increasingly divergent pathways that may need to be taken into account in adaptation planning. Even those aspects of climate change that increase monotonically over time are subject to some uncertainty with respect to rates of change. Figure 2 shows that the lifetime of the adaptation decision is a key factor determining whether planning needs to address a relatively certain set of changes, or allow for diverging, and potentially very different, climate futures.

We argue in this analysis that the interactions between three key factors determine the treatment needed for different adaptation decisions (table 2); and that these three factors help to elucidate when the other issues raised in §2 become important. The three factors are

(i) The *decision lifetime*, which may vary from *short* to *long* (figure 1): longer lifetime decisions must deal with a more widely divergent set of futures than short-lifetime decisions (figure 2), although whether this matters depends on the other two factors.

(ii) The nature of *driver uncertainty* for drivers of relevance to this decision: whether the driver is mainly *monotonic* or *indeterminate*. Decision drivers such as sea-level rise, mean temperatures, ocean and atmospheric CO_2 chemistry, and derived characteristics such as the likelihood of heat waves, length of growing seasons, or frequency of coastal inundation extremes, are essentially *monotonic* over at least the next 50–100 years in most places, whereas changes in rainfall, numbers of cyclones, relative humidity and the net effects of changing cloudiness and warming on numbers of frosts currently remain *indeterminate* in many regions. Of course, if the climate does recover, the monotonic changes will cease, but this is beyond the timeframe of most decisions at present. For monotonic drivers, uncertainty lies mainly in timing; for indeterminate drivers, even their effect is uncertain. Whether this in turn matters depends on the nature of the adaptation response.

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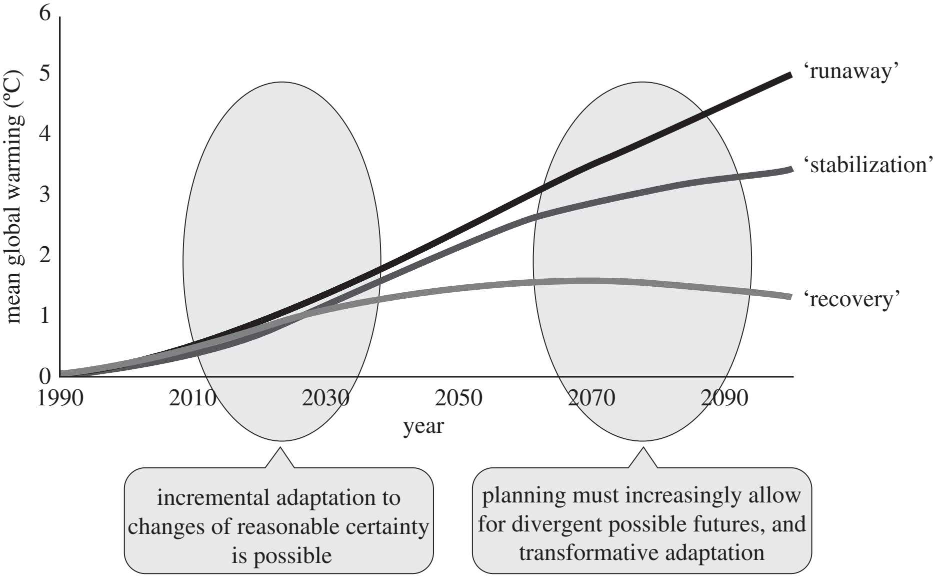

Figure 2. Future projections of climate change diverge over time as social uncertainty outstrips scientific uncertainty, with changing implications for adaptation. Adapted from stylized projections based on ('runaway') the A1FI+ scenario in Garnaut ([55], fig. 4.5), and ('stabilization') the MEP2030 reference and ('recovery') MEP2010-overshoot scenarios updated from Sheehan *et al.* ([56], fig. 8*c*; R. N. Jones (2010), personal communication).

(iii) The *adaptation response* in a decision may take one of three forms, which we characterize in terms of their *type* and *extent*.

- — The same type and extent whatever the uncertainty in the drivers—this is the rare but precious 'no regrets' decision, which may as well be taken regardless (subject to having a positive benefit–cost ratio). For example, it has been observed that the core rules for systematic selection of conservation reserves—the so-called CAR (comprehensive, adequate and representative) principles—remain the same under any future climate, since representing all environments in the reserve system is most likely to provide habitat for the maximum number of species even if these no longer occur in their current locations [48].
- — The same type but a different extent, depending on the uncertainty in the driver. Examples are the engineering temperature tolerance to be adopted for an electricity transformer in the face of an increasing risk of heatwaves and the height of a sea-wall relative to different sea-level rises.
- — A different type (and extent) in different future scenarios. For example, coastal defences in the form of barriers make sense up to a point, but beyond that point these will be maladaptive and coastal retreat policies may be preferred. In a smaller class of decisions, fundamentally different strategies must be chosen today according to different futures, as in the case of post-fire management in the Victorian alpine forests noted above [25].

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Table 2. Implications of different combinations of decision lifetimes, driver uncertainty type and adaptation response types for decision-making strategies and tactics under diverging climate futures.

	decision lifetime, relative to rate of climate change	type of driver uncertainty	type of adaptation response options	characteristics of decision-making about risk	some options available to reduce decision risk[a]
1	short- or long-term	monotonic or indeterminate	same type and extent of response under all scenarios	'no regrets': normal business planning to implement response cost-effectively	monitor to ensure no regrets response still suffices
2	short-term (easily reassessed)	monotonic or indeterminate	little divergence between scenarios over short-term means considering only one set of responses	ongoing, incremental adaptation in line with pace (and direction) of change	monitor rate of change to provide advanced warning of thresholds and need for transformation
3	long-term (implications may last for 50–100 years)	monotonic	same type but different extent of response for different scenarios	precautionary risk management: use benefit–costs analysis to determine appropriate level of response now	reassess regularly to ensure rate of change still in risk envelope; real options, safety margins, shortened decisions
4			different type (and extent) of response for different scenarios	risk-hedging against alternative futures (with gradual transfer of resources as uncertainty diminishes); act now, given monotonicity	high likelihood of need for transformation at some stage; reversible options, soft adaptations; shortened decisions often impossible
5		indeterminate	same type but different extent of response for different scenarios	robust decision-making paradigm in the face of uncertainty about direction of change	monitor change to identify if conditions are moving outside 'robust space'; reversible options, safety margins, soft adaptations, shortened decisions all useful
6			different type (and extent) of response for different scenarios	risk-hedging against alternative futures (with gradual transfer of resources as uncertainty diminishes); delay acting if possible	hardest combination: real options most likely to pay off if possible; likely to need support from higher levels of governance

[a] Abbreviated terms for some options from Hallegatte [8] and Dobes [49]: '*real options*'—conscious decision delay where benefits of improved information exceed risk of costs of delay; '*reversible options*'—favouring reversible and flexible options; '*safety margins*'—buying safety margins in new investments (e.g. bigger foundations pre-adapted to higher structures that are not yet built); '*soft adaptations*'—promoting changed behaviours and arrangements over physical infrastructure (e.g. reduced household water demand rather than a new dam); '*shortened decisions*'—reducing decision time horizons (e.g. housing with a short lifetime) within a long-term view.

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These three factors—decision lifetime, the nature of driver uncertainty and the form of adaptation responses—combine to require different approaches to risk management. They also highlight where the various risk mitigation tactics outlined by Hallegatte [8] are most likely to be applicable, as well as how to think about transformative as opposed to incremental adaptation now and at what institutional scale of decision-making. We now illustrate some of these implications summarized in table 2.

First (row 1 of table 2), where the adaptation response (same type and extent regardless of driver uncertainty) is no regrets, there is no reason to complicate decision-making any further. This is true for both short- and long-lifetime decisions, although decision-makers are probably already dealing successfully with the short-lifetime cases. We therefore devote no further space to these, other than noting that ongoing monitoring and reassessment are always required to ensure the decision space has not changed.

Second (row 2 of table 2), while short-lifetime decisions do face uncertainty, in general, future scenarios do not diverge much over the coming 10 years. In both monotonic and indeterminate cases, incremental adaptation is appropriate, reacting to change as it emerges. Where adaptation responses are of the same type, whether the drivers are monotonic or indeterminate, the extent of response can be gradually adjusted over time (e.g. gradually altering the choice of crop cultivar to plant). However, it is important to establish monitoring processes that provide plenty of lead time for when a more transformative change may be needed (e.g. when the regional climate moves outside the tolerance of any available cultivars), and this monitoring may require the involvement of a higher level of governance. Where adaptation responses may be of different types as change increases, there is likely to be a strong justification for deliberatively delaying decisions, applying the concepts of real options [49].

However, our main focus here is on long-lifetime decisions, given the increasing prospects of a 4°C world. Four combinations of driver uncertainty and adaptation response remain (rows 3–6 of table 2), and each requires different treatment.

- The key drivers may be monotonic, necessitating a variable extent of a fixed type of response; this is true for many aspects of setting design performance criteria and risk margins in engineering guidelines in the face of higher temperatures, and for standards such as concrete corrosion (e.g. [50,51]). For these decisions, risk management should adopt the precautionary principle, choosing a response extent (e.g. a new design extreme) through traditional benefit–cost analysis against the uncertainty in timing of change. Risks can be reduced by allowing extra safety margins where this is cheap to do, or deliberately shortening the lifetime of infrastructure where this is feasible and cost-effective.
- The key drivers may be monotonic, but such that different levels of change necessitate fundamentally different types of response. Examples include implementing incremental coastal defences up to some level of sea-level rise but then needing to consider planned retreat, or gradually adapting farming system practices and cultivars to a drying climate but eventually having to change land use (or location) all together. The example of post-fire management in the Victorian alpine forests given alternative future regional temperatures for trees establishing now, as noted above [25], also

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falls into this category. Risk-hedging in space against these alternatives (i.e. promoting different actions in different places) is an option to ensure that at least some coastal settlements or farming systems or conservation reserves are ready for whichever future eventuates. Over time, there can be a planned process through which resources are shifted towards whichever option looks more likely. This combination has certainty about direction of change, so that early action is likely to be economically sensible. As these examples show, this option is often associated with the need for early consideration of transformative adaptation. Risks can be reduced by adopting reversible options and soft adaptations that can be withdrawn if the future they were hedging against does not seem to be emerging. Early planning for transformation so that initial responses are compatible with this eventuality is also desirable. This will often require the intervention of higher levels of governance.

— The key drivers may be indeterminate, but nonetheless demand responses of a consistent type. Examples include the uncertainty over water supplies for many cities where rainfall may rise or fall. The response is still to manage supply against demand (usually in the context of increasing population), but the value of investing in expensive new infrastructure like dams or desalination plants is uncertain. Often risk management demands a robust decision-making paradigm, as illustrated for water utilities in California by Dessai *et al.* [10], making decisions that withstand alternative futures even if they are not optimal for any one of them. Ongoing re-assessment of change then allows the response to be finessed over time. Risks can be reduced in many ways. For water, risk can be reduced by investing in soft adaptations such as reducing water demand ahead of major infrastructure decisions. Where infrastructure investments are necessary, building in cheap safety margins or shortening the life of the infrastructure may be desirable.

— Finally, the key drivers may be indeterminate with very different response types needed under different futures. This is the hardest combination to deal with, and one where the possibility of consciously delaying the decision (‘real options’ analysis; e.g. [49]) is most likely to be cost-effective. An example is a major irrigation district that faces uncertainty in water futures. Even if rainfall decreases, increased storm intensity may result in more run-off and water storage. More irrigation water in the future may require agricultural expansion to help with food security whereas less water might mean the region moving out of agricultural altogether, decisions with major implications for investment in regional infrastructure. This category of decision is not common, although it will become of increasing concern as greater levels of global warming are contemplated.

We can only initiate this analysis here, but we argue it is a profoundly important and urgent issue to pursue, and to convert into guidelines for practice. Moving through table 2 from top to bottom, we anticipate a trend from adaptation options that could be seen as minor adjustments to ‘business as usual’ towards more transformative options. Where diverging climate futures require very different responses, there is likely to be at least one set of options that is transformative, and this possibility can be seen much more starkly through

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consideration of a 4°C world. By contrast, wherever adaptation decision-making (whether for short- or long-lifetime decisions) is currently conceptualized only as an issue for conventional business planning (i.e. designed to implement responses at the most cost-effective moment) the emphasis will be on building capacity and limited horizons, with little consideration of the effectiveness of actions against a dynamic and changing risk landscape. This mindset (which is legitimate and efficient for some decisions) is unlikely to be able to visualize the potential need for transformative adaptation, nor to be able to implement it effectively and efficiently. Evidence shows that many current societal adaptations are by-products of other activity [40], and so are unlikely to address the implications of a 4°C world.

Focusing on adaptation as a continual incremental process of adjustment is a useful means of helping decision-makers relate future climate change to current concerns and planning horizons. It also provides an easy means of 'selling' adaptation to stakeholders and thereby building capacity for future decisions. However, the approach does not cope well with larger climate changes or the possibility of very different responses under diverging climate futures.

Focusing on adaptation as a process that may involve 'continuous transformation', is more appropriate for decisions that may last into a 4°C world, although incremental steps may be required within the transformative approach. Flexible decision pathways that identify a wide range of adaptation options suitable for different extents of climate impact over different timeframes can provide the bridge between the incremental approach required for the pragmatic reasons of integrating with existing planning and management protocols, and the ability to learn and re-orientate as the future unfolds. Although pre-dating our analysis, the proposed flood risk-management plan for the Thames Estuary out to 2100 was developed through such an approach, as the following case study shows.

(*a*) *Case study: Thames Estuary 2100*

London and the Thames Estuary have always been subject to flood risk. Current high levels of protection are justified by the high value of the assets at risk. The Thames Barrier is one iconic feature of the current flood risk-management scheme. While the Barrier's original design allowed for some sea-level rise, it did not make any specific allowance for the range of possible climate changes. The Environment Agency set up the Thames Estuary 2100 project ('TE2100') to develop a Flood Risk-Management Plan for London and the Thames Estuary for the next 100 years [52,53].

Retrospectively, it is clear that the project was tackling a set of linked, long-lifetime decisions, mainly facing a monotonic driver in sea-level rise, but with a suite of adaptation responses available that varied from incremental (e.g. raised defences) to transformational (e.g. a completely new barrage location). TE2100 pioneered an approach to identifying adaptation options that specifically addressed the uncertainties in projections of future climate and development along the Thames River. The outcome was a set of adaptation options linked to different extents of climate change (see ch. 7 in [54] for further details); figure 3 illustrates the options produced in 2007. Each option consists of a decision pathway through the century to deal with different water-level rises. The pathway

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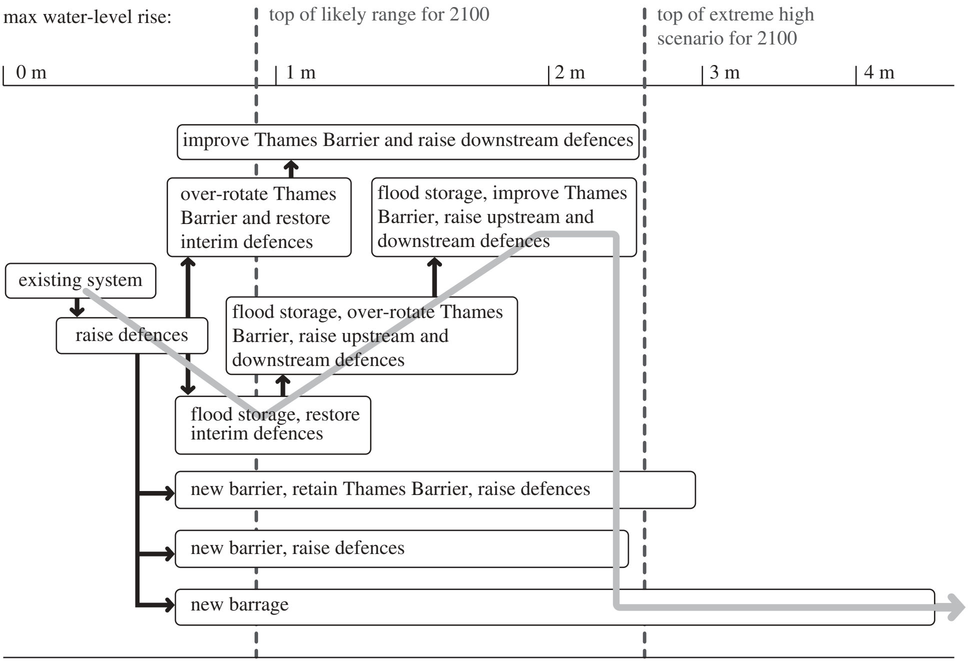

Figure 3. Adaptation options and a decision pathway for flood risk management in the Thames Estuary. The dashed lines indicate the extents of water-level rise projected for 2100 under different scenarios. The thick grey line shows one possible pathway for introducing different options to address rising water levels. This type of flexible pathway shows how incremental and transformative options can be combined. Adapted from Lowe *et al.* ([54], fig. 7.4). Boxes indicate measures for managing flood risk indicating effective range against water level.

can be adapted to the rate of change that eventuates. Planning decision lead times and consequence times created challenges, which were also explicitly addressed, with the timing of key decision points identified along the trajectory.

The TE2100 options were the subject of extensive stakeholder engagement, and subsequently formed the basis of the draft plan awaiting UK government approval in early 2010. In line with UK government guidance on climate change at the time, the plan focuses on a potential 1 m water-level rise over 100 years. It identifies the appropriate pathway to address that level of change, with actions for the short (to 2034), medium (to 2069) and long term (from 2070). Thus, the plan itself defines a set of incremental adaptation measures, rather than explicitly documenting the complexity of the underlying research. However, three important elements distinguish this approach from previous incremental analyses.

- Shorter term decisions are nested within a longer term framework that explicitly identifies key thresholds and options for dealing with much larger extents of change. (For example, 10 indicators for change will be formally monitored to identify if or when a switch to alternative options may be needed.)
- The plan allows for flexibility on the timing of introduction of different options and interventions, and the ability of the plan to change between options, based on the monitoring programme.

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— Detailed guidance is provided on how the recommendations contained in the plan should be applied in the event that more extreme change is realized; for example, if it becomes necessary to divert to an alternative adaptation pathway. This guidance also shows how lead times for major interventions need to take account of any such changes, and is underpinned both by the identification of key decision points and by the inclusion of the monitoring and review cycle.

The Thames Estuary case study provides one example of how adaptation decisions with long lifetimes can be assessed and framed in a way that can be absorbed in strategic planning. This includes, for example, safeguarding land allocations for future options, and considering whole of life costs for structures to justify higher initial costs that may provide benefits in terms of future flexibility, such as providing foundations now which could take higher barriers in future more cheaply than complete rebuilding.

Long-term development of physical (and ecological) infrastructure, and the organizations, institutions and policies that support it, usually occurs as the cumulative effect of many shorter term decisions (not least because these are demanded by political and financial cycles). The ability to 'nest' such short-term decisions within a longer term framework, which appropriately considers a range of possibly diverging climate futures, is likely to be critical in planning adaptation for a 4°C world. From this can emerge ongoing adaptive pathways that accommodate both incremental and transformational adaptation.

5. Conclusions

Given the prospects for a 4°C world, adaptation needs to be reconceptualized away from the incremental handling of residual risk to preparing for continuous (and potentially transformational) adaptation. One effect of contemplating projections with 4°C and more of warming is that the range of futures for planning long-lifetime decisions becomes greater and more uncertain, at least at first sight. These features are known to exacerbate psychological, cognitive and institutional barriers to action. We therefore show how it is possible to systematize an approach to the resulting decision-making challenges in ways that have the potential to reduce the disempowering impacts of uncertainty, by disaggregating the decision-making process into actionable steps that use well-established methodologies. To do this, we have shown how the lifetime of a decision interacts with the different types of uncertainty and the nature of potential adaptation responses. The resulting six categories of decision pathways require distinctive risk-management strategies and tactics, all of which are individually well understood.

Developing these ideas leads naturally into nesting decisions in scale, in terms of both time (thus creating adaptation pathways with continual re-evaluation) and process (such that more incremental and short-term decisions may be embedded within longer term transformational choices that define key decision points for reappraisal over time). These developments are well illustrated by the Thames Estuary case study, but require more systematization and absorption

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into decision-making at all levels of society. We have sought to advance this systematization here, recognizing that this can be developed and enriched much further.

This systematization aims to minimize the potential effects of various psychological, cognitive and institutional barriers on the decision-making process. While we have made the case that this outcome should follow, we present it as a hypothesis now more able to be tested with practitioners in the future. These barriers will not be entirely alleviated by a logical process alone and our approach needs translating and framing for any given institutional context. In practice, decisions about responding to climate change must be taken in the context of many other social and environmental changes, and may have trades-offs related to other decisions aimed at the more general achievement of sustainability. The further development and uptake of these ideas would thus benefit from building a set of practical examples that people can observe, a process that can be supported by governments at all levels. In this regard, the gradual emergence of case studies such as those noted in this paper is encouraging, and their systematization into frameworks such as that proposed in this paper to guide decision-makers in practice is an urgent task.

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The role of interactions in a world implementing adaptation and mitigation solutions to climate change

Rachel Warren

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REVIEW

The role of interactions in a world implementing adaptation and mitigation solutions to climate change

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The papers in this volume discuss projections of climate change impacts upon humans and ecosystems under a global mean temperature rise of 4°C above preindustrial levels. Like most studies, they are mainly single-sector or single-region-based assessments. Even the multi-sector or multi-region approaches generally consider impacts in sectors and regions independently, ignoring interactions. Extreme weather and adaptation processes are often poorly represented and losses of ecosystem services induced by climate change or human adaptation are generally omitted. This paper addresses this gap by reviewing some potential interactions in a 4°C world, and also makes a comparison with a 2°C world. In a 4°C world, major shifts in agricultural land use and increased drought are projected, and an increased human population might increasingly be concentrated in areas remaining wet enough for economic prosperity. Ecosystem services that enable prosperity would be declining, with carbon cycle feedbacks and fire causing forest losses. There is an urgent need for integrated assessments considering the synergy of impacts and limits to adaptation in multiple sectors and regions in a 4°C world. By contrast, a 2°C world is projected to experience about one-half of the climate change impacts, with concomitantly smaller challenges for adaptation. Ecosystem services, including the carbon sink provided by the Earth's forests, would be expected to be largely preserved, with much less potential for interaction processes to increase challenges to adaptation. However, demands for land and water for biofuel cropping could reduce the availability of these resources for agricultural and natural systems. Hence, a whole system approach to mitigation and adaptation, considering interactions, potential human and species migration, allocation of land and water resources and ecosystem services, will be important in either a 2°C or a 4°C world.

Keywords: climate change; integrated assessment modelling; adaptation; extreme weather events; ecosystem services; biodiversity

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One contribution of 13 to a Theme Issue 'Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications'.

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1. Introduction

The projections of climate change impacts under a 4°C mean global temperature rise contained in this volume, like most other assessments of future climate change impacts, generally consider impacts in each sector and region independently. Such projections often consider a set (or sets) of future socioeconomic futures, some of which may include a level of mitigation action. This is useful to indicate the levels of impacts that might occur, with and without mitigation, but the utility of such projections would be greatly improved by increased consideration of the interactions between sectoral and regional processes, including human adaptation to climate change impacts, as well as mitigation actions. Such interactions may have profound consequences for the future wellbeing of human and natural capital, particularly for global temperature rises as large as 4°C (relative to preindustrial levels). Many of these interactions are currently not considered, or not well integrated, into quantitative estimations of potential consequences of climate change, or of benefits of mitigation action. This is especially true given the potentially important feedback processes in the Earth system becoming evident through observations, yet not currently adequately simulated by global circulation models (GCMs). Such feedbacks could greatly exacerbate impacts for a given greenhouse gas emission scenario beyond those estimated by models.

This review provides a brief summary of some climate change impact estimates from this volume and elsewhere, comparing impacts under 4°C of global mean temperature rise (hereafter referred to as ‘a 4°C world’) with those under 2°C (hereafter referred to as ‘a 2°C world’). It discusses prominent examples of eight types of potentially significant interactions and the degree to which they have been handled in various modelling approaches. It does not, however, provide complete coverage of all types of interactions, or of all possible interactions within each type. It notes that these processes might be excluded from modelling exercises because of an inability to quantify the strength of the interaction, and also because of ignorance of the importance of interactions between disparate disciplines. It also suggests potential ways forward in modelling these interactions.

The types of interactions considered are:

- climate change-induced impacts in one sector affecting other sectors in the same region;
- human adaptation to climate change-induced impacts in one sector affecting other sectors in the same region;
- climate change impacts in one region having consequences for other regions;
- climate change mitigation and adaptation involving changes in land use, which then interacts in a complex fashion with climate change and its impacts;
- impacts in different sectors coincident in the same region having disastrous consequences therein;
- projected increases in extreme weather events exacerbating climate change impacts;
- interactions within sectors that are not combined in analyses; and
- feedback processes that could exacerbate climate change impacts.

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Table 1. Typology of IAMs focusing on their potential for representation of interactions between climate change impacts in various sectors, and between climate change impacts and mitigation/adaptation processes.

potential to represent interactions	none	low	high
question to which typically applied/ for which designed	cost–benefit analysis	scenario analysis or tolerable windows approach	scenario analysis
representation of climate change impacts	simple, either global (PAGE) or regional; sectoral detail only in FUND	look-up tables based on process-based model output	process based
representation of global economy	detailed	detailed	detailed
examples	FUND, PAGE, MERGE, DICE/RICE	ICLIPS, AIM	IMAGE, CIAS, GCAM

There are thousands of studies examining impacts on a single sector within a single region with no interactions. When considering impacts holistically at a global scale, Parry [1] provides one of the first studies providing a consistent assessment across global regions and sectors. This study used the full consistent set of SRES emissions scenarios [2], consistent downscaled climate scenarios and up-to-date climate and impact models.

Integrated assessment models (IAMs) were developed to encompass an interdisciplinary approach to the study of climate change and climate change policy. Goodess *et al.* [3] provide a full review and categorization of these models. A brief summary of the types of models is given here (table 1).

Biophysically based IAMs such as IMAGE, AIM, ICLIPS, GCAM and CLIMPACTS ([3] and references therein) variously examine sectors and/or regions of the world, spanning multiple disciplines, and thus theoretically allowing models to capture interactions between sectors. However, few have yet exploited their full potential to study interactions. Hence, table 1 refers to the *potential* for IAMs to represent interactions, rather than whether they actually do, or have done so. Representation of impacts varies significantly between these frameworks. In the case of IMAGE, they are detailed and include interactions such as carbon cycle-induced terrestrial vegetation die-back owing to climate change (leading to an accelerated rate of climate change), links between climate change, land-use change and changes to agricultural systems, and demographics [4]. In others, such as ICLIPS and AIM, look-up tables relating impacts to climate variables are used. This precludes detailed interaction between underlying impact model components. The CIAS integrated modelling framework [5] is designed to handle interactions between sectors.

Studies considering climate change impacts in a holistic fashion within or without an IA framework allow estimation of climate change impacts at a regional scale, and, in some cases, a relatively high spatial resolution. However, simple integrated models focusing on cost–benefit analysis provide only

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global-scale estimates. Such models typically represent climate change impacts as a combination of market and non-market economic damages, not in physical metrics [6], and do not consider the interactions listed earlier. Arguably, the most useful application of such models is in probabilistic analyses [7,8]. Such models use simple equations to detail the relationship between monetized impacts and temperature. The damage function shape used is theoretical and is often based on an arbitrary choice of function. Specifically, market damages are quadratic in DICE/RICE [9] and MERGE [10], between linear and cubic in a probabilistic fashion in PAGE, and take a variety of theoretical forms in FUND. Only FUND's damage functions take into account the rate of temperature change as well as its magnitude (in the agricultural and ecosystem sectors only). However, the representation of the climate system in some of these simple models often is not consistent [11] with that of the Intergovernmental Panel of Climate Change (IPCC) [12]; for example, FUND shows smaller temperature responses to reducing emissions than IPCC simulations, and PAGE assumes strong carbon cycle feedbacks. Modellers have updated their code to remove these inconsistencies [13,14]. While only FUND is sector-specific [7], interactions between sectors are not considered. Non-market damages are estimated through a willingness-to-pay approach, while only PAGE explicitly simulates adaptation [8]. Damage functions tend to be calibrated using studies of climate change impacts in the USA, scaled to represent impacts in other regions. In FUND, impacts cause only instantaneous damage, hence ignoring permanent loss of ecosystem services. Mastrandrea [6] discusses these issues in further detail.

Although some key insights about some interaction processes have been obtained from biophysically based IAMs (and these are highlighted in the review), only a small number of processes has so far been studied. This paper addresses this gap by considering a much wider range of potential interactions and their possible consequences.

2. Types of interactions

(a) *How impacts in one sector could affect another sector in the same region*

While some of the interactions between impacts in different sectors in the same location are commonly considered, others are not. Models simulating changes in crop yields generally take into account changes in precipitation and soil moisture, thus linking change in the agricultural and hydrological sectors. However, other interactions, such as the ways in which loss of ecosystem services affect human systems, are rarely considered. I attempt to divide interactions into those generally included in physically based modelling approaches and those rarely included. Table 2 summarizes the interactions discussed.

(i) *Some interactions between sectors affected by climate change that are generally covered in physically based impact models*

Hydrology has a strong interaction with agriculture through water availability. However, the relationship between (daily) precipitation and soil moisture is not constant and, therefore, hydrological processes need to be, and often are, incorporated into process-based models designed to simulate climate

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change impacts upon agriculture. Models such as CERESWheat [15] simulate physiological processes in plant development, growth and evapotranspiration, using detailed soil composition data to derive water availability. They underlie prominent analyses of global and regional climate change impacts on agriculture [1,16]. Other models relying on the hedonic method [17,18] assume that projected future regional precipitation and temperature may be used as proxies for agro-economical output. Here, the relationship between precipitation and soil moisture is assumed constant and hence hydrological processes are ignored [19].

Impacts on agriculture affect human health, largely through the potential for malnutrition, and hence a few studies have estimated millions at risk of hunger resulting from climate change impacts on crops [1,4,20]. Here, changes in yields produced by CERES crop models are aggregated to generate national cereal production estimates for input to a world food trade model that balances demand and supply of food according to *per capita* gross domestic product (GDP). However, most studies only provide estimates of yield reductions, without analysing changes in production or trade [21].

Changes in hydrology can also directly affect human health, through mortality (which tends to fall with rising GDP [22], water stress or loss of livelihoods), and hydrological changes are used in estimating potential future millions of people at risk of water stress [23,24]. Similarly persons at risk from fluvial and coastal flooding have been estimated using detailed spatially downscaled projections of future populations [1,25].

The impacts of sea-level rise upon coasts will interact with coastal ecosystems causing globally significant losses of coastal wetlands, saltmarsh and mangroves (e.g. [26,27]). It will also interact with the agricultural sector through inundation, with case studies illustrating effects in a number of vulnerable regions (e.g. [25,28,29]) and for the globe as a whole [30]. However, standard approaches to the simulation of agriculture impacts (e.g. [1,20]) do not include losses owing to salinization or inundation.

(ii) *Some interactions between sectors affected by climate change that are generally not included in physically based impact models*

Loss or disruption of natural ecosystems can lead to a breakdown of ecosystem functioning, leading to a loss of ecosystem services [32]. The large proportion of species is at risk of extinction from climate change (e.g. 40% of species studied in a 4°C world; table 3); together with the effects of increased extreme events, such as drought and forest losses due to fire, this means that such services are at risk. These include the water purification provided by wetlands, the purification of air provided by forests, the protection of coastal areas from storm surges by mangroves and coral reefs, the regulation of pests and disease, the recycling of waste nutrients and the removal of carbon from the atmosphere [32,33].

In the USA, at least half of the medicines used today derive from natural sources and 116 out of 158 new drugs licensed between 1998 and 2002 were derived from natural origins [34]. However, only 1 per cent of known plants have been analysed for their potential use in medicine. Animals and microbes also make vital contributions, and the exploration of the potential of marine organisms is

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Table 2. A variety of examples of cross-sectoral interactions: x-axis—driving sector, which incurs climate change impacts directly; y-axis—the incumbent sector, which incurs impacts indirectly as a result of the changes in the driving sector. Each example is followed by a (y) or an (n) indicating whether the driving sector impact has been quantified at all; secondly a (y) or an (n) indicating whether the effect of the interaction upon the incumbent sector has generally been included in physically based quantitative assessments of the impacts of climate change on the incumbent sector. Indirect effects that impact upon the incumbent sector as a result of human adaptation to impacts in the driving sector are also included.

driving sector → incumbent sector ↓	hydrology	agriculture	coasts	terrestrial ecosystems	oceans	biodiversity	human health
hydrology	* * * * *	adaptation to impacts increasing demand for water (n, n)	—	changes in biome type affect soil moisture content and evapotranspiration rates (some y, n)	—	as for terrestrial ecosystems	—
agriculture and food	water stress reducing crop yields (y, y)	* * * * *	farmland loss owing to sea-level rise and salinization (y, n)	loss of carbon from soils (y, n)	—	loss of pollinators (some y, n); loss of wild crop types (y, n); pests and diseases (some y, n)	—
coasts	changes in nutrient levels in estuaries (n, n)	agricultural intensification leading to increased nutrient run-off (n, n)	* * * * *	—	—	changes in coastal ecosystems (y, n)	—

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terrestrial ecosystems	changes in hydrology affect soil moisture content and evaporation rates (y, y)	land conversion owing to shifts in agricultural production (some y, n)	loss of saltmarsh and mangroves to sea-level rise (y, y)	∗∗∗∗∗	—	loss of keystone species (some y, n)	spread in mosquito-borne disease may encourage use of DDT (n, n)
oceans	—		—	declines in migratory freshwater fish (y, n)	∗∗∗∗∗	changes in marine productivity	
biodiversity	declines in species (some y, some y); construction of dams disrupts freshwater ecosystems	agricultural intensification reducing biodiversity (n, n)	loss of coastal wetlands (y, n)	changes in net primary production affect competition (e.g. savannah/scrub, lianas/trees) (some y, some y)	loss of calcifying species, potential disruption of marine ecosystem, in particular (n, n)	∗∗∗∗∗	declines owing to DDT use (n, n)
human health	water stress (y, y); construction of dams can lead to outbreaks of disease such as malaria and schistosomiasis (n, n)	malnutrition (y, y)	saltwater intrusion threatening water supplies; potential for disease post-coastal flooding (n, n)	loss of ecosystem services, e.g. C sinks, water purification, coastal protection; soil erosion, nature deficit syndrome (some y, n)	loss of fish stocks, loss of livelihoods of persons dependent on coral reef fish (y, y)	loss of medicinal plants (n, n); spread of infectious disease (y, y)	∗∗∗∗∗
settlements and infrastructure	subsidence (n, n); construction of dams can lead to inundation of settlements (n, n)	—	damage owing to storm surges (y, y)	—	—	—	—

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Table 3. Some projected quantitative estimates of climate change impacts at 4°C about preindustrial levels under the A1B scenario in the 2080s taken from this volume and elsewhere.

impact sector	projections at 4°C above preindustrial	projections at 2°C above preindustrial	sources
hydrology	15% world population exposed to water stress; 840 million people experience increase in water stress globally; increase from present-day 1%, to future 30%, of global land area experiencing drought at any one time	410 million people experience increase in water stress globally; water stress reduced compared with 4°C in most river basins; in a small number where this is not so, benefits offset by changes in seasonality	[27,46,92]
agriculture and food	50% of land on which crops currently grown becomes unsuitable for cultivation; 15% of the globe's dry land currently suitable for cultivation becomes unsuitable; 20% of globe's colder lands become suitable for cultivation; limited adaptation options in sub-Saharan Africa; threats to food security	32% of land on which crops currently grown becomes unsuitable for cultivation; carefully planned adaptation could maintain food security in sub-Saharan Africa	[27,47]
coasts	sea-level rise of 0.5–2.0 m if occurs in 2100 (range includes accelerated ice melt); for median sea-level rise of approximately 0.47 m in 2100, i.e. excluding accelerated ice melt (www.avoid.uk.net), more than 30-fold increase in population experiencing coastal flooding	low risk of accelerated ice melt; for median sea-level rise of approximately 0.35 m in 2100, i.e. excluding accelerated ice melt (www.avoid.uk.net); about a 15-fold increase in population experiencing coastal flooding	[25,27,87, 90]
ecosystems	functional extinction of coral reef ecosystems (converted to algal mats); risks of extinction to approximately 40% species studied globally, including losses of iconic species and associated ecotourism; disruption to functioning of major global ecosystems, Arctic and salvanization of Amazon rainforest; conversion of terrestrial carbon sink to a source exacerbating climate change; large increase in boreal and Mediterranean fire frequency; 50% of protected areas cannot fulfil objective; major widespread loss of ecosystem services worldwide	all coral reefs bleached; risks of extinction to approximately 20% of species studied; some increases in fire frequency; damage to Arctic ecosystem functioning; ecosystem services reduced in some areas; Amazon forest largely intact	[32,43,46, 80,93]

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oceans	further mean acidification by 0.26 pH units (in addition to the present-day change of 0.1 units); risk of disruption to marine ecosystems; risk of localized ocean anoxia	further acidification by up to 0.07 pH units; some damage to marine ecosystems	[89,94,95]
extreme weather	50% flood-prone people exposed to increased hazard; flood-affected population rises to 544 million annually (as defined by those experiencing a present-day 1 in 100 year flood)	25% flood-prone people exposed to increased hazard; flood-affected population rises to 211 million annually	[27,96]
human health	health hazards increasingly difficult to control	hazards reduced	[51]
impacts of feedback processes in the Earth system	loss of terrestrial carbon sink and hence large-scale loss of forests via dessication and fire (potentially including up to 50% Amazon (excluding deforestation) and uncertain fraction of boreal forest)	much reduced risk of loss of terrestrial carbon sink; Amazon likely to remain largely intact	[32,52,77,89, 93,98,99]

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just beginning. Hence, climate change impacts on ecosystems may threaten our future ability to protect human health, especially as pathogens evolve resistance to current treatments.

Disturbance to forests in proximity to human habitation can lead to increased prevalence of disease. For example, Olson *et al.* [35] identified a 48 per cent increase in malaria incidence associated with a loss of 4.3 per cent of forest cover in a 3 year period. This can be via a reduction in populations of the disease vector's predators, or because of changing environmental conditions allowing them to outcompete benign related species [36]. Modelling these interactions into the future needs to be a priority for future research.

A significant proportion of the world's population is entirely dependent on fish. Cheung *et al.* [37] report on dramatic turnovers in fish assemblages for climate changes well below 4°C, particularly in the Arctic and Antarctic, potentially disrupting ecosystem functioning and numerous local extinctions in the subpolar regions, the tropics and semi-enclosed seas. Communities particularly at risk from changing fisheries resources are on small reef islands on the rim of atolls such as the Maldives [25].

Important linkages between climate change impacts on ecosystems and those upon agricultural and other systems are generally omitted from impacts assessments. For example, as bioclimatic envelopes of pest and disease vectors change, new pests and diseases may invade systems, requiring new disease-resistant crop varieties to maintain agricultural productivity [38]. Wild crop genotypes are an important resource yet climate change impacts upon these have only recently been considered [31]. However, quantifying potential risks to food production owing to loss of wild crop genotypes is not currently feasible. Several recent studies consider crop damage owing to pests in future decades [21] and highlight the importance of interactions between CO_2 concentrations and temperature, and precipitation in determining the size of these effects. It would be useful and feasible to explore ways to combine such projections with global agricultural models of climate change impacts on crops, which typically omit impacts of pests.

While many of the world's staple crops reproduce vegetatively, or via wind pollination, many others rely on pollinators. Over 80 per cent of the 264 crops grown in the EU depend on insect pollination [38]. However, few pollinator distributions have been modelled in relation to climate change. Quantifying potential risks is difficult because limited information exists on the relationship between crops, their pollinators and climate change. It is recommended to collect such information and carry out bioclimatic or ecophysiological modelling of species, or species groups, identified as the key pollinators in relation to their crops. Much more severe and more difficult to model are the potential interactions between wild species and pollinators.

(*b*) *Interactions mediated by human adaptation to climate change*

A key interaction omitted from modelling approaches is that between impacts in one sector and adaptation by humans to impacts in another sector. For example, there are potential consequences to health and ecosystem sectors resulting from human adaptation in agricultural, hydrological and coastal sectors.

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Human adaptation to climate change-induced water stress can include anything from local collection of rainwater on buildings through the building of dams to unsustainable increases in groundwater abstraction. Dam construction can damage wetlands, inundate forests and may encourage reproduction of disease agents by concentrating them in lakes close to human habitation, as has occurred in Burkina Faso, Sudan and Egypt for schistosomiasis and malaria [36].

Even for small amounts of climate change it will become infeasible to continue to grow presently used crop varieties in tropical or desert areas where crops are already grown close to their thermal limits. By 4°C, crops in many regions are projected to be affected and adaptation over potentially large parts of the globe may be needed (table 3). This could include switching to new crop types, installing irrigation systems, agricultural intensification, shifting agricultural lands to new areas and/or the use of genetically modified crops resistant to future climates [1,4,17,20]. Changes to irrigation practices may exacerbate water stress and may reduce water supplies to wetlands, which themselves provide key ecosystem services. Agricultural intensification can have negative impacts, including increases in nutrient run-off into rivers and estuaries, where it may cause local anoxia and contribute to greenhouse gas emissions of N_2O [12]. The wholesale shifting of agricultural lands has profound implications, as discussed below.

Human adaptation responses to sea-level rise range from managed retreat, building of dykes and construction of flood barriers [26]. It is widely reported to be cost-effective to protect major cities against a sea-level rise of up to 2 m, but this, as the authors acknowledge, is only a partial analysis. The coastal protection considered only safeguards cities and does not protect coastal infrastructure away from cities, which may be extensive, nor does it avoid large-scale loss of coastal wetlands, mangroves and saltmarshes. Building of dykes to protect towns may be to the detriment of associated natural ecosystems [39], such as mangroves and saltmarshes where many marine fish species spawn. Such ecosystems also protect coastlines against storm surge and tsunamis [40]. Hence, cost-effectiveness analyses for coastal protection need to include losses of these ecosystems and the consequences for fisheries and coastal infrastructure.

This volume contains some of the few studies of climate change impacts considering climate change as great as 4°C. Table 3 collates some of the estimates appearing in this volume and elsewhere and compares them with estimates of impacts at 2°C. Several of these estimates are taken from the AVOID project [27]. Considering the large impacts in the agricultural, hydrological and ecosystem sectors expected in a 4°C world, future use of land and water would need to be carefully planned, taking into account the needs of humans, agriculture and ecosystems and their services.

In this context, limits (physical or financial) to simultaneous adaptation in multiple sectors need to be considered. The global cost of adapting to climate change from 2010 to 2050 (2°C) has been estimated to be $75–100 billion *each year* [41]. In the agricultural sector, Easterling *et al.* [21] estimated that climate change damages to wheat, rice and maize could be avoided by adaptation up to a limit of a temperature increase of 1.5–3°C in tropical regions and 4.5–5°C in temperate regions. Temperature changes of between 4 and 8°C are projected in the summer across various temperate and tropical regions for a global 4°C temperature rise [42]. This suggests that these adaptive capacities might be

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exceeded, especially in the areas with the larger temperate rises such as the USA, the Mediterranean and many parts of Africa [42]. Many of these studies do not include damage caused by concomitant increases in tropospheric ozone and extreme weather events, and so the estimated adaptive capacities might be over-optimistic. For ecosystems, while adaptation to a 2°C world is considered feasible, the options for adapting, either naturally or with human assistance, to a 4°C world are extremely limited, since at these temperatures few ecosystems would be expected to be able to maintain their current functioning [43].

(c) *Cross-regional interactions*

The mechanism by which climate change impacts in one region affect another can be direct, in which losses of human or natural capital in one region affect human or natural capital in another region, or indirect, in which the mechanism is via mitigation or adaptation practices taking place in one region having consequences for another. Declining agricultural yields in a given region can result in increased demand to import food from other areas. Such changes in supply and demand affect food prices globally [1,4,20].

Migration is already occurring away from some areas in response to desertification (Egypt) and flooding (Mozambique and Vietnam; [44]). Two billion people live in arid, semi-arid and sub-humid regions that are extremely vulnerable to water supply loss [45]. One-third of the world's population live in areas already under water stress, with the area of the planet subject to drought at any one time projected to dramatically increase ([46]; table 3). Some of these water-stressed areas are expected to become agriculturally or agro-economically non-viable. Table 3 shows the large numbers of people (some 800 million) exposed to increasing water stress, and 50 per cent of global cropland projected to become less suitable or unsuitable for cultivation in a 4°C world. In sub-Saharan Africa migration to highlands is a likely consequence [47]. Migration may be inevitable in areas where climate change will have a detrimental effect on already water-stressed agricultural areas such as northeastern Brazil [48]. Coastal systems currently hold some 40 per cent of the global population, and there is increasing immigration into these areas [25]. However, sea-level rises of 0.5–2.0 m are expected in a 4°C world (table 3). One estimate of climate change-induced migration suggests that 1.4–6.7 million Mexicans could migrate to the USA as a direct result of climate change-induced crop failure by the 2080s [49]. Estimates from empirical data about past climate variability and migration rates showed that a 10 per cent reduction in Mexican crop yields would lead to 2 per cent of the Mexican population emigrating. With larger reductions in crop yields projected for many parts of the world, notwithstanding the unique cross-border circumstances, this raises the potential for substantial human migrations, raising concerns about international stability [50]. Large-scale migration will also have impacts such as demand for land and water in the regions into which they move, not included in current assessments of impacts. This will be particularly important in a 4°C world. The synergy of these impacts shown in table 3 could induce dramatic changes in where people live and practise agriculture. Hunger, starvation, conflict and population movement may be widespread [51].

There has been little study of the potential mechanisms for cross-regional interaction in modelling exercises and a process-based simulation of migration is almost certainly infeasible owing to the complex nature of personal

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migration-related decision-making [52]. Rather, a scenario-based approach to possible future migration patterns is recommended, so that climate impact projections, already dependent on future downscaled population projections (e.g. [1]), can be made consistent with scenarios for population movement.

An estimated 50 per cent of the impacts on water stress and crop suitability could be avoided by constraining climate change to 2°C (table 3; [27]). In this situation, the potential for large-scale migration and displacement agriculture will therefore be less and potentially more likely to remain within the adaptive capacity of the human and natural systems concerned.

(*d*) *Climate change mitigation and land-use change*

Changes in land use can have large impacts on the global and local climate. For example, deforestation releases carbon from removed vegetation and soils, and the surface albedo changes significantly. Forests such as the Amazon 'recycle' their water and hence forest loss can contribute to drying [53]. Climate change mitigation could involve significant reductions in deforestation as this is regarded as one of the most cost-effective methods of reducing emissions, and there is widespread consideration of the introduction of a political mechanism for so-doing (Reducing Emissions from Deforestation and Degradation; REDD).

However, human adaptation to climate change impacts might induce shifts of agriculture away from drying areas and into areas currently covered by forests. Hence, projections of impacts on ecosystems might be exacerbated by further conversion of natural ecosystems to agricultural systems (table 2). This can have additional implications for human health, by creating conditions under which disease vectors thrive close to human habitation [36].

Afforestation can also contribute to climate change mitigation through carbon sequestration, with positive or negative implications for biodiversity and ecosystem services. Attempts to create forests in areas currently supporting high non-forest biodiversity, or by using non-native tree species, can have a negative impact on native biodiversity, and may not succeed since soils may not be suitable. Planting of native trees in previously degraded or deforested areas is beneficial to biodiversity and ecosystem services, and can enhance connectivity in forest ecosystems, aiding in adaptation [43]. Benefits of afforestation accrue slowly over the long time scales required to recapture the carbon lost from an area that has originally been deforested [54]. For this reason, 1 ha of afforestation does not effectively compensate for 1 ha of deforestation and this is an important factor in the interaction of climate change mitigation and land-use planning.

A 4°C world would induce changes in the distribution of the human population, its diet, its agricultural systems and its ecosystems, concentrating all three in areas remaining sufficiently wet. The study of these interactions is still in its infancy. IMAGE has been used to explore agricultural trade liberalization in the context of climate change, showing how it would encourage expansion of agricultural land in Latin America and southern Africa, increasing pressure on ecosystems [4]. The cost of reaching 2050 emissions reduction goals (80% lower than 2000 levels) could be cut by 50 per cent if agricultural production transitioned from meat-based to plant-based diets, based on the abandonment of 2700 Mha of pastureland and also from reductions in greenhouse gas emissions from agriculture [55]. Efforts to assist natural ecosystems to adapt to climate

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change include enhancing connectivity between areas. Spatial planning issues connected with planned adaptation in agricultural and human systems will need to be integrated with adaptation of ecosystems and ecosystem services.

Stringent mitigation of greenhouse gas emissions will require large-scale deployment of renewable energy generation and/or biomass cropping. Both of these have significant interactions with land use. For biofuel or biomass cropping, the land required for this must displace either agricultural land, marginal land or natural ecosystems [56]. This displacement of agricultural land may be increased by the negative climate change impacts on sugarcane yields [57]. Displacement of agricultural land will influence world food supply and prices, as has already occurred during the food price crisis of 2007/2008 [58], and will have impacts for risks of malnutrition. Holistic management of both fossil fuel emissions and the terrestrial biosphere through expansion of forests and unmanaged ecosystems would lower mitigation costs [59], but food prices could rise owing to the pressure on agricultural land. If, instead, shifting (adapting) agricultural systems causes deforestation or unmanaged ecosystem loss, this will reduce the resilience of ecosystems to climate change. Similarly, biofuel cropping, nuclear power plants and carbon capture and storage plants all require large amounts of water. Thus, mitigation efforts have potential complex interactions with climate change impacts on agriculture and ecosystems.

Key interactions also occur between climate change and the operation of renewable energy in the future, and between land-use planning and the siting of renewable energy plants. A major benefit of mitigation is the protection of vulnerable people and ecosystems from climate change, and unintentional negative impacts of renewable energy schemes can be prevented by careful siting of plant. Deployment of renewable energy, nuclear power, and carbon capture and storage schemes needs to be planned around future climates, rather than making an assumption that current wind, water or solar resources will be available for some decades in the same location in the future. Careful assessment can avoid potential ‘mal-mitigation’ where mitigation efforts could either fail entirely or produce largely avoidable local negative side effects.

(*e*) *Regionally coincident impacts*

Spatially coincident impacts in different sectors could have a disproportionate effect on the human population and ecosystems of a given region. Many climate change projections refer to large regions, while on the ground a diverse pattern of gains and losses may exist within an overall picture of regional loss. However, impacts that occur in the same region, even if not precisely spatially coincident, may have a disproportionate effect on a region’s economy owing to multiple stresses placed upon the system. The IPCC [46] reports on coincident hunger, sea-level rise and water resource scarcity impacts in Asia; and coincident water stress and malnutrition in Africa. Since most of the literature assessed by the IPCC [46] refers to global temperature rises of less than 4°C, such coincident impacts would be expected to be much more widespread and severe in a 4°C world.

(*f*) *Extreme weather events*

In the coming decades, one of the most serious impacts of climate change is projected to be the consequences of the projected increases in extreme weather events. For example, climate change-induced changes in precipitation

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patterns and changes in climate variability would increase the area of the globe experiencing drought at any one time from today's 1 per cent to a future 30 per cent by the end of the twenty-first century [46]. An increasing number of studies now project global trends in how extremes will change in the future using GCM and/or regional climate model (RCM) output (e.g. [60,61]). However, uncertainties in these projections are large, particularly for precipitation, with some changes of opposite sign. Some studies have focused on the regional uncertainties of projecting extremes, in particular for projection of increased European drought (e.g. [62,63] and references therein). Limited work exists for other continents.

Few studies examine the potential consequences of these increases in extreme weather upon individual sectors and/or regions, but these could be significant. Only a few days of high temperatures near flowering in wheat, groundnut and soybean can drastically reduce yield [64], while maize losses could potentially double owing to floods in the USA [65]; and the AVOID study [27] estimated that, in a 4°C world, 50 per cent of fluvial flood-prone people would be exposed to increased flood risk compared with approximately 25 per cent in a 2°C world.

Biophysical IAMs and other regionally and sectorally specific climate change impact models can simulate changes in the frequency and the intensity of extreme weather events if:

- the impact model is formulated to take account of, for example, the effect of continuous periods of dry days or dry months (for long-term drought), or the number of days over which temperatures exceed a particular threshold (for heatwaves), or daily time series of rainfall (for heavy precipitation events). Many process-based physical impact models require climate inputs in the form of a daily time series. Simple IAMs are not capable of representing such processes in detail, although PAGE attempts to provide a scenario that accounts for increases in extremes. Cumulative distribution functions might be constructed from statistical relationships between extremes and predictor variables used in these simple IAMs [3], enabling them to better represent the impacts of extremes.
- the climate change projections provided to the model are at the appropriate temporal resolution (monthly for droughts, and daily for most other extreme weather events), and include projected increases in extremes. Considering probability distributions (pdf) of climatic parameters, extreme events may increase for: a shift in the mean climate; a shift in the variance; or an increase in its skewness. For example, monthly future climates can be produced by pattern-scaling GCM outputs as in SCENGEN [66], after which a weather generator derives a daily time series. In these studies, changes in the frequency of extreme weather events can only occur as a result of changes in mean climate and as a result of changes in variability or skewness. However, the approach can capture long-term droughts since the monthly changes in precipitation derived from the GCM patterns are incorporated in the analyses [63]. New approaches in ClimGEN and/or the further development of weather generators may allow representation of changes in variability and/or skewness in biophysical IAMs [3,66,67].

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(g) Interactions within sectors generally not combined within analyses

Dynamic global vegetation models (DGVMs) and bioclimate envelope models are commonly used to project climate change impacts on ecosystems. DGVMs consider the cycling of biomass, carbon, nutrients and water between ecosystems and the atmosphere, using detailed land-surface schemes that capture interactions in detail [68]. However, they model ecosystems as plant functional types and do not consider responses of individual species. In contrast, bioclimatic models use empirical statistical correlations between meteorological variables and species presence [69,70] to derive predictors for species distributions. Such predictors appear to work well at large scales—with precipitation and temperature variables being tied to direct and indirect processes.

However, DGVMs treat ecosystems simply as a functional type, so that impacts on biodiversity are not adequately assessed, while the bioclimatic envelope approach is generally applied to one species at a time and interactions between species are not considered. A few studies examine the combined effects of climate change on plants and their pollinators [71] or on predators and their prey, or on how the spread of disease might induce extinction of some species (e.g. [72]). Attempts by one species to survive a changed climate by moving to higher latitudes and altitudes might result in that species becoming invasive in the new environment it has colonized. However, for the majority of species, the effects of climate change on such interactions have not been considered, and this is potentially significant in terms of unforeseen disruption to ecosystem functioning [73].

Climate change impacts to forest trees have been estimated by both DGVMs and bioclimatic models (e.g. [67,74,75]), while at the same time other models are used to project future incidence of forest fire (e.g. [76–78]), while still others simulate outbreaks of pests [79]. In a 4°C world, soil carbon cycle feedback processes are projected to lead to widespread forest loss, especially in the Amazon (e.g. [78,79]). These simultaneous effects have not yet been combined in any quantitative analysis, but overall must lead to a more pessimistic view.

Climate change impacts on species have been widely calculated (Warren *et al.* [80] present a meta-analysis), but there are only limited studies on keystone species that affect overall ecosystem functioning. For example, potential declines in krill, a keystone species in the Southern Ocean, have been identified [81] and this will have impacts on many other species. Ocean acidification threatens the potential for coral reefs, coccolithiphores, molluscs and other shell-forming ocean inhabitants to survive [82,83]. Only for coral reefs has this research been combined with impacts of increases in sea surface temperature in projecting thresholds for survival [84]. Changes in marine productivity might well be expected as the ocean acidifies, and the consequences of this are unknown [46]. Similarly, projected climate change impacts on fish [37] include climate change impacts on larval dispersal but omit loss of nursery habitat.

In agricultural systems, the wide range of studies reviewed by the IPCC [46] variously include CO_2 fertilization effects (in some cases with appropriate treatment of uncertainty therein), methods of adaptation, the potential for agriculture to move to new areas and global trade in crops. However, no single approach incorporates all of these features. As mentioned earlier, it would be useful to explore how climate change-induced projected increases in outbreaks

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of agricultural pests and diseases could be incorporated in agricultural models. Increases in fossil fuel burning also lead to increases in tropospheric ozone levels that damage crops and trees—also not generally included in models assessing climate change impacts on agriculture or ecosystems [1,20,85]. However, increases in tropospheric ozone and their impacts on crops and trees have been projected independently (Felzer *et al.* [86] review recent studies) and it would not be difficult to combine such models. Tropospheric ozone also damages human health, highlighting the need to combine assessments of climate change damage with those of the air pollution resulting from the emission of the same pollutants.

(*h*) *Feedback processes in the Earth system*

While many feedback processes are represented in global climate change models and thus indirectly in the simple models emulating them, recent observations are showing that some processes, in particular the melting of Greenland and West Antarctic Ice Sheets and the Arctic sea ice, are proceeding more rapidly than in models [87,88]. This indicates that the Earth may be more sensitive to the current levels of warming than GCMs are projecting. A more significant potential feedback is the release of marine methane hydrates. This could result in a progressive release, over a 1000–100 000 year time scale, of about twice the amount of fossil fuel carbon emitted [89]. The potential release rate on shorter time scales has not been estimated but could exacerbate warming, as could the currently increasing release of methane from permafrost [90]. Other feedback processes such as changes in albedo as a result of climate change-induced forest dieback, or increased desertification, are included in some GCMs [53]. However, some climate change impacts such as losses of forest owing to pine-bark or spruce-budworm attack, in combination with increased incidence of fire, might alter albedo in some areas. Such an interaction could usefully be modelled. As knowledge about the processes underlying feedbacks in the Earth system improves, they can be included in GCMs and thus be reflected also in projections of climate change impacts. Finally, climate change impacts are projected to cause reductions in economic growth, with estimated losses depending on the assumed discount rate, and rising as high as 5–20% of GDP [91]. Such losses might reduce anthropogenic greenhouse gas emissions: an effect potentially much larger than any increase in emissions caused by additional demand for air conditioning. However, models that provide integrated assessment of climate change impacts and the economy [1] generally represent climate change impacts poorly and usually omit Earth system feedback effects entirely [6].

3. Discussion

Table 3 shows that a 4°C world would be facing enormous adaptation challenges in the agricultural sector, with large areas of cropland becoming unsuitable for cultivation, and declining agricultural yields. This world would also rapidly be losing its ecosystem services, owing to large losses in biodiversity, forests, coastal wetlands, mangroves and saltmarshes, and terrestrial carbon stores, supported by an acidified and potentially dysfunctional marine ecosystem. Drought and desertification would be widespread, with large numbers of people experiencing

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increased water stress, and others experiencing changes in seasonality of water supply. There would be a need to shift agricultural cropping to new areas, impinging on unmanaged ecosystems and decreasing their resilience; and large-scale adaptation to sea-level rise would be necessary. Human and natural systems would be subject to increasing levels of agricultural pests and diseases, and increases in the frequency and intensity of extreme weather events.

In such a 4°C world, the limits for human adaptation are likely to be exceeded in many parts of the world, while the limits for adaptation for natural systems would largely be exceeded throughout the world. Hence, the ecosystem services upon which human livelihoods depend would not be preserved. Even though some studies have suggested that adaptation in some areas might still be feasible for human systems, such assessments have generally not taken into account lost ecosystem services. Climate change impacts, especially drought and sea-level rise, are likely to lead to human migration as people attempt to seek livelihoods elsewhere.

This paper has highlighted the further challenges presented by the interactions between climate change impacts, in which coincident or interacting impacts within and between sectors and regions may present a greater challenge than the sum of the challenge of adapting to each impact in each region if these were independent. It has drawn attention to the interaction between human adaptation processes and impacts in various sectors. Importantly, it has also highlighted the interaction between climate change impacts upon terrestrial and coastal ecosystems and human sectors such as agriculture and human health. These interaction processes will increase as their drivers increase, and will be much more significant in a 4°C world than in a 2°C world.

Were global average temperatures to rise by 2°C and not increase further, some 50 per cent of the impacts to human systems could potentially be prevented (table 3 and [27]), and ecosystem services would, in large part, be expected to be generally preserved (table 3). While some areas would experience drying, as table 3 shows the impacts on agriculture and hydrology, and sea-level rise, would be expected to be much lower than in the 4°C case, and similarly the challenge to adaptation to these effects and their interactions would also be much lower. Local-scale damage to some ecosystems, including extinctions, and disruption to coral reef and ice-based ecosystems would still be expected, but the worst losses might be prevented. Conservation planning might be able to assist with the adaptation of natural ecosystems to this level of temperature rise.

The role of land-use change at the nexus between climate change mitigation and adaptation and agricultural and natural ecosystems has been highlighted, with particular reference to biofuel cropping, agricultural intensification and diet. The spatial planning of land use when attempting to simultaneously adapt agricultural, human, coastal and natural ecosystems to a changing climate, with or without significant mitigation, has been highlighted as very important. This will be particularly important for mitigation planning when aiming for a 2°C world. Such an approach might be termed ‘ecosystem-based mitigation’.

Only a limited proportion of these interactions is currently captured by modelling processes, in particular the simple IAMs commonly used for cost–benefit analysis. While some interactions appear too uncertain to capture within models (e.g. with human migration), there is a need to represent others, especially the possible consequences of large-scale adaptation. Process-based IAMs such as

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IMAGE, CIAS and GCAM are best prepared to assess these interactions and IMAGE and GCAM have already been applied to examine some of the links between land-use change, climate change and agricultural systems.

As climate changes, the drier regions of the planet are projected to become less and less habitable owing to increases in drought and desertification. Many humans and ecosystems would be expected to be forced to adapt by attempting to move into areas remaining sufficiently wet and not inundated by sea-level rise. This would result in a concentration of the human population, agriculture and remaining biodiversity in a contracting land area, leading to increasing competition for land and water. Integrated models could usefully be applied to determine when land and water supplies may become insufficient to satisfy the needs of human systems and the ecosystem services (such as wetlands, forests and biodiversity in general) supporting livelihoods.

4. Conclusion

This paper has highlighted the complexity of a 4°C world and the wide-ranging consequences of direct and indirect human and natural impacts and adaptation to climate change. Only a limited number of these interactions has so far been captured by models.

Any attempt to debate an acceptable level of mitigation for global greenhouse gas emissions needs to take into account not only the projected climate change impacts but also the considered limits to adaptation in each sector and region; the potential for interactions between the impacts; the potential consequences of adaptation in one sector on other sectors and regions; whether there is sufficient land and water to deliver the required combination of adaptation and mitigation; and how land use, agricultural and climate policies are inextricably linked. This highlights the need for ecosystem-based mitigation as well as ecosystem-based adaptation. Lack of consideration of such key linkages risks a significant underestimation of the challenge that simultaneous adaptation in multiple sectors and regions at multiple scales, while subject to ever-increasing extreme weather, presents. Consideration of such linkages thus adds significantly to the incentive to avoid a 4°C world.

While the impacts of climate change are projected to be smaller and less widespread for global mean temperature rises of 2°C as opposed to 4°C, interactions between mitigation processes and adaptation and climate change impacts, and the resultant demands for land and water, will be of great importance.

Issues of land-use change and human migration are currently inadequately addressed in most studies, and there is a fundamental lack of incorporation of the role of ecosystem services. This review has suggested how modelling approaches might be improved to cover interactions more fully, while recommending that processes such as migration need to be handled using a scenario approach. Other omitted interactions are too difficult to quantify or to combine with mainstream sectoral studies and need to be combined qualitatively with modelling approaches.

The context of the potential for large-scale feedbacks in the Earth system to exacerbate climate change and consequent impacts and interactions for any given future emission scenario beyond levels currently estimated by state-of-the-art

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modelling approaches needs to be taken into account. Such feedbacks are much more likely to operate in a 4°C world, potentially increasing global mean temperature rise still further. These risks would be much reduced in a 2°C world.

Table 3's synthesis of impacts in a 2°C and 4°C world includes results produced by the AVOID project (www.avoid.uk.net), which is funded by the UK Department of the Environment, Food and Rural Affairs.

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Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications

Papers of a Theme Issue compiled and edited by Mark G. New, Diana M. Liverman, Richard A. Betts, Kevin L. Anderson And Chris C. West

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Editorial

Preface

Introduction

Articles

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