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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]

[1] *School of Geography and Environment and Tyndall Centre for Climate Change Research,* [2] *Institute of the Environment, University of Arizona and Environmental Change Institute, and* [3] *Environmental Change Institute, School of Geography and Environment, University of Oxford, Oxford, UK*
[4] *Tyndall Centre for Climate Change Research, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, PO Box 88, Manchester M60 1QD, UK*
[5] *School of Environmental Sciences and School of Development, University of East Anglia, Norwich NR4 7JT, UK*

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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[*] Author for correspondence (mark.new@ouce.ox.ac.uk).

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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].

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.

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 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 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

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 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* *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].

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 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].

References

1 Oppenheimer, M. & Petsonk, A. 2005 Article 2 of the UNFCCC: historical origins, recent interpretations. *Clim. Change* **73**, 195–226. (doi:10.1007/S10584-005-0434-8)

2 Liverman, D. M. 2009 Conventions of climate change: constructions of danger and the dispossession of the atmosphere. *J. Hist. Geogr.* **35**, 279–296. (doi:10.1016/j.jhg.2008.08.008)

3 UNFCCC. 2010 Copenhagen Accord 2010. See http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf.

4 Richardson, K. *et al.* 2009 Climate change—global risks, challenges & decisions. Synthesis report, Copenhagen University, Denmark.

5 IPCC. 2001 Summary for policymakers. Climate change 2001: impacts, adaptation, and vulnerability. See http://www.grida.no/climate/ipcc_tar/wg2/pdf/wg2TARspm.pdf.

6 Jordan, A. & Rayner, T. 2010 The evolution of climate policy in the European Union: an historical overview. In *Climate change policy in the European Union* (eds A. Jordan, D. Huitema, H. van Asselt, T. Rayner & F. Berkhout), pp. 52–80. Cambridge, UK: Cambridge University Press.

7 Tol, R. S. J. 2007 Europe's long-term climate target: a critical evaluation. *Energy Policy* **35**, 424–432. (doi:10.1016/j.enpol.2005.12.003)

8 Rogelj, J., Hare, B., Nabel, J., Macey, K., Schaeffer, M., Markmann, K. & Meinshausen, M. 2009 Halfway to Copenhagen, no way to 2°C. *Nat. Rep. Clim. Change* **3**, 81–83. (doi:10.1038/climate.2009.57)

9 Meilstrup, P. 2010 The runaway summit: the background story of the Danish presidency of COP15, the UN Climate Change Conference. In *Danish foreign policy yearbook 2010* (eds N. Hvidt & H. Mouritzen), pp. 113–135. Copenhagen, Denmark: Danish Institute for International Studies.

10 Bowerman, N. H. A., Frame, D. J., Huntingford, C., Lowe, J. A. & Allen, M. R. 2011 Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy. *Phil. Trans. R. Soc. A* **369**, 45–66. (doi:10.1098/rsta.2010.0288)

11 Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M. & Meinshausen, N. 2009 Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166. (doi:10.1038/nature08019)

12 Anderson, K. & Bows, A. 2011 Beyond 'dangerous' climate change: emission scenarios for a new world. *Phil. Trans. R. Soc. A* **369**, 20–44. (doi:10.1098/rsta.2010.0290)

13 Rogelj, J., Nabel, J., Chen, C., Hare, W., Markmann, K., Meinshausen, M., Schaeffer, M., Macey, K. & Hohne, N. 2010 Copenhagen Accord pledges are paltry. *Nature* **464**, 1126–1128. (doi:10.1038/4641126a)

14 Davis, S. J., Caldeira, K. & Matthews, H. D. 2010 Future CO_2 emissions and climate change from existing energy infrastructure. *Science* **329**, 1330–1333. (doi:10.1126/science.1188566)

15 O'Neill, B. C., Riahi, K. & Keppo, I. 2010 Mitigation implications of midcentury targets that preserve long-term climate policy options. *Proc. Natl Acad. Sci. USA* **107**, 1011–1016. (doi:10.1073/pnas.0903797106)

16 Calvin, K., Edmonds, J., Bond-Lamberty, B., Clarke, L., Kim, S. H., Kyle, P., Smith, S. J., Thomson, A. & Wise, M. 2009 2.6: Limiting, climate change to 450 ppm CO_2 equivalent in the 21st century. *Energy Econ.* **31**, S107–S120. (doi:10.1016/j.eneco.2009.06.006)

17 Betts, R. A., Collins, M., Hemming, D. L., Jones, C. D., Lowe, J. A. & Sanderson, M. G. 2011 When could global warming reach 4°C? *Phil. Trans. R. Soc. A* **369**, 67–84. (doi:10.1098/rsta.2010.0292)

18 Meehl, G. A. *et al.* 2007 Global climate projections. In *Climate change 2007: the physical science basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge, UK: Cambridge University Press.

19 Allen, M. R. & Ingram, W. J. 2002 Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**, 224–232. (doi:10.1038/nature01092).

20 Zhang, X. B., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., Stott, P. A. & Nozawa, T. 2007 Detection of human influence on twentieth-century precipitation trends. *Nature* **448**, 461–464. (doi:10.1038/nature06025)

21 Sanderson, M. G., Hemming, D. L. & Betts, R. A. 2011 Regional temperature and precipitation changes under high-end (≥ 4°C) global warming. *Phil. Trans. R. Soc. A* **369**, 85–98. (doi:10.1098/rsta.2010.0283)

22 Nicholls, R. J., Marinova, N., Lowe, J. A., Brown, S., Vellinga, P., de Gusmão, D., Hinkel, J. & Tol, R. S. J. 2011 Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. *Phil. Trans. R. Soc. A* **369**, 161–181. (doi:10.1098/rsta.2010.0291)

23 Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S. & Schellnhuber, H. J. 2008 Tipping elements in the Earth's climate system. *Proc. Natl Acad. Sci. USA* **105**, 1786–1793. (doi:10.1073/pnas.0705414105)

24 Boe, J. L., Hall, A. & Qu, X. 2009 September sea-ice cover in the Arctic Ocean projected to vanish by 2100. *Nat. Geosci.* **2**, 341–343. (doi:10.1038/ngeo467)

25 Hoegh-Guldberg, O. *et al.* 2007 Coral reefs under rapid climate change and ocean acidification. *Science* **318**, 1737–1742. (doi:10.1126/science.1152509)

26 Bjorkman, M. P., Morgner, E., Cooper, E. J., Elberling, B., Klemedtsson, L. & Bjork, R. G. 2010 Winter carbon dioxide effluxes from Arctic ecosystems: an overview and comparison of methodologies. *Global Biogeochem. Cycles* **24**, GB3010. (doi:10.1029/2009GB003667)

27 Huemmrich, K. F., Kinoshita, G., Gamon, J. A., Houston, S., Kwon, H. & Oechel, W. C. 2010 Tundra carbon balance under varying temperature and moisture regimes. *J. Geophys. Res. Biogeosci.* **115**, G00102. (doi:10.1029/2009JG001237)

28 Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. & Totterdell, I. J. 2000 Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* **408**, 184–187. (doi:10.1038/35041539)

29 Lynas, M. 2008 *Six degrees: our future on a hotter planet.* London, UK: Harper Perennial.

30 Zelazowski, P., Malhi, Y., Huntingford, C., Sitch, S. & Fisher, J. B. 2011 Changes in the potential distribution of humid tropical forests on a warmer planet. *Phil. Trans. R. Soc. A* **369**, 137–160. (doi:10.1098/rsta.2010.0238)

31 Fung, F., Lopez, A. & New, M. 2011 Water availability in +2°C and +4°C worlds. *Phil. Trans. R. Soc. A* **369**, 99–116. (doi:10.1098/rsta.2010.0293)

32 Milly, P. C. D., Dunne, K. A. & Vecchia, A. V. 2005 Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438**, 347–350. (doi:10.1038/nature04312)

33 Vorosmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. 2000 Global water resources: vulnerability from climate change and population growth. *Science* **289**, 284–288. (doi:10.1126/science.289.5477.284)

34 Easterling, W. E. *et al.* 2007 Food, fibre and forest products. In *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the 4th Assessment Report of the Intergovernmental Panel on Climate Change* (eds M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. v. d. Linden & C. E. Hanson), pp. 273–313. Cambridge, UK: Cambridge University Press.

35 Burke, M. B., Lobell, D. B. & Guarino, L. 2009 Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. *Glob. Environ. Change* **19**, 317–325. (doi:10.1016/j.gloenvcha.2009.04.003)

36 Thornton, P. K., Jones, P. G., Ericksen, P. J. & Challinor, A. J. 2011 Agriculture and food systems in sub-Saharan Africa in a 4°C+ world. *Phil. Trans. R. Soc. A* **369**, 117–136. (doi:10.1098/rsta.2010.0246)

37 Warren, R. 2011 The role of interactions in a world implementing adaptation and mitigation solutions to climate change. *Phil. Trans. R. Soc. A* **369**, 217–241. (doi:10.1098/rsta.2010.0271)

38 Stafford Smith, M., Horrocks, L., Harvey, A. & Hamilton, C. 2011 Rethinking adaptation for a 4°C world. *Phil. Trans. R. Soc. A* **369**, 196–216. (doi:10.1098/rsta.2010.0277)

39 Liverman, D. & Billett, S. 2010 Copenhagen and the governance of adaptation. *Environment* **52**, 28–36. (doi:10.1080/00139151003761579)

40 Roberts, J. T., Stadelmann, M. & Huq, S. 2010 Copenhagen's climate finance promise: six key questions. IIED briefing 2010. See http://www.iied.org/pubs/pdfs/17071IIED.pdf.

41 Schreurs, M. A. 2008 From the bottom up: local and subnational climate change politics. *J. Environ. Dev.* **17**, 343–355. (doi:10.1177/1070496508326432)

42 Burch, S. 2009 Transforming barriers into enablers of action on climate change: insights from three municipal case studies in British Columbia, Canada. *Glob. Environ. Change* **20**, 287–297. (doi:10.1016/j.gloenvcha.2009.11.009)

43 Okereke, C., Bulkeley, H. & Schroeder, H. 2009 Conceptualizing climate governance beyond the international regime. *Glob. Environ. Polit.* **9**, 58–78. (doi:10.1162/glep.2009.9.1.58)

44 Lovell, H., Bulkeley, H. & Liverman, D. 2009 Carbon offsetting: sustaining consumption? *Environ. Plan. A* **41**, 2357–2379. (doi:10.1068/a40345)

45 Bumpus, A. G. & Liverman, D. M. 2008 Accumulation by decarbonization and the governance of carbon offsets. *Econ. Geogr.* **84**, 127–155. (doi:10.1111/j.1944-8287.2008.tb00401.x)

46 Satterthwaite, D. 2008 Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. *Environ. Urban.* **20**, 539–549. (doi:10.1177/0956247808096127)

47 Schroeder, H. & Bulkeley, H. 2009 Global cities and the governance of climate change: what is the role of law in cities? *Fordham Urban Law J.* **XXXVI**, 313–359.

48 Betsill, M. & Bulkeley, H. 2004 Transnational networks and global environmental governance: the cities for climate protection program. *Int. Stud. Q.* **48**, 471–493. (doi:10.1111/j.0020-8833.2004.00310.x)

49 NRC. 2010 *Informing an effective response to climate change.* Washington, DC: National Academy Press.

50 Bianco, N. & Litz, F. 2010 *Reducing greenhouse gas emissions in the United States using existing federal authorities and state action.* Washington, DC: World Resources Institute.

51 Okereke, C. 2007 An exploration of motivations, drivers and barriers to carbon management: the UK FTSE 100. *Eur. Manage. J.* **25**, 475–486. (doi:10.1016/j.emj.2007.08.002)

52 Launder, B. & Thompson, J. M. T. (eds) 2008 Geoscale engineering to avert dangerous climate change. *Phil. Trans. R. Soc. A* (Theme Issue) **366**, 3841–4056.

53 Royal Society. 2009 *Geoengineering the climate: science, governance and uncertainty.* London, UK: Royal Society.

54 New, M., Liverman, D. & Anderson, K. A. 2009 Mind the gap—policymakers must aim to avoid a 2°C temperature rise, but plan to adapt to 4°C. *Nat. Rep. Clim. Change* **3**, 143–144. (doi:10.1038/climate.2009.126)