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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

[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.

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

[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).

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).

[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.

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.

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.

[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.

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.

[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.

(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.

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

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.

— 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

[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.

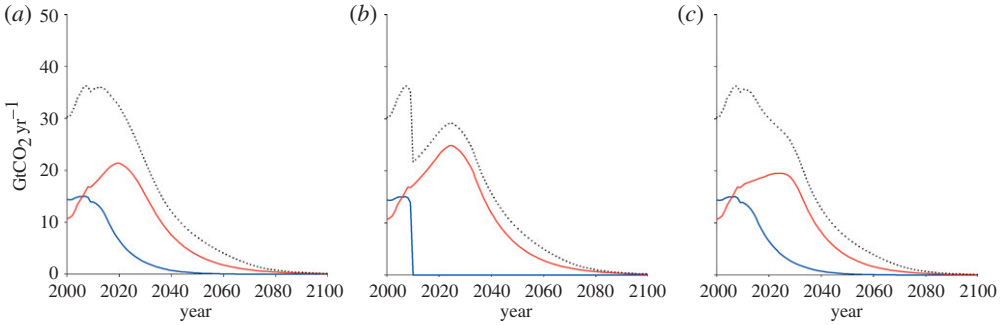

Figure 1. CO_2 scenarios for approximately 37% chance of not exceeding 2°C. All scenario pathways ((*a*) C+1, (*b*) C+2, (*c*) C+3) are for the same cumulative twenty-first century CO_2 budget of 1321 $GtCO_2$ (blue line, Annex 1; red line, non-Annex 1; dotted line, global including deforestation).

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

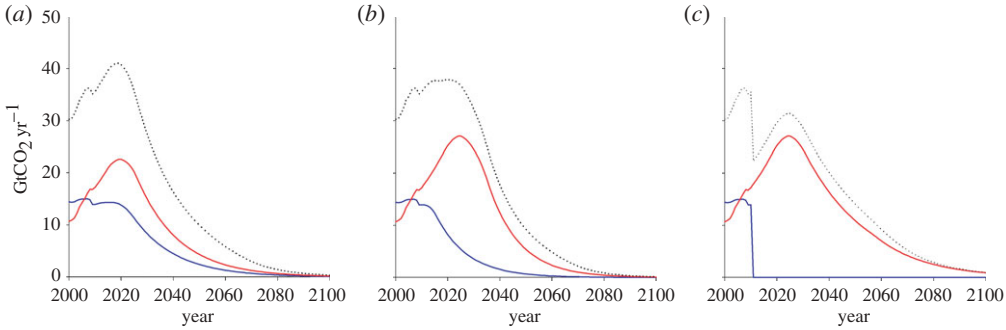

Figure 2. CO_2 scenarios for approximately 50% chance of not exceeding 2°C. All scenario pathways ((*a*) C+4, (*b*) C+5, (*c*) C+6) are for the same cumulative twenty-first century CO_2 budget of 1578 $GtCO_2$ (blue line, Annex 1; red line, non-Annex 1; dotted line, global including deforestation).

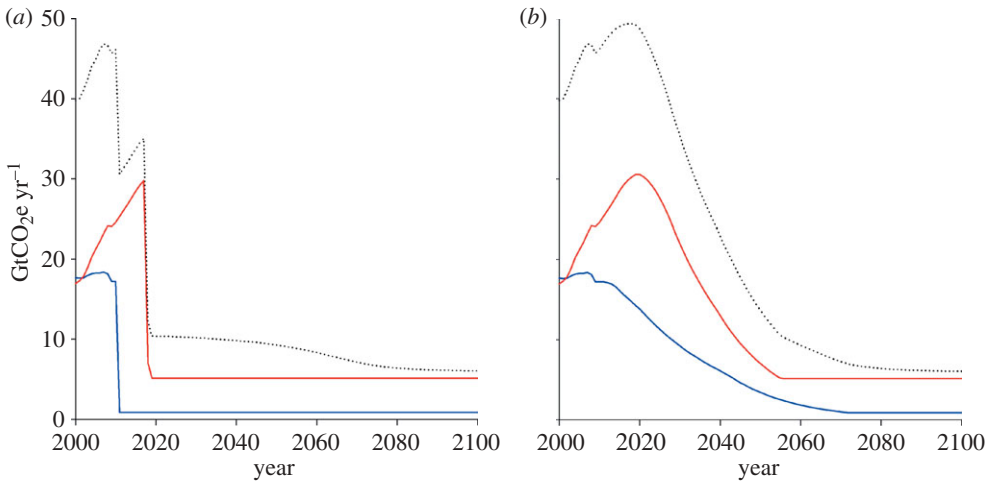

Figure 3. Kyoto gas scenarios for approximately 39–48% chance of not exceeding 2°C ((*a*) B6 1 not viable). For (*b*) B6 2, the cumulative twenty-first century CO_2e budget is 2202 $GtCO_2e$ (blue line, Annex 1; red line, non-Annex 1; dotted line, total including deforestation).

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]

[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.

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

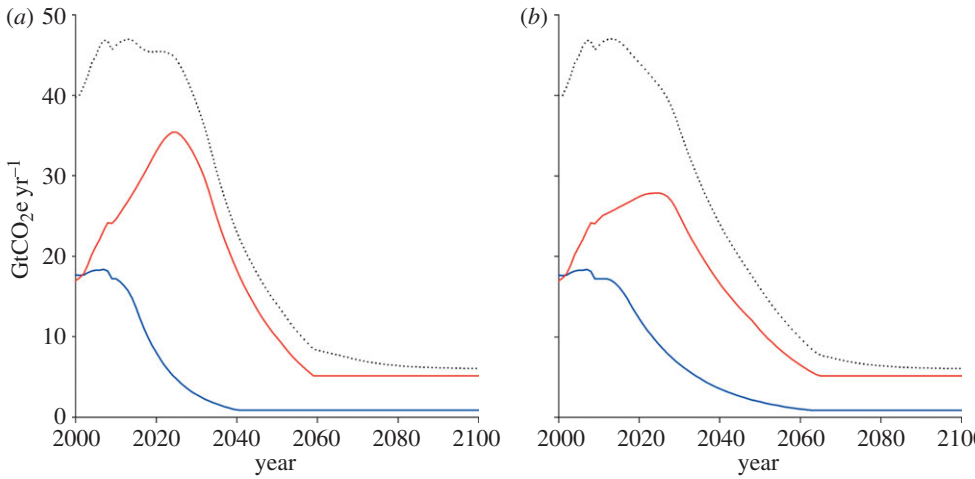

Figure 4. Kyoto gas scenarios for approximately 38–48% chance of not exceeding 2°C ((*a*) B6 3, (*b*) B6 4). The cumulative twenty-first century CO_2e budget is 2202 $GtCO_2$e. Blue line, Annex 1; red line, non-Annex 1; dotted line, total including deforestation.

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 $GtCO_2$e per year as opposed to 7.5 $GtCO_2$e 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 $GtCO_2$e 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 $GtCO_2$e as a minimum annual greenhouse gas emission for non-Annex 1 nations and 0.86 $GtCO_2$e 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 $GtCO_2$e. 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 $GtCO_2$e from greenhouse gases associated with

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

[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.

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.

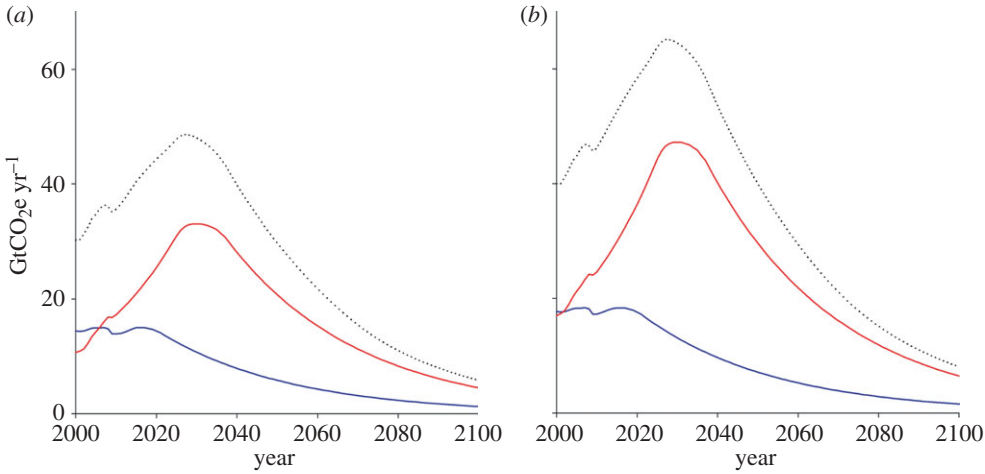

Figure 5. Emission scenarios for approximately 88–92% chance of not exceeding 2°C. Both plots illustrate 'orthodox' mitigation pathways with (*a*) C+ for CO_2 only (twenty-first century cumulative emissions: 2741 $GtCO_2$) and (*b*) B6 for Kyoto gases (twenty-first century cumulative emissions: 3662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

[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].

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

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

[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.

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?

[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.

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.

[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.

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

[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.

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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References

1 Copenhagen Accord. 2009 *FCCC/CP/2009/L.7*. Copenhagen, Denmark: United Nations Climate Change Conference.
2 Anderson, K. & Bows, A. 2008 Reframing the climate change challenge in light of post-2000 emission trends. *Phil. Trans. R. Soc. A* **366**, 3863–3882. (doi:10.1098/rsta.2008.0138)
3 Macintosh, A. 2010 Keeping warming within the 2°C limit after Copenhagen. *Energy Policy* **38**, 2964–2975. (doi:10.1016/j.enpol.2010.01.034)
4 Shell. 2008 *Shell energy scenarios to 2050*. The Hague, The Netherlands: Shell International BV.
5 IEA. 2009 *World energy outlook*. Paris, France: International Energy Agency.
6 Stern, N. 2006 *Stern review on the economics of climate change*. Cambridge, UK: Cambridge University Press.
7 Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J. & Allen, M. R. 2009 Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* **458**, 1158–1162. (doi:10.1038/nature08017)
8 CCC. 2008 *Building a low-carbon economy—the UK's contribution to tackling climate change*. Norwich, UK: The Stationery Office.
9 Hulme, M., Neufeldt, H., Colyer, H. & Ritchie, A. 2009 *Adaptation and mitigation strategies: supporting European climate policy*. Norwich, UK: University of East Anglia.
10 Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S. & Tavoni, M. 2009 International climate policy architectures: overview of the EMF 22 international scenarios. *Energy Econ.* **31**, S64–S81. (doi:10.1016/j.eneco.2009.10.013)
11 Anderson, K. L., Mander, S. L., Bows, A., Shackley, S., Agnolucci, P. & Ekins, P. 2008 The Tyndall decarbonisation scenarios—part II: scenarios for a 60% CO_2 reduction in the UK. *Energy Policy* **36**, 3764–3773. (doi:10.1016/j.enpol.2008.06.002)
12 Wang, T. & Watson, J. 2008 Carbon emission scenarios for China to 2100. Tyndall Centre working paper 121.
13 Sukla, P. R., Dhar, S. & Mahapatra, D. 2008 Low-carbon society scenarios for India. *Climate Policy* **8**, S156–S176.
14 Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J. & Richels, R. 2007 *Scenarios of greenhouse gas emissions and atmospheric concentrations*. Washington, DC: US Department of Energy.
15 European Commission. 2007 *Limiting global climate change to 2 degrees Celsius: the way ahead for 2020 and beyond*. Brussels, Belgium: European Commission.
16 Anderson, K., Starkey, R. & Bows, A. 2009 Defining dangerous climate change—a call for consistency. Tyndall Centre briefing note 40.
17 DECC. 2009 *The UK low carbon transition plan: national strategy for climate and energy*. London, UK: Department of Energy and Climate Change.
18 Miliband, D. & Miliband, E. 2009 *Copenhagen: in the balance press briefing*. London, UK: Foreign Office and Department for Energy and Climate Change.
19 Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. M, Tignor, M. & Millier, H. L. (eds) 2007 *Contribution of working group 1 to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, UK; New York, NY: Cambridge University Press.

20 Smith, J. B. *et al.* 2009 Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) 'reasons for concern'. *Proc. Natl Acad. Sci. USA* **106**, 4133–4137. (doi:10.1073/pnas.0812355106)
21 Mann, M. E. 2009 Defining dangerous anthropogenic interference. *Proc. Natl Acad. Sci. USA* **106**, 4065–4066. (doi:10.1073/pnas.0901303106)
22 New, M., Liverman, D. & Anderson, K. 2009 Mind the gap. *Nature* **912**, 143–144. (doi:10.1038/climate.2009.126)
23 Mander, S. L., Bows, A., Anderson, K. L., Shackley, S., Agnolucci, P. & Ekins, P. 2008 The Tyndall decarbonisation scenarios—part I: development of a backcasting methodology with stakeholder participation. *Energy Policy* **36**, 3754–3763. (doi:10.1016/j.enpol.2008.06.003)
24 Bows, A., Mander, S., Starkey, R., Bleda, M. & Anderson, K. 2006 *Living within a carbon budget*. Manchester, UK: Tyndall Centre.
25 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)
26 Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. 2009 The proportionality of global warming to cumulative carbon emissions. *Nature* **459**, 829–832. (doi:10.1038/nature08047)
27 Garnaut, R. 2008 *The Garnaut climate change review*. Cambridge, UK: Cambridge University Press.
28 PRIMAP. 2010 *The PRIMAP model*. Potsdam, UK: Potsdam Institute for Climate Impact Research.
29 IPCC, Pachauri, R. K. & Reisenger, A. (eds) 2007 *Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, UK; New York, NY: Cambridge University Press.
30 Boden, T., Marland, G. & Andres, R. 2009 *Global CO_2 emissions from fossil-fuel burning, cement manufacture, and gas flaring: 1751–2006*. Oak Ridge, TN: Oak Ridge National Laboratory.
31 Eyring, V. *et al.* In press. Transport impacts on atmosphere and climate: shipping. *Atmos. Environ.* (doi:10.1016/j.atmosenv.2009.04.059)
32 UNFCCC. 2010 *GHG data from UNFCCC*. New York, NY: United Nations.
33 IEA. 2009 *CO_2 emissions from fuel combustion*. Paris, France: International Energy Agency.
34 Eyring, V., Kohler, H. W., van Aardenne, J. & Lauer, A. 2005 Emissions from international shipping: 1. The last 50 years. *J. Geophys. Res.* **110**, D17305. (doi:10.1029/2004JD005619)
35 Corbett, J. J. & Kohler, H. W. 2003 Updated emissions from ocean shipping. *J. Geophys. Res.* **108**, 4650. (doi:10.1029/2003JD003751)
36 Anderson, K., Bows, A. & Mander, S. 2008 From long-term targets to cumulative emission pathways: reframing UK climate policy. *Energy Policy* **36**, 3714–3722. (doi:10.1016/j.enpol.2008.07.003)
37 Buhaug, O. *et al.* 2009 *2nd IMO GHG study*. London, UK: International Maritime Organisation.
38 Environmental Audit Committee. 2009 *Reducing the CO_2 and other emissions from shipping: fourth report of session 2008–2009*. London, UK: The Stationery Office.
39 Gilbert, P., Bows, A. & Starkey, R. 2010 *Shipping and climate change: scope for unilateral action*. Manchester, UK: University of Manchester.
40 Wood, F. R., Bows, A. & Anderson, K. 2010 Apportioning aviation CO_2 emissions to regional administrations for monitoring and target setting. *Transport Policy* **17**, 206–215. (doi:10.1016/j.tranpol.2010.01.010)
41 Global Carbon Project. 2009 Carbon budget and trends 2008. See www.globalcarbonproject.org/carbonbudget.
42 Houghton, R. A. 1999 The annual net flux of carbon to the atmosphere from land use 1850–1990. *Tellus B* **51B**, 298–313.
43 van der Werf, G. R., Morton, D. C., DeFries, R. S., Gigilo, L., Randerson, J. T., Collatz, G. J. & Kasibhatla, P. S. 2009 Estimates of fire emissions from an active deforestation region in the southern Amazon based on satellite data and biogeochemical modelling. *Biogeosciences* **6**, 235–249. (doi:10.5194/bg-6-235-2009)

44 EPA. 2006 Global anthropogenic non-CO_2 greenhouse gas emissions: 1990–2020. Office of Atmospheric Programs, Climate Change Division, US Environmental Protection Agency.
45 Jiankun, H., Wenying, C., Fei, T. & Bin, L. 2009 *Long-term climate change mitigation target and carbon permit allocation*. Beijing, China: Tsinghua University.
46 UN. 2010 UN Population Division's annual estimates and projections. See esa.un.org/UNPP.
47 Hof, A., den Elzen, M. G. J. & van Vuuren, D. 2009 *The use of economic analysis in climate change appraisal of post-2012 climate policy*. Bilthoven, The Netherlands: Netherlands Environmental Assessment Agency.
48 Köne, A. Ç. & Büke, T. 2010. Forecasting of CO_2 emissions from fuel combustion using trend analysis. *Renew. Sustainable Energy Rev.* **14**, 2906–2915. (doi:10.1016/j.rser.2010.06.006)
49 Nusbaumer, J. & Matsumoto, K. 2008 Climate and carbon cycle changes under the overshoot scenario. *Glob. Planet. Change* **62**, 164–172. (doi:10.1016/j.gloplacha.2008.01.002)
50 Schneider, S. H. & Mastrandrea, M. D. 2005 Probabilistic assessment of 'dangerous' climate change and emissions pathways. *Proc. Natl Acad. Sci. USA* **102**, 15 728–15 735. (doi:10.1073/pnas.0506356102)