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## Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets

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## EDITORIAL

### Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets

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#### Abstract

The *Environmental Research Letters* focus issue on ‘Cumulative Emissions, Global Carbon Budgets and the Implications for Climate Mitigation Targets’ was launched in 2015 to highlight the emerging science of the climate response to cumulative emissions, and how this can inform efforts to decrease emissions fast enough to avoid dangerous climate impacts. The 22 research articles published represent a fantastic snapshot of the state-of-the-art in this field, covering both the science and policy aspects of cumulative emissions and carbon budget research. In this Review and Synthesis, we summarize the findings published in this focus issue, outline some suggestions for ongoing research needs, and present our assessment of the implications of this research for ongoing efforts to meet the goals of the Paris climate agreement.

## 1. Introduction

To a good approximation, the climate challenge can be framed as one of limiting total cumulative emissions of carbon dioxide (CO<sub>2</sub>). While not the only contributor to global warming, CO<sub>2</sub> is the most important greenhouse gas, producing temperature changes that are largely irreversible by natural processes on timescales relevant to human societies. Halting climate change therefore requires that CO<sub>2</sub> emissions from all sources need to be either eliminated entirely, or matched by an equal amount of anthropogenic CO<sub>2</sub> removal from the atmosphere. This target of ‘net-zero’ emissions is reflected in the text of the Paris Agreement, which states that the world should aim ‘... to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.’

Also in the Paris Agreement is the aspiration for nations to adopt ‘... emission pathways consistent with holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C.’ These two statements are qualitatively consistent, in that stabilizing temperatures at any level is only consistent with net-zero anthropogenic CO<sub>2</sub> emissions, permanent removals of CO<sub>2</sub> by natural sinks being negligibly slow. The scientific challenge is therefore to

understand by what date we need to achieve net-zero emissions, and how much we can allow ourselves to emit along the way, so as to prevent temperatures from exceeding the (deliberately) ill-defined target of ‘well below 2 °C.’

It was to this end that we convened the *Environmental Research Letters* focus issue on the topic of ‘Cumulative emissions, global carbon budgets and the implications for climate mitigation targets.’ In this Review and Synthesis, we summarize the findings of the research published in this focus issue, suggest some implications of this research for ongoing global efforts to achieve the objectives of the Paris Agreement, and outline some potential avenues for further research.

## 2. Global temperature response to cumulative CO<sub>2</sub> emissions

Many studies have now shown that each emission of CO<sub>2</sub> leads to approximately the same increase in global temperatures, which results in a linear climate response to cumulative CO<sub>2</sub> emissions (Matthews *et al* 2009, Allen *et al* 2009, Raupach *et al* 2011, Friedlingstein *et al* 2014, Gillett *et al* 2013, Collins *et al* 2013, Matthews *et al* 2017, MacDougall 2016, Leduc *et al* 2015, Tokarska *et al* 2016, Leduc *et al* 2016, Ehlert *et al* 2017, Knutti and Rogelj 2015, Zickfeld *et al* 2009,

Zickfeld *et al* 2012, Steinacher and Joos 2016). This relationship between cumulative CO<sub>2</sub> emission and global temperature change has been defined as the transient climate response to cumulative CO<sub>2</sub> emissions (TCRE), which represents the global temperature change per tonne of emitted carbon (or CO<sub>2</sub>) (Collins *et al* 2013, Gregory *et al* 2009). The current generation of full-complexity Earth-system models exhibits a range of TCRE values of between 0.8 and 2.4 °C per trillion tonnes of carbon (TtC) emitted, with a median value of 1.6 °C per TtC; an observationally-constrained TCRE estimate gave a 5%–95% confidence range of 0.7 °C–2.0 °C per TtC, with a best-estimate of 1.35 °C per TtC (Gillett *et al* 2013).

The physical basis for a constant TCRE over time has been the subject of a number of analyses over the past several years. Most studies have suggested that the linearity of the climate response to cumulative emissions results from the compensation of two non-linear processes. The diminishing effectiveness of CO<sub>2</sub> radiative forcing with increasing CO<sub>2</sub> levels in the atmosphere would imply that the temperature response to CO<sub>2</sub> emissions should decrease at higher emission levels. However, as emissions increase, carbon sinks also become less effective at removing CO<sub>2</sub> from the atmosphere, which results in a higher airborne fraction of emitted CO<sub>2</sub> remaining in the atmosphere (Matthews *et al* 2009, MacDougall and Friedlingstein 2015, Leduc *et al* 2015, Gillett *et al* 2013, Matthews *et al* 2017, Millar *et al* 2017). In this focus issue, Williams and Goodwin (2016) provide a theoretical basis for understanding the evolution of the TCRE over time as a product of three terms: the dependence of surface warming on radiative forcing; the fractional dependence of radiative forcing contribution from atmospheric CO<sub>2</sub>; and the dependence of radiative forcing from atmospheric CO<sub>2</sub> on carbon emissions. Using two models and a range of RCP emission scenarios, they showed that there is a slight decrease in the TCRE as emissions continue, since in these models the rate of ocean carbon uptake decreases slightly faster than the rate of heat uptake. Williams and Goodwin (2016) attributed the increase in airborne fraction to oceanic process, though previous studies (e.g. Leduc *et al* 2015) have also pointed to the changing carbon uptake capacity of the terrestrial biosphere as an important contributing factor.

There may be important differences, however, in the behaviour of the TCRE during periods of increasing vs. decreasing or zero CO<sub>2</sub> emissions. Nohara *et al* (2015) compared the TCRE response in two comprehensive models for a scenario where CO<sub>2</sub> emissions peaked and declined to zero at a total of 1100 Gt C emitted. While both models simulated a near-constant TCRE during the period of increasing emissions, the models behaved differently during the period of declining followed by zero emissions: one model showed continued warming, while the other simulated stable

and then declining temperatures after the point of zero emissions.

The climate response after the point of zero emissions (sometimes called the zero-emissions commitment or ZEC) seems to vary considerably among models. Ehlert and Zickfeld (2017) showed that the ZEC depends primarily on the balance of ocean carbon and heat uptake after emissions reach zero. While continued ocean carbon uptake has a cooling influence on climate (ocean carbon cycle inertia), this is countered by a declining rate of ocean heat uptake, which tends to warm the atmosphere (ocean thermal inertia). Under conditions where these two processes balance, temperatures would be expected to remain stable after CO<sub>2</sub> emissions reach zero (Matthews and Solomon 2013, Solomon *et al* 2009, Solomon *et al* 2010). However, at higher amounts of cumulative emissions, the ocean uptake of CO<sub>2</sub> appears to be insufficient to counteract the continued warming from thermal inertia, resulting in a positive zero-emissions commitment (Ehlert and Zickfeld 2017). In some models, this feature appears to be particularly pronounced; Frölicher and Paynter (2015) showed that the GFDL Earth system model (ESM) is characterized by an unusually low fraction of realized warming as emissions increase, with the result that when emissions were zeroed in this model, atmospheric temperatures continue to increase for several decades before stabilizing. The authors suggest that comprehensive ESMs may be more likely to exhibit this pattern of continued warming after zero emissions as compared to simpler climate models. It is certainly true that linear impulse-response models such as those used by Joos *et al* (2013) tend to simulate decreasing temperatures following zero emissions, although the problem can be alleviated by explicit representation of weakening carbon sinks (Millar *et al* 2016). It is also the case that many comprehensive models do simulate stable or slightly declining global temperatures following zero emissions (Lowe *et al* 2009, Zickfeld *et al* 2012, Gillett *et al* 2011).

The climate response to zero emissions is therefore an important source of uncertainty in understanding the long-term climate response to a given quantity of cumulative emissions. This uncertainty is also relevant to stabilization scenarios: Tachiiri *et al* (2015) in this issue showed that the TCRE uncertainty may be considerably larger after the point of CO<sub>2</sub> stabilization, which they attributed largely to uncertainty associated with land carbon storage on longer timescales. Also important is the potential climate response to negative emissions scenarios, which was assessed in this issue by Zickfeld *et al* (2016); in this study they showed that even a small zero-emissions commitment can result in a different climate response during periods of positive vs. negative emissions. They showed that global temperatures are higher at a given level of cumulative emissions when this level is overshoot and then returned to via negative emissions, suggesting that CO<sub>2</sub> removal is initially less effective

at reversing global temperature change as compared to the effectiveness of the emissions themselves at increasing global temperature (Zickfeld *et al* 2016, MacDougall *et al* 2015).

Other studies in this focus issue assessed how the climate response to fossil fuel CO<sub>2</sub> might compare to other types of emissions. Simmons and Matthews (2016) assessed the question of whether CO<sub>2</sub> emissions from land-use can be well characterized by the same TCRE value as for fossil fuel CO<sub>2</sub>. They showed that while the climate response to the emitted CO<sub>2</sub> (biogeochemical effects of land-use) is unaffected by the source of the emissions, CO<sub>2</sub> from land-use change is also associated with land-surface changes (biogeophysical effects) that result in a different net climate response. This suggests that it may be more realistic to treat land-use and fossil-fuel CO<sub>2</sub> differently when assessing the climate response to cumulative emissions. In a similar vein, Pierrehumbert and Eshel (2015) emphasized the need to treat non-CO<sub>2</sub> emissions separately from CO<sub>2</sub> when assessing the climate response to activities that produce both CO<sub>2</sub> and non-CO<sub>2</sub> greenhouse gases. Here, they assessed the climate effect of beef consumption, and were able to translate a range of different types of emission into warming without the use of an aggregating metric.

### 3. Regional climate change and impacts of cumulative CO<sub>2</sub> emissions

While most of the TCRE literature has focused on the global temperature response to cumulative emissions, there is new evidence that regional climate changes may also scale approximately linearly with cumulative emissions (Leduc *et al* 2016, Seneviratne *et al* 2016). This finding can be thought of as an extension of the pattern-scaling approach, which is based on the finding that spatial patterns of temperature and precipitation changes remain quite stable when scaled by global-mean temperature change (Tebaldi and Arblaster 2014). In this issue, Partanen *et al* (2017) showed that annual and seasonal temperature and precipitation patterns from an ensemble of ESMs can also be scaled with cumulative emissions, and that these patterns remain relatively unchanged with increasing emissions. However, it is also possible that regional non-linearities may emerge that would complicate the robustness of pattern-scaling with cumulative emissions. For example, Liddicoat *et al* (2016) showed that in the HadCM3LC model, differences in the effect of climate change on forest cover in Amazonia could lead to differences in the climate state in simulations where the same quantity of CO<sub>2</sub> was emitted over different amounts of time. Similarly, Nohara *et al* (2015) showed that regional climate changes after the point of zero emissions in their simulations was sensitive to the different behaviour of the North Atlantic overturning circulation in the two models

they included in their study. Assessing the spatial climate response to cumulative emissions is therefore a promising new approach to pattern-scaling, although additional research is needed to assess its potential and limitations.

One interesting potential of this research direction is the possibility of linking regional climate impacts quantitatively to cumulative CO<sub>2</sub> emissions. LoPresti *et al* (2015) showed that the rate of increase of cumulative emissions (i.e. the more familiar annual emission rate) is an important driver of both the rate of global temperature increase, as well as the geographical velocity of change, which measures the speed of displacement of isotherms across the Earth's surface. Both the rate and velocity of climate change are important drivers of regional climate impacts, particularly in relation to ecological systems. LoPresti *et al* (2015) argued that the annual rate of emissions is therefore an important driver of some climate impacts, in addition to the total emissions over time. Harrington *et al* (2016) also presented a spatial analysis of the climate impacts from cumulative emissions, focusing on the emergence of daily temperature extremes. They showed that high-temperature extremes emerged from the range of natural variability earlier at lower latitudes, in areas where daily and seasonal temperature ranges are generally smaller. This result also underscores the important inequities in the distribution of climate impacts, whereby many of the regions which will experience the earliest emergence of these temperature extremes are also those who have contributed the least to historical warming (Harrington *et al* 2016, Green 2016, Mahlstein *et al* 2011).

### 4. Implications for global carbon budgets

A constant global (and potentially regional) temperature response to cumulative CO<sub>2</sub> emissions is a strong scientific rationale for the idea that stabilizing global temperatures requires net anthropogenic CO<sub>2</sub> emissions to be reduced to zero (Matthews and Caldeira 2008). Consequently, total allowable CO<sub>2</sub> emissions for any given temperature target are finite. This is the idea of a 'carbon budget', which represents the total quantity of CO<sub>2</sub> emissions that is consistent with remaining below a given level of global temperature change (Allen *et al* 2009, Meinshausen *et al* 2009, Zickfeld *et al* 2009).

There are a range of carbon budget estimates in the literature associated with global temperature targets (IPCC 2014, Friedlingstein *et al* 2014, Rogelj *et al* 2016b, Matthews *et al* 2017, Millar *et al* 2017). Some of this range reflects geophysical uncertainty associated with the climate response to CO<sub>2</sub> emissions (i.e. the range of the transient climate and carbon cycle responses to emissions), though there is also an important contribution to carbon budget uncertainty that arises from human mitigation decisions and the



contribution of non-CO<sub>2</sub> emissions to future climate warming (van Vuuren *et al* 2016, Matthews *et al* 2017).

Much of the geophysical uncertainty associated with carbon budget estimates is also reflected in the uncertainty range for the TCRE. By definition, a higher TCRE would result in a smaller carbon quota (and vice versa), and this by itself accounts for a large portion of the carbon budget uncertainty. However, uncertainty in the climate response after emissions have stopped (which is not captured by TCRE uncertainty) also has direct relevance for estimates of allowable emissions since carbon budget estimates would have to be adjusted downwards in anticipation of continued warming after the point of zero emissions (Frölicher and Paynter 2015). In this issue, MacDougall *et al* (2015) considered another important source of geophysical uncertainty arising from the effect of permafrost carbon feedbacks; they showed that the release of carbon from thawing permafrost has the potential to decrease total allowable CO<sub>2</sub> emissions for the 2 °C temperature target by about 100 GtC (about 8% of the total budget), though this effect may increase in importance for higher temperature targets.

In addition to geophysical uncertainty, carbon budget estimates are strongly affected by uncertainty related to human mitigation decisions (Matthews *et al* 2017). For example, choices regarding the timing of CO<sub>2</sub> emission reductions can affect carbon budgets, if delays in mitigation result in the overshoot of a carbon quota. MacDougall *et al* (2015) showed that net carbon budgets following overshoot of and return to a warming target through artificial removal of CO<sub>2</sub> from the atmosphere ('overshoot net carbon budgets') are generally smaller than carbon budgets consistent with achieving a warming target without overshoot (i.e. more CO<sub>2</sub> needs to be removed than the actual amount by which the cumulative emissions budget is exceeded). Simmons and Matthews (2016) highlighted the important role of land-use change as a contributor to both historical and future CO<sub>2</sub>; human decisions regarding future land-use are therefore an important uncertainty that will affect the size of the remaining carbon budget for fossil fuel CO<sub>2</sub> emissions.

The effect of non-CO<sub>2</sub> emissions on carbon budget estimates can also be characterized as a source of uncertainty that depends on human mitigation choices, given that the magnitude of the non-CO<sub>2</sub> contribution to future warming strongly reflects human decisions and effort in mitigating these emissions. MacDougall *et al* (2015) showed how carbon quotas are affected by non-CO<sub>2</sub> emissions, which have the potential to decrease carbon budget estimates by more than a third. Rogelj *et al* (2015a) also assessed the sensitivity of carbon budget estimates to non-CO<sub>2</sub> mitigation actions, showing that it is important to consider how co-emitted (non-CO<sub>2</sub>) species from fossil fuel combustion will change as fossil fuel CO<sub>2</sub> emissions decrease. They also highlighted the importance of the timing

of non-CO<sub>2</sub> mitigation decisions for carbon quotas, given that many non-CO<sub>2</sub> emissions have much shorter atmospheric lifetimes than CO<sub>2</sub> itself. In a separate analysis, Rogelj *et al* (2015b) highlighted how different mitigation decisions such as the choice of different mitigation technologies could influence both the size and the cost of the carbon budgets for different temperature targets; again, most of this effect resulted from the impact of mitigation choices on non-CO<sub>2</sub> emissions.

## 5. Requirements and mitigation options for meeting climate targets

Meeting the goals of the Paris climate agreement will clearly require immediate and considerable mitigation effort across all sectors of the global economy. In this issue Fyke and Matthews (2015) showed that in the absence of coordinated and stringent climate policy, global CO<sub>2</sub> emissions are very likely to exceed the carbon budget requirement for the 'well below 2 °C' climate target, leading to a median global temperature change of 4.7 °C above pre-industrial temperatures. In this analysis, the low-emission scenarios were those characterized by a high and rapidly increasing carbon price, combined with a low cost of non-fossil energy sources, suggesting the critical importance of these two policy levers to initiate and sustain the transition to decarbonized energy sources.

In general, below-2 °C scenarios are characterized by global CO<sub>2</sub> emissions that peak prior to 2020, followed by rapid emission decreases at rates reaching net-zero emissions during the second half of this century (van Vuuren *et al* 2016, Rogelj *et al* 2016b). As demonstrated here by van Vuuren *et al* (2016), any delay in reaching peak emissions will clearly require more rapid decreases thereafter so as to not exceed the fixed quantity of emissions represented by the below-2 °C carbon budget. They also note that in the current generation of climate-economy models, carbon capture and storage (CCS) as well as bioenergy with CCS (BECCS) play important roles in the transition to low-carbon energy sources. The role of BECCS in particular is seen as a potentially important negative-emissions technology, which may be required in order to achieve the net-zero emissions that are a requirement for stable global temperatures (Matthews and Caldeira 2008, Rogelj *et al* 2016b).

Rozenberg *et al* (2015) also assessed the mitigation requirement for a 2 °C climate scenario, from the perspective of the committed emissions that are embodied in our current technological infrastructure. Using a range of assumed economic lifetimes of currently-installed infrastructure, they calculated that future emissions associated with the continued use of this infrastructure would produce additional CO<sub>2</sub> emissions representing less than 40% (for low lifetimes) to more than 95% (for high lifetimes) of the

allowable carbon budget for a below-2 °C climate scenario. They emphasized therefore that any new infrastructure needs to be constructed at a much lower carbon intensity in order to remain below 2 °C without major cost to global GDP growth. Iyer *et al* (2015) also emphasized the need for early mitigation action to reduce the economic costs of remaining below 2 °C. They showed that if national emissions follow their Intended Nationally-Determined Contributions (INDCs) (leading to only moderate reductions in CO<sub>2</sub> emissions between now and 2030), the cost of mitigation action after 2030 would be substantially higher than a case where countries strengthen their mitigation efforts early and achieve reductions that exceed their INDCs prior to 2030.

Immediate global mitigation action to decrease CO<sub>2</sub> emission towards net zero is therefore a first-order requirement of any below-2 °C climate scenario. However, several authors in this issue also stressed the need to consider issues of international equity in the allocation of emissions to nations (Peters *et al* 2015, Gignac and Matthews 2015). The idea of a finite cap on global emissions raises important questions about who should fairly be entitled to emit this CO<sub>2</sub>, and what constitutes a fair share of the global emissions budget. Here, Peters *et al* (2015) considered two extreme sharing principles, that of allocation based on current national population shares (equity-based allocation), and that of allocating based on current national shares of global emissions (inertia-based allocation). They then compared the emissions allowance associated with these two sharing principles to countries' stated emission targets, showing that the emissions pledges of most major emitters fall far short of their equity-based allocation.

Gignac and Matthews (2015) also calculated national shares of the global carbon budget using the 'contraction and convergence' method (Meyer 2000), whereby national emission shares are constrained to converge from their current level to an equal per-capita share of global annual emissions at some future year. As with Peters *et al* (2015) they showed that the emissions pledges (INDCs) of the major emitters were not consistent with their allocated share of emissions, leaving insufficient room for emissions from the rest of the world. Gignac and Matthews (2015) also introduced the idea of national 'carbon debts' which represent the amount by which countries' emissions have exceeded their per-capita share of global emissions (Matthews 2016). They argued here that even the rapid emission reductions required to equalize global per-capita emissions may not be sufficient to achieve an equitable climate mitigation solution; in addition, they argued that countries who currently (and for the foreseeable future) are emitting more than their per-capita share can be seen to owe a considerable debt to the rest of the world, which could be considered as a rationale to mobilize climate finance to assist with both mitigation and adaptation efforts in lower-emitting vulnerable countries.

## 6. Future research needs and directions

Although significant advances have been made in understanding the constraints on global carbon budgets and emissions pathways consistent with the climate targets adopted in the Paris Agreement, some major research gaps remain. For instance, large uncertainties exist with regard to the size of the carbon budgets consistent with the 1.5 °C and 2 °C climate targets (Matthews *et al* 2017). As long as climate sensitivity uncertainty is not reduced, the uncertainty in TCRE (which combines climate and carbon cycle sensitivities) and therefore carbon budgets will remain large (Knutti *et al* 2017). This propagates onto significant uncertainties in the required emission reductions and associated costs. As discussed earlier in this paper, carbon budget uncertainty arises from uncertainties in the carbon cycle response to greenhouse gas emissions, the climate response to radiative forcing, and future emissions of non-CO<sub>2</sub> greenhouse gases and aerosol precursors.

Some recent research has suggested that global climate models may be missing important positive carbon cycle feedbacks that could accelerate the rate of future warming and hence decrease the carbon budget (Melillo *et al* 2017). However, it is important to note that the current TCRE range among models is larger than the uncertainty range derived from the observational record, and that the most sensitive climate models are outside of the range of observationally-constrained TCRE estimates (Matthews *et al* 2017, Millar *et al* 2017). This in turn suggests that there is little evidence at present that ESMs are missing major positive carbon cycle feedbacks that would significantly decrease the estimate of carbon budgets derived from model TCRE values. Clearly, however, this is an important uncertainty to address and narrow so as to increase our confidence in future climate projections. One promising research direction consists in constraining the carbon cycle response to changes in atmospheric CO<sub>2</sub> and surface air temperature by using observed seasonal and interannual atmospheric CO<sub>2</sub> variability (Cox *et al* 2013, Wenzel *et al* 2016). Jones *et al* (2017) combined multiple regional observational constraints on the carbon cycle sensitivity to temperature and CO<sub>2</sub> in order to reduce the spread of the TCRE probability distribution, thus lowering uncertainty in carbon budgets.

Uncertainty in the physical climate system response arises both as a result of uncertainty associated with physical climate feedbacks, as well as uncertainty associated with historical forcings. In the case of forcing uncertainty, low understanding of aerosols forcing in particular makes it difficult to derive precise climate sensitivity estimates from historical observations. Improved ability to constrain aerosol forcing (Stevens 2015) is therefore a promising research direction to reduce the uncertainty in the physical climate response and carbon budgets. This uncertainty is also likely to be reduced as CO<sub>2</sub> increasingly dominates over other

more uncertain forcings. Myhre *et al* (2015) argue that the uncertainty in the transient climate response, defined as the warming at the time of CO<sub>2</sub> doubling for a 1% per year CO<sub>2</sub> increase, can be expected to be halved by 2030 as CO<sub>2</sub> forcing becomes increasingly dominant; however recent work suggests that constraints based on past warming trends may be biased or overconfident as a result of assuming a single global feedback that is constant in time and identical for all forcings (Knutti *et al* 2017).

Significant uncertainty also exists regarding the zero emission commitment (ZEC) (Frölicher and Paynter 2015). Constraining the ZEC is crucial in the context of the Paris Agreement, as the warming commitment from emissions to date determines the remaining temperature leeway to 1.5 °C and 2 °C and therefore has a bearing on the attainability of these targets. Given that this leeway is very tight—Mauritsen and Pincus (2017) estimated the warming commitment from all past emissions at +0.26°C, which in addition to the observed warming of the past decade of 0.8°C–0.9°C relative to pre-industrial brings us to 1.1°C–1.2°C—even small uncertainties in the ZEC have a large effect on the emission reductions required to stabilize temperature at those levels. The zero emission commitment is determined by the balance between ocean heat and carbon uptake, which have opposite effects on global temperature (Williams and Goodwin 2016, Ehlert *et al* 2017). It is often assumed that the effects of these two processes cancel each other (Mauritsen and Pincus 2017), but this is unlikely to be the case due to different processes controlling ocean heat and carbon uptake (Frölicher and Paynter 2015, Winton *et al* 2013). Better understanding of these processes, particularly the role of ocean deep ventilation and mixing, would help to constrain the ZEC.

Several emissions scenarios consistent with limiting global temperature to well below 2 °C in the long term involve cumulative CO<sub>2</sub> emission (and hence temperature) overshoot (Fuss *et al* 2014, Smith *et al* 2016): that is, recovery to a cumulative CO<sub>2</sub> budget level through artificial removal of CO<sub>2</sub> from the atmosphere ('net-negative emissions'). Most studies to date have focused on exploring the climate system response to rising cumulative emissions (i.e. positive emission rates), and large uncertainties remain regarding the response to scenarios with cumulative emissions overshoot. For instance, MacDougall *et al* (2015) showed that carbon budgets following overshoot of and return to a warming target are smaller than conventional carbon budgets. This effect has been quantified with one Earth system model only, and it is unclear if it applies to low emissions scenarios limiting global temperature to below 1.5 °C and 2 °C. Another issue that warrants further exploration are the impacts associated with overshoot scenarios. The rate of temperature change is larger in overshoot than in scenarios that stabilize at a target temperature without overshoot, with potential negative impacts on ecosystems

(LoPresti *et al* 2015). Natural and human systems may also be affected by the temporary temperature overshoot itself, as it could lead to crossing critical thresholds and irreversibilities, effects that are largely unexplored. Finally, cumulative emission overshoot scenarios by definition require deployment of negative emission technologies, such as bioenergy with carbon capture and sequestration and direct air capture of CO<sub>2</sub>. Although a literature is emerging on negative emissions technologies, large uncertainties remain regarding their potential and side-effects (Smith *et al* 2016).

## 7. What needs to be done to remain 'well below 2 °C'?

As of the end of 2016, human-induced global warming has exceeded 1 °C above pre-industrial (1860–1880) temperature, and is currently increasing at a rate of 0.1 °C–0.2 °C per decade (Haustein *et al* 2017). At this rate of increase, human-induced global warming would exceed 1.5 °C within about 3 decades, though this timeline is of course sensitive to the rate of mitigation of both CO<sub>2</sub> and other greenhouse gas and aerosol emissions.

There is considerable disagreement among climate scientists and policy experts as to whether it will be possible to remain 'well below' 2 °C, let alone to avoid exceeding the aspirational goal of 1.5 °C (Victor and Kennel 2014, Peters 2016). Even more contentious is the question of whether either target will be possible to achieve without relying on considerable quantities of negative emissions, which carry the potential for significant economic and environmental costs (Fuss *et al* 2014, Smith *et al* 2016). Most current scenarios indicate that remaining 'likely below' 2 °C would require net global CO<sub>2</sub> emissions to reach zero by about the year 2070, or by 2050 for a 1.5 °C target (Rogelj *et al* 2016b), although (in contrast to the total emitted carbon over time) the timing of zero emissions is a relatively poor indicator of the likelihood of achieving a temperature target. Furthermore, for industrialized countries who have contributed the majority of historical emissions, international equity considerations suggest that emissions should reach net zero 1–2 decades earlier than the rest of the world (Robiou du Pont *et al* 2016). This would require mitigation rates considerably higher than has ever been achieved by any country in recent history (Raupach *et al* 2014), and certainly far greater than would be achieved by the current set of national emissions pledges (Rogelj *et al* 2016a).

On the other hand, global civilization has never faced an environmental challenge with as much potential for catastrophic consequences as is posed by unmitigated global warming. Though mitigation rates are not yet anywhere near what would be needed to avoid dangerous climate changes, it is also the case that mitigation effort has ranged from tentative to non-existent across nations over the past several decades. Furthermore, the political climate in several



countries remains mired in debate about the reality of global warming itself, which has prevented even modest progress on developing alternate energy sources that do not produce CO<sub>2</sub> emissions. Seen in this light, the world has not yet really even attempted the energy system transformation that will be required.

And yet, despite this limited and halting political effort, there is tentative evidence that global CO<sub>2</sub> emissions are beginning to decouple from economic growth, with the result that emissions have not increased appreciably since the year 2013 (Le Quere *et al* 2016). This change has emerged from several unanticipated developments, including the rapid decrease in the cost of solar and other renewable energy technologies, combined with a rapid move away from coal use in China, a shift to natural gas in several countries including the US, and moderating (although still robustly positive) growth in per capita consumption in the major emerging economies like China and India. This opens the possibility that we may be nearing peak global emissions several decades ahead of most predictions (Jackson *et al* 2015), although this may be only partly as result of deliberate mitigation to prevent climate change and mostly due to economic considerations. In any case, it is becoming increasingly clear that historical rates of energy system change do not constrain what may be possible in the future.

Large uncertainties remain as to both what the consequences of 1.5 °C–2 °C of climate warming will mean for human and environmental systems (Schleussner *et al* 2016), as well as how much we can allow ourselves to emit in order to remain below these thresholds (Matthews *et al* 2017). But the question of whether we will be able to achieve the targets written into the Paris Agreement is not a scientific one; rather it is a question of what we believe human societies to be capable of achieving. If we truly commit to solving this problem using all resources at our disposal, while also acknowledging and addressing fundamental principles of international and intergenerational equity, we have a good chance of avoiding the potentially catastrophic consequences of unmitigated global warming.

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