The exit strategy

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Emissions targets must be placed in the context of a cumulative carbon budget if we are to avoid dangerous climate change.

The build-up to the December 2009 Conference of the Parties to the Kyoto Protocol in Copenhagen has brought renewed impetus to calls for immediate action on climate change[1]. Many countries have agreed to aim to limit global warming to 2 °C above pre-industrial levels, with some calling for temperature targets as low as 1.5 °C (ref. 2). As past greenhouse gas emissions have already committed us to warming of around 1 °C, and given the inertia in both the climate system itself and in human systems such as energy, transport and food production, urgent action is clearly required if these targets are to be achieved. So far, so familiar: but this is where the agreement ends. Should we be aiming to stabilize atmospheric composition at (or at the equivalent of) CO_2 concentrations of 450 or 350 parts per million[2,3]? What should emission targets be for 2020 or 2050, and will they be low enough to avoid dangerous climate change? And why can't climate scientists just answer these simple questions?

Two companion papers[4,5] in this week's issue of *Nature*, addressing the question of what it will take to keep warming to 2 °C, present both a challenge and an opportunity for the climate-change mitigation debate. Both highlight the importance of the long view. Meinshausen *et al.*[4] argue that emission levels in 2050, or cumulative emissions to 2050, are robust indicators of the probability of temperatures exceeding 2 °C above pre-industrial values by 2100. Allen *et al.*[5] take an even longer view, exploring the impact of CO_2 emissions over the entire 'anthropocene'. They argue that keeping the most likely warming due to CO_2 alone to 2 °C will require us to limit cumulative CO_2 emissions over the period 1750–2500 to 1 trillion tonnes of carbon (1 Tt C; see Fig. 1). Warming due to other greenhouse gases[4] and uncertainty in the response[4,5] means that we may well have to accept an even lower limit to have any realistic chance of avoiding 2 °C of anthropogenic warming. So with more than 0.5 Tt C released already since pre-industrial times, it may well turn out that we can only afford to release less than the same again, possibly much less, with many times that amount in fossil-fuel reserves remaining underground[6].

Crucially, both studies argue that it is the accumulation over time of emissions of very-long-lived greenhouse gases like CO_2 that principally determines the maximum projected warming. In principle, emissions in any given decade matter only insofar as they contribute to the cumulative budget, although in practice, for most plausible emission scenarios, 2050 emissions are a strong indicator of the likely cumulative total[4]. These new results are not incompatible with current proposals for near-term emission targets: the small size of the cumulative emission budgets to 2050 reinforces the need for global CO_2 emissions to peak around or before 2020 so that emission pathways remain technologically and economically feasible[7].

The challenge these results present to the climate mitigation debate, however,

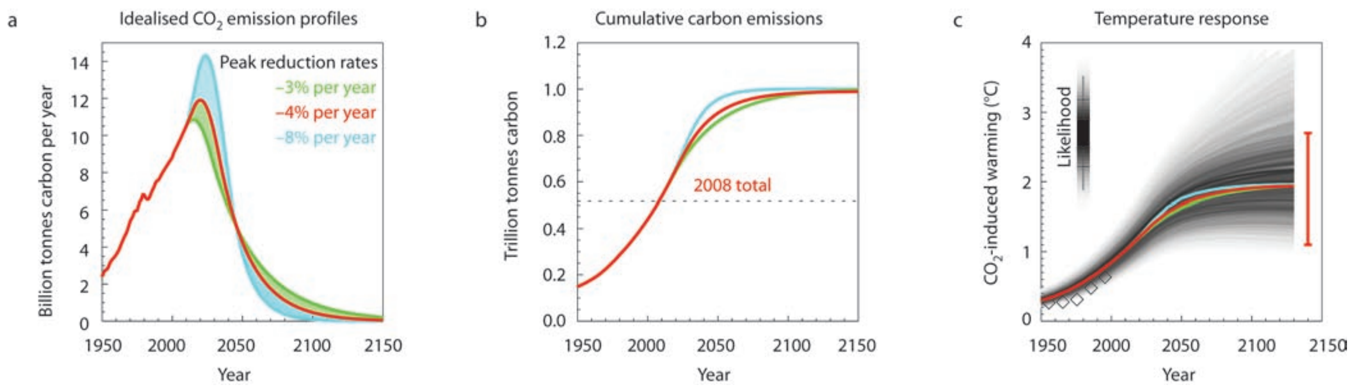

Figure 1 Idealized emissions. Shown are three idealized CO_2 emission paths (**a**) each consistent with total cumulative emissions (**b**) of 1 trillion tonnes of carbon. Varying the timing of emissions alone has almost no impact on projected temperatures (**c**) relative to uncertainty in the climate system's response (grey shading[5] and red error bar[4,5]), provided the cumulative total is unaffected (the two blue shaded regions in a have the same area, as do the green); but the higher and later emissions peak, the faster they have to decline to stay within the same cumulative budget. Diamonds in **c** indicate observed temperatures relative to 1900–1920.

is that some might seize upon them as evidence that, if cumulative emissions are what really matters, then there is no point in worrying about emissions next year. But having taken 250 years to burn the first half-trillion tonnes of carbon, we look set, on current trends, to burn the next half trillion in less than 40. No one could credibly suggest that we should carry on with business as usual to the 2040s and then somehow suddenly stop using fossil fuels, switch to 100 per cent carbon capture or just shut down the world economy overnight. Conversely, others might argue that CO_2 emissions will always continue "because we have to eat and breathe", so if warming scales with cumulative emissions, temperatures are doomed to rise forever and we may as well give up. Against this, we would argue that a world in which emissions are 80–90 per cent lower than they are now would be so different from anything we can conceive today that it is absurd to rule out categorically the possibility of zero net emissions for any sector.

But this new evidence also presents an opportunity to clarify the terms of the debate. As the impact of cumulative CO_2 emissions can now be inferred primarily from quantities we can observe, it is very difficult to fudge the implications: the more CO_2 we dump into the atmosphere, the higher the committed warming. A single simple metric linking cumulative emissions to peak warming, or 'cumulative warming commitment'[5], reduces the many 'degrees of freedom' that policy-makers have to contend with. For example, Meinshausen *et al.*[4] argue that peaking global emissions before 2020, cutting them at least 50 per cent below 1990 levels by 2050 and continuing reductions thereafter gives us a reasonable chance of staying within a budget consistent with limiting warming to 2 °C, but securing agreement on this will undoubtedly be hard. This is where acknowledging the principle of a cumulative budget could be helpful: the higher emissions are allowed to be in 2020, the lower they will need to be in 2050 to stay within the same overall budget. From this perspective, the argument for early emission cuts becomes primarily an economic and technical one: late and rapid reductions are risky, expensive and disruptive, and hence potentially politically infeasible. And the sooner we start, the more flexibility we have to adjust policies as new scientific information becomes available. Cutting emissions later also raises the issue of inter-generational equity, as the costs of very steep emission reductions in the future (assuming these are feasible) could well exceed the economic benefits of postponing mitigation.

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Half a trillion tonnes of carbon have been released into the atmosphere in the past 250 years.

Should we prescribe an explicit cap on cumulative CO_2 emissions alongside shorter-term targets? This is a political question, not a scientific one: as scientists, we can only note that the close link between cumulative CO_2 emissions and peak warming means that the scientific logic of some kind of limit is inescapable. More research is undoubtedly required to support a specific target, which would need to be further refined as soon as we have some real data on the climate system's response to falling emissions. At present, we can simply note that a limit on cumulative CO_2 emissions will be needed in principle, whether it is achieved through an explicit cap or emerges from a succession of shorter-term targets. Current evidence suggests that this limit is unlikely to be higher than 1 Tt C if the goal of limiting global warming to 2 °C is to have much chance of being met, and that it may need to be substantially lower.

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Even without specifying a number, acknowledging the principle of a cumulative budget for very-long-lived greenhouse gases has practical implications. Emission rates, not cumulative totals, matter for shorter-lived climate-forcing agents such as methane or aerosols. This places a fundamental limit on how far it makes sense to 'bundle' the impacts of different human influences on climate. So in agreeing on targets, trading systems and so on, we have to bear in mind what they mean for total cumulative emissions of CO_2 (and, perhaps, other very-long-lived species like nitrous oxide). Short-term measures that reduce 2020 emissions of potent but short-lived gases but commit to greater emissions of CO_2 overall could actually be counterproductive.

Any discussion of limits on cumulative emissions must not distract attention from the need for shorter-term targets. If the world's politicians were to stand shoulder-to-shoulder in Copenhagen and declare "we will not release the trillionth tonne" it would be an inspiring moment, but it would not actually require anyone to do anything before the next election. But by placing short-term targets in the context of a cumulative budget, we reduce the risk of missed targets breeding defeatism. Instead of "we missed the target for 2020, so we may as well give up" (or worse, "now there's nothing for it but geo-engineering") we'll be saying "we missed the intermediate target, so now it's going to be even more expensive to meet our overall goal of avoiding dangerous climate change". None of these messages is comforting, but at least the last one is accurate.

Given the scientific logic of a cumulative budget, it is also hard to avoid the conclusion that negative CO_2 emissions may eventually need to be considered. First, these may be needed to offset emissions from sources that cannot be eliminated quickly enough, such as food production. Second, if total emissions are limited, and we are not sure exactly what the limit is (but the evidence suggests it may not be too far away), then there is a good chance we will find out too late that we have exceeded it[8]. Our descendants in the second half of this century, knowing much more about climate change and its impacts than we do, may decide that they need to intervene actively to reduce atmospheric CO_2 concentrations. To be credible, a cumulative cap perhaps ought to be accompanied by a commitment to develop the technologies to enable such intervention if necessary. The more we emit in the next couple of decades, the greater the risk that avoiding dangerous climate change might require negative net emissions at some point this century. Compared to the cost and risks of free-air capture, early emission reductions could rapidly start to look very attractive.

Over the coming years, many of us are likely to be asked to accept what we perceive as significant sacrifices to prevent dangerous climate change. In response, it is entirely reasonable to ask "what is the exit strategy?" How do specific short-term measures contribute to our long-term goal? The tight link between cumulative CO_2 emissions and peak warming helps cut through the tangle of different proposals. A tonne of carbon is a tonne of carbon, whether released today or in 50 years time. Emitting CO_2 more slowly buys time, perhaps vital time, but it will only achieve our ultimate goal in the context of a strategy for phasing out net CO_2 emissions altogether.

At some point in the past few years, without any fanfare, we burned the half-trillionth tonne. Somewhere out there, in a coal seam, hydrocarbon reservoir or some as-yet-undiscovered exotic form of fossil carbon, lies the trillionth tonne. Its fate, perhaps more than any other consequence of climate-change policy, is inextricably linked to the risk of dangerous climate change. Where will it be in the twenty-second century?

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