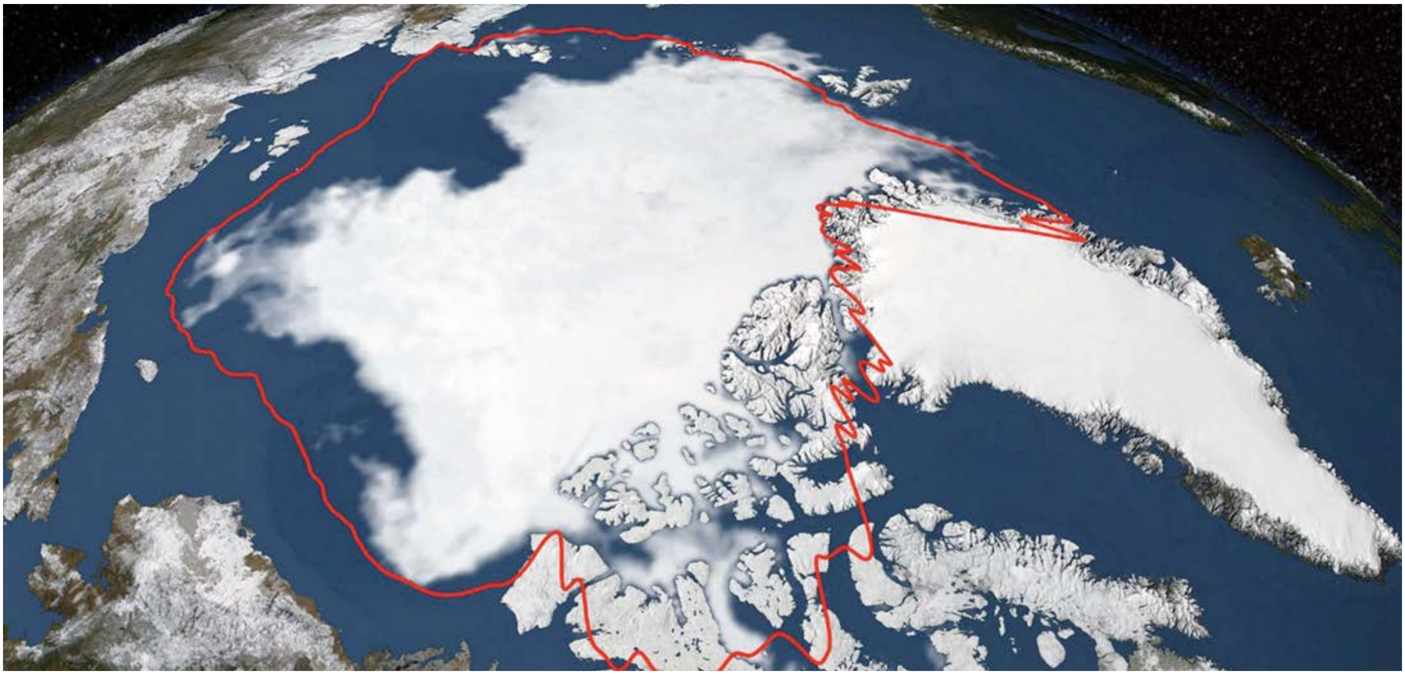

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The scientific case for a cumulative carbon budget

Climate change mitigation efforts must recognise that tackling current carbon dioxide flows is not enough; what matters is total emissions to date

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One of the most important new findings of the 2013 Scientific Assessment of the Intergovernmental Panel on Climate Change (IPCC) is that "cumulative emissions of carbon dioxide (CO_2) largely determine global mean surface warming by the late 21st century and beyond." Unlike most other climate pollutants, CO_2 emissions accumulate in the climate system. This simple fact has profound implications for climate policy. Stabilising global temperatures requires net global CO_2 emissions to be reduced to zero. What ultimately matters for climate is the total 'emissions stock', or cumulative CO_2 emissions over the entire industrial epoch, not the 'emissions flow', or the rate of emission of greenhouse gases in any given decade.

This is important, because many involved in climate change negotiations still think their ultimate objective is stabilisation of atmospheric greenhouse gas concentrations, and that the rates of emission in 2030 or 2050 are crucial determinants of success. In reality, stabilising atmospheric CO_2 concentrations is not enough to stabilise climate. The world would continue to warm for centuries even with CO_2 concentrations held constant. Stabilising temperatures requires net global CO_2 emissions to be reduced to zero, after which temperatures would remain constant even as atmospheric CO_2 concentrations gradually decline. While CO_2 was once thought to have an 'atmospheric lifetime' of about 200 years, it is now recognised that any fossil carbon released will continue to affect the climate for many thousands of years.

This is illustrated in Figure 1, which shows three idealised CO_2 emission paths. In the green path, global emissions peak around 2015 and decline thereafter at a peak rate of three per cent per year, while in the

▲ Arctic sea ice hit its annual minimum on 17 September 2014. The red line in this image shows the average minimum extent between 1981 and 2010 orange path, they peak in the late 2020s but decline at 10 per cent per year – which would be extremely expensive, and might not be technically or politically feasible. Although peak emissions are very different, total cumulative emissions up to the time emissions reach zero is the same in all three cases. The most likely temperature responses, shown by the coloured lines in the right panel, are almost identical, with the small differences dwarfed by uncertainty in the response (grey bands).

Figure 1 also illustrates the importance of the carbon budget over the entire industrial period, not just to the middle of this century. It shows that it is CO_2 over all time that matters, not cumulative emissions to 2050. The orange and green scenarios represent very different total emissions from now to 2050 but yield the same climate outcome. Conversely, constant emissions from now to 2050 would represent very similar cumulative CO_2 emissions to 2050 as the orange scenario, but a much greater climate commitment in the longer term, because it would imply a much greater emissions commitment after 2050.

Finally, Figure 1 also shows that the longer we postpone reducing CO_2 emissions, the faster they have to fall to achieve any given temperature goal (this would not be true of a short-lived climate pollutant like methane). Conversely, for any given rate of reduction after the emissions peak, we must note that committed peak warming has been rising over recent decades at approximately the same rate as cumulative emissions, which is about twice as fast as observed temperatures. Therefore, measures that would have limited CO_2-induced warming to 2°C if initiated in 1992 would yield a peak CO_2-induced warming of over 3°C if initiated today.

'Unemittable carbon'

This global carbon budget provides a simple and powerful way of framing the challenge of avoiding dangerous human-induced climate change. Figure 2 shows global average temperatures plotted against cumulative global CO_2 emissions, both measured from 19th century conditions. The thin grey line and grey shaded uncertainty plume shows the expected warming due to CO_2 emissions alone. The coloured lines and pink uncertainty plume, also plotted against cumulative CO_2 emissions, show expected total human-induced warming from all greenhouse gases and other forms of pollution, under a range of scenarios from sustained 'business-as-usual' (red line) to aggressive and immediate mitigation (dark blue line). The red scenario moves rapidly off to the top right corner of the figure, meaning CO_2 emissions continue to accumulate and temperatures keep rising past 4°C. In the blue scenario, net CO_2 emissions are reduced to zero before 2100, so CO_2 stops accumulating in the climate system and temperatures

Figure 1: the persistent effect of CO_2 on global temperature

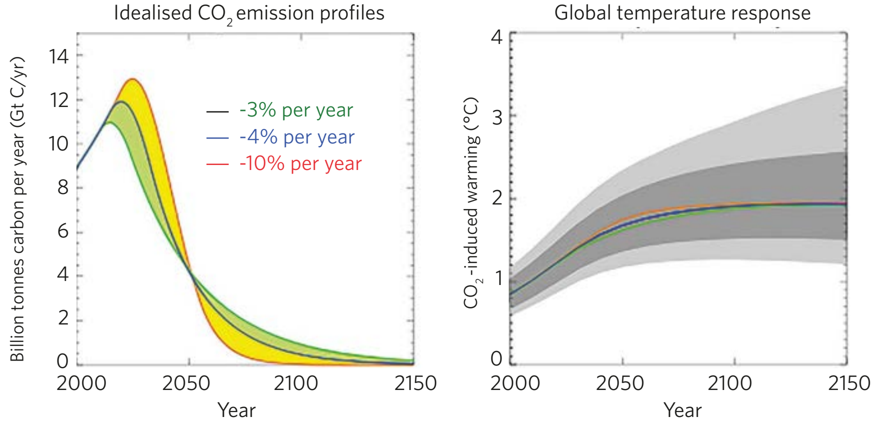
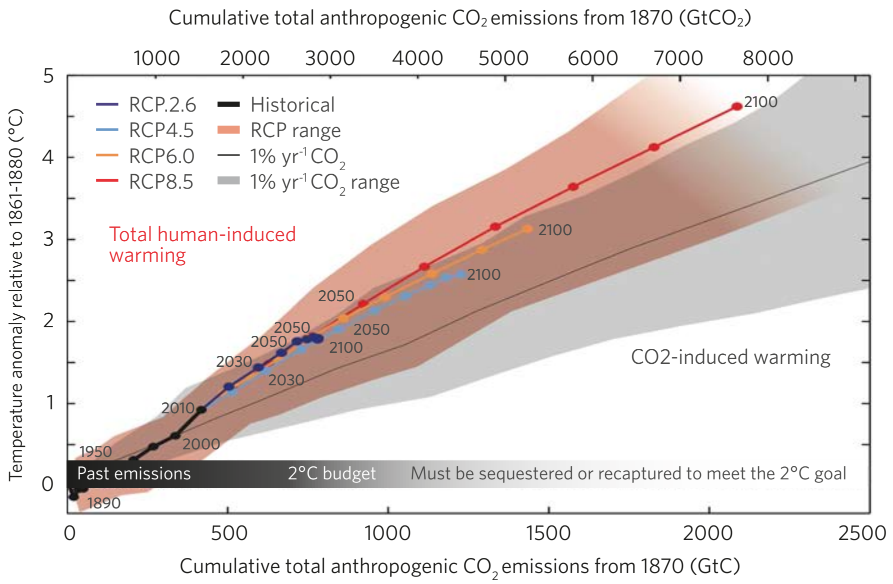


Figure 2: correlation between cumulative CO_2 emissions and global warming



Warming in the CMIP-5 multi-model ensemble under the Representative Concentration Pathway scenarios (coloured lines, with pink plume showing the range of uncertainty) and under idealised CO_2-only scenarios (grey line and plume) plotted as a function of cumulative total anthropogenic CO_2 emissions from 1870 onwards – figure SPM10 of IPCC (2013). Black horizontal bar shows historical emissions to date; dark grey bar shows the approximate cumulative emission budget consistent with limiting warming to 2°C; light grey bar shows carbon reserves that, if used, must be sequestered or recaptured if the 2°C goal is to be met.

stop rising before they reach 2ºC. But all scenarios follow roughly the same line: for a given level of cumulative CO_2 emissions, the planet experiences about the same level of warming irrespective of whether that CO_2 is emitted fast or slow. Warming from non-CO_2 sources adds 25-30 per cent to CO_2-induced warming from 2050 onwards in these scenarios.

The implications for the cumulative carbon budget are shown by the grey bar at the bottom of the figure. Past emissions from fossil fuel use and land-use change are over half a trillion tonnes of fossil carbon (black bar). Future CO_2 emissions must be limited to between half as much again and the same again (dark grey bar) if the goal of limiting global warming to 2ºC, set by the parties to the UN Framework Convention on Climate Change (UNFCCC) in Cancún

> *The discovery of the importance of the cumulative carbon budget has exploded the idea of 'CO₂-equivalence'*

in 2010, is to be achieved. The precise carbon budget depends on the probability we are prepared to accept of failing to meet the goal, and on what happens to non-CO_2 warming, but to have even a modest chance of meeting the 2ºC goal, total anthropogenic CO_2 emissions over the entire anthropocene must be less than one trillion tonnes of carbon (3.7 trillion tonnes of CO_2), well over half of which has already been emitted.

The IPCC estimates that available fossil fuel reserves (economically exploitable with current technology and prices) exceed this '2ºC budget' by a factor of two to three, with resources (potentially exploitable if prices rise) many times greater still. Hence, any fossil carbon used beyond the trillionth tonne (light grey bar) will have to be captured at source or recaptured from the atmosphere and disposed of if the 2ºC goal is to be met.

Implications for mitigation policy

Many national and international policies still treat climate change as a flow problem, focusing on reducing the overall rate of greenhouse gas emissions in 2020, 2030 or 2050. But while reducing the rate of accumulation of CO_2 emissions buys time, it does not solve the problem unless we succeed in the end of reducing CO_2 emissions to zero. This is important, because many of the most cost-effective measures for reducing emissions in the short term, such as improving energy efficiency, are not those that will ultimately be needed to reduce emissions to zero.

The key technology required to achieve net zero CO_2 emissions is carbon capture and storage (CCS). CCS is in a unique position among climate change mitigation measures: it is needed to allow exploitation of fossil fuel reserves that would otherwise be 'unburnable' in a climate-constrained world and also, in conjunction with biomass energy generation or other methods, can provide a means of extracting CO_2 from the atmosphere. This is almost certain to be needed either to offset remaining CO_2 emissions after temperatures stabilise or, if the safe cumulative carbon budget is exceeded, of drawing CO_2 down again.

Largely because of this unique long-term 'backstop' role, the IPCC finds that failing to deploy CCS more than doubles the cost of meeting the 2ºC goal (and in many models makes it impossible to meet it at all). Yet because it is expensive as a means of reducing short-term emissions flow, CCS remains a relatively low priority in many climate policy portfolios. Recognising the cumulative carbon budget is therefore essential for governments to recognise the importance of specifically supporting the development and deployment of backstop technologies like CCS.

Cumulative carbon versus short-lived climate pollutants

Limited progress on reducing CO_2 emissions has prompted interest in measures to address climate change by reducing emissions of so-called 'short-lived climate pollutants', or SLCPs, such as methane and black carbon (soot). Many of the measures required to reduce these emissions are relatively low cost and offer very substantial co-benefits. Their impact, in climate terms, is also relatively immediate. If we halve methane emissions then atmospheric methane concentrations would fall by a comparable amount within a couple of decades. In contrast, if we halve CO_2 emissions, atmospheric CO_2 concentrations would continue to rise, just half as fast as before.

Because measures to reduce CO_2 emissions take a long time to have a discernible impact, immediate measures to reduce SLCP emissions are undeniably the most cost-effective approach to reducing the rate of climate change over the next few decades. But immediate SLCP measures would only have an impact on peak warming if CO_2 emissions are reduced aggressively at the same time, such that temperatures are beginning to stabilise (for which CO_2 emissions must be approaching zero) soon after 2050. SLCP emissions only become important in the context of the overall goal of the UNFCCC when CO_2 emissions are already falling.

The myth of 'CO_2-equivalence'

The discovery of the importance of the cumulative carbon budget has exploded the idea of 'CO_2-equivalence', which is still widely used in climate policy and emission trading systems. Not all measures to reduce CO_2-equivalent emissions in 2030 are equivalent. Some, like CCS, provide a route to net zero or net negative CO_2 emissions. Others, like improved energy efficiency or reducing methane or soot emissions, do not.

Short-term measures can help limit warming until such time as CO_2 emissions can be reduced to zero, but in the absence of a plan to achieve net zero CO_2 emissions, they will ultimately fail. It is essential that the UNFCCC recognises the importance of achieving net zero CO_2 emissions such that additional policies can be put in place to work towards this long-term goal, supplementing short-term measures to reduce emissions of all climate pollutants over the coming decades. ●