nature climate change

PERSPECTIVE

PUBLISHED ONLINE: 21 NOVEMBER 2013 | DOI: 10.1038/NCLIMATE2077

Impact of delay in reducing carbon dioxide emissions

Myles R. Allen[1,2]* and Thomas F. Stocker[3,4]

Recent downward revisions in the climate response to rising CO_2 levels, and opportunities for reducing non-CO_2 climate warming, have both been cited as evidence that the case for reducing CO_2 emissions is less urgent than previously thought. Evaluating the impact of delay is complicated by the fact that CO_2 emissions accumulate over time, so what happens after they peak is as relevant for long-term warming as the size and timing of the peak itself. Previous discussions have focused on how the rate of reduction required to meet any given temperature target rises asymptotically the later the emissions peak. Here we focus on a complementary question: how fast is peak CO_2-induced warming increasing while mitigation is delayed, assuming no increase in rates of reduction after the emissions peak? We show that this peak-committed warming is increasing at the same rate as cumulative CO_2 emissions, about 2% per year, much faster than observed warming, independent of the climate response.

Recent downward revisions in the climate response to rising greenhouse gases[1–4] have been cited as evidence that the case for reducing CO_2 emissions to limit climate change is less urgent than previously thought[5]. Similarly, permanent reductions in non-CO_2 climate pollutants, which might reduce global temperatures by up to 0.5 °C (refs 6,7), have been reported to "give politicians two extra decades to tackle the less tractable question about what to do about CO_2"[8]. But what is the penalty for a delay in CO_2 mitigation[9]? Here we show that unless any delay in initiating emission reductions is compensated for by faster reductions later, then peak CO_2-induced warming is currently increasing at the same rate as cumulative CO_2 emissions themselves, independent of the climate system response. This is the rate at which rising emissions compensate for any reduction in estimated climate response or proposed non-CO_2 mitigation strategies. At almost 2% per year, it is much faster than observed warming. Hence 0.5 °C of non-CO_2 climate mitigation is 'worth' a delay in CO_2 mitigation of 12 (16) years if we assume a peak CO_2-induced warming of 2 °C (1.5 °C), and less than 10 years if we assume higher levels of peak warming.

Evaluating the impact of delay in reducing CO_2 emissions is complicated by the fact that these emissions accumulate over time, so what happens after they peak is as relevant for long-term warming as the size and timing of the peak itself[10–12]. A helpful simplifying constraint is the approximately linear relationship between cumulative CO_2 emissions and resultant peak warming, expressed as the transient climate response to cumulative carbon emissions[3], or TCRE (the parameter β in ref. [9]). TCRE is formally defined as the warming due to cumulative carbon dioxide emissions per trillion tonnes of carbon (TtC) released into the atmosphere (1 TtC is slightly less than double the emissions so far from fossil-fuel use and land-use change since 1750). TCRE is closely related to the more familiar transient climate reponse (TCR), which is defined as the warming at the time of doubling of CO_2 after it has increased at 1% per year for 70 years. TCR more generally indicates the warming due to any gradual increase in radiative forcing over a 50- to 100-year timescale[13,14]. Hence, if most of the 1 TtC injection occurs over this timescale, and accounting for the logarithmic dependence of forcing on CO_2 concentrations:

$$\mathrm{TCRE} = \mathrm{TCR}\left(\frac{F_1}{F_2}\right) = \frac{\mathrm{TCR}}{\ln(2)}\ln\left(1+\frac{\alpha_1 C_1}{C_0}\right) \quad (1)$$

where F_2 = 3.7 W m^{-2} is the forcing due to doubling CO_2 and F_1 is the forcing following an injection of C_1 = 1 TtC of cumulative carbon emissions, α_1 is the cumulative airborne fraction — the fraction of the 1 TtC that remains in the atmosphere after it has all been injected, and C_0 = 0.58 TtC (275 ppm) is the pre-industrial carbon content of the atmosphere. The instantaneous airborne fraction over recent decades has been slightly under 50% but is expected to increase with rising temperatures[15,16], so an approximate rule-of-thumb is that the TCRE is about 90% (±10%, arising from uncertainty in α_1) of the TCR[3]. Any revision in TCR will also be reflected in TCRE.

The increase in airborne fraction with rising temperature approximately compensates for the logarithmic relationship between CO_2 concentrations and radiative forcing[15], giving a nearly linear relationship between cumulative CO_2 emissions and peak warming[16], at least over the first two trillion tonnes released. The concept of TCRE is only relevant to those long-lived greenhouse gases with atmospheric residence times of a century or more, such as CO_2 and nitrous oxide, although TCRE has so far only been evaluated for CO_2. Emissions of short-lived climate pollutants such as methane and black carbon only affect peak temperatures if they are sustained to the time of peak warming[17].

Some early estimates of TCRE[18,19] suggested a value of about 2 °C per TtC, whereas the most up-to-date estimates from both observations and coupled climate-carbon-cycle models[3] suggest a range of 0.8–2.5 °C per TtC, consistent with revised estimates of TCR[3,4,20]. Hence the most likely values and estimated upper bounds on TCR and TCRE have been reduced by 25–30% from values estimated in 2007–2009.

The implications for climate change adaptation of a 25–30% downward revision in the transient response are minimal. The highest warming projections for the coming decades in the latest Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble of climate model simulations now look relatively unlikely[21], but the

[1]ECI, School of Geography and the Environment, University of Oxford, OX1 3QY, UK. [2]Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK. [3]Climate and Environmental Physics, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland. [4]Oeschger Centre for Climate Change Research, Zähringerstrasse 25, CH-3012 Bern, Switzerland. *e-mail: myles.allen@ouce.ox.ac.uk

majority of models and the multi-model mean remain consistent with these revised estimates of climate system properties. A 25–30% reduction in TCR means that the changes we would have expected between now and 2050 under a sustained increasing forcing scenario might not occur until the early 2060s, which is within the range expected from climate variability. But what are the implications for mitigation?

The overall case for mitigation is unaffected. Revised estimates of TCR and the relationship between forcing and response in equation (1) still imply a warming of 2–5 °C above pre-industrial by the early twenty-second century under the RCP8.5 scenario[20] (total radiative forcing of 8.5 W m^{-2} by 2100), which is consistent with current emission trends. But although substantial emissions reductions are still required if a warming greater than 2 °C is to be avoided, do these new estimates mean they can be delayed?

The simple relationship between warming and cumulative carbon emissions means that what really matters is the area under the CO_2 emissions curve. This permits the use of idealized scenarios[9] to demonstrate the policy implications of different TCRE values. Following ref. 9, and assuming that emissions decline exponentially after their peak, TCRE provides a simple relationship between peak CO_2-induced warming ΔT_{max}, current emissions E, historical cumulative emissions so far C_H, and the average future rate of emission decline s:

$$\Delta T_{\max} = \text{TCRE}\left(\frac{E}{s} + C_{\text{H}}\right) \quad (2)$$

Given that mitigation policies will take time to have an impact, some overshoot is inevitable[10,18,] which would need to be compensated for later, so the peak rate of emissions decline will always be greater than s. Nevertheless, these idealized trajectories simplify our understanding of the mitigation challenge.

Historical emissions from fossil-fuel use and land-use change C_H were 0.54 TtC by the end of 2010, when emissions E were 0.01 TtC per year[22] and have been increasing at a rate r = 1.8–1.9% per year. A TCRE of 2 °C per TtC would imply that, to limit CO_2-induced warming to 2 °C, global emissions must decline on average by 2.4% per year from now on, limiting total cumulative emissions to 1 TtC (green region in Fig. 1a). A revision of TCRE to 1.5 °C per TtC would imply emissions must decline by 1.4% per year from now on to give the same peak CO_2-induced warming (green region in Fig. 1b).

Because the difference between these required rates of reduction is smaller than the current rate of emissions increase, some might argue that this revision of TCRE has very few implications for the timing of mitigation, because governments do not, in reality, directly control emissions. A 25% revision in TCRE is small relative to the much larger uncertainties in the actual policy interventions that will be required to achieve either target, given we have no direct observations of economic behaviour in a period of sustained falling global emissions[12]. Given these uncertainties, however, it is helpful to separate economic and policy uncertainty from climate-response uncertainty.

A clear way of assessing the impact of delay is to assume a given average rate of s and consider the implications of delay in achieving it. It could be argued that this also represents a 'fair' assessment of the impact of delay in terms of inter-temporal equity, or the distribution of mitigation costs over time. Under the idealized but reasonable assumption that the burden of mitigation scales approximately with the percentage annual rate of reduction, delaying mitigation while assuming emissions will fall faster in future to compensate would increase asymptotically the mitigation burden placed on the future. Conversely, it might also be argued that delaying mitigation would reduce the cost of achieving a given rate of reduction through technology development: this, however, assumes that investment in the relevant technologies is made in the meantime. We should be clear that the delay we are referring to here is a 'pure procrastination' delay, as opposed to a period of investment aimed at achieving rapid reductions in future.

Under these assumptions, the rate of change of peak CO_2-induced warming, or 'mitigation delay sensitivity' (MDS) is given by:

$$\begin{aligned}\text{MDS} &= \frac{\mathrm{d}\Delta T_{\max}}{\mathrm{d}t} = \text{TCRE}\,\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{E_0 e^{r(t-t_0)}}{s} + C_{\text{H}}\right) \\ &= r\Delta T_{\max} + \text{TCRE}\,(E - rC_{\text{H}})\end{aligned} \quad (3)$$

using equation (2) and $\mathrm{d}C_H/\mathrm{d}t = E = E_0 e^{r(t-t_0)}$, where E_0 is emissions at a reference time t_0 and r is the current rate of emissions increase. If r = 0 (constant emissions) then ΔT_{max} increases at a rate TCRE·E irrespective of the value of ΔT_{max} or the assumed value of s after the peak. As long as emissions are rising exponentially, however, MDS also depends on s, or the value of ΔT_{max} itself. The higher we expect temperatures to peak, or the more pessimistic we are about future average rates of emissions decline, the higher the MDS.

At present, emissions happen to be increasing at a rate approximately equal to E/C_H, so the final $E - rC_H$ term in equation (3) is small. Hence, if future rates of emission decline do not increase to compensate for delay, peak warming ΔT_{max} is currently increasing at the same rate that emissions are increasing, independent of the climate response: the timing of the emission peaks corresponding to the same ΔT_{max} is identical in Fig. 1a and b, despite the different values of TCRE. This result holds for any given shape of post-peak emissions profile, defined in terms of fractional rate of decline as a function of time after emissions peak, not simply the idealized exponential profiles used here. If we are aiming for peak warming of around 2 °C, then as long as emissions are increasing at 1.8–1.9% per year, every year's delay in reducing emissions increases peak warming by 1.8–1.9% of 2 °C, or 0.04 °C. If the same level of effort required in 2010 to limit CO_2-induced warming to 2 °C were applied starting in 2015, the resultant peak warming would be 10% higher, at 2.2 °C.

Given the complexities of the climate issue, simple rules-of-thumb like this are a valuable way of comparing the impact of climate policies. If we are confident that we can and will reduce emissions fast enough to limit CO_2-induced warming to 2 °C, then a 0.5 °C reduction in future temperatures resulting from permanent reductions in non-CO_2 climate pollutants is apparently 'worth' a 12-year delay in the CO_2 emission peak (at present, 0.5 °C divided by the MDS for a 2 °C peak warming is 13–14 years, but equation (3) shows MDS is also increasing exponentially with rising emissions). If we believe that a lower TCRE and optimistic assumptions about future emissions mean we can limit CO_2-induced warming to 1.5 °C, then 0.5 °C from non-CO_2 forcing has the same impact on ΔT_{max} as a 16-year delay in CO_2 mitigation (Fig. 1c). Conversely, it could be argued[12] that even 2.4% per year sustained global reductions in CO_2 emissions might be very hard to achieve, so we should expect CO_2-induced warming to peak around 3 °C even with this lower value of TCRE (Fig. 1d). If this is the case, then 0.5 °C from non-CO_2 mitigation is 'worth' only a 9-year delay in the CO_2 emissions peak, reducing to 7 years for a peak warming of 4 °C. Proponents of climate mitigation through non-CO_2 measures rightly stress the difficulty of reducing CO_2 emissions[23]: what this result illustrates is that, the harder it turns out to be to mitigate CO_2, the smaller the impact of non-CO_2 climate pollutants on peak warming, in both relative and absolute terms.

All of these delays are also less than half those that would be implied if we assume stable CO_2 emissions (r = 0), illustrating the importance of allowing for ongoing emissions increase in assessing the impact of delay. They are also much less than half the time it would take for the climate system to warm by 0.5 °C, illustrating that,

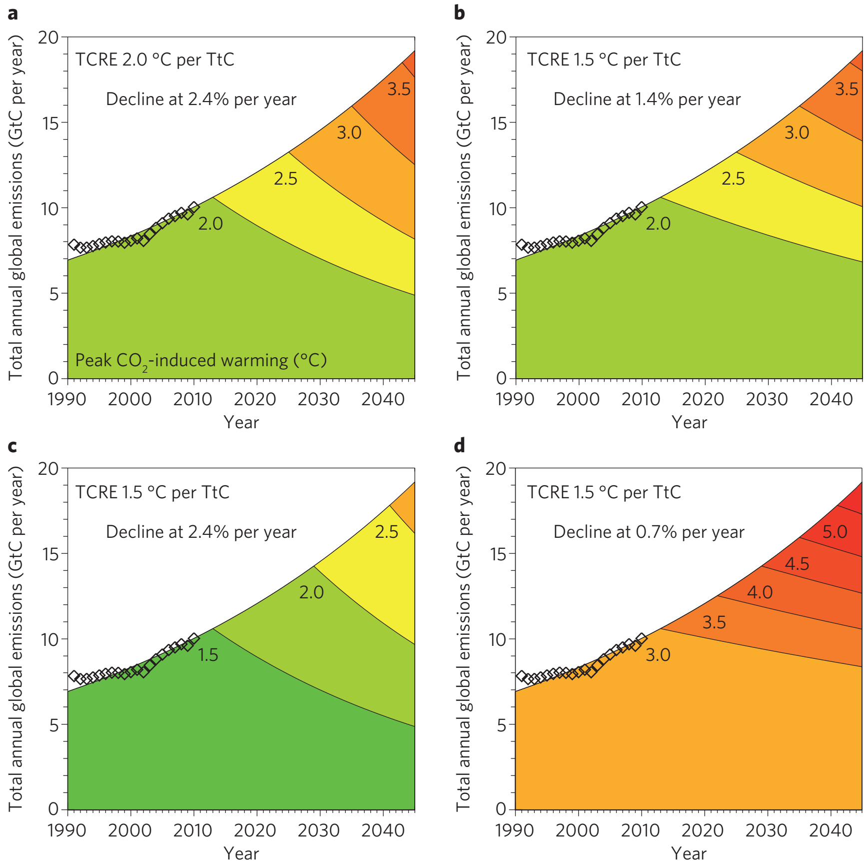

Figure 1 | Schematic emission scenarios illustrating the impact of different estimates of the climate system response to CO_2 emissions. a, Colours and inset numbers show peak CO_2-induced warming resulting from an average rate of global emissions decline s = 2.4% per year, sustained indefinitely, starting in 2013 and at various dates thereafter, this being the average rate of decline from 2013 required to meet a 2 °C peak warming goal assuming a TCRE of 2 °C per TtC. Diamonds show observed emissions; data from refs 9 and 22. **b**, Emission paths giving the same peak warming for a TCRE of 1.5 °C per TtC requiring s = 1.4% per year. **c**, Peak CO_2-induced warming under the lower value of TCRE but assuming a 2.4% per year decline. **d**, How committed warming rises faster with delay if we assume a slower average rate of decline and hence higher peak warming.

because CO_2 emissions cannot fall instantaneously, peak committed warming is rising substantially faster than observed warming.

The fact that the relative importance of non-CO_2 mitigation depends so heavily on assumptions about future CO_2 mitigation illustrates the potentially distortionary impact of very optimistic assumptions about the future if these turn out to be unrealistic. If we assume emissions will fall fast enough and the TCRE will be low enough to limit CO_2-induced warming to 1.5 °C, then 0.5 °C of permanent non-CO_2 mitigation would seem to be 'worth' more than a decade's delay in CO_2 mitigation. If it turns out we can only limit CO_2-induced warming to 3 °C, then 0.5 °C of non-CO_2 mitigation is worth a much smaller delay. It also illustrates the 'metric problem': the impact of emissions of short-lived climate pollutants on peak warming depends on both the timing of these emissions and what is done in future about long-lived climate pollutants[17,24]. In contrast, a tonne of CO_2 has much the same impact on peak warming regardless of when it is emitted or what is done about other pollutants. The fact that higher levels of peak warming will not be reached until later this century reduces the impact of early action on short-lived climate pollutants (current emissions of which will have little impact on temperatures half a century hence) in the absence of simultaneous CO_2 mitigation[24].

Given the cumulative nature of CO_2, sustained emissions reductions are necessary if warming is to be kept below any agreed limit. The simple considerations presented here permit an estimate of sustained emission reduction rates required for different values of the climate system response, and the rate at which warming commitments are increasing as mitigation is delayed. Beyond the inevitable consequence that delayed mitigation eliminates options regarding warming limits[9], it has also been argued[25] that temperature alone is an insufficient climate target if Article 2 of the UN Framework Convention on Climate Change is to be observed. Additional climate targets potentially call for even stronger mitigation efforts.

Received 24 July 2013; accepted 8 November 2013; published online 21 November 2013.

References

1. Aldrin, M. *et al.* Bayesian estimation of climate sensitivity based on a simple climate model fitted to observations of hemispheric temperatures and global ocean heat content. *Environmetrics* **23,** 253–271 (2012).
2. Lewis, N. An objective bayesian improved approach for applying optimal fingerprint techniques to estimate climate sensitivity. *J. Clim.* **26,** 7414–7429 (2013).
3. Gillett, N. P. *et al.* Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations. *J. Clim.* **26,** 6844–6858 (2013).
4. Otto, A. *et al.* Energy budget constraints on climate response. *Nature Geosci.* **6,** 415–416 (2013).
5. Ridley, M. Earth to Met Office: check your climate facts. *The Times* (20 May 2013, updated 24 May 2013); available via http://www.rationaloptimist.com/blog/the-implications-of-lower-climate-sensitivity.aspx
6. Shindell, D. *et al.* Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335,** 183–189 (2012).
7. Bond, T. C. *et al.* Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res.* **118,** 5380–5552 (2013).

8. Global warming: The new black. *The Economist* (19 January 2013).
9. Stocker, T. The closing door of climate targets. *Science* **339,** 280–282 (2012).
10. Huntingford, C. *et al.* The link between a global 2 °C warming threshold and emissions in years 2020, 2050 and beyond. *Environ. Res. Lett.* **7,** 14039 (2012).
11. Rogelj, J. *et al*. Probabilistic cost estimates for climate change mitigation. *Nature* **493,** 79–83 (2013).
12. Luderer, G. *et al*. Economic mitigation challenges: How further delay closes the door for achieving climate targets. *Environ. Res. Lett.* **8,** 034033 (2013).
13. Held, I. M. *et al.* Probing the fast and slow components of global warming by returning abruptly to preindustrial forcing. *J. Clim.* **23,** 2418–2427 (2010).
14. Gregory, J. M. & Forster, P. M. Transient climate response estimated from radiative forcing and observed temperature change. *J. Geophys. Res. Atmos.* **113,** D23105 (2008).
15. Zickfeld, K. *et al*. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl Acad. Sci. USA* **106,** 16129–16134 (2009).
16. Matthews, H. D. *et al*. The proportionality of global warming to cumulative carbon emissions. *Nature* **458,** 829–832 (2009).
17. Smith, S. M. *et al*. Equivalence of greenhouse-gas emissions for peak warming. *Nature Clim. Change* **2,** 535–538 (2012).
18. Allen, M. R. *et al*. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458,** 1163–1166 (2009).
19. Meinshausen, M. *et al.* Greenhouse gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
20. Stocker, T. F. *et al.* (eds) *Climate Change 2013: The Physical Science Basis. Summary for Policymakers* (IPCC, Cambridge Univ. Press, 2013).
21. Stott, P. A., Good, P., Jones, G., Gillett, N. P. & Hawkins, E. The upper end of climate model temperature projections is inconsistent with past warming. *Environ. Res. Lett.* **8,** 014024 (2013).
22. Andres, R. J. *et al*. A synthesis of carbon dioxide emissions from fossil-fuel combustion. *Biogeosciences* **9,** 1845 (2012).
23. Victor, D. G., Kennel, C. F. & Ramanathan, V. The climate threat we can beat. *Foreign Aff.* **91,** 112–114 (2012).
24. Bowerman, N. H. A. *et al*. The role of short-lived climate pollutants in meeting temperature goals. *Nature Clim. Change* **3,** 1021–1024 (2013).
25. Steinacher, M., Joos, F. & Stocker, T. F. Allowable carbon emissions lowered by multiple climate targets. *Nature* **499,** 197–201 (2013).

Acknowledgements

M.R.A. acknowledges support from the UK Department of Energy and Climate Change under contract TRN 317/11/2011 and from the Oxford Martin School.

Additional information

Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to M.R.A.

Competing financial interests

The authors declare no competing financial interests