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Embracing uncertainty in climate change policy

Friederike E. L. Otto[1]*, David J. Frame[2], Alexander Otto[1] and Myles R. Allen[1,3]

The 'pledge and review' approach to reducing greenhouse-gas emissions presents an opportunity to link mitigation goals explicitly to the evolving climate response. This seems desirable because the progression from the Intergovernmental Panel on Climate Change's fourth to fifth assessment reports has seen little reduction in uncertainty. A common reaction to persistent uncertainties is to advocate mitigation policies that are robust even under worst-case scenarios, thereby focusing attention on upper extremes of both the climate response and the costs of impacts and mitigation, all of which are highly contestable. Here we ask whether those contributing to the formation of climate policies can learn from 'adaptive management' techniques. Recognizing that long-lived greenhouse gas emissions have to be net zero by the time temperatures reach a target stabilization level, such as 2 °C above pre-industrial levels, and anchoring commitments to an agreed index of attributable anthropogenic warming would provide a transparent approach to meeting such a temperature goal without prior consensus on the climate response.

The primary reasons for the slow progress in global mitigation policy are not scientific. They are strategic — economic and political barriers to action arising from weak incentives to mitigate and strong incentives to free-ride on the efforts of others, internationally and inter-generationally[1–3]. To be successful, a climate change mitigation policy not only has to overcome those economic and political barriers, but also has to withstand and adapt to other external pressures that originate from shifts in the economy (for example, 'austerity') and political interests (for example, 'climate scepticism'). Attempts have been made to design policies that are more robust to these external pressures, for example, by attempting to find ways for regulators to credibly commit both themselves and their successors in an environment of changing power structures (for example, ref. 4), locking in certain policies through institutional design[5], capitalizing on emergent government structures (for example, ref. 6) and self-reinforcing effects of certain policies[7]. Connecting these lines of thought to those of adaptive management and the governance of complex systems[8], here we argue for a redesign of climate change mitigation policies to be 'anti-fragile'[9] with respect to scientific uncertainty.

Anti-fragile means that uncertainty and changes in scientific knowledge make the policy more successful by allowing for trial and error at low societal costs. Hence, anti-fragile re-design allows the incorporation of a wider range of risks of concern to policymakers, potentially allowing more successful mitigation policies. Arguably, a key pre-requisite for an anti-fragile climate policy is an index not beholden to high scientific uncertainty. Here we suggest 'attributable anthropogenic warming' as an anti-fragile index against which pledges could be reviewed, independent of the details of individual countries' mitigation policies.

Precautionary mitigation policies

The predominant approach to the design of climate mitigation policies refers to the precautionary principle, embedded in the United Nations Framework Convention on Climate Change (UNFCCC; ref. 10, Article 2). As any climate policy has the joint goals of enabling continued human development while staying within the boundaries posed by the limitations of the climate system, a trade-off between these goals has to be struck. The two main methods for implementing the trade-off are cost–benefit approaches and cost-effectiveness approaches. In the former, estimates of the costs and benefits of mitigation are evaluated, usually through the use of integrated assessment models (IAMs). The target is set where the marginal costs of climate damages are equal to the marginal costs of climate mitigation. In the cost-effectiveness approach, the target is set by capping damages, with subsequent emphasis on finding the least-cost way of achieving the target. Damages themselves are uncertain functions of global mean surface temperatures, but for simplicity we follow the usual practice of assuming a smooth and convex relationship between them. Discovering damages are a more convex function of temperature change than is usually supposed would simply reinforce the need for 'anti-fragile' mitigation policies — mitigation paths that look attractive under moderate mitigation scenarios may turn out to be impossible to scale up if mitigation becomes more urgent.

In many settings, cost–benefit approaches might be expected to predominate, since this is a very familiar and effective policy approach. In the case of climate change, significant caveats arise from the incompleteness of IAMs: it is often claimed that these models significantly underestimate climate change damages[11]. If this is so, and if there is no corresponding underestimate in the costs of mitigation, it introduces a significant bias to any cost–benefit analysis of climate change.

Partly for this reason, many have argued instead for a cost-effectiveness approach[12]. In the context of climate change, by far the most discussed structure pertaining to the cost-effectiveness approach is the 2 °C goal adopted by the UNFCCC in Cancun[13]. A substantial body of research into how we might achieve successful management of the climate change problem has focused on meeting the agreed 2 °C target — an approach that is especially common among physical climate scientists researching the problem. One of the most cited publications in recent years in this field, Meinshausen *et al.*[14], updated by Rogelj *et al.*[15] provides limits to cumulative carbon emissions up to 2050 with corresponding limits to the probability of exceeding the 2 °C target. Their analysis is based on the budget approach[16] considering an emittable CO_2 budget until 2050 under which "only a small amount of CO_2 may be emitted worldwide after 2050" (Summary for Policymakers in ref. 16). Their emittable

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[1]Environmental Change Institute, University of Oxford, Oxford OX1 3QY, UK. [2]New Zealand Climate Change Research Institute, Victoria University of Wellington, PO Box 600, Wellington, New Zealand. [3]Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford OX1 3PU, UK. *e-mail: friederike.otto@ouce.ox.ac.uk

budget is derived by limiting the probability of exceeding a 2 °C target to levels at or below 25%. The UNFCCC has not formally adopted a position on the allowable probability of temperatures exceeding 2 °C, although the focus on scenarios that are 'likely' to achieve this goal[17,18] might be interpreted as signalling a preference for a two-in-three odds or better of success.

The problem is that a policy that might be criticized for offering three-in-four or two-in-three odds of success in limiting impacts could also be criticized for offering similar odds of imposing excessive mitigation costs. This focus on reducing the risk of unfavourable outcomes represents one possible interpretation of the precautionary principle, prominently used by Weitzman[19]. In this interpretation of precaution, actions should be taken not only to avoid an expected unfavourable outcome, but also to protect against unlikely but high-impact possibilities. Governments and other stakeholders care not only about the environmental costs of inaction, but also about the economic costs associated with (perhaps unnecessarily) aggressive action on climate change. Any approach that considers only environmental risks cannot capture the full set of risks to which governments may be averse, and the failure to incorporate these risks, and thus their fragility towards the consequences of overestimation of environmental costs, seems to be a major reason why stringent mitigation policies have not been embraced by governments, in spite of their willingness to sign up to a globally stringent temperature target.

Interpreting 'precautionary' thinking in this way leads to two problems. First, minimizing the risk of high damages requires a huge and immediate mitigation effort that is too demanding of communities with multiple priorities. The stringency of the mitigation policies that appear to be needed to provide an acceptable chance of meeting the 2 °C goal have led to calls for the goal itself to be abandoned as unachievable[20] in favour of alternative targets, such as net radiative forcing in 2050. However, there are counter-arguments[21] and new targets present other challenges, not least that a net radiative forcing target could result in a cessation of mitigation activity on CO_2 emissions for the foreseeable future, since reducing these is a relatively expensive way of affecting near-term radiative forcing trends. Second, by focusing on the upper tail of the distribution of possible future warming, the required mitigation effort for meeting the climate target becomes very sensitive to the upper bound of the climate-system response, which is badly constrained by observations[22,23], and hence easily contested by different interest groups. The addition or retraction of a couple of papers at the high end could materially affect policy goals, and hence investment, leading to an unacceptable level of political risk.

Policies invoking this interpretation of the precautionary principle can, therefore, lead to high and uncertain mitigation costs to guard against potentially high but equally uncertain impacts. They are, therefore, 'fragile' in the sense that uncertainty in both mitigation costs and impacts make it more difficult for any policy to be adopted, providing a strong incentive to defer decisions until these uncertainties are resolved. Yet, this could mean a recipe for indefinite procrastination: some uncertainties, including the costs of mitigation and the speed at which temperatures respond to falling emissions, may only be resolved after substantial mitigation efforts are already under way. The potentially paralysing impact of uncertainty becomes particularly acute if rational fears of over-mitigating combine with the politics of special interests to create additional pressures on negotiations.

In view of these issues, we argue that an approach that (a) is less beholden to the contestable tails of climate distributions, (b) more fully accounts for the set of risks governments care about, and (c) is less dependent on a globally binding mandate, may be a better way of preserving flexibility in climate mitigation.

There are many currents of thought associated with adaptive management[8], resilience and more recently 'anti-fragility' that argue for a more iterative approach to the management of complex problems. Although these approaches are usually associated with environmental or natural resource management[24] or, when in the field of climate change, responses to climate change and adaptation strategies (for example, Netherlands Ministry of Infrastructure and the Environment[25]), we argue that some of this thinking could be constructively used in mitigation strategies, too.

Basing strategy on more robust statistical properties, such as median estimates of both climate impacts and mitigation costs, reduces dependence on contestable tails of these distributions. To be credible, however, such a policy must also adapt to new scientific findings in a predictable way that itself minimizes the risk of unacceptable outcomes, such as a sudden and precipitate revision in mitigation pathway, and avoids placing an intolerable burden on future decision-makers. Simply stating that policies will be revised in the light of new evidence is insufficient: some constraints are needed on the scale of these revisions if policies are to be used as a basis for investment.

Flexible policies have been advocated before that internalize costs of emission-externalities contingent on observed climate states[26] and thus adjust to new information about the uncertain climate response to emissions (for example, see ref. 27). Policies that automatically adjust expenditures or efforts on the basis of some numerical parameter (usually consumer prices) are commonplace[6]. Indexing makes it easier for politicians to commit to long-term stability than might otherwise be the case if explicit assent were required for every policy adjustment. It can also help create a normative aura around policies if they are seen to reflect an underlying fairness in the indexing[6].

An index of anthropogenic warming

A number of features are desirable in the index variable: first, it should be clearly relevant to the overall policy goal; second, it should evolve predictably to minimize short-term policy volatility; and third, it should be simple to calculate and update regularly. Since governments have already adopted the goal of limiting global average warming above pre-industrial temperatures to 2 °C, and recognizing that the majority of climate impacts scale more closely with this than any other readily accessible variable, an index based on global average near-surface temperature is a logical starting point.

Global temperature itself, however, is subject to natural interannual and interdecadal variability that would significantly increase the risks of indexing climate policy on this variable alone. Investments in energy infrastructure mature over timescales of decades. If a global carbon tax were anchored to global temperature, as proposed by ref. 26, then a large volcano or an upward fluctuation in the Pacific Decadal Oscillation could depress or inflate carbon prices for a decade or more. Neither is relevant to the long-term goal of limiting anthropogenic warming, but could unnecessarily bankrupt investors in either renewable or fossil energy supplies, respectively.

A more predictable variable that is also more closely tied to the overall policy goal would be an index of warming attributable to human influence: since the work of Hasselmann in the 1990s (ref. 28), this has been defined in terms of a weighted least-squares fit between observed temperatures and the expected temperature responses to anthropogenic and natural factors. Estimates of attributable warming are traditionally updated in the scientific literature when new statistical methods or new simulations of anthropogenic and natural warming become available, and assessed every few years by the IPCC. This would be inappropriate for an index variable: the method of calculating the index should be subject to scientific scrutiny, but if the value of the index itself were directly dependent on scientific judgement, this would place undue pressure on the scientists making the assessment.

Fortunately, when the target is net anthropogenic warming, very simple approaches based solely on global mean temperature and radiative forcing time-series give results that are statistically

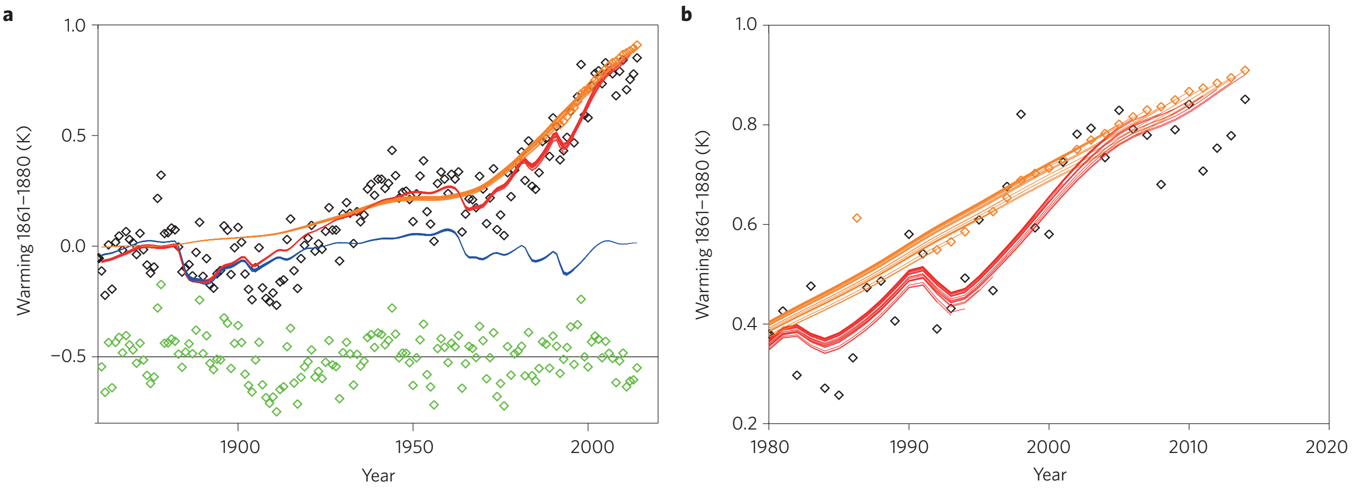

Figure 1 | An index of anthropogenic warming. a,**b**, Orange diamonds show anthropogenic warming estimated by a least-squares fit between observed temperatures (black diamonds) and the response to anthropogenic (orange lines) and natural (blue lines)forcing and their combination (red lines). Panel **a** shows the whole historical period and panel **b** zooms in on the anthropogenic warming since 1980. Green diamonds in panel **a** show regression residuals for data to 2014, offset by 0.5 °C.

indistinguishable from the most complex statistical and modelling tools available. The orange diamonds in Fig. 1 show how anthropogenic warming relative to the mid-nineteenth century has evolved since 1992, calculated every year using only data available up to that year. Observed temperatures (black diamonds) are decomposed into an anthropogenic (orange) and natural (blue) component, plus a noise residual (green), using an ordinary least-squares fit.

Expected responses to external forcing, normally obtained from complex atmosphere–ocean general circulation models, are here calculated from global mean radiative forcing series using the simple two-component impulse–response model already used for metric calculations by the IPCC and UNFCCC[29]. Crucially, because attributable warming is based on a least-squares fit to observed temperatures, it does not require an estimate of either the equilibrium climate sensitivity or transient climate response, and is only very weakly dependent on their ratio (the realized warming fraction, RWF) and the adjustment times in the impulse–response model (the figure uses the model settings documented in ref. 30). These give an attributable warming in 2014 of 0.91 °C, which varies by only one hundredth of a degree as the RWF is varied from 0.2 to 0.8 and the shorter thermal adjustment time from 2 to 10 years. Uncertainties in forcing have more impact, but are still small: setting anthropogenic aerosol forcing to zero, for example, only reduces estimated anthropogenic warming in 2014 to 0.88 °C.

This index of anthropogenic warming requires no complex model calculations and can be updated as soon as new figures for annual mean temperatures and radiative forcing are released. It would have been assigned a value of 0.54 °C in 1992, and has since monotonically increased by 0.37 °C. The rate of increase slowed slightly after 2000 in response to the so-called hiatus in observed warming, showing how this index responds to evolving observations, but it does so sufficiently slowly that it would not compromise its use as a policy index. A plot of regression residuals shows nothing unprecedented about the past two decades (Fig. 1a, green diamonds).

Anti-fragile policies

Given the burgeoning uptake of adaptive management techniques in the climate adaptation and natural resource management domains, their absence from mitigation discussions is striking. Using the index described above (or a variant of it), a range of automatically indexed policies could be explored: here we simply outline some illustrative examples reflecting the goal of limiting anthropogenic warming to 2 °C and the recognition that net emissions of long-lived greenhouse gases, including carbon dioxide and nitrous oxide, have to reach zero to stabilize temperatures.

The simplest policy would be indexed emission reductions: countries could commit to reduce their emissions from a predetermined baseline by a fraction proportional to anthropogenic warming from the time the policy is adopted, rising to 100% when this warming reaches 2 °C. Had such a policy been enacted in 1992, global emissions would now be 25% below baseline (anthropogenic warming since 1992 divided by the difference between 2 °C and anthropogenic warming in 1992). That would be 16% above 1992 emissions if the global baseline emissions had been assumed to increase at 2% per year, or about 10% below current emissions, but still rising. Countries would argue for different rates of baseline growth depending on their stages of development, leading to different times of peak national emissions, but all would converge to zero by the time anthropogenic warming reaches 2 °C. There is, of course, a risk that feedbacks in the climate system could lead to a further temperature increase even after net emissions reach zero, but in the absence of concrete evidence for this, reducing emissions of long-lived gases to zero by the time anthropogenic warming reaches 2 °C is a defensible and realistic goal.

Although attractively direct, an indexed emission cap, supported by a permit auction, would lead to potentially destabilizing price volatility should a national or regional economy over- or under-perform the expectations used in setting the baseline. An alternative would be an indexed carbon tax, but to be effective in achieving net zero, this would have to rise to a level that would discourage all further emissions by the time anthropogenic warming reaches 2 °C. This, in effect, means predicting the cost of capturing CO_2 directly from the atmosphere.

This has been recognized in an emerging literature on planning for climate change that emphasizes the 'stickiness' — the lack of immediate policy reversibility — of options as a way of embedding low carbon paths, as well as focusing on the durability and scalability of climate mitigation initiatives[5]. Part of this approach involves attempts at pre-commitment, which is a potentially central feature of a problem with inter-temporal incentives to free-ride[31]. Hence, arguably the simplest of all policies would be an indexed sequestration mandate: a regulation on fossil fuel extractors to sequester, or pay for the sequestration of, a monotonically increasing fraction of the carbon they extract, rising to 100% by the time attributable warming reaches 2 °C (ref. 32).

For any of these three policy approaches, indexing to attributable anthropogenic warming allows a transparent link between the policy instrument and the policy goal. It renders the policy 'anti-fragile' or 'adaptive' in the sense that disputes over the climate response are no longer an impediment to policy adoption. In fact, such disputes make the policy easier to adopt, as stakeholders who are convinced that future anthropogenic warming will be slower than current models predict will be reassured that the policy will 'bite' correspondingly more slowly, while the converse is also true for those concerned about unexpectedly rapid warming in the future.

Even if climate policies directly indexed to attributable anthropogenic warming are not adopted formally, this concept provides a simple and natural way of monitoring the overall consistency between the evolving climate change signal, individual countries' emission 'pledges' and the overall goal of achieving net zero emissions of long-lived greenhouse gases by the time anthropogenic warming reaches 2 °C. Annual updates of anthropogenic warming, based on a simple and transparent algorithm, should be as much a part of a full suite of climate services as an annual update of global temperature.

Methods

Methods and any associated references are available in the online version of the paper.

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References

1. Schelling, T. Some economics of global warming. *Am. Econ. Rev.* **82,** 1–14 (1992).
2. Barrett, S. The theory of international environmental agreements. *Handbook Environ. Econ.* **3,** 1457–1516 (2005).
3. Victor, D. G. Plan B for Copenhagen. *Nature* **461,** 342–344 (2009).
4. Pierson, P. The limits of design: explaining institutional origins and change. *Governance* **13,** 475–499 (2000).
5. Levin, K., Cashore, B., Berstein, S. & Auld, G. Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change *Policy Sci.* **45,** 123–152 (2012).
6. Weaver, K. *Automatic Government* (Brookings Institute, 1986).
7. Patashnik, P. *Reforms at Risk* (Princeton Univ. Press, 2008).
8. Holling, C. S. *Adaptive Environmental Assessment and Management* (Wiley, 1978).
9. Taleb, N. N. *Antifragile: Things That Gain From Disorder* (Pengiun, 2012).
10. *United Nations Framework Convention on Climate Change* (UN, 1992); https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf.
11. Stern, N. The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. *J. Econ. Lit.* **51,** 838–859 (2013).
12. Schneider, S. H. & Mastrandrea, M. D. Probabilistic assessment of "dangerous" climate change and emissions pathways. *Proc. Natl Acad. Sci. USA* **102,** 15728–15735 (2005).
13. UNFCCC The Cancun Agreements http://cancun.unfccc.int/ (2010).
14. Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
15. Rogelj, J. *et al.* Emission pathways consistent with a 2 °C global temperature limit. *Nature Clim. Change* **1,** 413–418 (2011).
16. German Advisory Council on Global Change *Solving the Climate Dilemma: The Budget Approach* (WBGU, 2009).
17. IPCC *Climate Change 2013: The Physical Science Basis.* (eds. Stocker, T. F. *et al.*) (Cambridge Univ. Press, 2013).
18. UNFCCC The Lima Decision https://unfccc.int/files/meetings/lima_dec_2014/application/pdf/auv_cop20_lima_call_for_climate_action.pdf (2015).
19. Weitzman, M. GHG targets as insurance against catastrophic climate damages. *J. Public Econ. Theory* **14,** 221–244 (2012).
20. Victor, D. G. & Kennel, C. F. Climate policy: ditch the 2 °C warming goal. *Nature* **514,** 30–31 (2014).
21. Jordan, A. *et al.* Going beyond two degrees? The risks and opportunities of alternative options. *Clim. Policy* **13,** 751–769 (2013).
22. 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).
23. Otto, A. *et al.* Energy budget constraints on climate response. *Nature Geosci.* **6,** 415–416 (2013).
24. Williams, B. K. Adaptive management of natural resources — framework and issues. *J. Environ. Manage.* **92,** 1346–1353 (2011).
25. *Delta Programme 2015. Working on the Delta: The Decisions to Keep the Netherlands Safe and Liveable* (Ministry of Infrastructure and the Environment, 2014).
26. McKitrick, R. A simple state-contingent pricing rule for complex intertemporal externalities. *Energ. Econ.* **33,** 111–120 (2011).
27. Leach, A. J. The climate change learning curve. *J. Econ. Dyn. Control,* **31,** 1728–1752 (2007).
28. Hasselmann, K. Multi-pattern fingerprint method for detection and attribution of climate change. *Clim. Dyn.* **13,** 601–611 (1997).
29. Boucher, O. & Reddy, M. Climate trade-off between black carbon and carbon dioxide emissions. *Energ. Policy,* **36,** 193–200 (2008).
30. Myhre, G. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 8 (Cambridge Univ. Press, 2013).
31. Lazarus, R. Super wicked problems and climate change: restraining the present to liberate the future. *Cornell Law Rev.* **94,** 1153–1233 (2009).
32. Allen, M. R., Frame, D. J. & Mason, C. F. The case for mandatory sequestration. *Nature Geosci.* **2,** 813–814 (2009).

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Author contributions

All authors contributed extensively to the writing of the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to F.E.L.O.

Competing financial interests

The authors declare no competing financial interests.

Methods

To estimate the anthropogenic warming we compute an ordinary least-squares regression with observed global mean temperatures from HadCRUT4 (ref. 33) as the dependent variable and global mean temperature responses to anthropogenic and natural forcing as the two independent variables. The responses are computed using the RCP6 (ref. 34) global annual mean radiative forcing time-series (www.pik-potsdam.de/~mmalte/rcps) and the impulse–response model used in ref. 35 and subsequently used in ref. 36. The parameters used are given in ref. 36. We varied the numbers of the climate system properties in the model but found very little influence on the index.

The excel-version of the model with the above data, which allows variation of parameters and timescales, is in the Supplementary Information.

References

33. Morice, C. P., Kennedy, J. J., Rayner, N. A. & Jones, P. D. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *J. Geophys. Res. Atmos*, **117,** D08101 (2012).
34. Meinshausen, M. *et al.* The RCP greenhouse gas concentration and their extensions from 1765 to 2300. *Climatic Change*, **109,** 213–241 (2011).
35. Boucher, O. & Reddy, M. Climate trade-off between black carbon and carbon dioxide emissions. *Energy Policy* **36,** 193–200 (2008).
36. Myhre, G. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 8 (IPCC, Cambridge Univ. Press, 2013).