that the ensemble of RCP8.5 hiatus runs has a significantly different warming distribution from the all-member ensemble to around 2040, but by the latter half of the twenty-first-century there is no significant difference in projected warming. This reflects the fact that the model hiatus events are linked to multi-decadal modes of climate variability (most notably the IPO), whose influence abates in time once global warming overwhelms interdecadal variability.

We have shown here that there is no significant shift in projected end-of-century global warming when considering hiatus-only ensemble sets in lieu of the full ensemble of available projections, or an ensemble sampled from only non-hiatus runs. This suggests that the recent surface warming slowdown is associated with variability not influencing long-term climate change, such as multi-decadal variability in the Pacific[1–4,7–9] and Atlantic[3,7,12] oceans. It also suggests that these climate oscillations largely operate without driving longer-term sequestration of heat into the deep ocean. In short, the drivers of the recent hiatus do not alter the century-scale warming associated with projected greenhouse gas increases. These findings increase confidence in the recent synthesized projections reported in the Intergovernmental Panel on Climate Change Fifth Assessment Report.

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References

1. Kosaka, Y. & Xie, S-P. *Nature* **501,** 403–407 (2013).
2. Trenberth, K. E. & Fasullo, J. T. *Earth's Future* **1,** 19–32 (2013).
3. Meehl, G. A. *et al. Nature Clim. Change* **1,** 360–364 (2011).
4. Easterling, D. R. & Wehner, M. F. *Geophys. Res. Lett.* **36,** L08706 (2009).
5. Otto, A. *et al. Nature Geosci.* **6,** 415–416 (2013).
6. Lewis, N. *J. Climate* **26,** 7414–7429 (2013).
7. Meehl, G. A. *et al. J. Climate* **26,** 7298–7310 (2013).
8. England, M. H. *et al. Nature Clim. Change* **4,** 222–227 (2014).
9. Watanabe, M. *et al. Nature Clim. Change* **4,** 893–897 (2014).
10. Maher, N. *et al. Geophys. Res. Lett.* **41,** 5978–5986 (2014).
11. Cowtan, K. & Way, R. *Q. J. R. Meteorol. Soc.* **140,** 1935–1944 (2014).
12. Chen X. & Tung, K. K. *Science* **345,** 897–903 (2014).

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Author contributions

M.H.E. conceived the analyses and wrote the first draft of the paper, J.K. analysed the CMIP5 simulations and undertook the statistical calculations, and N.M. analysed the observations and CMIP5 model trends. All authors contributed to interpreting the results and refinement of the paper.

Additional information

Supplementary information is available in the online version of the paper.

COMMENTARY:

Pricing climate risk mitigation

Joseph E. Aldy

Adaptation and geoengineering responses to climate change should be taken into account when estimating the social cost of carbon.

At the September 2014 United Nations Climate Summit, 73 countries and more than 1,000 companies advocated pricing carbon[1]. Economists have long called for pricing carbon to reflect the social damages associated with the impacts of carbon dioxide emissions on the global climate[2,3]. Such an approach generally reflects the polluter pays principle — as elaborated in the 1992 Rio declaration on environment and development, with its emphasis on the use of economic instruments to internalize environmental costs[4]. Scholars have also called for the organization of international negotiations around agreement on a carbon price to provide the basis for emission commitments[5,6].

The meaning of carbon pricing

For some policymakers, setting a price on carbon that reflects the cost of carbon pollution can inform the 'objective' of climate policy. For example, the US government uses an estimate of the social cost of carbon (SCC) — the present value of monetized damages associated with an incremental ton of carbon dioxide emissions — to evaluate standards for fuel economy, appliance efficiency and carbon emissions[7]. As some laws require regulations to reflect a weighting of benefits and costs, the application of the SCC could determine the ambition of energy and climate policies.

For other policymakers, pricing carbon is an 'instrument' of climate policy — such as carbon dioxide cap-and-trade programmes or a carbon tax. For example, the European Union emissions trading scheme and the British Columbia carbon tax impose a price that carbon dioxide-emitters must bear. Of course, these two interpretations can be mutually reinforcing. In a benefit–cost framework, a policy that maximizes net social benefits would equate the SCC with the price borne by emitters under a tax or cap-and-trade instrument[8].

Whether the SCC determines the objective of policy, informs the design of a pricing instrument, or serves as a focal point in international negotiations, it will play an important role in the future of climate change policy. The social damages of carbon emissions will depend on the impacts of a warming world, such as sea-level rise, extreme weather events and changes in agricultural productivity, as well as potential catastrophic harms, migration, conflict and so on[9]. The SCC will also vary with alternative efforts to mitigate climate change risks, such as adaptation and geoengineering. Thus, it is important to conceptualize the SCC in the context of the full suite of risk management policies for climate change.

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Managing risks posed by climate change

Policymakers, individuals and businesses can use three general approaches to mitigate the risks posed by climate change. First, they can halt the atmospheric accumulation of greenhouse gases, thereby preventing the problem through emission abatement. Second, they can avoid some climate change impacts by making investments in adaptation and resilience. Third, they can attempt to 'fix' the problem through geoengineering, such as solar radiation management strategies.

This multipronged approach to mitigating climate risk has emerged only recently in the debate over climate change policy. In the 1990s, international and domestic climate change policy focused almost exclusively on emission abatement. In the early 2000s, adaptation joined emission abatement in multilateral negotiations as well as development policy. In recent years, scholars have raised the prospect of geoengineering paired with emission abatement to avoid potentially catastrophic climate change[10–12]. Putting a price on carbon for emission abatement that fails to account for adaptation and geoengineering risks could leave too few resources for these options, which have potentially high returns in reducing climate change damages.

Role of adaptation and geoengineering

Pricing carbon within a comprehensive risk management framework requires continued work and advances in our understanding of climate change damages. Scholars from an array of disciplines have raised questions about the damage functions in the integrated assessment models that generate SCC estimates[9,13,14]. Improving the knowledge base on climate change impacts is a necessary foundation for evaluating the risk mitigation impacts of emission abatement, adaptation and geoengineering.

The status quo integrated assessment model approach produces an estimate of SCC without consideration of geoengineering and typically with incomplete or ad hoc attempts to represent adaptation[15]. Of the more than 400,000 SCC estimates produced by the US government in its 2013 report[15], 160 scenarios had a SCC in excess of US$1,000 per ton — or nearly US$10,000 in annual climate damages per US household — for its residential energy consumption. It is difficult to imagine that if the world were in such a dire state there would be no increase in adaptation investment or geoengineering deployment to offset at least some of these impacts.

Many individuals and businesses have strong incentives to mitigate their exposure to risks related to climate change. If the impacts of climate change become more severe, then they will increase their private adaptation investments. Moreover, governments are likely to increase outlays for resilience and adaptation if climate risks become more pronounced.

Adaptation will not fully offset the increase in damages, but it is likely to offset some climate change risk. As a result, the integrated assessment framework for evaluating the damages of an incremental emission of carbon dioxide should be expanded to include an 'adaptation response function'. Such a function (or system of functions) would represent how adaptation actions by governments and private agents respond to climate change, how adaptation affects the residual damages associated with another ton of carbon dioxide in the air, and how much this adaptation costs. This adaptation response function would result in lower monetized damages — because adaptation reduces the impacts of a changing climate — and an opportunity cost for these adaptation investments. If adaptation investments occur only when their returns (benefits of climate risk reduction) exceed their costs, then on net this adaptation function approach would result in a lower SCC than the status quo approach. If private agents, however, make adaptation investments that are privately welfare-improving, but impose local negative externalities (for example, damming a waterway), then the SCC could increase when accounting for adaptation response.

Similarly, a 'geoengineering response function' could be incorporated into integrated assessment models. Such a function would be likely to focus on state behaviour and, possibly, multilateral coordination. This response function could represent a future multilateral governance regime, especially if such a regime provided clear guidance on the use of geoengineering. Alternatively, the response function could model the incentives and behaviour of various countries likely to react to adverse climate impacts through unilateral geoengineering actions. Just as in the case of adaptation response, a geoengineering response would be likely to reduce some climate risks (for example, temperature-related impacts) at the cost of designing and implementing the geoengineering actions. It is important to recognize that these costs would include those associated with launching the geoengineering solution (for example, injecting reflective particles into the stratosphere) as well as possible unintended side effects. Based on the first-order effects, accounting for geoengineering response would be likely to reduce the SCC — again, through lower impacts net of the direct cost of implementing geoengineering — but the unintended side effects may increase social losses and could potentially offset the social gains.

Constructing such response functions requires, at a minimum, research on three dimensions of the problem. First, greater spatial and temporal resolution in estimating impacts can inform the consideration of adaptation and the incentives for any given state to launch geoengineering. Second, the construction of such response functions should explicitly enable uncertainty analysis. Just as there are uncertainties in how emissions translate into impacts, meaningful uncertainties characterize the form, timing and efficacy of adaptation and geoengineering responses. Third, these functions could inform a richer application of game theory, drawing from international relations and economics, to understand the likely reactions of countries to a changing climate and the prospects for building a credible international climate policy architecture. As the incentives for free-riding differ dramatically across these three general approaches[16], explicit modelling of behaviour may be important in constructing the response functions.

Policy implications

A conventional economic approach to this kind of risk management problem would call for evaluating the returns (say, in reduced damages) associated with incremental investments along each of these three approaches. A policy that maximizes the risk reduction for a given expenditure of resources would equate the marginal return on emission abatement with the marginal return on adaptation, and with the marginal return on geoengineering. This is simply an extension of the same cost-effectiveness analysis that underlies the case for putting a common price on carbon across all emission sources to maximize emission reductions for a given expenditure of resources on abatement. Even if there is no explicit policy effort to equate the marginal returns with actions along these three approaches, the avoided damages associated with emission abatement are likely to be affected by adaptation and geoengineering responses that could occur in the future.

The use of a SCC enhances the transparency of public decision-making and can facilitate the identification of opportunities to mitigate climate change risks. The failure to meaningfully slow the growth in global greenhouse-gas emissions in recent decades suggests that

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driving emission abatement through carbon pricing is important, but only part of the risk management portfolio. There will be hard decisions in the future. Policymakers will need rigorous tools that account for all available options for the risk management of climate change to inform these decisions. ❐

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References

1. *We Support Putting a Price on Carbon* (World Bank, 2014); http://go.nature.com/X48JO5
2. Nordhaus, W. D. *Am. Econ. Rev.* **67,** 341–346 (1977).
3. Aldy, J. E., Krupnick, A. J., Newell, R. G., Parry, I. W. H. & Pizer, W. A. *J. Econ. Lit.* **48,** 903–934 (2010).
4. *Rio Declaration on Environment and Development 1992* Principle 16 (United Nations, 1992); http://go.nature.com/fOMXht
5. Cooper, R. N. in *Post-Kyoto International Climate Policy: Implementing Architectures for Agreement* (eds Aldy, J. E. & Stavins, R. N.) 151–178 (Cambridge Univ. Press, 2010).
6. Weitzman, M. L. *J. Assoc. Environ. Resour. Econ.* **1,** 29–50 (2014).
7. *Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (Interagency Working Group on Social Cost of Carbon, 2010); http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf
8. Nordhaus, W. D. *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World* (Yale Univ. Press, 2013).
9. Revesz, R. L. *et al. Nature* **508,** 173–175 (2014).
10. Crutzen, P. J. *Climatic Change* **77,** 211–219 (2006).
11. Wigley, T. M. L. *Science* **314,** 452–454 (2006).
12. Keith, D. *A Case for Climate Engineering* (MIT Press, 2013).
13. Pindyck, R. S. *J. Econ. Lit.* **51,** 860–872 (2013).
14. Pizer, W. *et al. Science* **346,** 1189–1190 (2014).
15. *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (Interagency Working Group on Social Cost of Carbon, 2013); http://go.nature.com/WGV5Cs
16. Barrett, S. in *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World* (eds Aldy, J. E. & Stavins, R. N.) 237–259 (Cambridge Univ. Press, 2007).

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COMMENTARY:

Representation of nitrogen in climate change forecasts

Benjamin Z. Houlton, Alison R. Marklein and Edith Bai

The models used by the IPCC are yet to provide realistic predictions for nitrogen emissions from the land to the air and water. Natural isotopic benchmarks offer a simple solution to this emerging global imperative.

We must make progress in our ability to represent nitrogen (N) in global models if we are to reduce uncertainty in climate change projections and develop more insightful impact scenarios for decision-makers. Nitrogen can both warm and cool the climate system, depending on its form, phase and flux, and interaction with the biosphere's natural CO_2 sinks[1], with non-trivial effects on Earth's heat balance[2,3]. For instance, gaseous N emissions from the soil limit the availability of this nutrient for plant CO_2 capture — an indirect warming effect — yet can simultaneously cool global temperatures via the N-based aerosols that alter the planet's reflectance[4]. Once in the atmosphere, gaseous N species can directly increase the Earth's greenhouse effect, particularly when incomplete soil denitrification releases nitrous oxide (N_2O), the third most important greenhouse gas in modern climate change[2]. Moreover, downstream and downwind transport of N accelerates eutrophication, decreases aquatic biodiversity, impairs water- and air-quality for human health, and contributes to N_2O emissions in coastal ecosystems[1,5,6]. A recent assessment[7] in the European Union (EU27) showed that the externality damages associated with excess N spillovers are roughly equivalent to the gross profits attributable to enhanced food production via N-based fertilizers, at around €100 billion annually.

Terrestrial N fates are therefore vital to many aspects of the environment, society and climate system; but the models used by the IPCC have been criticized for their lack of constraint on terrestrial N balances and loss pathways[8]. We suggest that including the ratios of natural N isotopes ($^{15}N/^{14}N$ or $\delta^{15}N = [(^{15}N/^{14}N_{sample})/(^{15}N/^{14}N_{standard})] - 1$ where the standard is atmospheric N_2) can improve the efficacy of Earth system models generally, and N-based projections of modern climate change in particular. As a case study, we demonstrate here how natural N isotope composition can be used to validate and advance N cycle predictions in the Community Land Model with Coupled Carbon Nitrogen (CLM-CN, hereafter just CLM)[9]. We focused on this model because of its historical importance in setting climate science and policy: CLM was the only model to consider the effect of N in CO_2 and climate change simulations in the Fifth Assessment Report from the IPCC (ref. 2).

Towards a benchmarking scheme

We conducted our investigation in two sequential steps. First, we used empirical relationships to project patterns of soil $\delta^{15}N$ throughout the land surface and thereby develop an observation against which the efficacy of global models can be quantitatively appraised. The $\delta^{15}N$ of plant and soil pools varies systematically as a function of mean annual temperature and precipitation ($r^2 = 0.39$)[10]; hence climate correlations have been widely used to estimate soil $\delta^{15}N$ globally, capturing biome-scale patterns to within ~1‰ of empirical observations and latitudinal differences in soil $\delta^{15}N$ equal to ~10‰ (ref. 11). Such patterns in soil $\delta^{15}N$ reflect N losses to fractionating (denitrification) relative to non-fractionating (leaching) pathways[11], with the highest proportions of denitrification (relative to total N losses) observed for desert ecosystems, and lowest denitrification proportions in high-latitude boreal regions where N leaching losses are generally high (Fig. 1a,b).

Second, we used the N loss proportions from CLM (versions 4.0 and 4.5) under the present climate to inversely model soil $\delta^{15}N$ and compared these results to the empirically projected patterns as described

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