nature climate change

LETTERS

PUBLISHED ONLINE: 12 JANUARY 2015 | DOI: 10.1038/NCLIMATE2481

Temperature impacts on economic growth warrant stringent mitigation policy

Frances C. Moore[1,2]* and Delavane B. Diaz[3]

Integrated assessment models compare the costs of greenhouse gas mitigation with damages from climate change to evaluate the social welfare implications of climate policy proposals and inform optimal emissions reduction trajectories. However, these models have been criticized for lacking a strong empirical basis for their damage functions, which do little to alter assumptions of sustained gross domestic product (GDP) growth, even under extreme temperature scenarios[1–3]. We implement empirical estimates of temperature effects on GDP growth rates in the DICE model through two pathways, total factor productivity growth and capital depreciation[4,5]. This damage specification, even under optimistic adaptation assumptions, substantially slows GDP growth in poor regions but has more modest effects in rich countries. Optimal climate policy in this model stabilizes global temperature change below 2 °C by eliminating emissions in the near future and implies a social cost of carbon several times larger than previous estimates[6]. A sensitivity analysis shows that the magnitude of climate change impacts on economic growth, the rate of adaptation, and the dynamic interaction between damages and GDP are three critical uncertainties requiring further research. In particular, optimal mitigation rates are much lower if countries become less sensitive to climate change impacts as they develop, making this a major source of uncertainty and an important subject for future research.

Integrated assessment models (IAMs) have traditionally captured the negative impacts of climate change with a damage function that relates global temperature change to a loss of current economic output. This formulation captures the transient effects of climate on the economy such as lost agricultural output, increased cooling demand, or lower worker productivity due to hotter temperatures[7–9]. Factors of production, namely labour and capital, and their total factor productivity (TFP) are not directly impacted, meaning that climate change has no effect, or only a very weak effect, on GDP growth. Two IAMs recently used for the US government social cost of carbon (SCC) estimate, FUND and PAGE, assume that GDP growth is entirely exogenous[10,11]. In the DICE model, labour and TFP are specified exogenously and capital formation is determined through endogenous investment decisions[5]; temperature shocks can therefore alter economic growth through capital stock reductions, but this effect is small and indirect[12].

Table 1 | Parameters used to calibrate the gro-DICE damage functions, reported in Dell *et al.* Table 3, column 4 (ref. 4).

	Effect 1 °C temp increase on GDP growth rates (γ_0)	Effect 1 °C temp increase on economic output (β_0)
Poor	−1.171 pp	−0.426%
Rich	−0.152 pp	0.371%

This specification includes 10 temperature lags and no precipitation controls. A brief summary of the estimation strategy used in ref. 4 is given in the Supplementary Information. pp: percentage point.

Damages from climate change that directly affect growth rates have the potential to markedly increase the SCC because each temperature shock has a persistent effect that permanently lowers GDP below what it would otherwise be (Supplementary Fig. 1). Continued warming therefore has a compounding effect over time, so that even very small growth effects result in much larger impacts than the traditional damage formulation[12]. Examples of pathways by which temperature could affect the growth rate of GDP include damage to capital stocks from extreme events, reductions in TFP because of a change in the environment that investments were originally designed for, or slower growth in TFP because of the diversion of resources away from research and development and towards climate threats[1]. Empirical evidence that these impacts exist is mounting. Two studies have found a reduced-form relationship between temperature shocks and GDP growth[4,13], and other studies have demonstrated plausible pathways including increasing conflict risk[14] and changes in labour supply[15]. Previous work has demonstrated that DICE results are sensitive to the inclusion of growth impacts[12,16], but no previous studies have calibrated these damages using empirically grounded results from the econometrics literature. Given the potentially first-order impacts of these growth effects, understanding their implications for climate policy is of critical importance.

Here we examine alternative formulations of the DICE damage function based on empirical estimates of the impact of inter-annual temperature variability on national economic output and growth rates by Dell and colleagues[4]. They find large, statistically significant negative effects of hot temperatures on growth rates in poor countries, smaller effects in rich countries, and mixed effects on output (Table 1). To implement these parameters in an IAM, we develop a two-region version of DICE (ref. 17; DICE-2R). We then modify the damage pathway so that warming affects either TFP growth or capital depreciation as per results in ref. 4 (gro-DICE) and investigate sensitivities to the parameters used by Dell *et al.*[4] (Methods). We present results of the TFP pathway here, but the capital pathway gives quantitatively similar results and is discussed further in the Methods and Supplementary Information.

As Dell *et al.*[4] use transient and largely unanticipated weather shocks in their estimation, the growth-rate sensitivities (reduction

---

[1]Emmett Interdisciplinary Program in Environment and Resources, Stanford University, California 94305, USA. [2]Center on Food Security and Environment, Stanford University, California 94305, USA. [3]Department of Management Science and Engineering, Stanford University, California 94305, USA.
*e-mail: fcmoore@stanford.edu

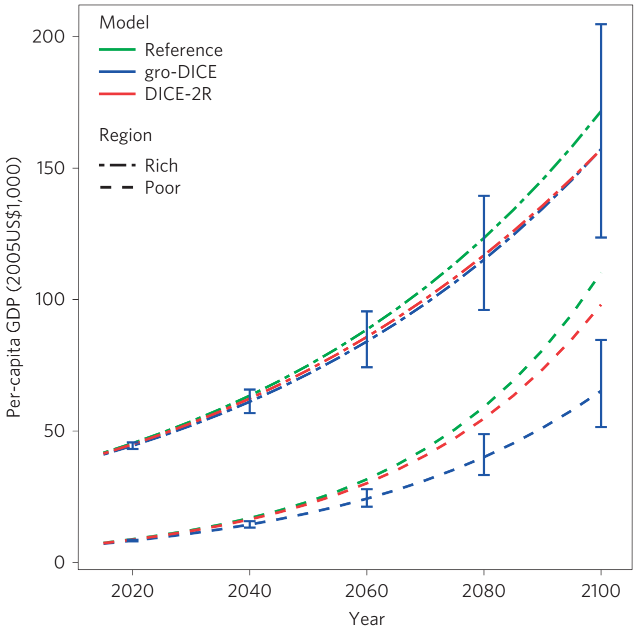

Figure 1 | Per-capita GDP for rich and poor regions for the reference (no damages) run and DICE-2R and gro-DICE models under business-as-usual. Temperature in the reference reaches 5 °C above pre-industrial by 2100. The error bars show results using ± one standard error (68% confidence interval) around the growth-rate damages reported in ref. 4 (Table 1).

in growth rate from 1 °C of warming) shown in Table 1 are the short-run impacts of higher temperatures. Long-run impacts of the permanent warming associated with climate change could be either larger (owing to intensification) or smaller (owing to adaptation) than this short-run effect[9], although several studies show evidence for some adaptation[18–20]. We adopt optimistic adaptation assumptions in gro-DICE by assuming that the long-run effect of temperature on GDP growth is zero and that the short-run impacts decay exponentially at a constant adaptation rate (Methods). As there is a very limited empirical basis for the rate of adaptation, we assume a value of 10% per year and examine sensitivity to this parameter (Supplementary Fig. 2).

Figure 1 shows the trajectory of per-capita GDP under business-as-usual for the reference (no climate damages), DICE-2R and gro-DICE models. Temperatures exceed 4.5 °C by 2100, causing economic losses in both models with damages. Impacts in DICE-2R are modest because impacts are transient and offset by sustained growth in TFP, labour and capital: the difference from reference GDP is less than 12% in both poor and rich regions by 2100. In contrast, the growth effects in gro-DICE compound over the century, leading to much larger impacts. The average annual growth rate in poor regions is cut from 3.2% to 2.6%, which means that by 2100 per-capita GDP is 40% below reference. The much smaller growth effects in rich countries, combined with the fact that warming slightly improves economic output, means the gro-DICE and DICE-2R timepaths are very similar in the rich region. Figure 1 also shows the effect of increasing and decreasing the growth-rate sensitivity parameter by one standard error. The large negative impact in poor countries is robust, but uncertainty around the magnitude of growth impacts in rich regions means that they could benefit from warming.

Figure 2 shows results if mitigation levels are chosen to maximize global discounted social welfare. Optimal climate policy in DICE-2R demonstrates a classic 'policy-ramp' in which mitigation efforts increase gradually over the century, with emissions peaking in 2060 and warming of over 3.5 °C by 2100. In contrast, optimal mitigation in gro-DICE consists of eliminating emissions in the very near future to stabilize global temperatures below 2 °C above pre-industrial. Even optimistic assumptions about temperature effects on GDP growth (the upper bound on the error bars in Fig. 2) lead to more stringent near-term mitigation than DICE-2R and elimination of emissions by 2070. The findings of near-term decarbonization and global temperature stabilization below 2 °C are robust to changes in the adaptation rate, which we vary between 0 and 20% per year (Supplementary Fig. 3). A variant of gro-DICE in which temperatures affect the depreciation of capital rather than TFP growth also gives quantitatively similar results (Supplementary Fig. 4).

The motivation for rapid decarbonization can be illustrated with the high SCC in gro-DICE (Fig. 2). One additional ton of CO_2 emitted in 2015 reduces net social welfare by US$33 in DICE-2R but by US$220 in gro-DICE. This value is higher both because climate damages are larger in gro-DICE and because slower economic growth leads to a lower discount rate[5]. The trajectory of the SCC over time has an inverted U-shape determined by relative changes in the marginal utility of emissions and the marginal utility of consumption over time (Supplementary Fig. 5). The additional mitigation undertaken in the gro-DICE optimal run does reduce damages compared to business-as-usual, but poor countries still suffer substantial impacts, with per-capita GDP in 2100 still 20% lower than the reference.

Our results thus far assume a static damage function, but the relationship between economic growth and temperature is likely to change over time. Dell *et al.*[4] find much higher sensitivity of GDP growth rates to warming in poor countries than in rich (Table 1), which could result from two possible mechanisms. One is that high sensitivity may result from biophysical temperature thresholds, beyond which warming becomes particularly damaging[8,21]. As poor countries are, on average, hotter than rich countries, they are exposed more frequently to damaging temperatures and therefore show higher sensitivity to temperature. Under this mechanism, the sensitivity of rich countries would increase as they warm. Alternatively, higher temperatures may be more damaging in poor countries because their economies are reliant on climate-exposed sectors such as agriculture and natural resource extraction, or because risk management options such as insurance or air conditioning are not as widely available. In this case we would expect the sensitivity of poor regions to warming to decrease as per-capita GDP increases. We call these two mechanisms the 'temperature' and 'resilience' mechanism respectively and implement each separately in gro-DICE by making the growth-rate damage parameters a function of either temperature change or per-capita GDP (Methods).

Although both the temperature and resilience mechanisms could explain the different sensitivities of rich and poor countries to higher temperatures observed today, they have contrasting implications for how damages might evolve over time and for optimal climate policy (Fig. 3). As mitigation is already so high in the standard gro-DICE model, adding the temperature mechanism has little additional effect. However, the resilience mechanism results in a very different mitigation trajectory. Early mitigation serves to slow the rate of climate change but is later relaxed because of the benefits of economic growth in poor regions in terms of reduced sensitivity to warming (Supplementary Fig. 6). Once sensitivity in poor regions stabilizes in 2070 at the level observed at present in rich countries, mitigation gradually increases so that emissions peak in 2120 and are eliminated by 2150, stabilizing global temperatures at 6 °C above pre-industrial. The evolution of the damage function over time therefore has important policy implications for balancing the dual priorities of increasing resilience through economic growth and decarbonization.

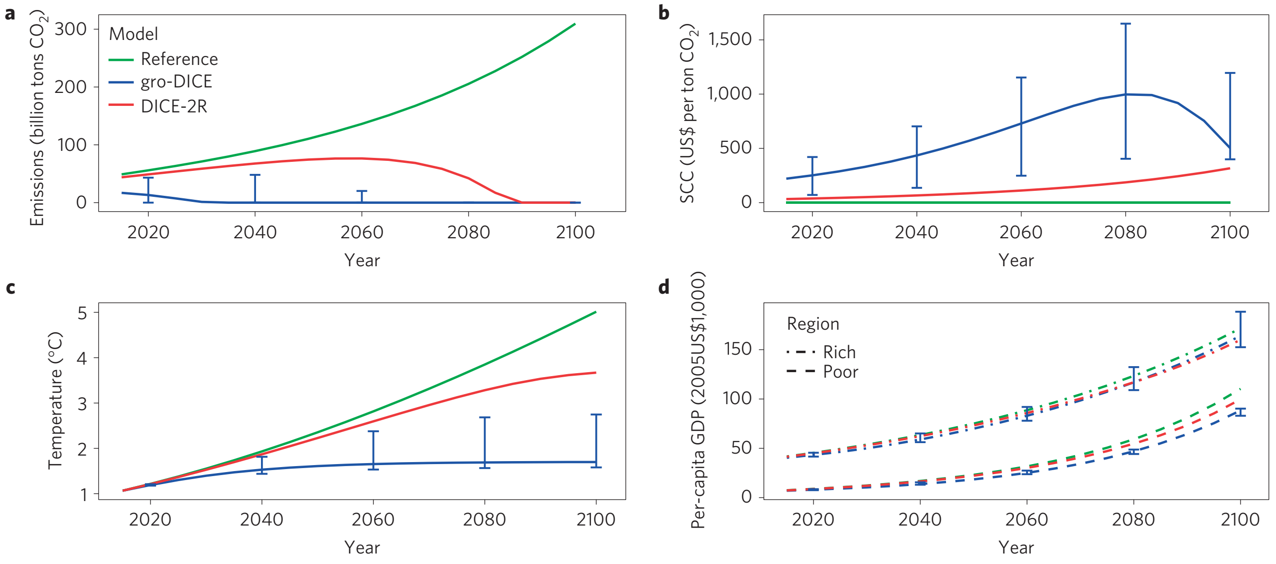

Figure 2 | Results of Pareto optimal runs of DICE-2R and gro-DICE. a–d, Annual global emissions (**a**), SCC (**b**), global temperature (**c**) and regional per-capita GDP (**d**). The error bars show results from Pareto optimal runs of gro-DICE using ± one standard error (68% confidence interval) around the growth-rate sensitivity reported in ref. 4. The reference is defined as a model run with no climate damages and therefore has zero SCC by definition.

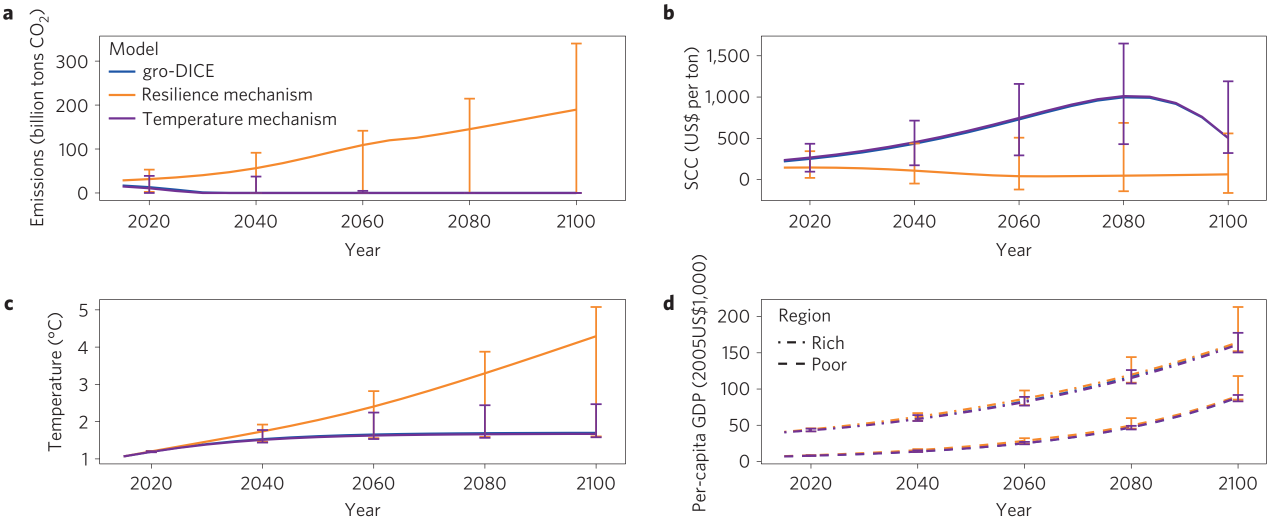

Figure 3 | Results of Pareto optimal runs of gro-DICE, and versions of gro-DICE that include dynamic damage functions based on either the temperature or resilience mechanisms (Methods). a–d, Annual global emissions (**a**), SCC (**b**), global temperature (**c**) and regional per-capita GDP (**d**). The gro-DICE and temperature mechanism lines are indistinguishable. The error bars show Pareto optimal runs using ± one standard error (68% confidence interval) around the growth-rate sensitivity reported in ref. 4.

One limitation of the DICE model is the simplicity of the reduced-form mitigation function[5,22]. First, the mitigation level can fluctuate freely, with no expansion constraint from period to period. This fails to capture real-world inertia, represented in other energy system IAMs, which limits the rate of decarbonization owing to delayed availability of low-emitting technologies, construction lead times, stranded assets, or other capital turnover factors[23,24]. Second, the simple mitigation cost function constitutes a claim on current output without affecting the factors of production or TFP. Mitigation at the rate implied by gro-DICE could well impose its own persistent impacts on economic growth, as suggested by some previous research[25]. Although gro-DICE was designed to investigate the effects of temperature on growth, it does not include the converse effect of mitigation, something beyond the scope of this paper but a priority for future research. For both these reasons, the results regarding very rapid, near-term mitigation should not be over-interpreted as evidence that such a policy would necessarily be economically optimal. Nevertheless, the findings that temperature effects on growth rates imply much larger climate damages and, correspondingly, more stringent mitigation than is justified by transient impacts on economic output are probably robust to more realistic modelling of mitigation costs.

Historically, attention has narrowly focused on climate sensitivity and the discount rate in driving uncertainty in IAM results[26,27]. We compare these two uncertainties with the new factors introduced in this paper. Figure 4 shows that the magnitude of GDP growth-rate sensitivity, the rate of adaptation, and how sensitivity to warming changes with per-capita GDP are at least as important as climate sensitivity and the pure rate of time preference in determining optimal climate policy over the next century.

This paper has shown that allowing climate change to directly affect economic growth through impacts to TFP or capital can

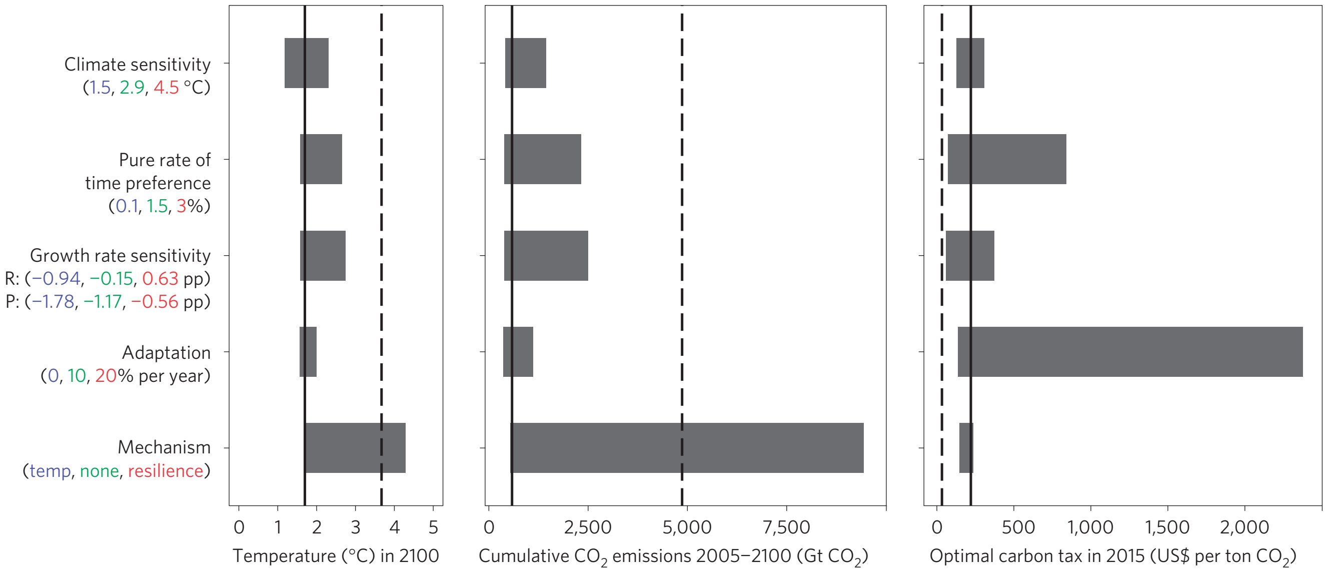

Figure 4 | Sensitivity of three key indicators of twenty-first century climate policy to climate sensitivity, the pure rate of time preference (PRTP), the sensitivity of economic growth rates to temperature, adaptation rate, and the temperature or resilience mechanisms. The lower, main and upper values of the parameter range are labelled in blue, green and red, respectively. The climate sensitivity range is derived from the 66% confidence (likely) interval given by the Intergovernmental Panel on Climate Change Fifth Assessment Report[30]. The values for the pure rate of time preference do not correspond to a confidence interval, but to noted low and high values from the literature. The growth-rate sensitivities are based on ± one standard error (68% confidence interval) as reported in ref. 4. Results for the gro-DICE model (solid line) and DICE-2R model (dashed line) are shown for comparison.

significantly increase the SCC and the optimal rate of near-term mitigation. This finding holds for empirically derived estimates of the magnitude of temperature effects on growth rates using optimistic adaptation assumptions, and is robust to uncertainty in the sensitivity parameter and the rate of adaptation, but not to the mechanism driving different growth-rate impacts in rich and poor regions. Although the simplified representation of mitigation in DICE means the optimal level of near-term mitigation may be overestimated here, the higher marginal damage of CO$_2$ emissions should be robust to higher mitigation costs. The sensitive dependence of model results on the magnitude of growth-rate impacts, the adaptation rate, and the interaction of temperature sensitivity with per-capita GDP indicate that these topics should be a priority for future empirical work. If further studies confirm that climate change has the potential to adversely affect TFP, capital stocks or labour supply then aggressive, near-term mitigation could well be warranted.

Methods

To study the growth effects as presented in Dell *et al.*[4] (DJO in this section) we created a two-region version of DICE (DICE-2R). The rich and poor regions are parameterized on the basis of output-weighted regional values from the 2010 RICE model[5,17] (Supplementary Table 1). DICE-2R chooses mitigation and savings so as to maximize the discounted sum of utility in both regions, weighted by regional Negishi weights[28]. We also altered DICE by fixing emissions in 2005 and 2010, making 2015 the first year when mitigation is possible. As the parameterization of the rich and poor regions in DICE-2R, although consistent with RICE2010, differs from the DICE-2013R aggregate, DICE-2R does not exactly reproduce the most recent DICE results[5]. Specifically, the slightly faster TFP growth in DICE-2R means that incomes and emissions are higher in DICE-2R than in DICE-2013R in the second half of the twenty-first century.

We investigate two alternative pathways by which warming could affect economic growth: slowing the growth of TFP or accelerating depreciation of the capital stock. For the first pathway, climate damages impact the growth rate of TFP, reflecting the fact that climate change could affect the productivity of the research sector or existing investments[12]:

$$A_{j,t} = (1 + r_{\mathrm{TFP}_{j,t}} - r_{\mathrm{DJO}_{j,t}})^{\Delta t} A_{j,t-1}$$
$$r_{\mathrm{DJO}_{j,t}} = \tilde{\gamma}_{0_j} T_t \qquad (1)$$

where $A_{j,t}$ is TFP in region j in time period t, r_{TFP} is the exogenous annual TFP growth rate, T is the global temperature change from pre-industrial, Δt is the model time step, and $\tilde{\gamma}_{0_j}$ is the regional growth-rate sensitivity to temperature, calibrated to reproduce the DJO result (Table 1). Calibration is necessary because economic growth is not completely exogenous in DICE but is partly determined by an endogenous capital stock, meaning that reductions in TFP affect economic growth both through lower productivity and through lower capital. Details on the calibration are given in the Supplementary Information. The gro-DICE model also includes transient impacts of temperature on regional output estimated by DJO ($\beta_{0_j} T_t$, Table 1), but this effect is small compared with the growth-rate damages.

The second pathway assumes climate damages fall on the capital depreciation rate. This simulates the impact of climate change on physical infrastructure through more frequent or larger extreme events or on institutional capital through, for example, increased risk of civil conflict[14]. We calibrate the relationship between temperature change and depreciation rate for the DJO results for values of capital stock, investment, TFP and labour in the reference run for a range of temperatures up to 6 °C (calibration details in Supplementary Information and Supplementary Fig. 9). This gives a concave, quadratic function relating warming and depreciation rate (Supplementary Fig. 10). We find comparable implications for climate policy along both the TFP and depreciation pathways. In reality, both impact pathways (as well as others) are likely to be important in determining climate change damages, but we present them separately here for clarity and because of the lack of empirical studies on their relative roles.

We model adaptation in gro-DICE using an exponential decay curve in which the initial impact of a change in temperature (determined by parameters calibrated to the DJO results) declines over time at the rate of adaptation. We introduce a new variable, the effective temperature, which is the sum of all residual temperature shocks:

$$\mathrm{ET}_t = \sum_{i=1850}^{t} (T_i - T_{i-1}) \mathrm{e}^{-a(t-i)}$$

where ET_t is the effective temperature at time t, T_i is the temperature in year i, and a is the rate of adaptation. For runs with a positive adaptation rate, ET_t replaces T_t in the calculation of damages (equation (1)). As there is a very limited empirical basis for the rate of adaptation, we use a value of 10% per year and vary it between 0 and 20% per year in a robustness check. Ten per cent per year is equivalent to a 95% reduction in the impact of a temperature shock after a 30-year adjustment period (Supplementary Fig. 2). The contribution to effective temperature of temperature change before the start of the model time horizon is based on the global surface temperature record since 1850 (ref. 29). The effective temperature rather than absolute temperature is then used to define damages on output and TFP or capital. This formulation means that impacts depend both on the magnitude and the rate of temperature change because faster warming results in larger disequilibrium and therefore higher adjustment costs.

The temperature and resilience mechanisms are implemented such that the growth-rate damage parameters $\tilde{\gamma}_{0_j}$ are a function of either temperature or per-capita GDP, respectively. In the temperature mechanism, sensitivity in poor regions remains constant but increases with warming in rich regions, not exceeding the sensitivity observed at present in poor regions (Supplementary Fig. 11). The resilience mechanism causes sensitivity in poor regions to decrease until they reach the per-capita GDP of rich regions today, reducing damages from warming over time as poor regions develop (Supplementary Fig. 12).

The effect of parametric uncertainty in five factors is investigated by independently varying each parameter from its reference value to a high or low value using one-at-a-time sensitivity analysis (Fig. 4). The uncertainties captured and not captured by this approach are discussed more fully in the Supplementary Information.

Received 24 June 2014; accepted 25 November 2014;
published online 12 January 2015; corrected after print
28 January 2015

References

1. Pindyck, R. S. Uncertain outcomes and climate change policy. *J. Environ. Econ. Manage.* **63,** 289–303 (2012).
2. 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).
3. Revesz, R. L. *et al.* Global warming: Improve economic models of climate change. *Nature* **508,** 173–175 (2014).
4. Dell, M., Jones, B. F. & Olken, B. A. Temperature shocks and economic growth: Evidence from the last half century. *Am. Econ. J. Macroecon.* **4,** 66–95 (2012).
5. Nordhaus, W. D. & Sztorc, P. *DICE 2013R: Introduction and User's Manual* 1–102 (2013); http://www.econ.yale.edu/~nordhaus/homepage/documents/DICE_Manual_103113r2.pdf
6. IAWG, U. *Technical support document: Technical update of the social cost of carbon for regulatory impact analysis under executive order 12866.* 1–22 (US government, 2013).
7. Deschênes, O. & Greenstone, M. Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the US. *Am. Econ. J. Appl. Econ.* **3,** 152–185 (2011).
8. Schlenker, W. & Roberts, D. L. Nonlinear temperature effects indicate severe damages to US corn yields under climate change. *Proc. Natl Acad. Sci.* **106,** 15594–15598 (2009).
9. Dell, M., Jones, B. F. & Olken, B. A. What do we learn from the weather? The new climate-economy literature. *J. Econ. Lit.* **52,** 740–798 (2014).
10. Hope, C. W. The marginal impact of CO_2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. *Integr. Assess. J.* **6,** 19–56 (2006).
11. Anthoff, D. & Tol, R. S. J. *The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Technical Description, Version 3.6.* (2012); http://www.fund-model.org/versions
12. Moyer, E., Woolley, M. M., Matteson, N. J., Glotter, M. M. & Weisbach, D. Drivers of uncertainty in the Social Cost of Carbon. *J. Leg. Stud.* **43,** 401–425 (2014).
13. Bansal, R. & Ochoa, M. *Temperature, Aggregate Risk, and Expected Returns* (National Bureau for Economic Research, 2011).
14. Hsiang, S. M., Burke, M. & Miguel, E. Quantifying the influence of climate on human conflict. *Science* **341,** 1235367 (2013).
15. Graff Zivin, J. & Neidell, M. Temperature and the allocation of time: Implications for climate change. *J. Labor Econ.* **32,** 1–26 (2014).
16. Dietz, S. & Stern, N. *Endogenous Growth, Convexity of Damages and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions* (Center for Climate Change Economics and Policy, 2014).
17. Nordhaus, W. D. Economic aspects of global warming in a post-Copenhagen environment. *Proc. Natl Acad. Sci. USA* **107,** 11721–11726 (2010).
18. Moore, F. C. & Lobell, D. B. The adaptation potential of European agriculture in response to climate change. *Nature Clim. Change* **4,** 610–614 (2014).
19. Hornbeck, R. The enduring impact of the American dust bowl: Short and long-run adjustments to environmental catastrophe. *Am. Econ. Rev.* **102,** 1477–1507 (2012).
20. Hsiang, S. M. & Narita, D. Adaptation to cyclone risk: Evidence from the global cross-section. *Clim. Change Econ.* **03** (2012).
21. Lobell, D. B., Banziger, M., Magorokosho, C. & Vivek, B. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Clim. Change* **1,** 42–45 (2011).
22. Keller, K., McInerney, D. & Bradford, D. F. Carbon dioxide sequestration: How much and when? *Climatic Change* **88,** 267–291 (2008).
23. Ha-Duong, M., Grubb, M. & Hourcade, J. Influence of socioeconomic inertia and uncertainty on optimal CO_2-emission abatement. *Nature* **390,** 270–273 (1997).
24. Richels, R. G. & Blanford, G. J. The value of technological advance in decarbonizing the US economy. *Energy Econ.* **30,** 2930–2946 (2008).
25. Hogan, W. W. & Jorgenson, D. W. Productivity trends and the cost of reducing CO_2 emissions. *Energy J.* **12,** 67–85 (1991).
26. Weitzman, M. L. GHG targets as insurance against catastrophic climate damages. *J. Public Econ. Theory* **14,** 221–244 (2012).
27. Stern, N. & Taylor, C. Climate change: Risk, ethics, and the Stern review. *Science* **317,** 203–204 (2007).
28. Stanton, E. A. Negishi welfare weights in integrated assessment models: The mathematics of global inequality. *Clim. Change* **107,** 417–432 (2010).
29. NASA GISS Surface Temperature Analysis (GISTEMP) (Goddard Institute for Space Studies, 2014); http://data.giss.nasa.gov/gistemp/graphs_v3/Fig.A2.txt
30. IPCC *Summary for Policymakers in Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) (Cambridge Univ. Press, 2013).

Acknowledgements

We would like to thank J. Koomey, C. Reichard and M. Craxton for comments on the manuscript. F.C.M. is supported by the Neukermans Family Foundation Stanford Interdisciplinary Graduate Fellowship.

Author contributions

F.C.M. and D.B.D. designed the analysis. D.B.D. performed the analysis. F.C.M. and D.B.D. analysed results and wrote 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.C.M.

Competing financial interests

The authors declare no competing financial interests.

ERRATUM

Temperature impacts on economic growth warrant stringent mitigation policy

Frances C. Moore and Delavane B. Diaz

Nature Clim. Change **5,** 127–131 (2015); published online 12 January 2015; corrected after print 28 January 2015

In the version of this Letter originally published, in equation (1) and in the explanatory sentence following the equation, j_{TFP} should have read r_{TFP}. In the second line of the equation, $j_{\mathrm{DJO}_{j,t}}$ should have read $r_{\mathrm{DJO}_{j,t}}$. These errors have been corrected in the online versions of the Letter.