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Economic damages from on-going climate change imply deeper near-term emission cuts

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Abstract

Current analyses of pathways limiting global warming to well below 2°C, as called for in the Paris Agreement, do not consider the climate impacts already occurring below 2°C. Here we show that accounting for these damages significantly increases the near-term ambition of transformation pathways. We use econometric estimates of climate damages on GDP growth and explicitly model the uncertainty in the time that damages persist and in the climate sensitivity. We find that carbon prices in 2030 are higher compared to the case where only the 2°C is considered; the median value is \$115 per tonne of CO_2. The long-term persistence of damages, while highly uncertain, is a main driver of optimal near-term climate policy. Accounting for damages on economic growth increases the gap between the currently pledged nationally determined contributions and the welfare-optimal 2030 emissions for 2°C by two thirds, compared to pathways considering the 2°C limit only.

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Climate-change mitigation is motivated by the risk of large, pervasive and persistent impacts of climate change. Policies aiming to mitigate climate change in a welfare-optimal way are usually derived from two fundamentally different approaches: cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA). These approaches account for climate impacts in different ways. CBA weighs climate damages against mitigation costs to find optimal temperature levels and climate policies in an integrated model system[1–3]. A comprehensive CBA requires monetizing all climate impacts, including non-market damages, and allowing trade-offs between costs and benefits even in the presence of deep uncertainty about those. Particularly hard to evaluate is the risk of large-scale, irreversible disruptions triggered by warming beyond a threshold value (tipping point)[4]. Examples include the melting of the ice sheets of Greenland and West Antarctica or the dying of coral reefs[4–6]. As a result, many CBA do not account for the risk of climate impacts from crossing tipping points. The few that do show a significantly larger social cost of carbon and more ambitious emissions reductions[7].

CEA is used to model pathways that minimize mitigation costs subject to a temperature guardrail. CEA is directly applicable to the climate-policy paradigm of preventing dangerous anthropogenic interference with the climate system[8] and the associated target to keep warming well below 2°C or even 1.5°C[9]. From an outcome-oriented perspective, CEA is motivated by temperature guardrails beyond which the risk of climate impacts from passing tipping points in the Earth System rises rapidly[10,11]. Another important motivation for temperature guardrails is the precautionary principle which calls for avoiding areas of deep uncertainty about the impacts of climate change where trade-offs between costs and benefits of mitigation can no longer be assessed properly[8,12]. In its Fifth Assessment Report[13] and Special Report on Global Warming of 1.5°C[14] the Intergovernmental Panel on Climate Change drew on the CEA insights from detailed-process Integrated Assessment Models[15] for its climate mitigation scenario assessment. In contrast to CBA, CEA does not account for any climate impacts that occur below the temperature guardrail.

With accumulating evidence of economic damages, even at low levels of warming, this omission becomes increasingly relevant. Gradually intensifying impacts of climate change include, for example, changes in agricultural yields, water availability, the occurrence and intensity of extreme events, sea-level rise, effects on health, labor productivity, and ecosystem services[16]. Many of these already occur throughout societies and economies today[17]. There is evidence that such gradual impacts from climate change can cause persistent socio-economic effects, for example by affecting long-run economic growth or societal stability[17–20]. The uncertainty about the degree of long-term consequences of such gradual climate damages however, remains large.

The contrast between CBA and CEA can be illustrated in terms of their (implicit) damage

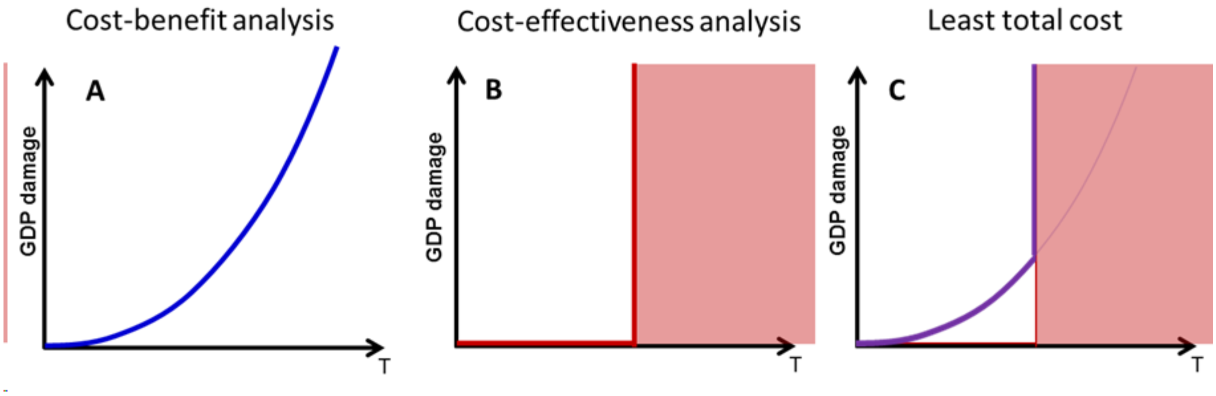

Figure 1: **Explicit or implicit economic damage functions in climate policy analysis** Cost-benefit analysis (CBA) accounts for gradual economic damages in deriving optimal climate change mitigation pathways (A). Cost-effectiveness analysis (CEA) seeks to minimize mitigation costs for limiting warming below a threshold, implicitly assuming zero damage below and infinite damages above the threshold (B). Least-total cost (LTC) analysis, as introduced here, combines the two approaches by exploring welfare-optimal strategies that account for damages occuring below the threshold, while limiting warming to below the threshold.

cost functions (Fig. 1). The economic damage function in CBA models is continuous and an explicit element of the analysis. By contrast, the damage function implied by CEA assumes no damages below the temperature limit and infinite damages above that. Both can be reconciled in a new integrated assessment paradigm, the Least-Total-Cost (LTC) approach. LTC pathways are welfare-optimal climate change mitigation strategies for staying below a long-term temperature in the presence of gradual climate change damages that already occur below this temperature limit[21].

The three main contributions of this study are: First, we construct a damage function based on empirical damage estimates of temperature increases on GDP that explicitly reflects uncertainty about the long-term persistence of such gradual climate damages. Second, we implement LTC pathways in an Integrated Assessment Model (IAM) with high process detail in mitigation technologies. Third, we derive implications for emissions pathways and near-term ambition for international climate policy.

Persistence of climate damages and the social costs of carbon

Many empirical studies quantify impacts of global warming on economic output. Recent studies find impacts through changes in the growth rate of GDP with increasing temperatures[18,22–26]. These studies are not conclusive about whether the income reductions due to these growth damages are temporary, called a “level effect”, or permanent, termed a "growth effect" by Burke *et al.* [23] - abbreviated BHM15 in the following. The presence of growth effects implies a slow or no recovery from income damages from global warming.

Most integrated analyses of impacts and mitigation, however, model damages purely as level effects. Technically, this is implemented as a contemporaneous reduction in economic output through a damage function[3,27,28]. The damage function in a given year is assumed to be affected only by temperature in that year, but not by temperature in the past. In these models, economic growth is, except through investment effects, not affected by rising temperatures. These studies commonly find moderate overall damages and costs from global warming.

A number of recent studies, by contrast, model economic climate damages as growth rate effects. Such studies find much higher overall damages[23,29] and consequently much more stringent optimal mitigation action[30–34]. Two controversial aspects in those studies are the application of the empirical estimates for out-of-sample climate change in the future and the implied total lack of adaptation despite continually increasing climate impacts.

The question of whether level or growth effects are more dominant - with the resulting stark differences in the long-term consequences - is thus a key driver and source of uncertainty of long-term economic impacts of global warming[35]. Piontek *et al.* [36] show that cumulative climate damages depend on the persistence of annual climate impacts. This persistence depends in turn on whether output losses, impacts on production factors or labor productivity are incurred. These different impact channels are not comprhensively quantified as of today. Consequently, our study includes the persistence time - the typical time a damage in a given year persists into the future - as a key parameter. This parametric approach to macro-economic damages better captures the out-of-sample uncertainty due to economic impact channels and the scope for adaptation under future climate change. A range of persistence times interpolates between a level effect (a persistence time of zero) and growth effect (a persistence time of infinity), thus allowing to spell out the consequences of the uncertainty over damage estimates on mitigation policy.

To compare different empirical damage specifications and persistence times, we calculate the social cost of carbon (SCC), that is, the damage caused by the additional emission of one ton of CO2. We use the IAM REMIND (see next section for details) to derive the SCC in the welfare-optimal model solution. The persistence time strongly influences the SCC (Fig. 2): Whereas the SCC is 201$/(tCO_2)$for the original specification from BHM15 with its infinite persistence time (consistent with Ricke *et al.* [29]), it is only 9$/(tCO_2)$for a persistence time of zero years. The often used damage function from the DICE2016 model, for comparison, yields an SCC of 11$/(tCO_2)$.

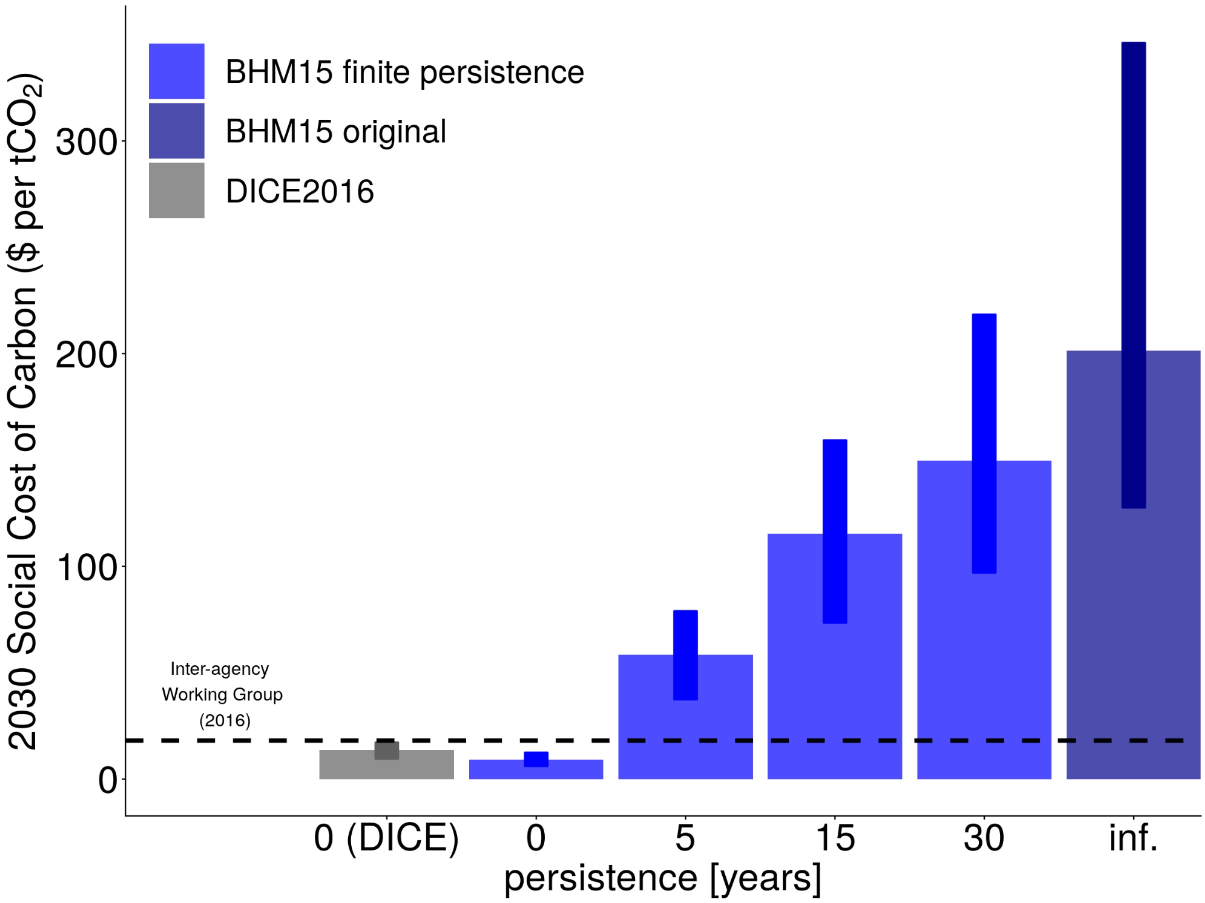

Figure 2: **The social costs of carbon in 2030 critically depend on the persistence of damages.** Shown for different damage functions, implemented as a CBA in the REMIND model. Shown persistence times are 5, 15, and 30 years. Ranges are the 20-80th percentile interval over the two empirical damage specifications from BHM15 (see Supplement for details) and climate uncertainty. Infinite persistence is the original specification from BHM15. A persistence time of zero and the DICE2016 damage function are included for comparison. The dashed line is the value of the SCC put forward by the Interagency Working Group on Social Costs of Greenhouse Gases (for a discount rate of 5%).

In agreement with the CBA literature[33,34], the resulting level of warming in our model is 1.7°C above pre-industrial for the original BHM15 damage function with infinite persistence. By contrast, the DICE2016 damage function - without any persistence in damages - results in a warming of 2.7°C above pre-industrial in our model. In recent literature, parameter updates for the DICE model[37] yield optimal temperatures below 2°C. DICE-like models, in contrast to detailed-process IAMs, typically neither have the regional resolution nor the representation of mitigation technologies in the energy and land sector that enables meaningful modeling of near-term mitigation pathways.

Modeling mitigation pathways with climate damages

We use the IAM REMIND to derive welfare-optimal transformation pathways. REMIND includes an energy-system representation with high process detail in mitigation and emissions abatement technologies with a Ramsey-type macro-economic growth model and the reduced-form climate model MAGICC6[38] (also see Methods). The linked system of macro-economy, energy- and land-system, climate and climate damages is solved ensuring full consistency between the various model components (Fig. 3). In contrast to DICE-like IAMs[3,34,39], REMIND has the mitigation technology and energy system detail required to describe near-term climate policy and its emission response. Consequently, detailed-process IAMs are key contributers to international climate policy assessments[13,14].

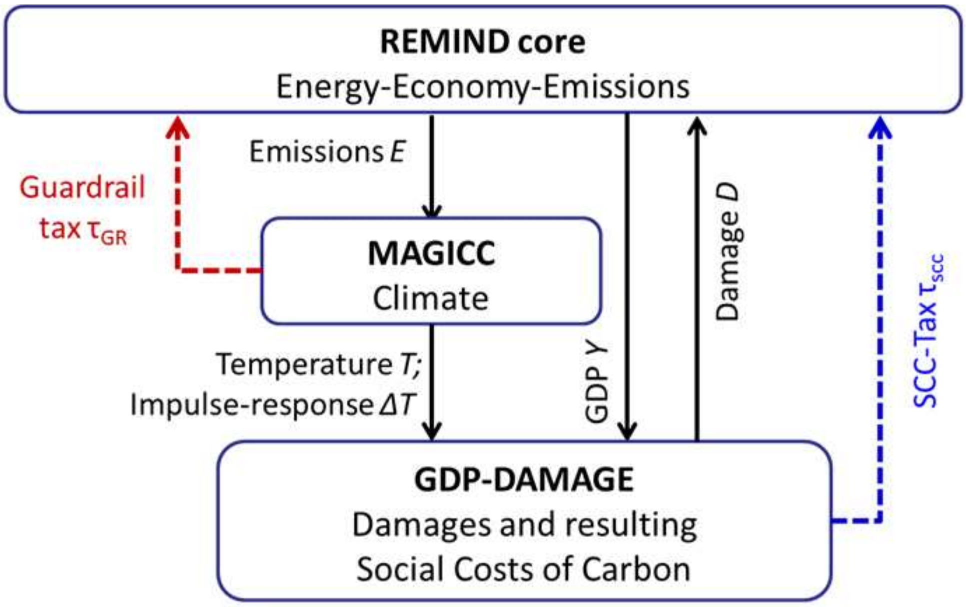

Figure 3: **Illustration of the Integrated Assessment Model REMIND** Emission and GDP pathways derived in the REMIND core model are fed into the climate model MAGICC6; resulting in temperature and the temperature impulse responses. Climate damages, the social cost of carbon and the guardrail tax are calculated from this information, and used in the next iteration of the REMIND core model. At the fixed point of this iteration, the solution is the same as if a single numerical optimization model was run (Supplementary Material, Section 2).

Welfare-optimal pathways for gradual damages and a temperature guardrail

Whereas the social cost of carbon in the CBA accounts for the gradual climate damages based on empirical estimates, the well-below-2°C temperature guardrail of the Paris Agreement is largely motivated by the precautionary principle, in view of tipping elements and potentially unknown climate impacts if warming increases beyond the range experienced in the Holocene[10].

Our model framework includes both gradual damages and a temperature guardrail (Fig. 1c). LTC pathways minimize the sum of mitigation costs for limiting warming to below the guardrail and the costs of economic damages. It is known from the theoretical literature that in the presence of both climate damages and a temperature guardrail, the welfare-optimal carbon price is the sum of the SCC and a price component related to the temperature guardrail[21]. In our model, the LTC pathway contains an additional emissions price component, if required in order to keep temperature increase below 2°C. This price component, the shadow price of the temperature guardrail, is called guardrail tax in the following. The guardrail tax rises exponentially at the interest rate, following Hotelling's rule[13,40], until carbon emissions go to zero. After that, the guardrail tax is adjusted to keep carbon emissions at zero.

The welfare-optimal carbon price in our framework is thus the sum of the SCC and the guardrail tax at the solution point of our model framework (Section 2 of the Supplementary Material). The optimal carbon price is globally uniform, levied as a tax on all greenhouse gas emissions, and implemented from 2025 on. The tax revenue is redistributed lump-sum to households.

To better understand the distinctive features of LTC pathways, we also implement CEA pathways, which minimize only the cost of limiting warming to below a temperature guardrail. Gradual climate impacts still do occur in the CEA pathways, but are not reflected in the carbon price - the carbon price in CEA consists only of the guardrail tax.

In comparing LTC with CEA pathways, we include three key components of uncertainty: (i) the persistence time in the damage function; (ii) physical uncertainties in the climate system; (iii) future socio-economic, demographic, technological and institutional development.

The damage function uses estimates from two empirical specifications from BHM15 for the reduction of GDP growth through local temperature changes, called "long-run" and "short-run". In contrast to their original construction of damage functions based on these estimates, we express the uncertainty over the persistence time scale by using a model ensemble with persistence times of 5, 15, and 30 years, as well as their original estimate (with the implied infinite persistence time). Together, the product of two empirical specifications and four persistence times yield eight damage specifications that span the damage-related dimension of the model run ensemble.

Physical uncertainties in the climate system are covered by sampling configurations of the MAGICC6 model along temperature outcomes. Different possible future socioeconomic trends are represented by different assumptions described by the Shared Socioeconomic Pathways (SSPs)1, 2, and 5[41,42]. We sample 80 runs of the REMIND model system along the damage and climate physics uncertainty dimensions under SSP2 as the ensemble for the main results. Additionally, we sample another 80 runs each for SSP1 and 5 for a sensitivity analysis – the full ensemble including all three SSPs is 240 runs.

Near-term emission reduction efforts and the adequacy of the nationally determined contributions

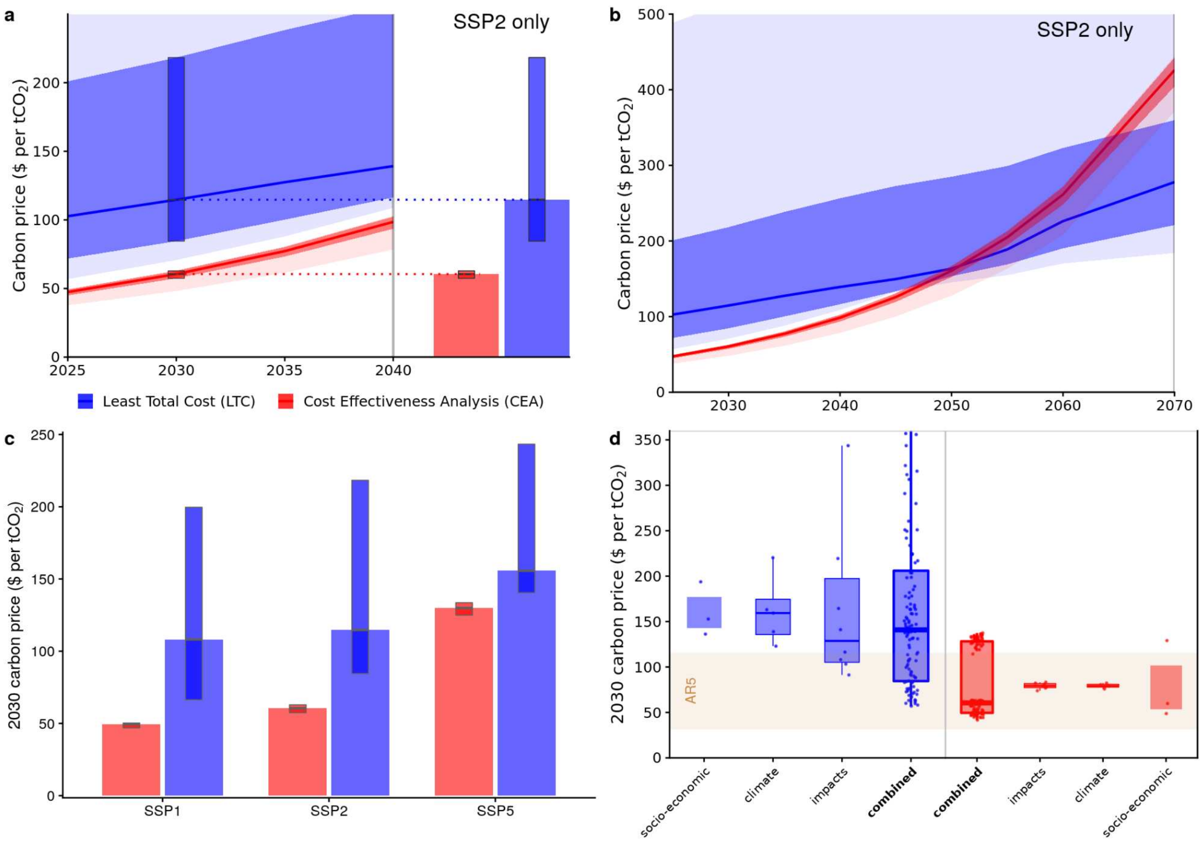

Figure 4: **Carbon prices for 2°C in welfare-optimal LTC pathways (blue) are higher in the near-term than for CEA (red).** (a) Median carbon prices in 2030 are \$115 (\$85-218) for LTC, significantly above the \$61 (\$57-63) for CEA. The range in brackets are the 20th-80th percentiles, also indicated in dark ribbons in the plot; light ribbons are the min-max range. (b) Higher near-term carbon prices of LTC are mirrored by lower prices from 2050 on; ribbons as in a. (c) Effect of different socio-economic baselines. (d) Uncertainty decomposition of the full ensemble of 240 runs into contributions of socio-economic baseline, climate, and impact specifications.

The difference in near-term carbon prices between LTC and CEA pathways for the 2°C limit is large (Fig. 5a). In 2030, the LTC carbon price is \$115 (\$85-218), as against \$61 (\$57-63) in the CEA case (single numbers are medians and brackets the 20-80th percentile range of the ensemble for SSP2 only, unless otherwise stated; all dollar values are US$$_{2015}$.). Whereas the CEA carbon price rises exponentially over time, the LTC carbon price rises much slower (Fig. 4b). A consequence of the high near-term ambition in the LTC pathway is that in the long term, much lower carbon prices are required to reach the 2°C target than in the CEA pathway.

These results are robust against different socio-economic baselines: Larger challenges for mitigation, such as in SSP5, require higher carbon prices than baselines with lower challenges, such as SSP1, to meet the 2°C limit (Fig. 5c). This is consistent with earlier studies[42]. The range of 2030 carbon prices is dominated by uncertainty about the damage function in LTC pathways, whereas uncertainty about socio-economic baselines explains most of the range of CEA carbon prices of the full scenario ensemble (Fig. 5d). Compared to the range of LTC pathways, the range of CEA pathways is much smaller. Note that the uncertainty for CEA pathways would be larger if the uncertainty about the carbon budget for 2°C would be included (see Supplementary Figure 5 for other temperature targets).

Near-term emission reductions are more stringent in the median LTC pathway than in the CEA counterpart. In 2030, global CO2 emissions are 28 (23-31) GtCO2 in the LTC paradigm, compared to 33 (33-33) GtCO2 for CEA. The near-term ambition of the median LTC pathway is similar to 1.5°C pathways with temperature overshoot from the SR1.5 (median 29.1 Gt CO2), whereas the CEA pathway is in line with their higher-2°C scenarios (median 33.5 Gt CO2). The gap between 2030 emissions projected under the currently pledged nationally determined contributions (taken from the SR1.5 database) and the welfare-optimal LTC pathway for the 2°C limit is two thirds larger compared to what a CEA assessment indicates. In the median LTC pathway, the average emission reduction rate from 2020 to 2030 is 3.2% yr^{-1}, around double the rate of the median CEA pathway - indicating the much higher near-term mitigation effort.

To sum up, CEA pathways systematically underestimate the optimal near-term policy ambition and overestimate the long-term ambition if climate damages are non-negligible below warming levels of 2°C. This conclusion holds for other temperature limits as well, but the difference between LTC and CEA decreases with increasing stringency of the temperature limit, with only a minor effect remaining for 1.5°C pathways (Supplementary Material).

Conclusion

The climate crisis is a great challenge of the 21st century. Mitigation policies, in particular the ambition of mitigation efforts in the current decade, not only influence the likelihood of meeting the temperature limit set forth in the Paris Agreement, but also the severity

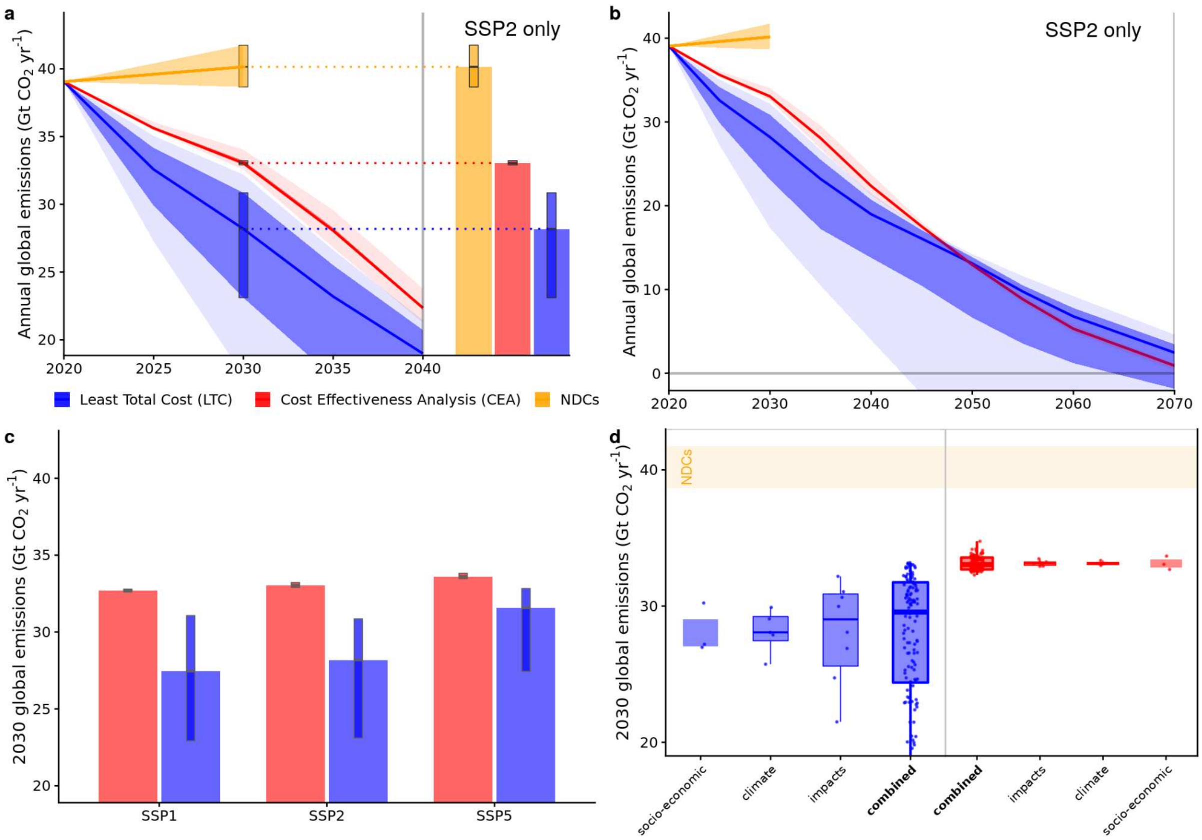

Figure 5: **Global CO2-only emissions for 2°C in welfare-optimal LTC pathways (blue) are below emissions for CEA (red) in the near term.** Projections under the nationally determined contributions (NDCs) (yellow) are included. (a) Median emissions in 2030 are 28 (23-31) $GtCO_2$ $yr^{-1}$for LTC, significantly below the 33 (33-33) $GtCO_2$ $yr^{-1}$for CEA, increasing the gap to the NDCs. The range in brackets are the 20th-80th percentiles, also indicated in dark ribbons in the plot; light ribbons are the min-max range. (b) Lower near-term emissions of LTC are mirrored by higher emissions from 2050 on. (c) Effect of different socio-economic baselines on 2030 emissions. (d) Uncertainty decomposition of the full ensemble of 240 runs into contributions of socio-economic baseline, climate, and impact specifications. See Supplementary Figure 3 for a plot that includes many greenhouse gases.

of climate impacts realized. Whereas the policy debate largely focuses on the impacts beyond the 1.5°C and 2°C thresholds, near-term impacts at lower warming levels can be substantial and have persistent consequences beyond their immediate effect.

This study combines recent empirical damage estimations and modeling of the persistence time, a key uncertainty, into a new damage function. This damage function is evaluated within an IAM with high technological detail and a state-of-the-art climate model. We demonstrate that welfare-optimal mitigation pathways, minimizing the total costs of near-term damages and a Paris-based temperature guardrail, result in substantially greater near-term mitigation efforts than a pure cost-effectiveness analysis. A pure cost-effectiveness analysis, which postpones climate policy ambition until later in the century, yields more costly pathways to achieving the 2°C target than least-total cost pathways.

Future research could include damages beyond reductions in economic output. To reduce the uncertainty over optimal policies, it is crucial to further the empirical understanding of channels of impacts, their persistence over time, and adaptation to them.

Despite the significant uncertainties, our results have important implications for climate policy. Previous research based on cost-effectiveness analysis has pointed to the inadequacy of currently committed mitigation efforts to achieve the Paris Agreement at lowest cost. Our results demonstrate that current climate policy efforts fall even shorter than previously thought as soon as climate damages below the temperature threshold are taken into account. Therefore we argue that the LTC approach is a better guideline to climate policy in particular with respect to near-term action.

References

1. Hope, C. & Hope, M. The social cost of CO2 in a low-growth world. *Nature Climate Change* **3,** 722–724. doi:10.1038/nclimate1935 (2013).
2. Tol, R. S. J. The economic impact of climate change in the 20th and 21st centuries. *Climatic Change* **117,** 795–808. doi:10.1007/s10584-012-0613-3 (2013).
3. Nordhaus, W. Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists* **1,** 273–312. doi:10.1086/676035 (2014).
4. Lenton, T. M. *et al.* Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences* **105,** 1786–1793. doi:10.1073/pnas.0705414105 (2008).
5. Kriegler, E., Hall, J. W., Held, H., Dawson, R. & Schellnhuber, H. J. Imprecise probability assessment of tipping points in the climate system. *Proceedings of the national Academy of Sciences* **106,** 5041–5046 (2009).
6. Frieler, K *et al.* Limiting global warming to 2 C is unlikely to save most coral reefs. *Nature Climate Change* **3,** 165–170 (2013).
7. Cai, Y., Lenton, T. M. & Lontzek, T. S. Risk of multiple interacting tipping points should encourage rapid CO 2 emission reduction. *Nature Climate Change* **6,** 520–525 (2016).
8. *United Nations Framework Convention on Climate Change* 1992. https://unfccc.int/resource/docs/convkp/conveng.pdf.

9. United Nations. *Paris Agreement* 2015. http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.
10. Schellnhuber, H. J., Rahmstorf, S. & Winkelmann, R. Why the right climate target was agreed in Paris. *Nature Climate Change* **6,** 649–653. doi:10.1038/nclimate3013 (2016).
11. Steffen, W. *et al.* Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences* **115,** 8252–8259 (2018).
12. Umweltveränderungen, Wissenschaftlicher Beirat der Bundesregierung Globale. *Wege zur Lösung globaler Umweltprobleme: Jahresgutachten 1995* (Springer, 1996).
13. *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014).
14. Rogelj, J. *et al.* Mitigation pathways compatible with 1.5 C in the context of sustainable development (2018).
15. Weyant, J. Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy* **11,** 115–137. doi:10.1093/reep/rew018 (2017).
16. *IPCC, 2014: Summary for policymakers in Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Field, C. *et al.*) (Cambridge University Press, Cambridge, United Kingdom and New York,USA, 2014).
17. Carleton, T. A. & Hsiang, S. M. Social and economic impacts of climate. *Science* **353.** doi:10.1126/science.aad9837 (2016).
18. Dell, M., Jones, B. F., Olken, B. a. & Gates, M. What Do We Learn from the Weather? The New Climate-Economy Literature. *Journal of Economic Literature* **52,** 740–798. doi:10.3386/w19578 (2014).
19. Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production. *Nature,* 1–16. doi:10.1038/nature15725 (2015).
20. Carleton, T., Hsiang, S. & Burke, M. Conflict in a changing climate. *The European Physical Journal Special Topics* **225,** 489–511. doi:10.1140/epjst/e2015-50100-5 (2016).
21. Dietz, S. & Venmans, F. Cumulative carbon emissions and economic policy: in search of general principles. *Journal of Environmental Economics and Management* **96,** 108–129 (2019).

22. Bansal, R., Ochoa, M. & Kiku, D. *Climate change and growth risks* tech. rep. (National Bureau of Economic Research, 2016).

23. Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production. *Nature* **527,** 235–239. doi:10.1038/nature15725 (2015).

24. Henseler, M. & Schumacher, I. The impact of weather on economic growth and its production factors. *Climatic Change* **154,** 417–433 (2019).

25. Kahn, M. E. *et al. Long-term macroeconomic effects of climate change: A cross-country analysis* tech. rep. (National Bureau of Economic Research, 2019).

26. Burke, M. & Tanutama, V. *Climatic Constraints on Aggregate Economic Output* Working Paper 25779 (National Bureau of Economic Research, 2019). doi:10.3386/w25779.

27. Hope, C. The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern. *The Integrated Assessment Journal* **6,** 19–56 (2006).

28. Diaz, D. & Moore, F. Quantifying the economic risks of climate change. *Nature Climate Change* **7,** 774–782. doi:10.1038/nclimate3411 (2017).

29. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. *Nature Climate Change* **8,** 895–900 (2018).

30. Moore, F. C. & Diaz, D. B. Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change* **5,** 127–132. doi:10.1038/nclimate2481 (2015).

31. Dietz, S. & Stern, N. Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal* **125,** 574–620 (2015).

32. Moyer, E., Woolley, M., Matteson, N., Glotter, M. & Weisbach, D. A. Climate Impacts on Economic Growth as Drivers of Uncertainty in the Social Cost of Carbon. *The Journal of Legel Studies* **43,** 401–425 (2014).

33. Ueckerdt, F. *et al.* The economically optimal warming limit of the planet. *Earth System Dynamics* **10** (2019).

34. Glanemann, N., Willner, S. N. & Levermann, A. Paris Climate Agreement passes the cost-benefit test. *Nature communications* **11,** 1–11 (2020).

35. Estrada, F., Tol, R. S. & Gay-García, C. The persistence of shocks in GDP and the estimation of the potential economic costs of climate change. *Environmental Modelling & Software* **69,** 155–165 (2015).

36. Piontek, F. *et al.* Economic growth effects of alternative climate change impact channels in economic modeling. *Environmental and Resource Economics* **73,** 1357–1385 (2019).

37. Hänsel, M. C. *et al.* Climate economics support for the UN climate targets. *Nature Climate Change,* 1–9 (2020).

38. Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2 degrees C. *Nature* **458,** 1158–62. doi:`10.1038/nature08017` (2009).

39. Hope, C. The 10 trillion value of better information about the transient climate response. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **373,** 20140429. doi:`10.1098/rsta.2014.0429` (2015).

40. Rogelj, J. *et al.* A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573,** 357–363 (2019).

41. O'Neill, B. C. *et al.* The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* **42,** 169–180. doi:`10.1016/j.gloenvcha.2015.01.004` (2017).

42. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42,** 153–168. doi:`10.1016/j.gloenvcha.2016.05.009` (2017).

Supplementary Information

Supplementary information are available.

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The authors declare no competing financial interests. Correspondence should be addressed to A.S..

Methods

Model framework We assess trade-offs between CEA and LTC mitigation pathways for the 2°C target by modeling both in an energy-economy-climate model framework. Our model framework can be classified as a detailed process IAM (DP-IAM)[15,28]. Such DP-IAMs were used extensively in the AR5 of the Intergovernmental Panel on Climate Change for quantitative analysis of transformation pathways. An earlier version of our model framework, the REMIND model, was one of the major contributors to the AR5 and SR15 scenario database[43,44]. Transformation pathways explored in the AR5, however, do not include climate impacts. Cost-benefit IAMs[1–3], by contrast, are models that do include climate impacts, but have less process detail and are thus not as useful in describing transformation pathways. In this paper, we aim (a) to demonstrate the importance of economic climate impacts for optimal climate change mitigation strategies, and (b) to quantify how crucial uncertainties affect these optimal strategies. We do so by integrating climate impact estimates into our DP-IAM, and contrasting CEA pathways that follow the rationale of the models used in the AR5, which do not reflect climate impacts in the price of carbon emissions, with welfare-optimal transformation pathways, named LTC pathways. An comparision our of paper with the literature across key features is found in Supplementary Table 2. The relation of our LTC approach with the CEA and CBA approaches from the literature is discussed in Section 6 of the Supplementary Material and Supplementary Figure 9.

We analyse uncertainties and sensitivities along three dimensions: Socio-economic trends, climate system physics, and climate damage estimates. Assuming realizations across these three dimensions to be equally likely and independent, we use a full factorial ensemble design of 80 models for the ensemble for the main results (SSP2 only) and 240 model runs (SSP1, 2, and 5) for the full ensemble runs. The ensemble range in an outcome is then a measure of its uncertainty. We explain all three uncertainty dimensions in this Methods section starting from from socio-economic scenarios as drivers of emissions, to the climate system, and to climate impacts. The focus in this Methods section is on our two main methodological contributions: a damage function reflecting finite persistence of damages over time and a method to derive welfare-optimal climate policy in a coupled energy-economy-climate model.

Socio-economic and energy systems We use the energy-economy model REMIND-Luderer *et al.* [45] in its version 2.1. The source code of REMIND is available open source at . Its core is a welfare-maximizing, Ramsey-type general equilibrium model with eleven world regions that spans the 21st century[46,47]. Regional utilities are aggregated into global welfare using Negishi weights (thus equalizing the utilities of one additional unit of consumption across regions). The energy system model, hard-coupled to the economic core, captures inertia and path-dependencies by representing more than 50 energy conversion technologies as capital stocks, subject to adjustment costs. Energy prices reflect resource scarcities, resource trade, and final energy taxes. This combination of both high detail in abatement options and long-term scope allows for the assessment of near-term climate policies compatible with long-term climate targets[48–50]. The most relevant greenhouse gas emissions in energy and land-use systems are accounted for[45].

Future developments of populations, economies, technologies, and institutions are highly uncertain. These socio-economic uncertainties are reflected in three different baselines consistent with the Shared Socioeconomic Pathways (SSPs)[41]: Sustainable development in SSP1, a fossil-fuel intensive high growth scenario in SSP5, and the middle-of-the-road scenario SSP2. Assumptions for the global population in 2100 stretch from 7 to 9 billion[51] across scenarios. GDP per capita in 2050 is around twice as high in SSP5 as in SSP1[52]. Energy demand in 2100 is assumed to be more than double and baseline emissions are around double already in 2050 in SSP5 compared to SSP1[42]. Baseline radiative forcing in 2100 is slightly above RCP8.5 for SSP5, indicating high challenges, and somewhat below RCP6.0 for SSP1, indicating lower challenges for mitigation[42].

Climate system We use MAGICC6[38], iteratively soft-coupled to REMIND, to translate greenhouse gas emissions into global mean temperature change. MAGICC6 emulates the results from atmosphere-ocean general circulation models well[53] and has been used extensively by the Intergovernmental Panel on Climate Change[13]. Temperature increase has been assessed to be approximately linear in cumulative CO_2 emissions (see also Supplementary Figure 4), though this relationship is subject to large uncertainties[38,54–56]. This uncertainty is accounted for by different MAGICC6 parameter configurations representative of the spread in temperature outcomes. From a probabilistic run of MAGICC6 with 600 outcomes for an RCP2.6 emissions scenario, we select MAGICC6 configurations at certain percentiles of the temperature distribution in 2100. To quantify the influence of climate uncertainty in our results, we run the model framework using configurations at the 5th, 30th, 50th, 70th, and 95th percentile. Regional temperatures, which drive the damage functions, are derived from global mean temperature using a statistical downscaling based on CMIP5 results[57] (Section 3 of the Supplementary Material).

Climate impacts Our climate damage specification is based on the empirical findings of Burke *et al.* [23] and derived in full detail in Section 1 of the Supplementary Material. Burke *et al.* [23] use year-to-year temperature variation to identify the effect of temperature on economic growth. Their main finding is a nonlinear dependence of GDP growth on the climate only through local temperature. Damages to the growth rate, in contrast to previously assumed damages to the level of GDP[58], have recently come into focus in the literature since they result in persistent and much larger economic impacts[35,59–61]. There is some ambiguity in the estimates of Burke *et al.* [23] on whether temperature affects the growth rate or the level of GDP and consequently on how persistent those impacts are in the long term[62]. To reflect this uncertainty we use two different empirical specifications and parameterize a finite persistence time.

We use two different specifications of the climate-dependent GDP growth rate $h(T)$ from Burke *et al.* [23]: 1) The central estimate in which only the temperature in a given year affects GDP growth in that year ("short run") – it shows positive marginal effects on the growth rate of GDP in countries with an average temperature below $\sim 13°$C and strongly negative effects at higher temperatures. 2) A specification derived by regressing GDP growth on the last five year's temperatures ("long run") – it shows negative marginal growth effects at all temperatures.

In the damage function $\delta_{r,t}$, the specification $h(T)$ reduces the growth rate of GDP in every year t in which yearly average temperature $T_{r,t}$ in region r is above the base year's temperature $\bar{T}_r$:

$$\delta_{r,t} = h(T_{r,t}) - h(\bar{T}_r).$$

Typical values for the global aggregate of $\delta_{r,t}$ are somewhat smaller than in, for example, DICE2016 (Supplementary Figure 1a), although these two damage functions are not fully comparable: DICE-like damage functions describe the reduction in the *level* of GDP, whereas our damage function describes growth *rate* reductions that may persist and compound over time. Burke *et al.* [23] show that there is some evidence of persistence in the damages, but also note that the degree of persistence is highly uncertain. By parameterizing the degree of persistence we reflect two key uncertainties: The persistence of climate damages and possible future adaptations to those damages.

The empirical specifications we use reflect adaptations to increasing temperatures to the degree they occurred between 1960-2010[23] through the finite persistence time. In our parameterization of persistence, the effect of each single damage shock $\delta_{r,t}$ declines exponentially over time. We do not know of reliable empirical estimates of the typical half-time of climate damage shocks on GDP. There are, however, some indications: Dell *et al.* [59] conclude that climate damages on GDP persist for at least 10-15 years, and Dell *et al.* [63] find that only around half of the GDP damages are offset in the long term. Impacts of hurricanes on economic growth, as an example of climatic extreme events, have been shown to persist beyond 20 years[64]. For the time τ_H after that half of the damage shock remains, we choose a range from an optimistic 5 years to a rather pessimistic 30 years (which corresponds to adaptation rates between 1% yr^{-1} and 13% yr^{-1}). Consequently, the damage factor

$$D_{r,t} \equiv \prod_{t'=2005}^{t} \left(1 + \delta_{r,t'}\, 2^{-(t-t')/\tau_H}\right), \tag{1}$$

reduces before-damage GDP $Y_{r,t}$ according to

$$\bar{Y}_{r,t} = Y_{r,t}\, D_{r,t}.$$

The damage factor translates growth rate damages from the damage function into a reduction of the level of GDP. Our assumption of a finite and non-zero persistence time τ_H interpolates between two extreme cases found in the literature, as illustrated in Supplementary Figure 2: No persistence at all in DICE-like damage functions[3] (a temperature shock in one year means $D < 1$ only in that year), in contrast to infinite persistence, as in the damage factor of Burke *et al.* [23] or Pindyck [60] (a temperature shock in one year means $D < 1$ for all future). With a finite persistence time we effectively assume that the damages due to one year with above-historical-average temperatures eventually disappear: there is always a "return to trend" ($D \to 1$) in the long run. This also implies that after stabilizing temperature at a level above today's, damages are still incurred every year; this is the case in most of the literature[2,3,27,58,60].

Our preferred damage function specification leads to a median damage of around 9% of GDP in 2100 across the LTC pathways – a much higher damage than in, for example, DICE2016, but significantly less than in the original Burke estimates (Supplementary Figure 1). The magnitude of our main result – near-term climate policy is more stringent in LTC than in CEA pathways – depends strongly on the damage function, as illustrated in Supplementary Figure 9.

Climate policies We derive the two components of the optimal carbon price, the SCC and the guardrail tax, consistently in our model framework (for technical details, see Section 2 of the Supplementary Material). In brief, we find analytical expressions for both price components in a reduced model (i.e., the relevant first-order conditions of the optimization problem), evaluate them using variables from the REMIND and MAGICC6 models and iteratively price them into REMIND as taxes on emissions. The SCC p_t is the sum of discounted future damages due to one unit of emissions along a GDP growth path,

$$p_t = \sum_{r'} \sum_{t'=t}^{\mathcal{T}} \Phi_{t',t} Y_{r',t'}\, D_{r',t'} \sum_{t''=t}^{t'} 2^{-(t'-t'')/\tau_H}\, \Theta_{r',t',t''}\, \kappa_{r',t''}\, \Delta T_{t'',t}. \tag{2}$$

It depends on regional GDPs as well as the discount factor $\Phi_{t',t}$ from the REMIND model, damage factors, the derivative of the damage function with respect to temperature $\Theta_{r',t',t''}$, regional temperatures (through $\kappa_{r',t''}$), and the temperature impulse response to an additional unit of emissions $\Delta T_{t'',t}$.

We derive the temperature impulse response from MAGICC6 using a pulse experiment (Supplementary Figure 4b). The solution of this coupled model framework is almost identical to the case in which the framework's components were combined into a single optimization model (as is the case for traditional Integrated Assessment Models such as DICE). Our method has the advantage of decoupling the complexities of the climate system and the damage function from the REMIND model while keeping all relevant interactions, allowing for greater modelling detail on all sides.

We implement the temperature guardrail as a limited CO_2 budget until the time of CO_2 neutrality; the stringency of this budget approximately determines the temperature at peak warming[40]. As an implementation of the 2°C limit we use a budget of 1300 Gt CO_2 from 2011 onwards, which is derived from the budgets given in Chapter 2 of the SR1.5[14] for 67% likelihood of stabilizing below 2°. As long as cumulative emissions are below the budget, the guardrail tax takes the well-known Hotelling form and rises exponentially at the interest rate[13]. After the budget constraint has been reached - which happens around 2070 in most pathways - the level of the guardrail tax is adjusted to keep CO2 emissions to zero.

Both carbon price components are globally uniform, as the socially optimal policy takes into account the global effects of each region's emissions. The optimal carbon tax is levied on CO_2, CH_4, and N_2O emissions, aggregated using global warming potentials[65]. We assume that the resulting tax revenue is recycled lump-sum to households in each model region. All of our pathways assume the full availability of mitigation technologies. The LTC pathways are welfare-optimal ("first-best") in the sense that the temperature target and the social cost of carbon are both fully internalized. By contrast, in CEA pathways are sub-optimal ("second-best") in the sense that although the temperature target is internalized, climate damages expressed in the social cost of carbon are not, even though the damages are present.

References

43. Krey, V. *et al. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Edenhofer, O. & al., E.) (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014).

44. Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. & Riahi, K. A new scenario resource for integrated 1.5 C research. *Nature climate change* **8,** 1027–1030 (2018).

45. Luderer, G. *et al.* Description of the REMIND model (Version 1.6). *SSRN Electronic Journal* **2697070** (2015).

46. Leimbach, M., Bauer, N., Baumstark, L. & Edenhofer, O. Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R. *Environmental Modeling and Assessment* **15,** 155–173. doi:10.1007/s10666-009-9204-8 (2010).

47. Leimbach, M., Schultes, A., Baumstark, L., Giannousakis, A. & Luderer, G. Solution algorithms for regional interactions in large-scale integrated assessment models of climate change. *Annals of Operations Research.* doi:10.1007/s10479-016-2340-z (2016).

48. Bauer, N., Brecha, R. J. & Luderer, G. Economics of nuclear power and climate change mitigation policies. *Proceedings of the National Academy of Sciences* **109,** 16805–16810. doi:10.1073/pnas.1201264109 (2012).

49. Luderer, G. *et al.* Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters* **8,** 034033. doi:10.1088/1748-9326/8/3/034033 (2013).

50. Bertram, C. *et al.* Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change* **5,** 235–239. doi:10.1038/nclimate2514 (2015).

51. KC, S. & Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change* **42,** 181–192. doi:10.1016/j.gloenvcha.2014.06.004 (2017).

52. Dellink, R., Chateau, J., Lanzi, E. & Magné, B. Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change* **42,** 200–214. doi:10.1016/j.gloenvcha.2015.06.004 (2017).

53. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. *Atmospheric Chemistry and Physics* **11,** 1417–1456. doi:10.5194/acp-11-1417-2011 (2011).

54. Allen, M. R. *et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458,** 1163–1166. doi:10.1038/nature08019 (2009).

55. Collins, M. *et al. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on*

Climate Change. (eds Stocker, T. F. *et al.*) 1029–1136 (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013).

56. Millar, R., Allen, M., Rogelj, J. & Friedlingstein, P. The cumulative carbon budget and its implications. *Oxford Review of Economic Policy* **32,** 323–342. doi:10.1093/oxrep/grw009 (2016).

57. *CMIP5 Coupled Model Intercomparison Project – WCRP World Climate Research Programme* http://cmip-pcmdi.llnl.gov/cmip5/.

58. Kopp, R. E., Golub, A., Keohane, N. O. & Onda, C. The Influence of the Specification of Climate Change Damages on the Social Cost of Carbon. *Economics* **6,** 1. doi:10.5018/economics-ejournal.ja.2012-13 (2012).

59. Dell, M., Jones, B. F. & Olken, B. a. Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics* **4,** 66–95. doi:10.1257/mac.4.3.66 (2012).

60. Pindyck, R. S. Uncertain outcomes and climate change policy. *Journal of Environmental Economics and Management* **63,** 289–303. doi:10.1016/j.jeem.2011.12.001 (2012).

61. Stern, N. The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature* **51,** 838–859. doi:10.1257/jel.51.3.838 (2013).

62. Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production - Supplementary materials. *Nature* **527** (2015).

63. Dell, M., Jones, B. F. & Olken, B. a. Temperature and Income: Reconciling New Cross-Sectional and Panel Estimates. *American Economic Review* **99,** 198–204. doi:10.1257/aer.99.2.198 (2009).

64. Hsiang, S. M. & Jina, A. S. The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6700 cyclones. *NBER Working Paper Series.* doi:10.3386/w20352 (2014).

65. Myhre, G. *et al. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. *et al.*) chap. 8 (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013).

Supplementary material for "Economic damages from on-going climate change imply deeper near-term emission cuts"

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1 Climate damages

1.1 Damage estimates

Our damage function is based on the empirical estimates of Burke *et al.* [1]. They find a nonlinear dependence of GDP growth on the climate that only depends on the average yearly temperature of a specific country. The climate-dependent part of the GDP growth rate h depends on local temperature $T_{r,t}$ through

$$h(T_{r,t}) = \beta_1 T_{r,t} + \beta_2 T_{r,t}^2. \tag{1}$$

We use two different empirical specifications for the β parameters: In the "short run" specification marginal GDP effects are positive at temperatures below $\sim 13°$C, but strongly negative at higher temperatures. The "long run" specification shows negative marginal effects at all temperatures. The "short run" specification is derived by regressing GDP growth in a given year on the temperature in that specific year only. The regression for the "long run" specification, by contrast, additionally includes temperature lags of the five preceding years, reflecting the dynamic reaction to temperature shocks and their persistence. Burke *et al.* [2] describe this in more detail in their section on level vs. growth rate effects. By using these two parameter sets we reflect parts of the ambiguity in whether climate damages affect the growth rate or the level of GDP. Both specifications are reproduced by us based on the replication data set by Burke et al.[3] and summarized in Table 1.

1.2 Damage function

We derive a damage function and a damage factor for the REMIND model based on the concept in Burke *et al.* [2]. Let net GDP (after climate damages) per capita in model

	β_1	β_2
short run	0.0127	-0.0005
long run	-0.0037	-0.0001

Table 1: Specifications for our damage function (Eq.(1)), derived by us based on the replication data set of Burke [3].

region r be $\bar{y}_{r,t}$. Then, break down the GDP growth rate into a growth rate in the absence of climate change $\eta_{r,t}$ and a climate-dependent part $\delta_{r,t}$:

$$\bar{y}_{r,t} = \bar{y}_{r,t-1}\left(1 + \eta_{r,t} + \delta_{r,t}\right),$$

and as both growth rates are small[i],

$$\begin{aligned}
&\approx \bar{y}_{r,t-1}\left(1+\eta_{r,t}\right)\left(1+\delta_{r,t}\right) \\
&= y_{r,0}\prod_{t'=1}^{t}\left(1+\eta_{r,t'}\right)\left(1+\delta_{r,t'}\right) \\
&= \underbrace{y_{r,0}\prod_{t'=1}^{t}\left(1+\eta_{r,t'}\right)}_{\equiv y_{r,t}}\underbrace{\prod_{t'=1}^{t}\left(1+\delta_{r,t'}\right)}_{\equiv D'_{r,t}} \\
&= y_{r,t}\,D'_{r,t}.
\end{aligned}$$

As population is not affected by climate change in our model, this holds for aggregate GDP as well,

$$\bar{Y}_{r,t} = Y_{r,t}\,D'_{r,t}.$$

In the baseline of the REMIND model (i.e., no climate change impacts, no climate policy) , GDP $Y_{r,t}$ is calibrated to reproduce trajectories of a given SSP scenario[4] and to GDP data in 2005. Climate change reduces the growth rate, $\delta_{r,t} > 0$, and thus gross GDP through $D'_{r,t}$ from the base year 2005 on. As gross GDP $Y_{r,t}$ is endogenous to the model, it may slightly differ from the baseline itself through second order effects, for example reduced capital accumulation[ii].

[i] This is a good approximation, and we derive here an upper bound on the error caused by it: By this approximation, we over- or underestimate the regional damage factor $D_{r,t}$ by a factor of $x = \prod_{t'=1}^{t}\left(1-\eta_{r,t'}\delta_{r,t'}\right)$. The median in absolute error $|x-1|$ in 2100 across our ensemble of runs is $x < 1\%$, and the 95th percentile is $x < 2\%$.

[ii] One way to interpret this is that we assume the GDP growth rate damages from the literature to act as total factor productivity growth rate damages in our model. We do this as there is currently no reliable breakdown of GDP damages into the different drivers of growth. Attributing GDP damages to total factor productivity damages may result in an overestimation of the income reduction caused by

Climate change damages on the growth rate $\delta_{r,t}$ are driven by the deviation of the regional annual mean temperature $T_{r,t}$ from the observed historical mean temperature $\bar{T}_r$ through the damage function

$$\delta_{r,t} = h(T_{r,t}) - h(\bar{T}_r), \tag{2}$$

where $\bar{T}_r$ is the historically observed temperature in 2005 (see Section 3 for details).

As Burke *et al.* [1] note, there is some ambiguity about whether the damages affect the level or the growth rate of GDP. This is most relevant, as growth rate damages lead to much larger impacts over time[5–8]. We use a single formulation to parameterize persistence of damages and adaptations to damages beyond the historically observed degree: Each single growth rate damage shock $\delta_{r,t'}$ declines exponentially over time t according to $\delta_{r,t'} 2^{-(t-t')/\tau_H}$. The parameter τ_H is time after which only half of the initial damage shock remains. The declining effect of damage shocks over time can be understood as a limited persistence of the shock or as some unspecified form of costless adaption to the shock that is autonomously deployed.

The damage factor compounds all past growth rate damage shocks, which decline exponentially over time:

$$D_{r,t} \equiv \prod_{t'=1}^{t} \left(1 + \delta_{r,t'}\, 2^{-(t-t')/\tau_H}\right). \tag{3}$$

To illustrate the persistence mechanism, assume that there is only one region and one damage shock today at time $t' = 1$, so $\delta_{t'=1} > 0$, and $\delta_{t' \neq 1} = 0$. In the resulting damage factor

$$D_{t \geq 1} = 1 + \delta_1\, 0.5^{(t-1)/\tau_H},$$

the effect of the damage shock δ_1 declines exponentially with t. A DICE-like damage factor does not show persistence[9,10], $\tau_H = 0$, such that the effect of the damage δ_1 would only last for one year. On the other end, an infinite persistence time[1,5], $\tau_H \to \infty$, means that the effect of the damage δ_1 is permanent, as $D_t < 1$. In our study, we assume finite and non-zero persistence times, interpolating in between these two extreme cases found in the literature.

We emphasize that our inclusion of the declining effect of damage shocks (or equivalently here: adaptation) results in a significant weakening of the damage factors found in Burke *et al.* [1], as we effectively assume that no climate damages do persist in the very long

climate change. For our application though, these effects are dominated by the large uncertainties in damage estimates, which we parametrize in the persistence/adaptation mechanism.

run. The damage factor used in Burke *et al.* [1], by contrast, corresponds to an infinite persistence time ($\tau_H \to \infty$).

Our low end estimate of a persistence time of 5 years requires adaptation beyond what is observed historically in order to be consistent with the empirical estimates cited above. Missing reliable data, we assume that adaptation measures are deployed optimally, autonomously, and at no cost. This results in a downwards bias of our estimates of the costs of climate impacts as adaptation measures in the real world are costly and not deployed without effort.

2 Internalizing climate damages and temperature targets

In this section we describe the integration of climate damages and the social cost of carbon (SCC), as well as temperature targets and the according guardrail tax, into the REMIND model. Our derivation of the expressions for the SCC borrows from the literature[11–13], but is somewhat more involved due to our inclusion of growth rate damage.

We derive an analytical expression for the SCC and the guardrail tax in a reduced model, and levy those in the REMIND model as taxes on emissions. In effect, the solution is the same as if calculated within a fully endogenous cost-benefit optimization (under an additional temperature constraint), even though we evaluate the SCC and guardrail tax iteratively outside the REMIND optimization. This allows inclusion of additional complexity along the causal chain from emissions to temperature to damages, such as for example the MAGICC6 climate model.

The two concerns for climate change here, a temperature target and damages, lead to two carbon price components, their sum being the optimal carbon tax at the fix point of the iteration. We use a reduced model mimicking REMIND to derive the first-order condition for the optimal carbon tax by comparing the baseline solution (i.e., climate change is an externality) to the socially optimal solution (i.e., climate damages and a temperature target are fully internalized).

First, consider a single, independent model region as a Ramsey model with one year time steps t. Utility U is standard (i.e., constant relative risk aversion), depends only on regional per capita consumption $c_{r,t}$; the intertemporal elasticity of substitution is η^{-1} and the pure rate of time preference is ρ. Capital $K_{r,t}$ is accumulated endogenously through investments $I_{r,t}$ through $I_{r,t} = K_{r,t+1} - (1 - \delta_k)K_{r,t}$, in which δ_k is the depreciation rate. Population $N_{r,t}$ is exogenous. Capital variable names denote here economy-wide values in contrast to per capita values in small letters (for example for GDP: $Y_{r,t} = y_{r,t}N_{r,t}$).

Production $Y_{r,t}(E_{r,t})$ has regional emissions as an input, meaning there is some value of emissions in production. $\Gamma_{r,t}$ is a unit tax on emissions. The constant $E^{'}_{r,t}$ stands for last iteration's emissions, does not influence the first order conditions, and is explained later on in this section – think of it as being zero for now.

The Lagrangian of the finite-time optimization problem[iii] for a single region r is

$$\mathcal{L}_r = \sum_{t=0}^{\mathcal{T}} \Big(N_{r,t} U(c_{r,t}) \, (1+\rho)^{-t} \\ + \lambda_{r,t} \Big(\left(D(T_{r,t}) + \Lambda(T_t)\right) Y_{r,t}(E_{r,t}) \, - c_{r,t} N_{r,t} - I_{r,t} - \Gamma_{r,t} \Big(E_{r,t} - E^{'}_{r,t} \Big) \Big) \Big). \quad (4)$$

There are climate damages $D(T_{r,t})$ that depend on regional temperatures $T_{r,t}$ and a damage term associated with the temperature limit $\Lambda(T_t)$ that depends on global mean temperature T_t only. The term $\Lambda(T_t)$ is zero below the temperature limit and unity above the limit.

In the first-order condition associated with emissions $E_{r,t}$ the terms involving D and Λ are additive[iv]. Consequently we split up the carbon tax $\Gamma_{r,t}$ in two parts,

$$\Gamma_{r,t} = p_{r,t} + \tau_{r,t}, \quad (5)$$

and derive the expression for the SCC $p_{r,t}$ and the guardrail tax $\tau_{r,t}$ separately in the following two sections.

2.1 Expression for the SCC

The part of the regional Lagrangian associated with the SCC is

$$\mathcal{L}_r = \sum_{t=0}^{\mathcal{T}} \Big(N_{r,t} U(c_{r,t}) \, (1+\rho)^{-t} \\ + \lambda_{r,t} \Big(Y_{r,t}(E_{r,t}) \, D(T_{r,t}) - c_{r,t} N_{r,t} - I_{r,t} - p_{r,t} \Big(E_{r,t} - E^{'}_{r,t} \Big) \Big) \Big). \quad (6)$$

We solve this Lagrangian for a regional social planner, with full control over consumption $c_{r,t}$, capital stock $K_{r,t}$, and emissions $E_{r,t}$. The first order conditions are the following:

[iii] The time horizon is $\mathcal{T} = 2150$, and we do not list the associated complementary-slackness conditions here. In the REMIND model, we make sure these conditions are fulfilled. Furthermore, we define climate targets until the year 2100 and use only results until that year; the extended model horizon until 2150 minimizes the influence of the model's finite time on the results. The horizon of the SCC calculation can be chosen to be different from the one of the REMIND model itself; a sensitivity analysis shows that this affects the optimal carbon tax, with stronger effects for a smaller time horizon than for an extended one.

[iv] Our results do not depend on the assumption of the two damage terms being additive in the Lagrangian. Similar results can be derived for multiplicative damages on output or utility damages due to the temperature limit.

First, the shadow price of consumption is

$$\lambda_{r,t} = \omega_r\, c_{r,t}^{-\eta}\, (1+\rho)^{-t} \qquad \forall\, t, r. \tag{7}$$

Second, in combination with the first order condition for capital accumulation, a Ramsey rule results

$$1 + r_{r,t} \equiv \frac{\partial \bar{y}_{r,t}}{\partial K_{r,t}} + (1 - \delta_k) = (1+\rho)\left(\frac{c_{r,t-1}}{c_{r,t}}\right)^{-\eta} \qquad \forall\, t, r \tag{8}$$

which defines the interest rate $r_{r,t}$. Third, the marginal value of emissions in production is only determined by the emissions tax

$$p_{r,t} = D_{r,t}\frac{\partial Y_{r,t}}{\partial E_{r,t}} \qquad \forall\, t, r. \tag{9}$$

In this baseline solution, each region does not recognize the link between their own emissions $E_{r,t}$ and global temperature, and consequently, climate damages – climate change is fully external.

In contrast to the solution of a single region, consider the globally social optimal solution that fully internalizes climate damages and the temperature target. The global Lagrangian is

$$\mathcal{L} = \sum_{t=0}^{\mathcal{T}} \sum_{r} \Big(\omega_r N_{r,t} U(c_{r,t})\,(1+\rho)^{-t} + \lambda_{r,t}\,(Y_{r,t}(E_{r,t})\,D(T_{r,t}) - c_{r,t}N_{r,t} - I_{r,t})\Big). \tag{10}$$

Production damages depend on regional temperature $D(T_{r,t})$ and the social planner realizes that temperature is a function of past global emissions $T_{r,t}(E_t, E_{t-1}, .., E_0)$. The first two first-order conditions are unchanged, but the marginal value of emissions in production in each region is equal to the capitalized value of marginal damages in all regions:

$$D_{r,t}\frac{\partial Y_{r,t}}{\partial E_{r,t}} = -\sum_{r'}\sum_{t'=0}^{\mathcal{T}} \lambda_{r',t'} Y_{r',t'} \frac{\partial D_{r',t'}}{\partial E_{r',t'}} \qquad \forall\, t, r \tag{11}$$

Comparing Eq. (11) to Eq. (9) gives the optimal, regional carbon tax that decentralizes the socially optimal, global solution:

$$p_{r,t} = -\lambda_{r,t}^{-1} \sum_{r'}\sum_{t'=0}^{\mathcal{T}} \lambda_{t',r'} Y_{r',t'} \frac{\partial D_{r',t'}}{\partial E_{r,t}}.$$

Using the definition of D_t, the dependence of T on all past emissions, and the product rule,

$$= -\lambda_{r,t}^{-1} \sum_{r'} \sum_{t'=0}^{\mathcal{T}} \lambda_{t',r'} Y_{r',t'} \, D_{r',t'} \sum_{t''=1}^{t'} \left(1 + 2^{-(t'-t'')/\tau_H} \, \delta(T_{r',t''})\right)^{-1} 2^{-(t'-t'')/\tau_H} \frac{\partial \delta(T_{r',t''})}{\partial E_{r,t}}$$

$$= -\lambda_{r,t}^{-1} \sum_{r'} \sum_{t'=0}^{\mathcal{T}} \lambda_{t',r'} Y_{r',t'} \, D_{r',t'} \sum_{t''=1}^{t'} \left(1 + 2^{-(t'-t'')/\tau_H} \delta(T_{r',t''})\right)^{-1} 2^{-(t'-t'')/\tau_H} \frac{\partial \delta(T_{r',t''})}{\partial T_{r',t''}} \frac{\partial T_{r',t''}}{\partial E_{r,t}}.$$

$\Delta T_{r',t'',t}$ is the temperature response at time t'' to an emissions pulse at t and it is zero for $t'' < t$ (by way of causality). It does not depend on regional, but only on global emissions (i.e., the derivative of global emissions with respect to regional emissions is one), such that:

$$= \lambda_{r,t}^{-1} \sum_{r'} \sum_{t'=t}^{\mathcal{T}} \lambda_{t',r'} Y_{r',t'} \, D_{r',t'} \sum_{t''=t}^{t'} 2^{-(t'-t'')/\tau_H} \, \Theta_{r',t',t''} \, \Delta T_{r',t'',t} \tag{12}$$

In the following, I discuss three factors in this expression: temperature response to emissions, marginal damages, and welfare weights.

Temperature response

The regional temperature response to global emissions $\Delta T_{r',t'',t}$ is derived in two steps: the global temperature impulse response, then a downscaling from global to regional temperatures:

$$\Delta T_{r,t',t} = \frac{\partial T_{r,t',t}}{\partial E_t} = \frac{\partial T_{t',t}}{\partial E_t} \frac{\partial T_{r,t',t}}{\partial T_{t',t}}$$

The temperature impulse response (TIR) in response to emissions is

$$\Delta T_{t',t} \equiv \frac{\partial T_{t',t}}{\partial E_t}.$$

The shape of the TIR and its derivation in our model framework is discussed in detail in section 4.

We approximate the change in regional temperature with global temperature

$$\frac{\partial T_{r,t',t}}{\partial T_{t',t}} \equiv \kappa_{r,t'}$$

by replacing the dependence on the emission time t with a dependence on a certain emissions scenario. Concretely, $\kappa_{r,t'}$ is the scaling from global mean temperature to regional temperature, evaluated for a given RCP scenario. The details of the underlying statistical downscaling are described in Section 3.

Taken together, the temperature response is

$$\Delta T_{r,t',t} = \kappa_{r,t'} \, \Delta T_{t',t}.$$

Marginal damages

The marginal change in the growth rate with temperature is

$$\Theta_{r',t',t''} \equiv -\frac{\partial \delta(T_{r',t''})}{\partial T_{r',t''}} \left(1 + 2^{-(t'-t'')/\tau_H} \delta(T_{r',t''})\right)^{-1}. \tag{13}$$

The factor in the parenthesis is very close to 1. The derivative follows from the definition of the damage function (Eq. (2) and Eq. (1)):

$$\begin{aligned} \frac{\partial \delta(T_{r,t})}{\partial T_{r,t}} &= \frac{\partial h(T_{r,t})}{\partial T_{r,t}} \\ &= (\beta_1 + 2\beta_2 T_{r,t}) \end{aligned}$$

Welfare weights and discount factor

We assume the welfare weights ω_r to be Negishi weights, which is a common choice in the literature. Negishi weights equalize the marginal utility of consumption across regions. We verify numerically that the time-independent Negishi weights ω_r in a converged REMIND run[v], deviate only very slightly from the regional share in the inverse of the marginal utility of consumption:

$$\omega_r \approx \frac{c^\eta_{r,t}}{\sum_{r'} c^\eta_{r',t}} \qquad \forall t.$$

We use this expression to simplify the Lagrange multiplier of the budget equation to:

$$\begin{aligned} \lambda_{r',t'} &= \omega_{r'} c^{-\eta}_{r',t'} \, (1+\rho)^{-t'} \\ &= \left(\sum_{r''} c^\eta_{r'',t}\right)^{-1} \left(\frac{c_{r',t}}{c_{r',t'}}\right)^\eta (1+\rho)^{-t'} \end{aligned}$$

[v]For detail on the solution procedure of such a run, see Leimbach *et al.* [14].

As t can be freely chosen, we also set $t = t'$, which yields a useful identity:

$$\lambda_{r,t} = \left(\sum_{r''} c^{\eta}_{r'',t} \right)^{-1} (1+\rho)^{-t}$$

Using this, the discount factor can be written compactly as

$$\begin{aligned} \Phi_{t',t} &= \lambda^{-1}_{r,t} \lambda_{r',t'} \\ &= \prod_{t''=t+1}^{t'} (1 + r_{t''})^{-1}, \end{aligned}$$

where we suppress the regional dependence as trade in capital good in the REMIND model leads to a globally uniform interest rate r_t.

Finally, putting together expressions for temperature response, marginal damages, and discounting, the expression for the SCC (from Eq. (12)) is

$$p_{r,t} = \sum_{r'} \sum_{t'=t}^{\mathcal{T}} \Phi_{t',t} Y_{r',t'} \, D_{r',t'} \sum_{t''=t}^{t'} 2^{-(t'-t'')/\tau_H} \, \Theta_{r',t',t''} \, \kappa_{r',t''} \, \Delta T_{t'',t}, \tag{14}$$

where we set $\eta = 1$. Equation (15) is the discounted sum of future marginal damages due to the temperature increase of an additional unit of emissions. As we consider growth rate damages, marginal damages along the entire growth path have to be summed up (the t'' sum in the expression), weighted by their persistence. This equation nests the special case of damages without persistence ($\tau_H = 0$), in which case an expression similar to the ones in the literature can be recovered[11–13]. The SCC is globally uniform (Eq.15 is independent of index r).

An estimate for the SCC can be dervied by a back-of-the-envelope calculation. Assume a global version of our model with constant GDP growth at 2%, a constant interest rate of 5%, instantaneous rise of temperature with emissions (not a bad assumption considering Fig. 4), damages of a couple of percent of GDP only such that $D_{r,t} \approx 1$. From Fig. 1, a rough estimate for the marginal damages with temperature is $\Theta \approx 0.6$. The scaling factor from global to regional temperature is around 1.2 on global average.

$$\begin{aligned} p_{r,t} &= \sum_{r'} \sum_{t'=t}^{\mathcal{T}} \underbrace{\Phi_{t',t} Y_{r',t'}}_{\approx 1.05^{-(t'-t)}} \quad \underbrace{Y_{r',t'}}_{\approx Y_t 1.02^{+(t'-t)}} \quad \underbrace{D_{r',t'}}_{\approx 1} \sum_{t''=t}^{t'} 2^{-(t'-t'')/\tau_H} \quad \underbrace{\Theta_{r',t',t''}}_{\approx 0.6} \underbrace{\kappa_{r',t''}}_{\approx 1.2} \quad \underbrace{\Delta T_{t'',t}}_{\approx \mathrm{TCRE}\,\theta(t''-t)} \\ &\approx \sum_{t'=t}^{\mathcal{T}} Y_t \, 1.03^{-(t'-t)} \; \mathrm{TCRE} \; 1.2 \; 0.6 \; \sum_{t''=t}^{t'} 2^{-(t'-t'')/\tau_H} \end{aligned} \tag{15}$$

For an estimate of the 2030 SCC, plug in our pathway's mean GDP in 2030 of Y_t = US$90 trillion and $\tau_H = 30$ years. TCRE is estimated at 0.0015°C per GtC (Fig. 4). The inner sum sums up declining damages over time; it grow from 1 to around 30 over time t'. Numerically evaluting this expression gives an SCC of $p_{2030} \approx 150$ US$ per tonne of CO_2 – not too far from the median optimal carbon tax of 115 US$ per tonne of CO_2 from the full analysis.

2.2 Guardrail tax

The guardrail tax $\tau_{r,t}$ internalizes a limit on global mean temperature T_{LIM}.

We implement the temperature guardrail as a limited CO_2 budget until the time of CO_2 neutrality; the stringency of this budget approximately determines the temperature at peak warming[15]. As an implementation of the 2°C limit we use a budget of 1300 Gt CO_2 from 2011 onwards, which is derived from the budgets given in Chapter 2 of the SR1.5[16] for 67% likelihood of stabilizing below 2°.

As long as cumulative emissions are below the budget, the guardrail tax takes the well-known Hotelling form and rises exponentially at the interest rate[17]. After the budget constraint has been reached - which happens around 2070 in most pathways - the level of the guardrail tax is adjusted to keep CO2 emissions to zero.

Most CEA models in the literature (i.e., cost-effectiveness models without climate impacts) and most Integrated Assessment Models used for the Fifth Assessment Report of the IPCC show a Hotelling-like carbon price path[vi].

2.3 Integration into REMIND

The expression for the SCC (Eq. 15) is evaluated for paths for consumption, GDP, and interest rates from REMIND[vii], as well as temperature paths from the MAGICC6 model. We limit the time horizon for the SCC evaluation to 100 years by default, $\mathcal{T} = t + 100$. Because the results depend on the horizon[19], we show a sensitvity analysis with respect to the time horizon in Supplementary Figure **??**. As the SCC evaluation may involve model variables at times beyond the end of the REMIND horizon (2150), we extrapolate GDP, consumption, temperature, and temperature impulse response as constant after 2150.

This SCC price path is then fed back into the REMIND model, and the procedure is iterated to a fixed point. In effect, the first order-condition for optimal emissions Eq.

[vi] Most models in the Fifth Assessment Report show Hotelling-like behaviour: Across all models that reach the 430-480ppm climate target with immediate climate policy and full technology choice, the median decadal carbon price growth rate until 2100 is 2.8-5.5% per year (annualized)[17,18].

[vii] the interest rate falls from 6% p.a. to 4% p.a. throughout the century in an exemplary SSP2

(15) is satisfied asymptotically. The guardrail tax $\tau_{r,t}$ is fed into the REMIND model as well, either by adjusting the level of a Hotelling tax path until the emissions budget associated with the given temperature targets is observed, or by evaluating Eq. **??** in the case of a not-to-exceed temperature limit. We argue that the resulting solution is the same (or at least very similar) to the one where the full causal chain from emissions to temperature to damages were endogenously included in the model – which we elaborate on in Section 2.4.

In the REMIND model, only the difference to last iteration's emissions $E'_{r,t}$ is priced in: In effect, the tax revenue term in the budget equation,

$$(p_{r,t} + \tau_{r,t}) \left(E_{r,t} - E'_{r,t} \right), \tag{16}$$

approaches zero at the fixed point of the iteration, but the marginal emission is still priced at $p_{r,t} + \tau_{r,t}$. The welfare-economic assumption behind that is that lump-sum tax revenue recycling is possible within every region. Although the temperature path calculated by MAGICC6 is based on detailed emissions paths of different greenhouse gases species from REMIND, we aggregate emissions using global warming potentials into CO_2 equivalents to price them in according to Eq. 16.

2.4 Equivalence of endogenous to iterative method

We argue here that the iterative solution of our soft-coupled model framework is very close to the solution where the entire causal chain from emissions to damages would be endogenously included in one hard-coupled model. From theory, there is little reason to expect the solutions would differ. At the fixed point of the iteration, at which $p_{r,t}$ and $\tau_{r,t}$ are converged, the first-order conditions of our reduced model as well as the ones of REMIND are fulfilled: The ones from the reduced model that determine the optimal carbon prices by construction of the iterative solution algorithm and all the other ones implicitly as a result of the REMIND optimization. As there are no links from emissions to temperature or climate impacts in REMIND except for the ones also covered by our reduced model, all the relevant first-order conditions are fulfilled.

Comparing the solutions of the iterative and the endogenous formulation numerically requires a simple climate model, as it is infeasible to include the full MAGICC6 climate model into REMIND due to the numerical complexity of both models. We thus choose a very stylized climate model: Temperature rises instantaneously with emissions (which is the $k_s \to \infty$ limit the model in Eq.(3) of Allen [20]). This very stylized temperature impulse response function still bears resemblance to the one derived by MAGICC6.

We benchmark our iterative solution against the endogenous formulation in which a social planner derives the globally optimal climate policy[viii]. Both model formulations use the same stylized climate model and damage functions. The two solutions – the one for the iterative model and the endogenous model – are very close: The maximum deviation of the emission time paths throughout the 21st century is below 1% of today's global emissions.

3 Temperature downscaling

We describe regional temperature $T_{r,t}$ as a function of global mean temperature T_t (from MAGICC6) through a statistical downscaling approach based on the multi-model data set from CMIP5[21].

Take $\tilde{T}_{r,2005}$ to be the historically observed temperature in 2005, calculated as the average temperature from from 2000 to 2010 from the University of Delaware Air Temperature and Precipitation data set[22,23]. We aggregate this gridded temperature data to REMIND regions using 2005 population[24] as weights [ix].

From 2005 on, regional temperature depends on global mean temperature T_t and the time-dependent scaling factor $\kappa_{r,t}$ through

$$\begin{aligned} T_{r,t} &= \mathrm{F}(T_t) \\ &= \tilde{T}_{r,2005} + \underbrace{\frac{\bar{T}_{r,t} - \bar{T}_{r,2005}}{\bar{T}_t - \bar{T}_{2005}}}_{\equiv \kappa_{r,t}} (T_t - T_{2005}) \,, \end{aligned}$$

where T_t is the global mean temperature from the MAGICC6 model and the temperatures from CMIP5 are $\bar{T}_t$ and $\bar{T}_{r,t}$.

We use statistical downscaling to derive $\kappa_{r,t}$: We use gridded global mean temperature anomaly data from CMIP5 at 2.5 degree resolution[25]. We choose the mean across all CMIP5 models for the RCP2.6 scenario, as our model ensemble has climate outcomes close to RCP2.6. We aggregate these data down to REMIND regions using constant 2005 population weights with 0.1 degree resolution[24]. The resulting $\kappa_{r,t}$ are all greater than one (as land tends to warm faster than the oceans), and range from slightly above 1 in Latin America and South-east Asia to 1.6 in Russia (when averaged over the 21st century).

[viii] The endogenous model derives optimal climate policy by optimization of global welfare, aggregated from regional utilities using Negishi weights. The optimal carbon price is then the shadow price of the equation aggregating global emissions. For details on this solution procedure, see Leimbach *et al.* [14].

[ix] This aggregation multiplies temperature and population at every grid cell, sums up all grid cells in a model region, and normalizes to total population in that region. The resulting population-weighted temperature is strictly speaking not a physical quantity, but, we argue, the temperature value most relevant to economic activity and thus climate damages.

4 Temperature impulse response

We here characterize the temperature impulse response (TIR) which is used in the evaluation of the SCC and the guardrail tax. The TIR is the global mean temperature increase due to an additional unit of emissions. We derive it for CO_2 emissions here and convert other greenhouse gases to CO_2-equivalents through global warming potentials before pricing them in.

The shape of the TIR for CO_2 emissions is a key finding of climate science: Temperature rises for around a decade following the emission, levels off, and stays constant for more than 100 years[26–28]. The amount of temperature increase is closely related to the transient response to cumulative emissions (TCRE)[26,27,29]. The shape of the TIR is quite independent of the emissions scenario, but we still use the MAGICC6 model to derive $\Delta T_{t',t}$ specifically for the emissions pathway from the REMIND model.

We derive the TIR from a pulse experiment using MAGICC6. Since the dependence of the TIR on the pulse size is negligible on the scale of today's emissions, we choose an emissions pulse of 1GtC on top of the emissions path (from REMIND) at different times between 2010 and 2150. The TIR is then fed back into REMIND, used for the evaluation of the SCC, and updated iteratively.

For an overview of the resulting TIRs, see Fig. ED3b, which agrees well with results of more elaborated models[26,27,29,30].

5 Discounting

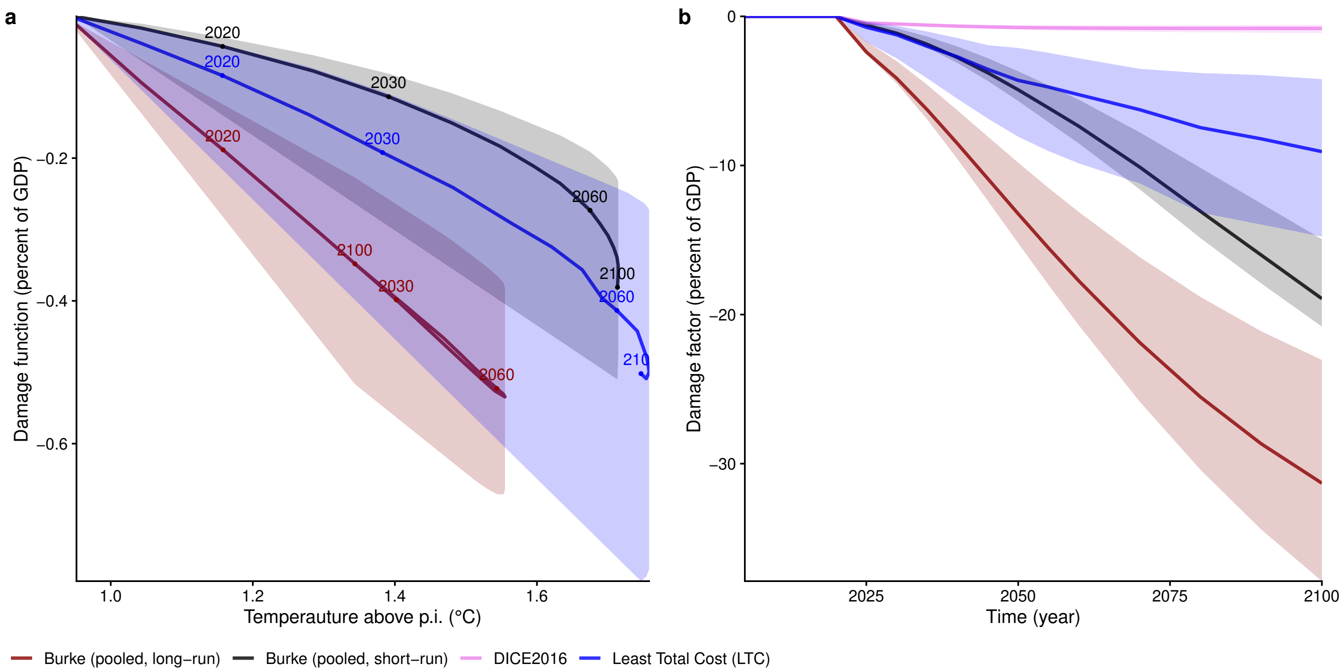
Discounting strongly influences the social cost of carbon and the guardrail tax. The welfare economic framework used here, a Ramsey-type infinitely-lived-agent model, does not distinguish private discounting of households from social discounting. Allowing for a meaningful evaluation of different discounting choices requires a model that distinguishes private discounting, consistent with observed market outcomes, from social discounting based on ethical choices (along with other parameters based on ethical choices, such as inequality aversion). There are many arguments to use social discount rates much below private discount rates in the evaluation of climate policy[31–33]. The results of a model distinguishing private and social discounting would only coincide with a simple Ramsey framework if private and social preferences were equal, no other fiscal distortions were present, and access to lump-sum transfers between individuals of different ages were possible[34]. These conditions are clearly not perfectly fulfilled in the real world, leaving much room for future studies.

As the main point of this paper is to highlight the differences between LTC and CEA pathways, we perform a sensitivity analysis of the discount rate used in the evaluation of the SCC and the guardrail tax. For a a discount rate of ∼3% p.a., in contrast to the ∼5% p.a. in our default case, we find that median LTC emissions in 2030 decreases by around 7.3 $GtCO_2eq\ yr^{-1}$, while the CEA emissions in 2030 decreases by around 2.3 $GtCO_2eq\ yr^{-1}$. The optimal 2030 LTC carbon tax increases to around US$300. Note that this sensitivity analysis can only be seen as a rough indication, for the reasons discussed in the last paragraph. To properly assess the influence of the discount rate on optimal policy, social and private discounting would have to be distinguished concerning all decisions in the economy, not just in the evaluation of optimal climate policy.

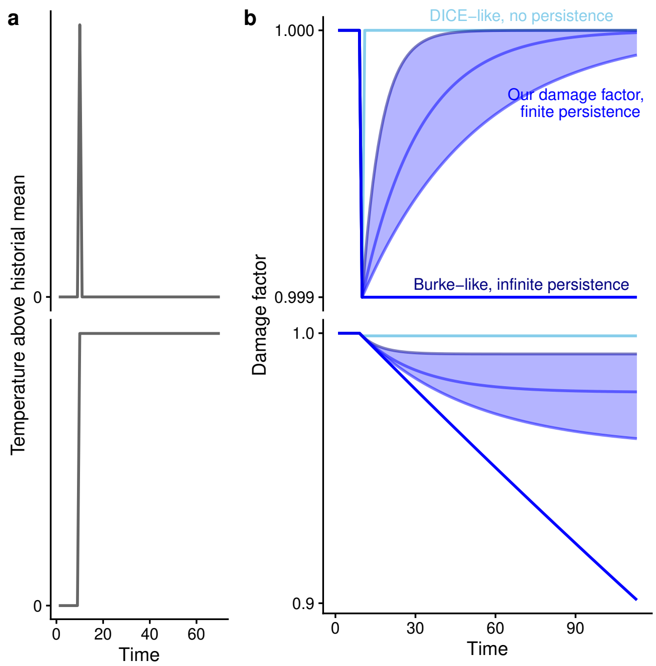
6 Uncertainty in empirical specifications

As discussed in Section 1.1 of the Supplementary Material we include both the ”long run” and the ”short run” specification of Burke et al. (2015) in the analysis. As shown in Fig. 9 the ”long run” specification, which takes into account temperature lags of the 5 preceding years, leads to much higher damages, more stringent mitigation and therefore slightly lower warming by the end of the century. With increasing persistence times, the differences between the effects of the two specifications increase, as damages accumulate when the growth rate is affected. However, the debate is still open whether climate change really affects the growth rate[35,36] or is a level effect[37].

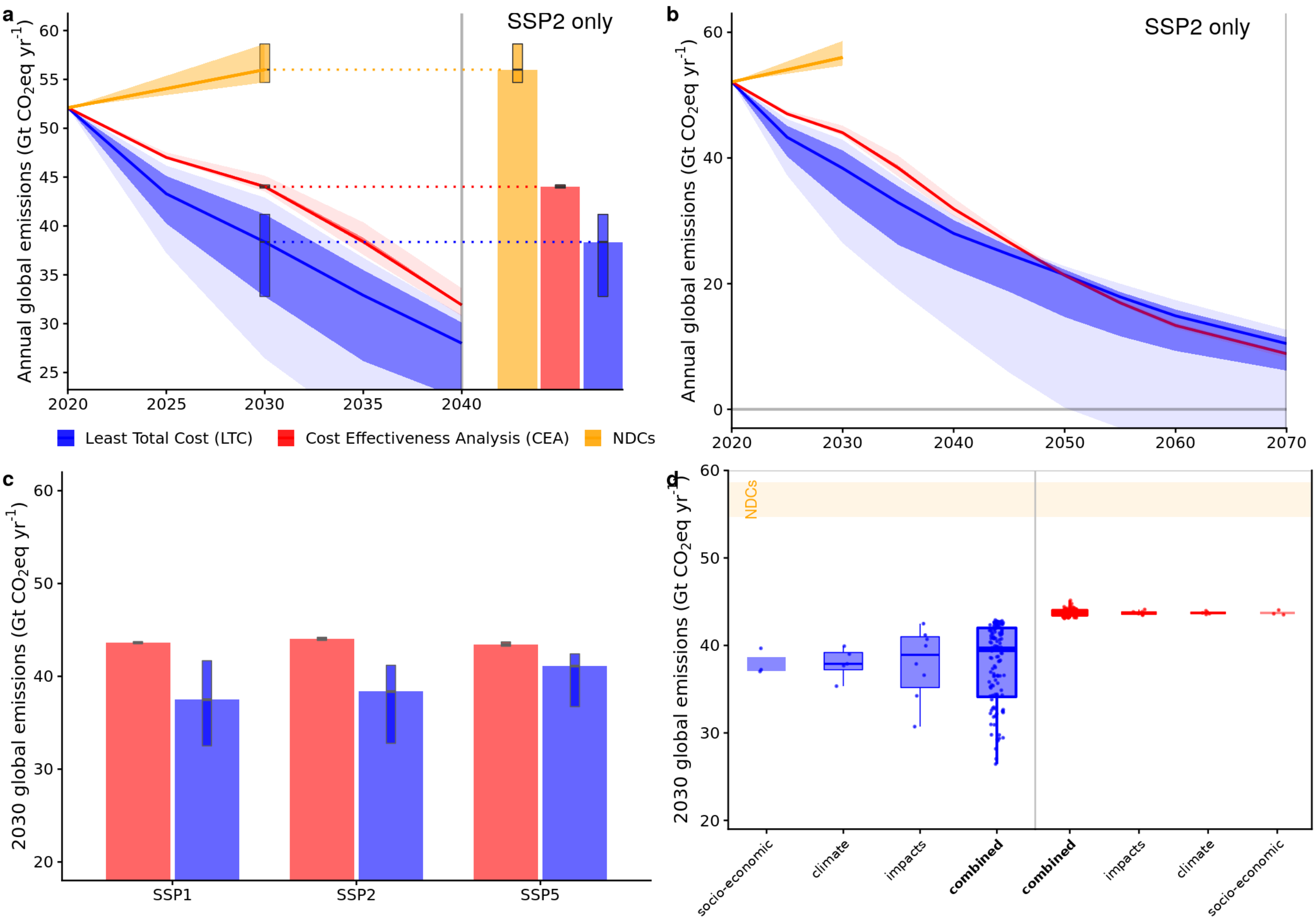
The damage specification has a strong effect on the difference between LTC and CEA pathways. As shown in Fig. 10 the gap in 2030 emissions is considerably larger for the ”long run” specification than for the ”short run”. As additional sensitivity we perform the calculations using the damage the specification by Burke & Tanutama [38] who repeat the analysis of Burke et al. (2015) with subnational GDP data. They confirm the non-linear relationship between temperature and income, but find a much lower optimal temperature of below 10° compared to around 13° before. This increases the negative effects of additional warming, as more countries are at or above the optimal temperature than before. The effects of this specification without lags is comparable to the lagged specification of Burke et al. (2015) (”long-run”, see Fig. 10). This further highlights the tremendous uncertainty still surrounding these empirical estimates.



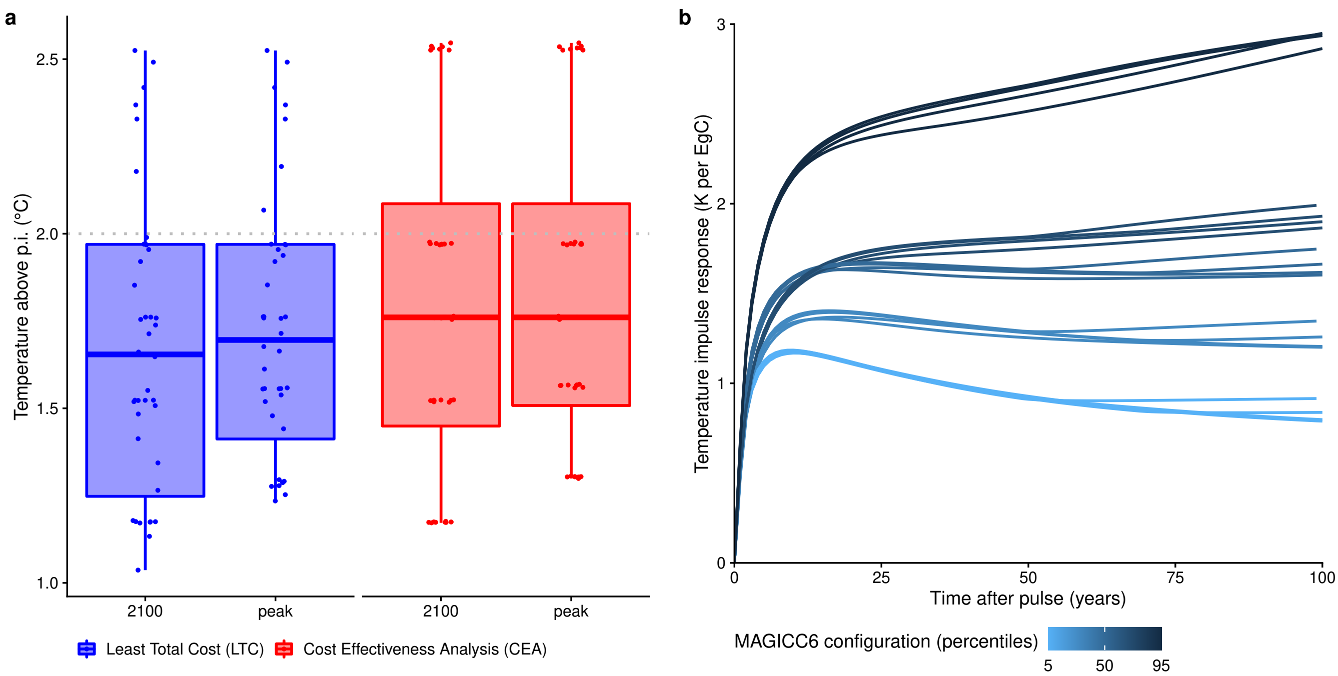
Supplementary Figure 1: **Climate damages on GDP**. **a**, our damage function for the growth rate $\delta(T_{r,t})$ over temperature increase above pre-industrial and **b**, the cumulative damage factor $D_{r,t}$ over time, both in global aggregate (LTC, blue), compared to the literature. Comparisons are made with two estimates from Burke *et al.* [1] (red and black) and the DICE2016 function[10,39] (pink). We implemented their damage functions into our model framework as alternative LTC-type pathways towards 2°C. The Burke et al. damages show infinite persistence time of damage shocks, while the DICE2016 damages have zero persistence (see Fig. 2). Our damage factor uses a range of finite persistence times around a mean of 15 years and the original Burke specification. The statistics are over climate uncertainty in all cases and additionally over the damage function specifications in the LTC case (lines: median, shades: 20-80th percentile).



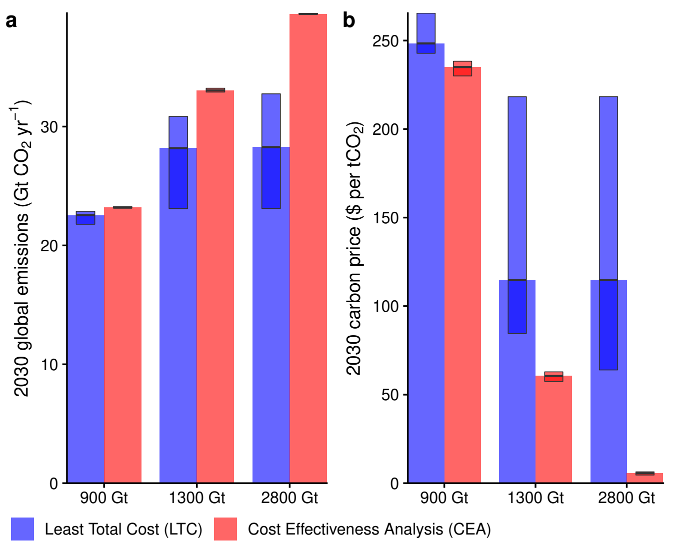
Supplementary Figure 2: **Persistence of shocks is key to climate damages.** Two stylized temperature signals in **a**, a one-off shock and a permanent increase above the historical mean, are translated into **b**, damage factors (Eq. 3). DICE-like damage functions assume no persistence at all (light blue; $\tau_H = 0$). For infinite persistence (dark blue; $\tau_H = \infty$), the damage function eventually approaches zero in response to a permanent temperature increase, as is the case for the original damage factor from Burke *et al.* [1]. Our damage factor uses a range of finite nonzero persistence times (median blue; $\tau_H \in [5, 30]$ years): The impact of a one-off temperature shock on the economy vanishes exponentially; shocks from a permanent increase in temperature compound to a rising damage factor that eventually levels off.



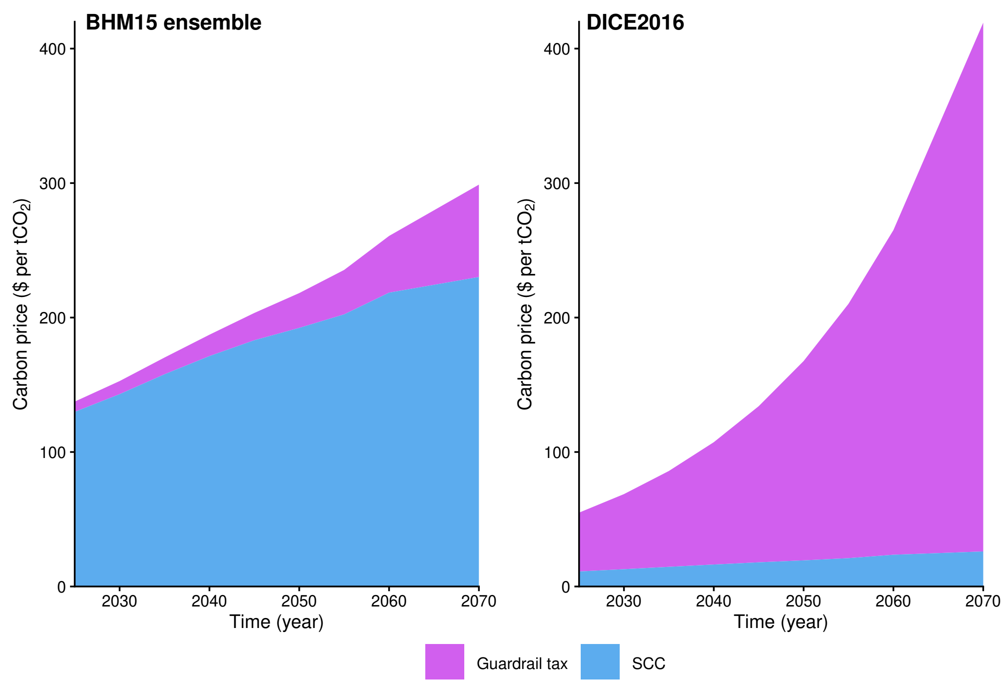
Supplementary Figure 3: **Global emissions in LTC and CEA settings.** Replication of Main Figure 5 but for total emissions in units of Gt CO_2eq yr^{-1} instead of CO2-only emissions. Note that global warming potentials from the IPCC Second Assessment Report are used for this calculation. The gap between 2030 emissions under the NDCs and the optimal mitigation pathways increases by 50% when damages are included (LTC) compared to the standard CEA analysis. The LTC pathway is in line with the goal set out by the Paris Agreement of 40 Gt CO_2eq yr^{-1}in 2030.



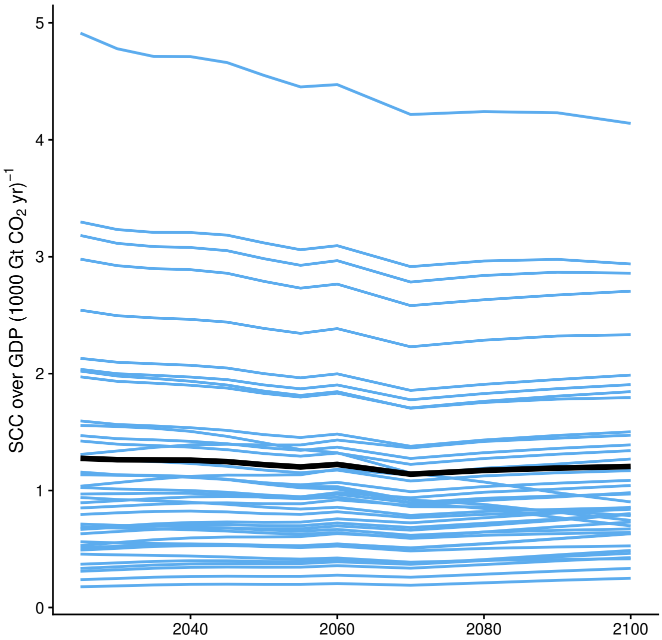
Supplementary Figure 4: **Global mean temperature response.** **a**, peak and end-of-century temperature outcomes for LTC and CEA pathways. **b**, the temperature impulse response for different MAGICC6 climate model configurations (colors). Darker colors indicate MAGICC6 configurations at higher percentiles in the temperature outcome for a RCP2.6 scenario (Methods for details). The plot shows the temperature impulse response over time after the CO_2 emission pulse; lines of the same color belong to pulse emission times between 2020 and 2100. There is good agreement with the literature[26,27,29,30]. Also see Section 4 in the Supplementary Material.



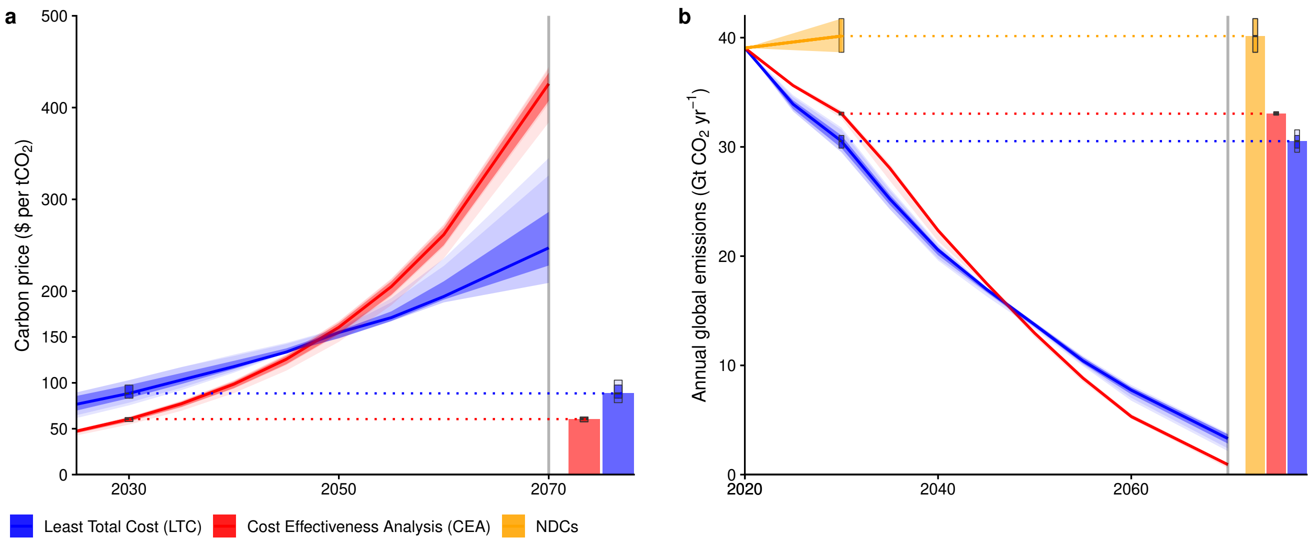
Supplementary Figure 5: **Sensitivity to the choice of carbon budget**. The carbon budget influences the stringency of near-term LTC mitigation less strongly than in the CEA case. **a)** compares emissions and **b)** carbon prices in 2030 across across three carbon budgets: The default budget of 1300 $GtCO_2$ (in alignment with the 2°C target of the Paris agreement); a budget of 900 $GtCO_2$ (1.5°C target); and a 2800 $GtCO_2$ budget (3°C target). The bars shows medians and the narrower ribbons show 20-80th percentile ensemble ranges.



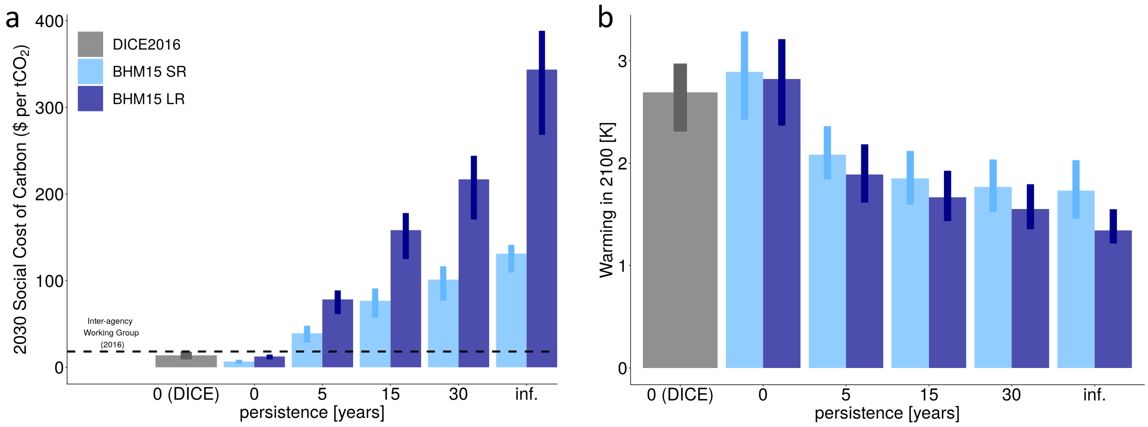
Supplementary Figure 6: **The SCC component dominates the carbon tax in LTC.** The mean SCC tax (blue) and mean guardrail tax (violet) over time (each as mean over the LTC pathway ensemble). The SCC rises much slower over time than the exponential guardrail tax. As level damages for the DICE specification are so small, the guardrail tax dominates in that case(right panel), while the SCC dominates for Burke-type growth-rate damages. In that case the LTC guardrail tax is much smaller than in typical CEA cases.



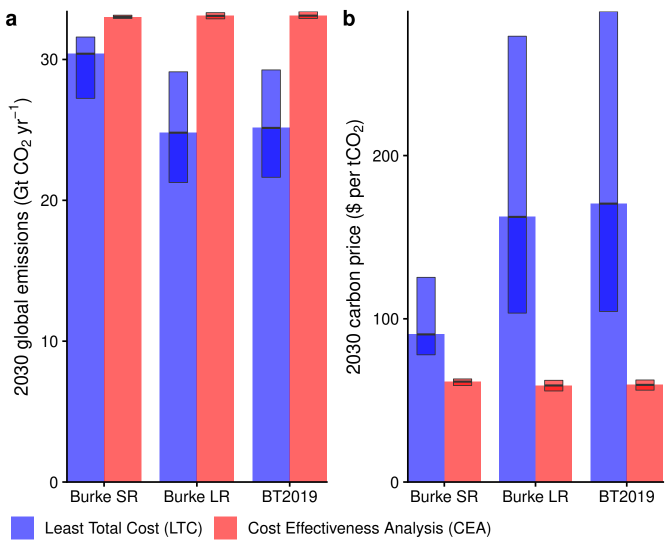
Supplementary Figure 7: **The SCC rises more or less linearly with GDP.** The SCC component of the optimal carbon price relative to GDP for all LTC pathways over time (mean in black). A roughly linear dependence of the SCC on GDP is suggested by simpler models[11,12]. While the SCC in our LTC pathways are far form strictly linear, the trend, especially in aggregate over all pathways, roughly is.



Supplementary Figure 8: **The main results are partly driven by lower temperature outcomes in LTC.** Carbon prices (a) and emissions (b), including only the subset of LTC pathways for which the emissions budget is binding (around 53% of all). The gap between LTC and CEA pathways shrinks somewhat, the median LTC carbon price is US$88.5 per tonne of CO_2 and global emissions 30.5 GtCO_2 in 2030. The pathways with non-binding budget which are excluded happen to be the ones where the realization of uncertainties includes severe damages, or high climate sensitivity. Compared to our default results, the LTC pathway shown here is *not* optimal, as the pathways with non-binding budget were excluded in the derivation of the optimal policy.



Supplementary Figure 9: **Social cost of carbon for "short run" vs. "long run" specification.** The 2030 social cost of carbon (panel a) and global mean temperature in 2100 (panel b) under cost-benefit analysis for different persistence times, but separating the "short run" and the "long run" specification of Burke et al. (2015).



Supplementary Figure 10: **Effect of uncertainty in damage specification.** Stronger damages widen the gap between LTC and CEA considerably. "Burke SR" and "Burke LR" refer to the different specifications of damages in Burke et al. (2015). The "short run" specification does not capture lagged effects of temperature, while the "long run" specification takes into account the effects of the 5 preceding years. "BT2019" refers to the "short run" specification found in Burke & Tanutama [38], based on subnational instead of country-level income data. The ensemble contains the uncertainty from the level of persistence as well as the climate uncertainty.

References

1. Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production. *Nature* **527,** 235–239. doi:10.1038/nature15725 (2015).
2. Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production - Supplementary materials. *Nature* **527** (2015).
3. Burke, M. *Replication data for Burke, Hsiang, Miguel 2015* 2015. https://purl.stanford.edu/wb587wt4560.
4. Dellink, R., Chateau, J., Lanzi, E. & Magné, B. Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change* **42,** 200–214. doi:10.1016/j.gloenvcha.2015.06.004 (2017).
5. Pindyck, R. S. Uncertain outcomes and climate change policy. *Journal of Environmental Economics and Management* **63,** 289–303. doi:10.1016/j.jeem.2011.12.001 (2012).
6. Moyer, E., Woolley, M., Matteson, N., Glotter, M. & Weisbach, D. A. Climate Impacts on Economic Growth as Drivers of Uncertainty in the Social Cost of Carbon. *The Journal of Legel Studies* **43,** 401–425 (2014).
7. Moore, F. C. & Diaz, D. B. Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change* **5,** 127–131. doi:10.1038/nclimate2481 (2015).
8. Estrada, F., Tol, R. S. & Gay-García, C. The persistence of shocks in GDP and the estimation of the potential economic costs of climate change. *Environmental Modelling & Software* **69,** 155–165 (2015).
9. Nordhaus, W. D. Rolling the 'DICE': An optimal transition path for controlling greenhouse gases. *Resource and Energy Economics* **15,** 27–50 (1993).
10. Nordhaus, W. Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists* **1,** 273–312. doi:10.1086/676035 (2014).
11. Golosov, M., Hassler, J., Krusell, P. & Tsyvinski, A. Optimal Taxes on Fossil Fuel in General Equilibrium. *Econometrica* **82,** 41–88. doi:10.3982/ECTA10217 (2014).
12. Rezai, A. & van der Ploeg, F. Robustness of a simple rule for the social cost of carbon. *Economics Letters* **132,** 48–55. doi:10.1016/j.econlet.2015.04.007 (2015).
13. Emmerling, J. & Anthoff, D. Inequality and the Social Cost of Carbon. *CESifo Working Papers* **5989** (2016).

14. Leimbach, M., Schultes, A., Baumstark, L., Giannousakis, A. & Luderer, G. Solution algorithms for regional interactions in large-scale integrated assessment models of climate change. *Annals of Operations Research.* doi:10.1007/s10479-016-2340-z (2016).

15. Rogelj, J. *et al.* A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573,** 357–363 (2019).

16. Rogelj, J. *et al.* Mitigation pathways compatible with 1.5 C in the context of sustainable development (2018).

17. *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014).

18. *AR5 WG III Scenario Database* https://tntcat.iiasa.ac.at/AR5DB.

19. Wong, K. Y., Chuah, J. H. & Hope, C. The impact of time horizon on integrated climate assessment models. *Clean Technologies and Environmental Policy* **17,** 2361–2374. doi:10.1007/s10098-015-0978-x (2015).

20. Allen, M. R. Drivers of peak warming in a consumption-maximizing world. *Nature Climate Change* **6,** 684–686. doi:10.1038/nclimate2977 (2016).

21. *CMIP5 Coupled Model Intercomparison Project – WCRP World Climate Research Programme* http://cmip-pcmdi.llnl.gov/cmip5/.

22. Willmott, C. J. & Matsuura, K. *Terrestrial Air Temperature and Precipitation: Monthly and Annual Time Series (1950 - 1999)* 2001. http://climate.geog.udel.edu/~climate/html_pages/README.ghcn_ts2.html.

23. *University of Delaware Air Temperature and Precipitation v4.01* http://www.esrl.noaa.gov/psd/.

24. Center for International Earth Science Information Network - CIESIN - Columbia University. *Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals.* 2016. doi:10.7927/H4SF2T42. http://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-adjusted-to-2015-unwpp-country-totals/data-download (2016).

25. *KNMI Climate Explorer* https://climexp.knmi.nl/selectfield_cmip5.cgi.

26. Joos, F. *et al.* Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics* **13,** 2793–2825. doi:10.5194/acp-13-2793-2013 (2013).

27. Ricke, K. L. & Caldeira, K. Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters* **9,** 124002. doi:10.1088/1748-9326/9/12/124002 (2014).

28. Williams, R. G., Goodwin, P., Roussenov, V. M. & Bopp, L. A framework to understand the transient climate response to emissions. *Environmental Research Letters* **11,** 015003. doi:10.1088/1748-9326/11/1/015003 (2016).

29. Steinacher, M. & Joos, F. Transient Earth system responses to cumulative carbon dioxide emissions: linearities, uncertainties, and probabilities in an observation-constrained model ensemble. *Biogeosciences* **13,** 1071–1103. doi:10.5194/bg-13-1071-2016 (2016).

30. Millar, R. J., Nicholls, Z. R., Friedlingstein, P. & Allen, M. R. A modified impulse-response representation of the global response to carbon dioxide emissions. *Atmospheric Chemistry and Physics Discussions,* 1–20. doi:10.5194/acp-2016-405 (2016).

31. Dasgupta, P. Discounting climate change. *Journal of Risk and Uncertainty* **37,** 141–169. doi:10.1007/s11166-008-9049-6 (2008).

32. Sterner, T. & Persson, U. M. An Even Sterner Review: Introducing Relative Prices into the Discounting Debate. *Review of Environmental Economics and Policy* **2,** 61–76. doi:10.1093/reep/rem024 (2008).

33. Van den Bergh, J. C. J. M. & Botzen, W. J. W. A lower bound to the social cost of CO2 emissions. *Nature Climate Change* **4,** 253–258. doi:10.1038/nclimate2135 (2014).

34. Schneider, M. T., Traeger, C. P. & Winkler, R. Trading off generations: Equity, discounting, and climate change. *European Economic Review* **56,** 1621–1644. doi:10.1016/j.euroecorev.2012.08.006 (2012).

35. Kahn, M. E. *et al. Long-term macroeconomic effects of climate change: A cross-country analysis* tech. rep. (National Bureau of Economic Research, 2019).

36. Dell, M., Jones, B. F. & Olken, B. a. Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics* **4,** 66–95. doi:10.1257/mac.4.3.66 (2012).

37. Kalkuhl, M. & Wenz, L. The impact of climate conditions on economic production. Evidence from a global panel of regions (2018).

38. Burke, M. & Tanutama, V. *Climatic Constraints on Aggregate Economic Output* Working Paper 25779 (National Bureau of Economic Research, 2019). doi:10.3386/w25779.

39. Nordhaus, W. D. *DICE code* https://sites.google.com/site/williamdnordhaus/dice-rice.