nature climate change

LETTERS

PUBLISHED ONLINE: 23 MARCH 2015 | DOI: 10.1038/NCLIMATE2570

Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy

Thomas S. Lontzek[1]*, Yongyang Cai[2,3], Kenneth L. Judd[2,4] and Timothy M. Lenton[5]*

Perhaps the most 'dangerous' aspect of future climate change is the possibility that human activities will push parts of the climate system past tipping points, leading to irreversible impacts[1]. The likelihood of such large-scale singular events[2] is expected to increase with global warming[1–3], but is fundamentally uncertain[4]. A key question is how should the uncertainty surrounding tipping events[1,5] affect climate policy? We address this using a stochastic integrated assessment model[6], based on the widely used deterministic DICE model[7]. The temperature-dependent likelihood of tipping is calibrated using expert opinions[3], which we find to be internally consistent. The irreversible impacts of tipping events are assumed to accumulate steadily over time (rather than instantaneously[8–11]), consistent with scientific understanding[1,5]. Even with conservative assumptions about the rate and impacts of a stochastic tipping event, today's optimal carbon tax is increased by ∼50%. For a plausibly rapid, high-impact tipping event, today's optimal carbon tax is increased by >200%. The additional carbon tax to delay climate tipping grows at only about half the rate of the baseline carbon tax. This implies that the effective discount rate for the costs of stochastic climate tipping is much lower than the discount rate[7,12,13] for deterministic climate damages. Our results support recent suggestions that the costs of carbon emission used to inform policy[12,13] are being underestimated[14–16], and that uncertain future climate damages should be discounted at a low rate[17–20].

Integrated assessment models (IAMs) are key tools to assist climate policymaking[7,12,13], which attempt to capture two-way interactions between climate and society. There is much debate over what discount rate to assume for evaluating future damages due to global temperature rise[17], which in turn partly determines how much we should be willing to pay now to avoid or delay those damages. The Stern Review[21] followed a prescriptive (and controversial[22–24]) approach; based on ethical arguments it assumed a near-zero rate for discounting the utility of future generations, implying a low discount rate for monetized damages of climate change and a high willingness to pay now. In contrast, studies using a descriptive approach[7,12,13] generally evaluate the costs of climate change using much higher market rates of return as discount rates. Most studies are deterministic, but uncertainty will also affect the rate at which future levels of climate damage are discounted[17–20]. Climate tipping points and their impacts are a key source of uncertainty, for several reasons[1,3,4]. First, our knowledge of thresholds, in terms of, for example, regional warming, is imperfect, and the mapping from global temperature rise to regional thresholds is also uncertain. Second, even if we knew a tipping point precisely, stochastic internal variability in the climate system could trigger tipping at a range of times and corresponding global temperatures[4]. Several IAM approaches to model climate tipping points are fundamentally deterministic[8,9,14,25,26], whereas only a few studies include stochastic climate damages[10,11,27] (see Supplementary Discussion). In common with deterministic IAMs, they generally assume[10,11] that the impacts of passing a tipping point are felt instantaneously, whereas in reality impacts will accumulate over time at a rate determined by the dynamics of the system that has been tipped[1]. One recent study[27] assumes that tipping instantaneously increases climate sensitivity or weakens carbon sinks, which then causes damages to accumulate at an increased rate; but this is scientifically questionable (see Supplementary Discussion) and leads to increased discounting of future damages[27].

Here, we examine how a more realistic treatment of stochastic climate tipping points affects the optimal policy choice, including the discount rate to evaluate future damages. Our stochastic integrated assessment model[6], DSICE (Fig. 1a), builds on the deterministic Dynamic Integrated Climate and Economy (DICE) model[7] (2007 version) as used in the 2010 US federal assessment of the social cost of carbon[12]. The federal assessment[13] and the DICE model[28] have since been updated, in ways that tend to increase the estimated social cost of carbon (see Supplementary Methods). Hence the reader should focus on our relative changes in carbon tax due to stochastic climate tipping more than the absolute values.

DSICE uses a dynamic programming framework, representing the decision maker's uncertainty by a stochastic formulation of a tipping event as a Markovian process (see Methods and Supplementary Methods). Specifically, for a potential hazard event the model specifies a hazard rate—that is, the conditional probability that a tipping point will be passed in a particular year given the temperature that year. The decision maker is assumed to use the hazard rates inferred from an expert elicitation study[3] (see Methods and Supplementary Methods). The average experts' hazard rate has a default value of 0.0025 °C^{-1} yr^{-1}—for example, if we observe 1 °C of warming, the conditional probability of having a tipping event in that year is 0.25%, rising to 0.5% yr^{-1} for 2 °C of warming. Following the expert elicitation[3], the tipping event could be one out of five candidates: reorganization of the Atlantic meridional overturning circulation; irreversible melt of the Greenland Ice Sheet; collapse of the West Antarctic Ice Sheet; dieback of the Amazon rainforest; or an increase in the amplitude

---

[1]Department of Quantitative Business Administration, University of Zurich, CH 8008, Zürich, Switzerland. [2]Hoover Institution, Stanford University, Stanford, California 94305, USA. [3]Becker Friedman Institute, University of Chicago, Chicago, Illinois 60636, USA. [4]National Bureau of Economic Research, Cambridge, Massachusetts 02138, USA. [5]Earth System Science Group, College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4QE, UK. *e-mail: lontzek@gmail.com; t.m.lenton@exeter.ac.uk

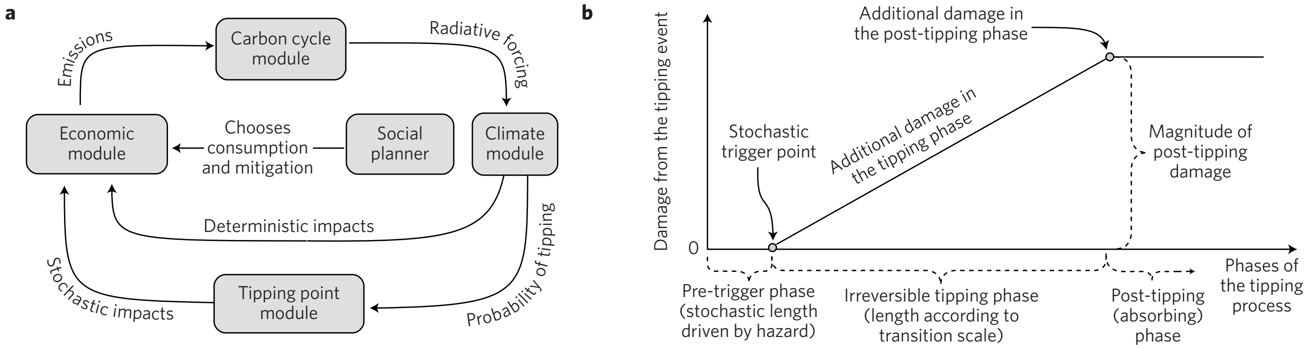


Figure 1 | Schematic of the DSICE model. a, The forward-looking decision-maker (social planner) chooses mitigation and consumption to maximize the sum of discounted expected utilities over some time horizon. Increased mitigation must be traded off against consumption and savings. Global warming adversely impacts the economy and increases the probability of a tipping point with additional irreversible economic impacts. **b**, The length of the pre-tipping phase is stochastic, and its likelihood depends on global warming. Once tipping is triggered, damages increase linearly over a specified transition time (5–500 years here) to a specified final level (2.5–20% of World GDP here).

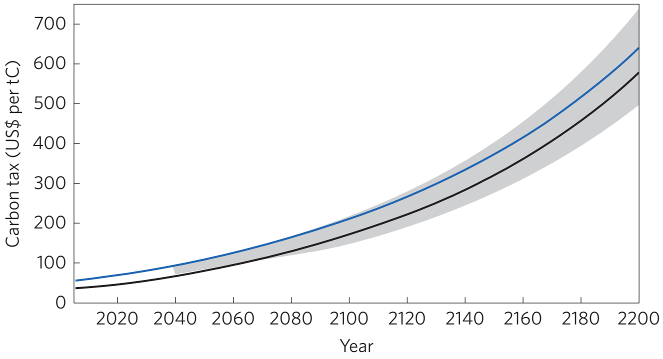


Figure 2 | Optimal carbon tax path. Grey-shaded area: range of stochastic carbon tax paths from 10,000 simulations of the optimal model's solution. Blue line: expected carbon tax from the stochastic model (average of 10,000 simulations). Black line: optimal carbon tax from a deterministic version of the model in which the decision maker ignores the tipping point (consistent with the DICE model path).

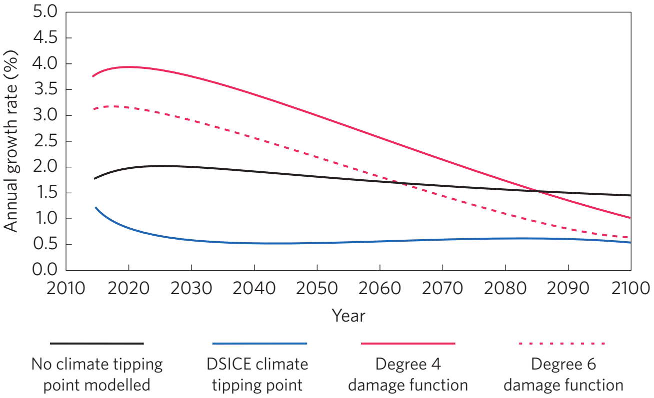
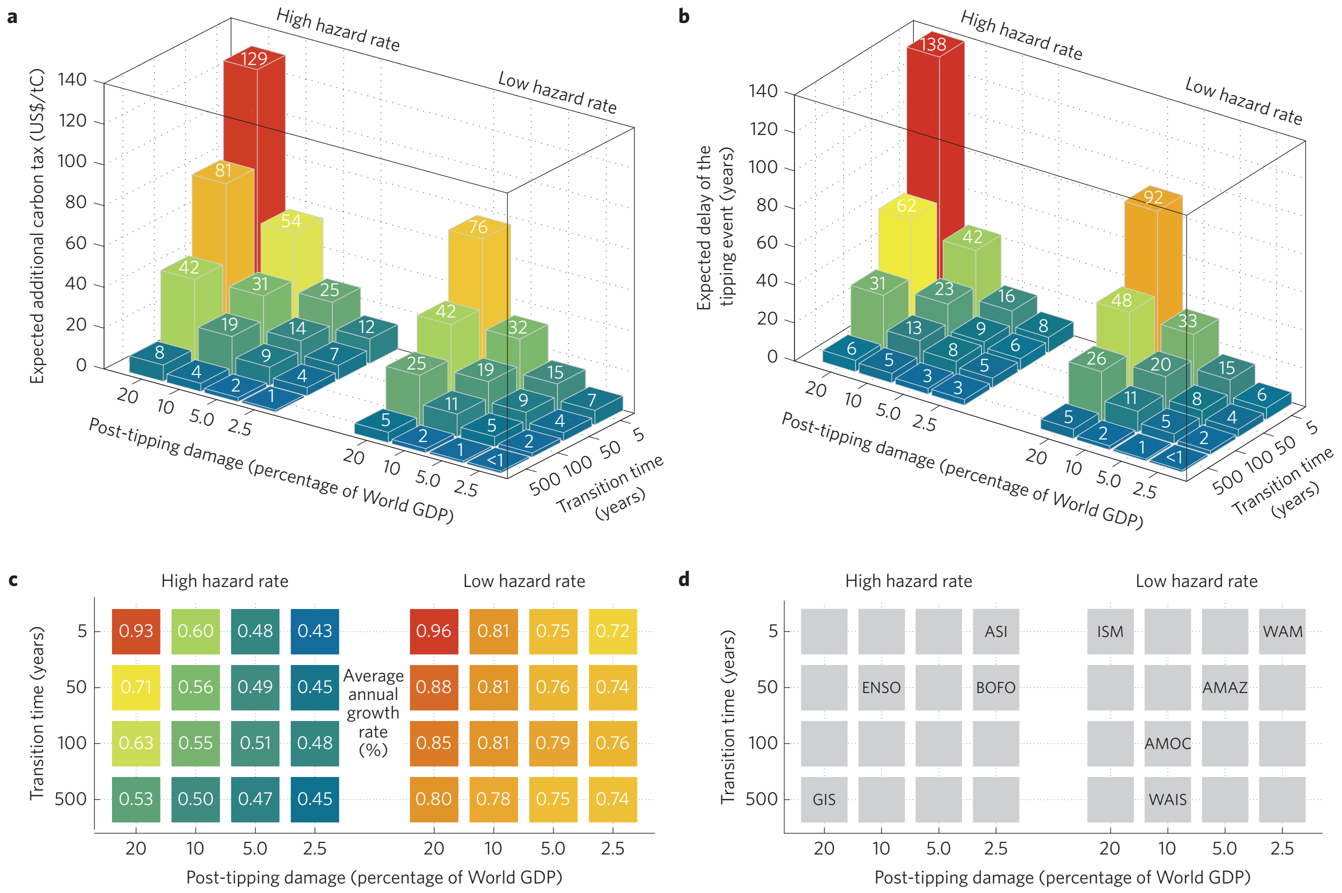


Figure 3 | Growth rates of carbon tax. The baseline carbon tax in the deterministic DICE model (with no tipping point) is shown in black. The expected additional carbon tax when including a stochastic tipping point (that is, the difference between the blue and black lines in Fig. 2) is indicated in blue. Red lines indicate the additional carbon tax when the exponent of the damage function in the deterministic DICE model is increased to fourth (solid line) and sixth (dashed line) order.

of the El Niño Southern Oscillation. We conservatively assume that whatever the tipping event is, it leads to only modest damages—our default setting is a 10% reduction in global GDP—and that these damages take significant time to unfold (Fig. 1b)—with a default setting of 50 years (appropriate, for example, for Amazon rainforest dieback). Incorporating this stochastic potential tipping event into the DSICE model, the resulting cumulative probability of tipping is $\sim$2.5% in 2050, $\sim$13.5% in 2100 and $\sim$48% (that is, as likely as not) in 2200 (see Supplementary Results), in good agreement with the expert elicitation results[3].

Despite our conservative default assumptions, the prospect of an uncertain future tipping point causes an immediate increase in the initial (2005) carbon price (Fig. 2, blue line) by $\sim$50%, from US\$36.7 per ton of carbon (tC) to US\$55.6 tC^{-1} (all prices are in 2005 US\$, multiply by 1.16 for 2013 US\$). The relatively low carbon price when the tipping point is ignored, and its high average growth rate of 1.68% yr^{-1} (from $\sim$US\$36.7 tC^{-1} in 2005 to US\$173 tC^{-1} in 2100: Fig. 2, black line), is the response to the steadily increasing, deterministic effect of rising temperature on economic output. It reflects the DICE preferences of discounting future welfare at a high rate. In contrast, the expected additional carbon tax to address the tipping point threat (difference between black and blue lines in Fig. 2) grows at roughly half the average rate (0.81% yr^{-1}) of the baseline DICE carbon tax (Fig. 3). Such a flat carbon tax path is also obtained when the discount rate is prescribed to be lower (as in, for example, the Stern Review[20]). Thus, despite assuming the same dynamic preferences of discounting welfare of future generations as Nordhaus[7], our model indicates that the appropriate discount rate for climate tipping damages is a low one.

This can be understood by considering the expected returns on mitigation investment. Tipping points add a source of risk to the economic system, which increases the variance of future output. Hence mitigation expenditures have two effects on economic output. First, they increase expected output (by reducing expected damages). Second, they reduce the variance of output, further increasing social welfare. This means decisions on capital investment and mitigation expenditures will face different criteria. Increasing the capital stock in the DICE model will increase future expected output, and the marginal benefit from investment today is discounted at the market interest rate. Increasing mitigation expenditures will increase future expected output (again discounted at the market interest rate), but will also reduce the variance of future output. Therefore, mitigation expenditures to address stochastic damages will exceed the level justified by the discounted impact on expected output[17,19,20]. This implies a discount rate that is less than the interest rate. It explains why the increase in the carbon tax from tipping events exceeds that from the change in future expected output.



c — High hazard rate

Transition time (years)	20	10	5.0	2.5
5	0.93	0.60	0.48	0.43
50	0.71	0.56	0.49	0.45
100	0.63	0.55	0.51	0.48
500	0.53	0.50	0.47	0.45

c — Low hazard rate

Transition time (years)	20	10	5.0	2.5
5	0.96	0.81	0.75	0.72
50	0.88	0.81	0.76	0.74
100	0.85	0.81	0.79	0.76
500	0.80	0.78	0.75	0.74

Post-tipping damage (percentage of World GDP)

d — High hazard rate

Transition time (years)	20	10	5.0	2.5
5				ASI
50		ENSO		BOFO
100				
500	GIS			

d — Low hazard rate

Transition time (years)	20	10	5.0	2.5
5	ISM			WAM
50			AMAZ	
100		AMOC		
500		WAIS		

Post-tipping damage (percentage of World GDP)

Figure 4 | Sensitivity analysis. Sensitivity of DSICE model results to varying the likelihood (hazard rate), transition time, and final impact of the tipping event. **a**, Expected additional carbon tax in 2005. **b**, Expected delay of the tipping event. **c**, Average (2005–2100) annual growth rate of the expected additional carbon tax. **d**, Illustrative categorization of elements that could be tipped: Arctic summer sea-ice (ASI), Greenland Ice Sheet (GIS), West Antarctic Ice Sheet (WAIS), Atlantic meridional overturning circulation (AMOC), El Niño Southern Oscillation (ENSO), Indian summer monsoon (ISM), West African monsoon (WAM), Amazon rainforest (AMAZ), boreal forests (BOFO).

The optimum way of dealing with the threat of a tipping point event also resembles characteristics of an insurance policy. Insurance purchases have a negative rate of return as insurance premiums are much higher than the expected loss. The expected additional carbon price thus balances discounting of the future with the desire for insurance, resulting in its slower growth rate. It can be thought of as a premium that is levied on society with the purpose of delaying potential damage from the tipping event.

Previous deterministic IAM studies[14,25,26,29] have suggested that increasing the convexity of the damage function in the DICE model could represent the characteristics of a tipping point. As a comparison exercise we studied the implications for climate policy of doubling or tripling the exponent of the damage function. Unsurprisingly, these deterministic approaches enhance the growth rate of the carbon price (implying a higher discount rate; Fig. 3, red lines), whereas our stochastic treatment decreases it (Fig. 3, blue line). Hence, existing studies[16,26–29] that adjust the shape of a deterministic damage function qualitatively fail to capture the implications of stochastic tipping points.

Candidate tipping points differ in their intrinsic timescales and impacts[1,5]. Hence, in a sensitivity study (Fig. 4), we considered tipping processes that take 5, 50 (default), 100 and 500 years to fully unfold, with final stage impacts of 2.5%, 5%, 10% (default) and 20% damage to output. We also looked at how a higher hazard rate (0.0045 °C^{-1} yr^{-1}) affects the optimal climate policy. This gives a total of 32 combinations, each of which can be thought of as hypothetically representing the characteristics of some tipping event. The additional carbon price significantly decreases with increasing transition time (Fig. 4a), suggesting that previous studies[10,11] (see Supplementary Discussion), assuming an instantaneous full impact of climate tipping, bias the carbon price upward. The additional carbon price also increases with increasing damage and likelihood of the tipping point event (Fig. 4a). As the final stage damage doubles, the additional carbon price also roughly doubles. Furthermore, a higher hazard rate amplifies the effect of shorter transition scales on the additional carbon price.

The additional carbon tax delays the expected occurrence of the climate tipping point (Fig. 4b) in our default scenario by 20 years (from year 2214 to 2234). This expected delay time increases with increased damage, shorter transition periods, and with higher likelihood of tipping, to more than a century in our extreme cases (Fig. 4b). The expected additional carbon tax (in US$/tC) correlates with the length of the expected delay (in years), such that each dollar added to the carbon tax correlates with a delay of the tipping event by a year.

The growth rate of the additional carbon price is relatively insensitive to varying damage level or transition time, ranging over 0.43–0.96% yr^{-1} in our sensitivity analysis (Fig. 4c). This is 40–70% less than the growth rate of the baseline carbon price (1.68% yr^{-1}) in the deterministic model without tipping.

Actual candidate tipping elements in the climate system[1] can be tentatively related to modelled combinations of hazard rate, tipping duration, and final damages (Fig. 4d), based in part on previous reviews of the literature[1,5]. This is necessarily somewhat subjective.

Nevertheless, it serves to qualitatively illustrate that the optimal policy response for different specific climate tipping points could differ profoundly.

In conclusion, the optimal policy in response to the threat of a stochastic, irreversible tipping point differs substantially from the policy response to the deterministic effect of temperature on output. The damages associated with the stochastic possibility of a future climate tipping point should be discounted at a low rate[17]. This calls for a higher carbon price and increased efforts to mitigate emissions now—without even considering other co-benefits of mitigation[30], such as decreased air pollution and greater energy security. Thus, when appropriately treating the intrinsic uncertainty in the climate system—in this case the stochastic nature of future climate tipping points—a strict climate policy can emerge from a pure market-based approach. It does not have to be based on moral judgements about sustainability and the wellbeing of future generations[21]—although these are, of course, legitimate and important concerns.

Methods

We use DSICE (ref. 6), a multidimensional stochastic integrated assessment model (IAM) of climate and the economy, based on the DICE model[7]. DICE has been applied in numerous studies, for example, refs 9,14,26, and the main drivers of its behaviour have been analysed[7]. DSICE computes the optimal, global greenhouse gas emission reduction. Higher emission control at present mitigates the damage from climate change in the future but limits consumption and/or capital investment today. The global economy (the social planner) is set to weigh these costs and benefits of emission control to maximize the expected present value of global social welfare. DSICE includes the possibility of a climate tipping point with potential damages to economic output. The occurrence of a climate tipping point is modelled by a Markov process (with a hazard rate) and its timing is not known at times of decisions. Because DSICE is a stochastic model, it can compute the optimal policy response—that is, a tax on carbon emissions to address the uncertain climate tipping event. See Supplementary Methods for a full model description.

The hazard rate for a tipping event represents the conditional probability that a tipping point will occur in a particular year given the actual degree of global warming in that year (above year 2000). Previous work[3] from a range of experts has elicited imprecise cumulative probabilities for passing five different tipping points under three different temperature corridors up to the year 2200. Each temperature corridor spans an uncertainty range, and together they range over 0–8 °C warming (above year 2000) depending on the year and the scenario. Here, we calibrate the hazard rate for the tipping event by reverse engineering the contemporaneous conditional probability of tipping from the cumulative probabilities from the expert elicitation study[3]. See Supplementary Methods for full details of the hazard rate calibration.

Received 21 January 2015; accepted 11 February 2015;

References

1. Lenton, T. M. *et al.* Tipping elements in the Earth's climate system. *Proc. Natl Acad. Sci. USA* **105,** 1786–1793 (2008).
2. IPCC *Climate Change 2014: Impacts, Adaptation and Vulnerability* (eds Field, C. B. *et al.*) (Cambridge Univ. Press, 2014).
3. Kriegler, E., Hall, J. W., Held, H., Dawson, R. & Schellnhuber, H. J. Imprecise probability assessment of tipping points in the climate system. *Proc. Natl Acad. Sci. USA* **106,** 5041–5046 (2009).
4. Lenton, T. M. Early warning of climate tipping points. *Nature Clim. Change* **1,** 201–209 (2011).
5. Lenton, T. M. & Ciscar, J-C. Integrating tipping points into climate impact assessments. *Climatic Change* **117,** 585–597 (2013).
6. Cai, Y., Judd, K. L. & Lontzek, T. S. *The Social Cost of Stochastic and Irreversible Climate Change* (National Bureau of Economic Research Working Paper Series No. 18704, NBER, 2013).
7. Nordhaus, W. D. *A Question of Balance: Weighing the Options on Global Warming Policies* (Yale Univ. Press, 2008).
8. Mastrandrea, M. D. & Schneider, S. H. Integrated assessment of abrupt climatic changes. *Clim. Policy* **1,** 433–449 (2001).
9. Kosugi, T. Integrated assessment for setting greenhouse gas emission targets under the condition of great uncertainty about the probability and impact of abrupt climate change. *J. Environ. Inform.* **14,** 89–99 (2009).
10. Gjerde, J., Grepperud, S. & Kverndokk, S. Optimal climate policy under the possibility of a catastrophe. *Resour. Energy Econ.* **21,** 289–317 (1999).
11. Castelnuovo, E., Moretto, M. & Vergalli, S. Global warming, uncertainty and endogenous technical change. *Environ. Model. Assess.* **8,** 291–301 (2003).
12. Interagency Working Group on Social Cost of Carbon *Social Cost of Carbon for Regulatory Impact Analysis—Under Executive Order 12866* (United States Government, 2010).
13. Interagency Working Group on Social Cost of Carbon *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis* (United States Government, 2013).
14. Ackerman, F. & Stanton, E. A. Climate risks and carbon prices: Revising the social cost of carbon. *Economics* **6,** 1–25 (2012).
15. Van den Bergh, J. C. J. M. & Botzen, W. J.W. A lower bound to the social cost of CO_2 emissions. *Nature Clim. Change* **4,** 253–258 (2014).
16. Revesz, R. L. *et al.* Improve economic models of climate change. *Nature* **508,** 173–175 (2014).
17. Arrow, K. *et al.* Determining benefits and costs for future generations. *Science* **341,** 349–350 (2013).
18. Barro, R. J. Rare disasters, asset prices, and welfare costs. *Am. Econ. Rev.* **99,** 243–264 (2009).
19. Gollier, C. *Pricing the Planet's Future: The Economics of Discounting in an Uncertain World* (Princeton Univ. Press, 2012).
20. Pindyck, R. S. & Wang, N. The economic and policy consequences of catastrophes. *Am. Econ. J.* **5,** 306–339 (2013).
21. Stern, N. *The Economics of Climate Change: The Stern Review* (Cambridge Univ. Press, 2006).
22. Dasgupta, P. Commentary: The Stern Review's economics of climate change. *National Inst. Econ. Rev.* **199,** 4–7 (2007).
23. Nordhaus, W. D. A review of the Stern Review on the economics of climate change. *J. Econ. Lit.* **45,** 686–702 (2007).
24. Weitzman, M. L. A review of the Stern Review on the economics of climate change. *J. Econ. Lit.* **45,** 703–724 (2007).
25. Weitzman, M. L. GHG targets as insurance against catastrophic climate damages. *J. Public Econ. Theory* **14,** 221–244 (2012).
26. Ackerman, F., Stanton, E. A. & Bueno, R. Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE. *Ecol. Econ.* **69,** 1657–1665 (2010).
27. Lemoine, D. & Traeger, C. Watch your step: Optimal policy in a tipping climate. *Am. Econ. J.* **6,** 137–166 (2014).
28. Nordhaus, W. *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World* (Yale Univ. Press, 2013).
29. Nordhaus, W. D. *An Analysis of the Dismal Theorem* (Cowles Foundation for Research in Economics, Yale Univ., 2009).
30. McCollum, D. *et al.* Climate policies can help resolve energy security and air pollution challenges. *Climatic Change* **119,** 479–494 (2013).

Acknowledgements

We thank K. Arrow, B. Brock, L. Goulder and participants of the 2014 Workshop on the Economics of Complex Systems at the Beijer Institute of Ecological Economics for comments. Y.C., K.L.J. and T.S.L. were supported by NSF (SES-0951576). T.S.L. was also supported by the Züricher Universitätsverein, the University of Zurich and the Ecosciencia Foundation. T.M.L. was supported by a Royal Society Wolfson Research Merit Award and the European Commission (ENV.2013.6.1-3) HELIX Project. Part of this study was done while T.S.L. was visiting the Hoover Institution. Supercomputer support was provided by Blue Waters (NSF awards OCI-0725070 and ACI-1238993, and the state of Illinois) and by NIH (1S10OD018495-01).

Author contributions

Y.C., K.L.J. and T.S.L. developed the model with input from T.M.L. Y.C. and K.L.J. developed the computational method and Y.C. developed the code. All authors analysed the results. T.S.L. and T.M.L. took the lead in writing the paper with inputs from Y.C. and K.L.J.

Additional information

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

Competing financial interests

The authors declare no competing financial interests.