nature climate change

ARTICLES

PUBLISHED ONLINE: 3 JUNE 2012 | DOI: 10.1038/NCLIMATE1548

Transfer payments in global climate policy

Florian Landis[1]* and Thomas Bernauer[2]

Many scientists and policymakers agree that large financial flows from richer to poorer countries will be necessary to reach an agreement on reducing greenhouse-gas emissions enough to keep global warming below 2 °C. But the required amounts of transfer payments and justifications for them remain contested. We contribute to this debate by developing an argument for transfer payments that derives from the differences between carbon prices that different countries may set in light of two distinct criteria for appropriate levels of emission reductions. If, for reasons of cost efficiency, a globally uniform carbon price was installed, transfer payments would be required to offset these differences. We combine global climate modelling with regional welfare analysis to estimate regional carbon prices under various climate change, emissions and economic scenarios. The estimated ratios between regional carbon prices are surprisingly robust to different modelling assumptions. To the extent that burden-sharing choices in global climate policy are motivated by regional carbon prices, our analysis allows for a quantification of required transfer payments. Assuming a global carbon price of US\$35 per t CO_2, for example, our estimates would justify transfer payments of the order of US\$15–48 billion per year.

Although global climate negotiations are progressing only very slowly, the European Union and several other countries have declared that they will unilaterally reduce their greenhouse-gas emissions until 2020. Climate scientists argue, however, that even if these unilateral promises are fully implemented, they might add up to no more than an optimistic business-as-usual scenario of total global emissions[1]. To keep the risk of exceeding global warming by 2 °C below 50%, emissions cuts on a much larger scale will be necessary.

One important obstacle for attempts to reach an effective global climate agreement is that emerging and developing economies expect more rapid economic growth, relative to advanced industrialized countries. To support and sustain their growing economic activity in the short term, they prefer to rely on cheap sources of energy, such as oil and coal. Even though emerging economies, such as China, are becoming increasingly aware of the environmental implications of their fossil-fuel use in general[2] and climate change in particular[3], they argue that industrialized countries are, historically, responsible for the largest part of the climate change problem up until now. Hence they argue that richer countries should reduce their emissions first and/or compensate emerging and developing economies for participating in mitigation efforts. They also note that burden-sharing in greenhouse-gas mitigation efforts should, in addition to historical responsibility, take into account differences in present economic and technological capacity to abate[4]. These views and positions have become very firm in the negotiations leading to the Bali action plan, adopted at the 13th Conference of the Parties in Bali[5]. They have led to an informal agreement on so-called fast-start finance at the 16th Conference of the Parties in Cancún[6].

Here, we develop an argument for transfer payments that has, thus far, received only little systematic attention. Various normative criteria give rise to regional carbon prices, and thus to appropriate levels of emissions reductions. We restrict our analysis to two criteria, both of which call for large-scale effective emissions reductions. We label these two criteria liability criterion and utilitarian criterion[7]. Given that different countries hold different views on what the carbon price should be, agreement on any policy that implicates a globally uniform price for emission rights requires transfer payments to offset these differences. Very few studies have examined the issue of regional carbon prices and none has dealt with how these could relate to transfer payments[7].

Carbon pricing and transfer payments

The liability criterion advocates that emitters of greenhouse gases should be held liable for the damages their emissions are causing now and in the future. Such liability would not only motivate emitters to internalize the damages they impose on others. It would also ascertain that those who are vulnerable to climate change are compensated for the involuntary hardship they experience. Such a liability scheme would offer a solution that redresses the unfairness arising from the asymmetric distribution of responsibility for and vulnerability to climate change[8].

In reality, establishing and enforcing such liability would be extremely difficult. Major industrialized countries have already refused to include liability clauses for climate change-related damages in the Kyoto Protocol and potential follow-up agreements[9]. Even if liability provisions were included in a global treaty, it would be quite difficult to identify and monetize the full impact of climate change and its distribution over different countries, social groups and time.

The political feasibility problem notwithstanding, it is, in principle, possible to characterize the basic features that a global liability scheme in climate policy should have. As in the case of earlier international agreements on environmental issues, liability for climate change damages could be conceptualized as joint and several liability among countries[9]. The responsibility for climate change damages could then be identified and assigned according to responsibility shares, as discussed in the climate science literature at present[10,11].

If one accepts liability as the normative foundation of burden-sharing in climate policy, it would seem fair to let countries take and implement abatement decisions in ways that correspond to rational reactions to impending liability. Owing to widely differing economic growth prospects, countries would discount future damages with different social discount rates and would thus

[1]ETH Zürich, Centre for Energy Policy and Economics (CEPE), ZUE E1, Zürichbergstrasse 18, CH-8032, Zürich, [2]ETH Zürich, Center for Comparative and International Studies (CIS) and Institute for Environmental Decisions (IED), IFW C45.1, Haldeneggsteig 4, CH-8092, Zürich. *e-mail: landisf@ethz.ch.

base their abatement decisions on different social costs of carbon and set carbon prices accordingly.

Another line of reasoning that can be used to estimate regional carbon prices derives from a utilitarian criterion void of liability. This approach assumes that adding or subtracting a given amount of yearly per capita income implies bigger changes in (per capita) welfare for a poor than for a rich country. If one then tries to maximize a population-weighted sum of welfare functions of countries, this leads to big differences in regional carbon prices as well[7]. Because we cannot see a valid scientific reason for prioritizing one type of reasoning over the other, we compare the implications of the liability and utilitarian criteria for required transfer payments.

If countries accept either the liability or utilitarian criterion, they should in principle regard country- or region-specific carbon prices as fair. But such pricing comes at an opportunity cost in terms of overall global efficiency in reducing greenhouse-gas emissions. Most environmental economists believe that major efficiency gains in reducing greenhouse-gas emissions can be achieved by equalizing marginal abatement costs across all countries[12]. Achieving such efficiency gains would require a global carbon price. The latter could be arrived at by means of a global CO_2 tax[12,13] or a cap-and-trade system under which yearly emission caps are set for individual countries or groups of countries and emission rights can be traded freely worldwide.

A globally applied CO_2 tax would, however, lead to differences between the global carbon price thus generated and the social cost of carbon preferred by different countries. To achieve political consensus, the global carbon price could be designed as a compromise between different countries' preferred social cost of carbon. Countries whose preferred carbon price (assuming full internalization of future damages) turns out to be above the global carbon price could then compensate those that would prefer a carbon price below the global price. Such transfer payments should make countries or regions indifferent between incurring abatement cost according to a national social cost of carbon and incurring abatement cost induced by the global carbon-price net of transfers.

Regional carbon prices

We now estimate regional carbon prices and analyse how uncertainty about future climate change and economic development as well as adopting the liability or utilitarian criterion influences these prices.

Starting with the liability criterion, if each country individually determined the social cost of carbon on the basis of its respective contribution to worldwide damages, all countries would attribute the same amount of damages to a unit of CO_2 emissions. Differences in the preferred carbon price would then derive exclusively from discounting. When rules of discounting determine the benchmark against which transfer payment mechanisms are designed, expected economic growth rates determine transfer requirements.

To avoid overly complex negotiations on what future economic growth rates are realistic or appropriate, the rules on how to attribute growth rates to countries should be kept as simple as possible. Countries could, for example, be grouped into regions with similar economic properties that are bound to have a strong effect on growth perspectives. For our calculations, we used the regions and economic projections of the Intergovernmental Panel on Climate Changes's (IPCC's) *Special Report on Emissions Scenarios* (SRES)[14]. The regions are Africa and Latin America (ALM), Asia (ASIA), and transition economies (REF) as well as the Organisation for Economic Co-operation and Development (OECD) countries as of 1990 (OECD90). Although the IPCC's choice of regions was only to a minor degree driven by considerations of economic growth perspectives, the countries in each region show at least some economic similarities. Hence these regions are appropriate for examining the implication of our argument for transfer payments at this point.

Inspired by the liability criterion discussed above, we use the social cost of carbon to represent the discounted increases in the mentioned regions' share of global climate change damages at all future points in time. Shares of responsibility of different emitters are calculated with the marginal method described by den Elzen *et al.*[10] and Trudinger and Enting[11], using projections of emissions in combination with climate models (Methods).

Uncertainties concerning the relationships between emissions and temperature changes and between temperature changes and economic losses, but also uncertainties concerning future emissions, must be taken into account in a systematic assessment of transfer requirements. We use a sensitivity analysis to this end, employing climate predictions from three climate models, the four SRES scenarios A1B, A1T, B1 and B2 for both emissions and economic growth, as well as three different damage factors (damage factors describe the relationship between temperature change and economic losses; see Methods).

Taking these uncertainties into account produces a wide range of estimates for the social cost of carbon. This finding corresponds to the range of estimates for the social cost of carbon in the existing literature[15]. More notably, however, we find that in spite of all of these uncertainties the ratios between the estimated carbon prices of different regions are surprisingly robust.

Let us start with estimates of the ratios of regional carbon prices for the year 2010 according to SRES scenario, climate model and damage function used for the estimate (Fig. 1a; Methods). The most obvious sources of variation in regional carbon prices are the SRES scenarios. Differences in projected economic growth—and the associated discounting—influence relative regional carbon prices much more than differences in modelling climate and climate-change-related damages.

The estimates based on the B2 scenario are particularly noteworthy. If we rely on this scenario, the region ALM seems willing to price carbon at a rate that is considerably closer to the OECD90 price than in the other scenarios. The reason is that the B2 scenario predicts relatively (compared with other scenarios) low economic but high population growth for this region; that is, per capita gross domestic product in this region increases to only a minor extent for the first few decades in the B2 scenario. Because of small per capita economic growth the social discount rate is relatively low and the ALM region does not discount future climate damages as much as regions with more rapid economic growth.

Besides the uncertainties associated with economic growth scenarios, the existing literature disagrees on how to parametrize discounting rules[16]. Different parameter choices for discounting can lead to vastly different social costs of carbon. In our context, using different parametrization (Methods) for estimating social discount rates influences the ratios of regional carbon price to a similar degree as using different economic growth scenarios (Fig. 1b).

Negotiators could chose the parameters that are used to obtain the social discount rate (Methods) before attempting to put a price on carbon emissions. However, the other elements in our analysis (economic scenarios, climate, damages from climate change) cannot be determined *ex ante* with certainty. When deciding on a regional carbon price, policymakers would thus need to assign (perhaps implicitly) probabilities to different combinations of scenarios, climate models and damage functions. But no matter how they weigh different possible futures, the carbon-price ratios are unlikely to exceed the range of our estimates, as long as our sensitivity analysis has covered all economic and climate scenarios (Supplementary Information).

Overall, the results based on the liability criterion indicate that estimates of relative regional carbon prices are surprisingly robust to a vast range of alternative assumptions about climate change and damages. But the estimates strongly depend on

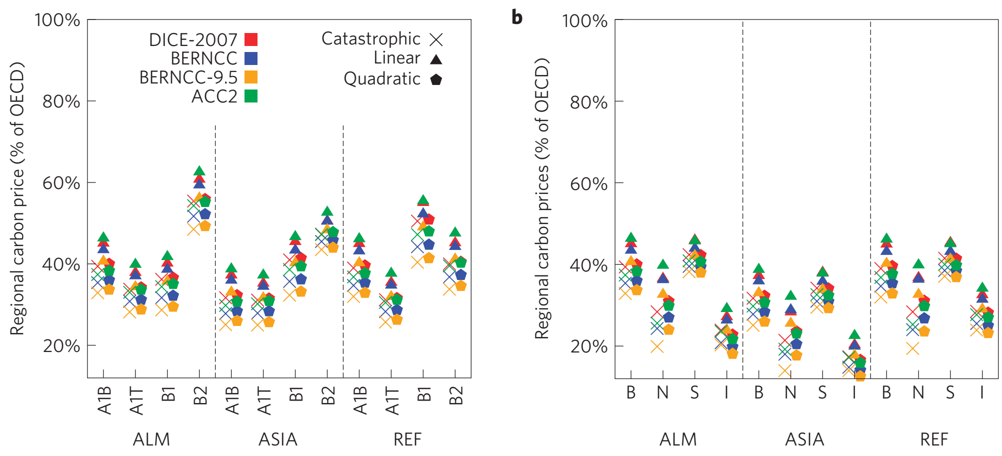

Figure 1 | Sensitivity of price ratios to scenarios and discounting parameters (liability criterion). Carbon prices relative to the OECD90's carbon price for SRES regions ALM, ASIA and REF. **a**, Sensitivity to scenarios. **b**, Sensitivity to discounting parameters. The different parameter choices for discounting are referred to as base case (B), Nordhaus[12] (N), Stern[22] (S) and increasing EIS (I) (see Methods). Results based on the four climate models are in different colours. Different marker types denote the results based on the three damage functions. Relative carbon prices vary considerably with economic scenarios, but less so with climate and damage modelling.

Table 1 | Regional abatement costs at a globally uniform carbon price of US$35 per t CO_2 and at regionally differing carbon prices (utilitarian criterion).

Region	Uniform pricing	Regional pricing base case			Increasing EIS		
	Cost (US$ billions)	Price ratio	Price (US$ per t CO_2)	Cost (US$ billions)	Price ratio	Price (US$ per t CO_2)	Cost (US$ billions)
ALM	10.4	0.112	7.9	0.85	0.041	3.0	0.13
ASIA	29.8	0.087	6.2	2.0	0.026	1.9	0.16
OECD90	25.7	1	71	69	1	74	74
REF	10.3	0.258	18	3.9	0.172	13	2.1

The inverse of the EIS is $\sigma = 1.3$ in the base case and is assumed to be a function of income in the increasing EIS case (see Methods). Price ratios denote the ratio between the social cost of carbon that the respective region should choose and the OECD90's social cost of carbon.

parameter choices for discounting and on economic growth perspectives of the regions.

Estimating ratios of regional carbon prices based on the utilitarian criterion is much simpler. According to this criterion, each country should reduce emissions until the marginal reduction in its own welfare resulting from emission reduction equals the marginal improvement of all countries' intertemporal welfare caused by this self-restraint. If all countries fully consider all welfare impacts of their actions on the other regions, the benefits of reducing emissions are viewed as the same by all parties. The only reason social costs of carbon can still differ between regions is that costs for present emissions reductions have different impacts on the different countries' present welfare. The implication is that ratios of regional carbon prices do not, in this case, depend on predictions of climate change and its impacts. Regional carbon-price ratios solely depend on the relative welfare impacts of present abatement efforts (Supplementary Information). Table 1 shows the regional carbon-price ratios based on the utilitarian criterion, assuming the same welfare functions that were also used to derive discount rates.

Required transfer payments

According to our argument, at present transfer payments should compensate developing countries and emerging economies for accepting a global carbon price that is higher than the respective regional social cost of carbon. Advanced industrialized countries, in turn, should be willing to pay for such transfers if the global carbon price is lower than the regional carbon price they would be willing to pay. Let us assume that the global carbon price results from a compromise between different regional social costs of carbon, and that this compromise equalizes global abatement costs under the global compromise with those under the regional pricing scheme. In that case, transfer payments that make industrialized countries indifferent between the global and the regional carbon pricing scheme are equal to the demands for transfers that make the rest of the world indifferent as well.

Based on these assumptions and appropriate abatement-cost curves, we can estimate the annual transfer payments that would be required at a given global carbon price that is explicitly or implicitly set by international climate policy. Let us assume that the global carbon price is US$35 per t CO_2. This price comes close to the €24 per t CO_2 that in reality prevailed in the European Union's emission trading system in the first half of 2008 (ref. 17). We infer regional carbon prices that could lead to this global compromise by varying the OECD90 carbon price and setting the price chosen by the other regions ALM, ASIA and REF according to the price ratios estimated in the previous step of our analysis. The carbon price of OECD90 is set such that global abatement costs are the same under regional and globally uniform carbon pricing.

Given a specific parametrization of the welfare function (we assume that the international community has agreed on these parameters before the amount of transfer payments is identified), we can now estimate requirements for transfer payments for all four SRES scenarios and all models of climate change and damages. We discuss two parametrizations that the international

Table 2 | Regional abatement costs at a globally uniform carbon price of US$35 per t CO_2 and at regionally differing carbon prices (liability criterion).

	Region	Uniform pricing	Regional pricing base case		Increasing EIS	
		Cost (US$ billions)	Price (US$ per t CO_2)	Cost (US$ billions)	Price (US$ per t CO_2)	Cost (US$ billions)
A1B	ALM	10.4	20–26	4.4–6.3	12–19	1.9–3.7
	ASIA	29.8	15–21	10–16	8.7–15	4.1–9.4
	OECD90	25.7	54–62	47–57	62–70	58–67
	REF	10.3	19–25	4.3–6.3	16–22	3.1–4.9
A1T	ALM	10.4	17–23	3.5–5.2	10–16	1.3–2.8
	ASIA	29.8	15–21	10–16	8.8–14	4.2–9.1
	OECD90	25.7	56–63	50–59	64–71	61–69
	REF	10.3	16–22	3.1–4.9	11–17	1.8–3.3
B1	ALM	10.4	16–22	3.2–4.9	10–16	1.5–2.9
	ASIA	29.8	18–25	14–19	11–18	6.7–13
	OECD90	25.7	51–59	44–53	59–67	55–64
	REF	10.3	23–29	5.7–7.7	18–25	3.9–5.9
B2	ALM	10.4	26–31	6.6–8.5	17–24	3.6–5.5
	ASIA	29.8	23–26	18–21	16–19	11–21
	OECD90	25.7	48–54	41–48	52–63	45–59
	REF	10.3	18–24	3.8–5.6	15–20	2.8–4.2

In the base case, $\sigma = 1.3$ and in the increasing EIS case, an income-dependent $\sigma(i_t)$ was chosen. Remaining variance of results for any combination of scenario and region comes from different assumptions about climate change and damages.

community might agree on before deciding on transfer payments: first, base-case parametrization and second, parametrization using an elasticity of intertemporal substitution (EIS) that is a function of the per capita income level (increasing EIS; see Methods). The first reflects a compromise between prominent parameter choices in the integrated assessment model literature. The second has a plausible theoretical foundation[18] and also some empirical support[19].

The abatement cost that different regions incur when applying a globally uniform carbon tax of US$35 per t CO_2 is shown in the first column in Table 2. Using the liability criterion, regional carbon prices are of the order of p_{OECD90} = US$48–63 per t CO_2, p_{ALM} = US$16–31 per t CO_2, p_{ASIA} = US$15–26 per t CO_2, and p_{REF} = US$16–29 per t CO_2 for the base-case parametrization of the EIS. Assuming the base-case choice of EIS, at present the OECD90 region would have to pay US$15–34 billion per year to compensate the rest of the world for reducing emissions according to a global carbon price of US$35 per t CO_2, rather than by internalizing damages according to regional preferences. Required transfer payments increase to US$19–44 billion if the increasing EIS parametrization is used (Table 2, Fig. 2). Finally, if the utilitarian criterion for carbon prices motivates the global compromise, transfer payments in the range of US$43–49 billion would be necessary (Table 1). For the two parametrizations of the welfare function (base case and increasing EIS), this means that, assuming acceptance of the utilitarian criterion, the OECD90 countries would incur 90% or more of global abatement costs.

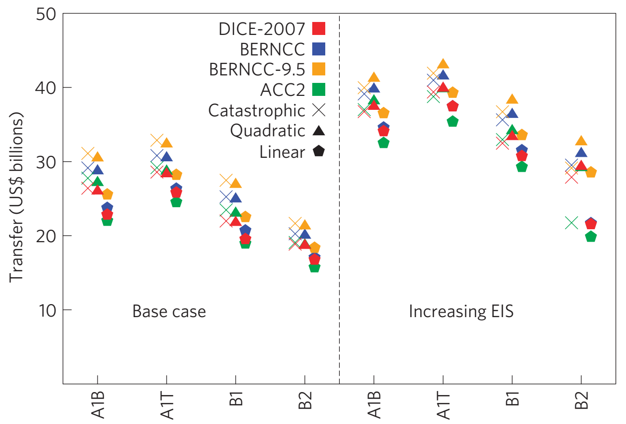

Figure 2 | Transfer payments depending on scenarios and discounting parameters (liability criterion). Transfer payments from OECD90 to the rest of the world. Transfers make the world regions indifferent between abating according to regional carbon prices and abating at an agreed global carbon price of US$35 per t CO_2 that implies the same global abatement cost. Results based on the four climate models are in different colours. Marker types distinguish the results obtained from different damage functions.

Discussion

Our approach to estimating required transfer payments in global climate policy takes into account the trade-offs that countries are likely to make between the costs and benefits of emissions reductions under the liability and utilitarian criterion, respectively. The uncertainty about climate change and future economic growth is accounted for by extensive sensitivity analysis.

The approach presented here is a first step towards enhancing the scientific foundations of a burgeoning political debate about transfer payments that will be required to motivate emerging economies and developing countries to accept constraints on their rights to emit greenhouse gases. The main advantage of our approach is that it is explicit and transparent with respect to the key assumptions that drive estimates of required transfer payments. Both the liability and the utilitarian criterion produce large differences between estimated regional carbon prices and thus support the need for large-scale transfer payments in global climate policy.

Further research could address several issues that are left open by the approach presented here. First, our research does not address how institutional mechanisms for transfer payments could be designed. Setting up and operating such mechanisms over decades raises enormous challenges that extend beyond the scope of the analysis here. In the case of liability, for example, methods and mechanisms for evaluating the responsibility for hypothetical past emissions under regional carbon prices would have to be developed. Countries would also have to agree on how to deal with loss compensation for those parts of climate change that cannot be avoided.

Second, the fact that regional carbon pricing based on the liability criterion implicates that poor low-growth regions should use a relatively high regional carbon price obviously violates the principle of burden-sharing according to capacity. This would be acceptable to these countries only if liability and loss compensation in the future could be strictly enforced because they would then owe less loss compensation to damaged parties at future points in time. Further research could explore to what extent principles of contemporaneous economic capacity could be combined with the reasoning based on liability.

Third, although the utilitarian criterion might be easier to implement in practice because it does not require a strong, enforceable contract over generations, it results in larger transfer payments by industrialized countries for abatement cost. Hence there seems to be an economic and political trade-off between the two principles and their application to transfer payments that deserves more systematic attention.

Fourth, there are several methods to establish abatement-cost curves for deducting abatement levels and cost from carbon prices. Sensitivity analysis considering different assumptions about abatement cost would be useful.

Methods

Estimating responsibility. The share of responsibility for global temperature change at a given future point in time, caused by regional emissions up to that time, can be determined according to den Elzen *et al.*[10] and Trudinger and Enting[11]. We assume that countries, as small parts of the world, pay attention only to this responsibility share and ignore the marginal effect of their emissions on global temperature. They will then put a price on CO_2 emissions that equals the sum of discounted (with a regional discount rate) future marginal increases in liability. We assume that countries will be held liable only for damages that materialize within 100 years (Supplementary Information).

Economic scenarios and social discount rates. Assuming the welfare function of the Ramsey growth model, the social planner regards a unit increase in consumption at time t as being equivalent to an increase in consumption by $1+r_s$ at time $t+1$, where

$$r_s=(1+\rho)\left(\frac{c_{t+1}}{c_t}\right)^{\sigma}-1$$

where r_s denotes the social discount rate, c_t is the per capita consumption level, ρ is the pure rate of time preference and σ the inverse of the EIS.

Parameters σ and ρ from the literature include: $\rho=0, \sigma=1.5$ (ref. 20); $\rho=1.5\%$ per year, $\sigma=2$ (ref. 12); $\rho=3.0\%$ per year, $\sigma=1$ (ref. 21); and $\rho=0.1\%$ per year, $\sigma=1$ (ref. 22). In our analysis, we use

$$\rho=1.5\% \quad \text{and} \quad \sigma=1.3 \quad \text{(base case)}$$

as the base case[23] and conduct a sensitivity analysis using the alternative parameter choices

$$\rho=0.1\% \quad \text{and} \quad \sigma=1 \quad \text{(Stern)}$$

$$\rho=1.5\% \quad \text{and} \quad \sigma=2 \quad \text{(Nordhaus)}$$

$$\rho=1.5\% \quad \text{and} \quad \sigma(i_t)=1+\exp\left(\frac{i_t-i_a}{i_o-i_a}\ln 0.3\right) \quad \text{(increasing EIS)} \qquad (1)$$

$\sigma(i_t)$ in equation (1) accounts for the fact that, according to several studies[19,24], the EIS $1/\sigma$ grows with per capita income levels i_t. With our parametrization, in the year 2000, the OECD90 countries with a per capita income of $i_o=$ US\$29,383 are at $\sigma(i_o)=1.3$ and ASIA with per capita income $i_a=$ US\$3,858 is at $\sigma(i_a)=2$.

We base our analysis on the IPCC's SRES (ref. 14) and use the scenarios A1B, A1T, B1 and B2. We assume that these scenarios cover an appropriately wide range of possible socioeconomic futures (Supplementary Information).

Climate models. To account for uncertainties that affect climate modelling and the resulting projections, we use three different climate models. First, we use the climate module from the Dynamic Integrated Model of Climate and the Economy (DICE-2007) model by Nordhaus[25]. This model is a simple representation[26] of the Earth's climate based on seven equations, which runs on the timescale of decades. We ran this model using its standard setting for climate sensitivity of 3.0. The magnitude of climate sensitivity describes a long-run equilibrium temperature increase (in °C) if atmospheric CO_2 concentration can be limited to twice the preindustrial level.

Second, we use a customized version of the Bern carbon-cycle–climate (BERNCC) model[27]. Besides a radiative forcing, climate and carbon-cycle module, the BERNCC model also includes a model of atmospheric chemistry. The carbon-cycle module couples the atmosphere to the two carbon sinks, the ocean and the land biosphere. We used the BERNCC with a setting of the climate sensitivity parameter of 3.2 and conducted a sensitivity analysis with a climate sensitivity parameter of up to 9.5 (Supplementary Information). A climate sensitivity of 9.5 or higher cannot be completely ruled out, but can be considered highly unlikely[28].

Third, we use the aggregated carbon cycle, atmospheric chemistry and climate model (*ACC* 2) of the Max Planck Institute for Meteorology in Hamburg[29]. This model includes the same types of modules as BERNCC (that is, radiative forcing, climate, carbon cycle and atmospheric chemistry). It uses a maximum likelihood estimation with historical data to determine climate sensitivity internally and uses a value of 4.0.

Damage functions. Estimates of how temperature increases will affect the world economy are still mainly based on expert assessments and guesstimates of the modellers[30]. We assume that damages are proportional to world gross domestic product[25,31–33] and that the proportionality factor depends on temperature increase, ΔT, alone. Existing research employs linear[31] and (approximately) quadratic[25,31–33] specifications of the proportionality factor. Besides linear and quadratic factors, we use

$$\delta(\Delta T)=1-\left(1+0.085164\cdot\Delta T^2\right)^{-1} \quad \text{(catastrophic)}$$

which is a variant of what is used in by Nordhaus[25] and predicts catastrophic damages from climate change even for temperature increases of around 2 °C.

Abatement cost. To estimate marginal abatement cost a general equilibrium model of the world economy[34] based on Global Trade Analysis Project (GTAP7) data[35] was used (see Supplementary Information).

Received 28 April 2011; accepted 26 April 2012; published online 3 June 2012

References

1. Rogelj, J. *et al.* Copenhagen accord pledges are paltry. *Nature* **464,** 1126–1128 (2010).
2. Liu, J. & Diamond, J. China's environment in a globalizing world. *Nature* **435,** 1179–1186 (2005).
3. Seligsohn, D., Heilmayr, R., Tan, X. & Weischer, L. *China, the United States, and the Climate Change Challenge* WRI Policy Brief (World Resource Institute, 2009).
4. Dellink, R. *et al.* Sharing the burden of financing adaptation to climate change. *Glob. Environ. Change* **19,** 411–421 (2009).
5. Ott, H. E., Sterk, W. & Watanabe, R. The Bali roadmap: New horizons for global climate policy. *Clim. Policy* **8,** 91–95 (2008).
6. Cozier, M. Restoring confidence at the Cancun climate change conference. *Greenhouse Gases: Sci. Technol.* **1,** 8–10 (2011).
7. Anthoff, D. & Tol, R. S. On international equity weights and national decision making on climate change. *J. Environ. Econ. Manag.* **60,** 14–20 (2010).
8. Füssel, H. How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: A comprehensive indicator-based assessment. *Glob. Environ. Change* **20,** 597–611 (2010).
9. Tol, R. S. J. & Verheyen, R. State responsibility and compensation for climate change damages—a legal and economic assessment. *Energ. Policy* **32,** 1109–1130 (2004).
10. den Elzen, M. *et al.* Analysing countries' contribution to climate change: Scientific and policy-related choices. *Environ. Sci. Policy* **8,** 614–636 (2005).
11. Trudinger, C. & Enting, I. Comparison of formalisms for attributing responsibility for climate change: Non-linearities in the Brazilian proposal approach. *Climatic Change* **68,** 67–99 (2005).
12. Nordhaus, W. D. To tax or not to tax: Alternative approaches to slowing global warming. *Rev. Environ. Econ. Policy* **1,** 26–44 (2007).
13. Barrett, S. *Environment and Statecraft: The Strategy of Environmental Treaty-Making* (Oxford Univ. Press, 2006).
14. Nakicenovic, N. & Swart, R. (eds) *IPCC Special Report on Emissions Scenarios* (Cambridge Univ. Press, 2000).

15. Yohe, G. W. *et al.* in *IPCC Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E.) 811–841 (Cambridge Univ. Press, 2007).
16. Dasgupta, P. Discounting climate change. *J. Risk Uncertainty* **37,** 141–169 (2008).
17. Committee on Climate Change *Meeting Carbon Budgets—The Need for a Step Change* Progress Report to Parliament (2009).
18. Rebelo, S. Growth in open economies. *Carnegie–Rochester Conf. Ser. Public Policy* **36,** 5–46 (1992).
19. Ogaki, M., Ostry, J. D. & Reinhart, C. M. Saving behavior in low- and middle-income developing countries: A comparison. *Int. Monet. Fund S. Pap.* **43,** 38–71 (1996).
20. Cline, W. R. *The Economics of Global Warming* (Peterson Institute, 1992).
21. Nordhaus, W. D. *Managing the Global Commons: The Economics of Climate Change* (MIT Press, 1994).
22. Stern, N. H. *The Economics of Climate Change: The Stern Review* (Cambridge Univ. Press, 2007).
23. Evans, D. J. & Sezer, H. Social discount rates for six major countries. *Appl. Econ. Lett.* **11,** 557–560 (2004).
24. Guvenen, F. Reconciling conflicting evidence on the elasticity of intertemporal substitution: A macroeconomic perspective. *J. Monetary Econ.* **53,** 1451–1472 (2006).
25. Nordhaus, W. D. *A Question of Balance: Weighing the Options on Global Warming Policies* (Yale Univ. Press, 2008).
26. Joos, F., Müller-Fürstenberger, G. & Stephan, G. Correcting the carbon cycle representation: How important is it for the economics of climate change? *Environ. Model. Assess.* **4,** 133–140 (1999).
27. Joos, F. *et al.* Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. *Glob. Biogeochem. Cycles* **15,** 891–908 (2001).
28. Knutti, R. & Hegerl, G. C. The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geosci.* **1,** 735–743 (2008).
29. Tanaka, K. *et al. Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2)—Description of the Forward and Inverse Modes* Tech. Rep. 40 (Max Planck Institute for Meteorology, 2007).
30. Füssel, H. Modeling impacts and adaptation in global IAMs. *WIREs Clim. Change* **1,** 288–303 (2010).
31. Manne, A. & Richels, R. *Energy and Environment* 175–189 (Springer, 2005).
32. Yang, Z. & Nordhaus, W. D. Magnitude and direction of technological transfers for mitigating GHG emissions. *Energ. Econ.* **28,** 730–741 (2006).
33. Bosetti, V., Carraro, C., Galeotti, M., Massetti, E. & Tavoni, M. A world induced technical change hybrid model. *Energy J.* **27,** 13–37 (2006).
34. Böhringer, C., Hoffmann, T. & Manrique-de-Lara-Peñate, C. The efficiency costs of separating carbon markets under the EU emissions trading scheme: A quantitative assessment for Germany. *Energ. Econ.* **28,** 44–61 (2006).
35. Badri, N. G. & Walmsley, T. L. *Global Trade, Assistance, and Production: The GTAP 7 Data Base* (Center for Global Trade Analysis, Purdue Univ., 2008).

Acknowledgements

We are grateful to C. Böhringer, F. Joos, and T. Rutherford for comments and support. C. Böhringer kindly provided us with estimates of marginal abatement-cost curves and F. Joos supplied us with a version of the BERNCC climate model and instructed us on how to run it.

Author contributions

F.L. carried out the climate modelling and economic computations. T.B. and F.L. developed the research idea and main concepts and jointly wrote the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to F.L.