Inequality, climate impacts on the future poor, and carbon prices

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Integrated assessment models of climate and the economy provide estimates of the social cost of carbon and inform climate policy. We create a variant of the Regional Integrated model of Climate and the Economy (RICE)—a regionally disaggregated version of the Dynamic Integrated model of Climate and the Economy (DICE)—in which we introduce a more fine-grained representation of economic inequalities within the model's regions. This allows us to model the common observation that climate change impacts are not evenly distributed within regions and that poorer people are more vulnerable than the rest of the population. Our results suggest that this is important to the social cost of carbon—as significant, potentially, for the optimal carbon price as the debate between Stern and Nordhaus on discounting.

climate change | RICE | inequality | damage distribution | social cost of carbon

The most prominent debate on cost-benefit evaluation of climate policy has been on the discount rate (see, e.g. refs. 1–4).* One of the important principles this debate has highlighted is that the effect of climate impacts are discounted when they are borne by more affluent—future—generations.† However, despite Schelling's early remarks (9) that this principle should also apply across contemporaries with different levels of affluence, the interaction between climate impacts and economic inequality has only been studied by looking at inequality between regions (10, 11). This is potentially an important oversight, because in leading cost–benefit integrated assessment models (IAMs) much of the poverty associated with high levels of vulnerability is masked by regional averaging of economic variables.‡

In light of this, we modify a leading climate-economy model, Regional Integrated model of Climate and the Economy (RICE), to include what is known about economic inequality within regions and countries. This representation of economic inequality allows us to investigate the effect on optimal policy of different assumptions about the distribution of damages by economic strata.§

When subregional differences are modeled in this way, several policy-relevant aspects of the model can change dramatically even when other assumptions and parameters from RICE are held constant. As we show below, even when RICE regional damage functions are used to establish the damage level of each region, the distribution of damage within regions can cause some members of future generations to be less affluent than their current counterparts.¶ If the distribution of damage is less skewed to high incomes than the distribution of consumption, then weak or no climate policy will result in sufficiently large damages on the lower economic strata to eventually stop their welfare levels from improving, and instead cause them to decline. This paints a different picture from the standard narrative in leading cost–benefit IAMs, where regional average consumptions continue to grow even under business-as-usual (BAU).

The implications for policy recommendations are striking, both by the standard utilitarian metric and by metrics of sustainability (18) and justice (19) emphasized by alternative normative frameworks. If the future poor bear more than their proportional share of the damage, significantly more mitigation effort is optimal than in existing models. For example, if damages are distributed inversely proportionally to income, then the utilitarian optimal mitigation effort under the discounting assumptions of Nordhaus (2) in our disaggregated model is equivalent to the optimal mitigation in the more aggregated RICE model under the low discounting assumptions of the Stern Review (1), as we show below. Therefore, properly accounting for the distribution of consumption and damage within regions may be as important for climate policy as the debate over discounting.

Making RICE NICE

To model distributional differences within regions of both consumption and damages, the key modification of RICE is to split each of its 12 regions into population quintiles. We use the most recent available World Bank data (20) on national income

Significance

Hundreds of published papers produce "optimal" trajectories of global emissions of carbon dioxide, and corresponding carbon prices, over this century, taking into account future damages inflicted by climate change. To our knowledge, in all instances the models ignore inequalities in economic variables beyond regional differences. Here, we introduce heterogeneous subregional populations (distributed by income) and explore how the optimal trajectories are affected by whether regional damage afflicts the poor predominantly. We find that when future damage falls especially hard on the poor, considerably greater global mitigation effort is optimal than when damage is proportional to income.

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*The question of fat tails in the distribution of damage (5, 6) and more recently the climate impact on growth (7, 8) have also received much attention.

†This is one of the two substantive issues in the discounting debate. The other is whether future generations should be given less weight simply because they are in the future.

‡For instance, the models used by the US Environmental Protection Agency to estimate the social cost of carbon [DICE (12), FUND (13), and PAGE (14); see ref. 15)] do not disaggregate below the level of continental regions. In particular, the entire population of each region is taken to consume the regional average. (And DICE does not disaggregate below the global level.)

§This more fine-grained disaggregation of damage and consumption is somewhat analogous to the treatment of heterogeneous emitters in ref. 16, who find that 1 billion high emitters are spread across all the regions of the world.

¶A similar damage distribution is considered in ref. 17 in the context of the DICE model, but it is not coupled with heterogeneous income as we do here and therefore the impact they get is much smaller in magnitude.

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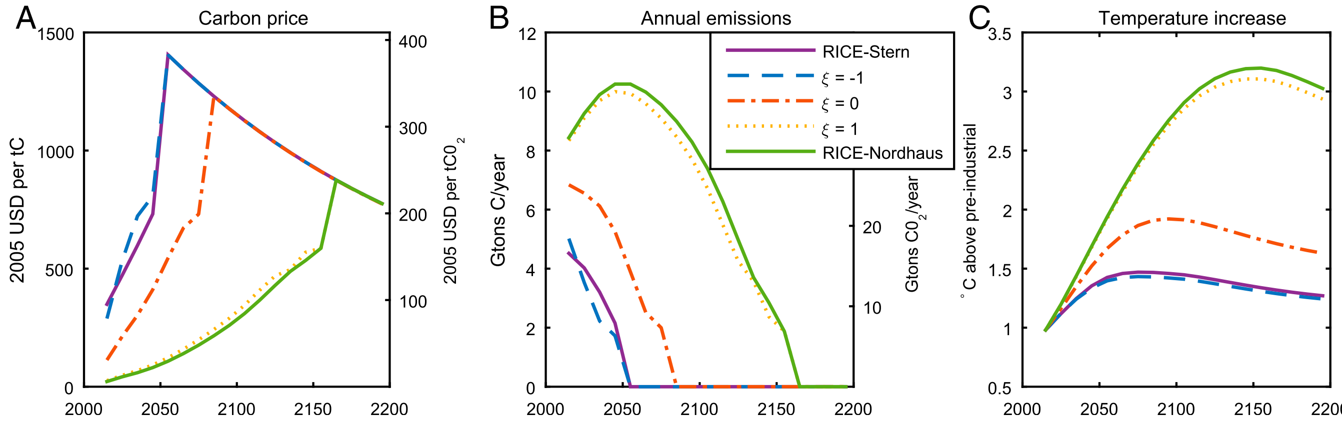

Fig. 1. The three panels plot model outcomes in NICE for different values of the income elasticity of damage: $\xi = 1, 0,$ and -1. Also shown are the optimal policies in our implementation of RICE for the (different) specific assumptions about discounting endorsed by Nordhaus vs. Stern. RICE-Nordhaus and $\xi = 1$ are similar, as are RICE-Stern and $\xi = -1$. (*A*) Optimal policy (carbon price trajectories). The descending line eventually joined by all price trajectories is the assumed trajectory of the maximum of the regional backstop prices. (*B*) The total emission rates for these policies. (*C*) The corresponding atmospheric temperatures.

distributions to calculate current quintile distributions for the RICE regions. We assume that in all periods of the model consumption before damages is distributed in this way in each of the regions. Damages reduce consumption according to a parameterized damage distribution function that allows for investigation of alternative assumptions about the relationship between income and damage. To distinguish the resulting model from RICE, we call it NICE, for Nested Inequalities Climate-Economy model.[#]

We represent the relationship between the damage distribution and the income distribution by the income elasticity of damage, which we denote by ξ (see Eq. **6**). Elasticities of 1,0, and -1 correspond to damage being proportional, independent, and inversely proportional to income. To illustrate, consider a population of two equally large income groups *A* and *B*, with *A* earning USD 4,000, and *B* USD 40,000 a year.[||] If this "economy" suffers 5% damage, they jointly lose USD 2,200. If $\xi = 1$, *A* loses 200 and *B* loses 2,000. If $\xi = 0$, both *A* and *B* lose 1,100. If $\xi = -1$, *A* loses 2,000 and *B* loses 200. *B* goes from losing 5% to 2.75% to 0.5%, whereas *A* goes from losing 5% to 27.5% to 50%. The value of ξ affects only the distribution, and not the total amount of damage.

Although limited, the available empirical evidence indicates that the poor are likely to suffer disproportionate damage from climate change, and thus that the value of ξ is likely less than 1 (21–24), and even negative for certain types of damage (25).[**]

There are two key normative parameters in climate-economy models. The pure rate of time preference, ρ, which is the rate at which the weight of the future declines with time, and the degree of aversion to inequality in consumption, η, which represents the diminishing marginal utility of consumption (i.e., the lesser importance of consumption as one gets richer). In this paper, we retain the values of these parameters (i.e., $\rho = 1.5\%$ and $\eta = 2$) adopted by William Nordhaus, the architect of RICE (2). In retaining the Nordhaus values, we do not take a stance on whether these particular values are justified. Rather, our aim is to illustrate the relative importance of accounting for inequalities in such models compared with the importance of the debate over discounting. So, our results are not driven by any change to the weight given to the poor vs. the rich, or the future vs. the present. In fact, to ensure that our results are only driven by the additional description of inequality, we keep almost all parameters as in RICE.[††]

Fig. 1 plots the implications for optimal policy in NICE of different assumptions about the elasticity of damage, ξ.[‡‡]

When damages are proportional to income ($\xi = 1$), the optimal carbon price is very similar to that obtained when we assume no income inequality at all within regions (what is called the "RICE-Nordhaus" case in the legend of the Fig. 1). It is clear that a significant increase in effort (in the form of a higher carbon price) is associated with the reduction of ξ from 1 to 0 (in the latter case, all quintiles within a region bear an equal share of the regional damages). The effort required with the inversely proportional damage distribution ($\xi = -1$) is even larger and similar to the "RICE-Stern" price. The latter is the optimal price calculated in our implementation of the RICE model[§§] under the discounting and inequality aversion assumptions of the Stern Review, which are quite different from those used by Nordhaus and in our optimizations.[¶¶]

In his critique of the Stern Review, Weitzman (4) disparages Stern's normative assumptions but claims that the urgency of the Review's conclusions is warranted on account of the uncertain distribution of damage. Here we claim that the same urgency would

[#]Inequalities appear at three nested levels: between generations, within generations between regions, and within regions between income strata. NICE also differs from RICE in a few other ways. For more detail, see *Materials and Methods* and *Modifications to RICE2010*.

[||]The ratio between the bottom and the top quintiles' income in China is approximately 1:10.

[**]Few contributions provide a numerical estimate of the "spatial" income elasticity (i.e., focusing on differences in income across the distribution) in a given country or region. An analysis of tropical storm-related damages (25) estimates an income elasticity of 0.4. Anthoff and Tol (26) estimate the elasticity of damage to GDP when GDP grows over time, which is a different concept than the relative vulnerability of income strata at any given time. In RICE, as in our model, total damages are proportional to total production in every region (which is not far off the long-term estimate of this temporal elasticity in ref. 26).

[††]See *Modifications to RICE2010* for details.

[‡‡]The descending line that all prices join in the leftmost graph is the maximal backstop price. This is the price at which full mitigation is achieved in all regions. In the figure, the optimal price curves have kinks due to the fact that backstop prices vary across regions, making some regions abate fully at lower prices.

[§§]This is essentially the RICE2010 model, with the modifications outlined in *Modifications to RICE2010*.

[¶¶]Nordhaus (2) sets $\rho = 1.5\%$ and $\eta = 2$, whereas Stern (1) sets $\rho = 0.1\%$ and $\eta = 1$. We could repeat the comparative analysis with respect to ξ at different values of η as well as ρ. At lower values of ρ the three relevant price paths in Fig. 1 are raised, and the difference between the prices is less. Lowering the degree of inequality aversion, η, has the effect of making the spread between the paths for different values of ξ less important, as well as raising the path for $\xi = 1$. In the extreme case of $\eta = 0$, total intertemporal consumption is maximized. The price paths for all values of ξ are then necessarily the same, because in this case inequality is unimportant. The more affluent future is no longer discounted on account of its affluence, thus raising the carbon price significantly relative to the baseline RICE-Nordhaus case.

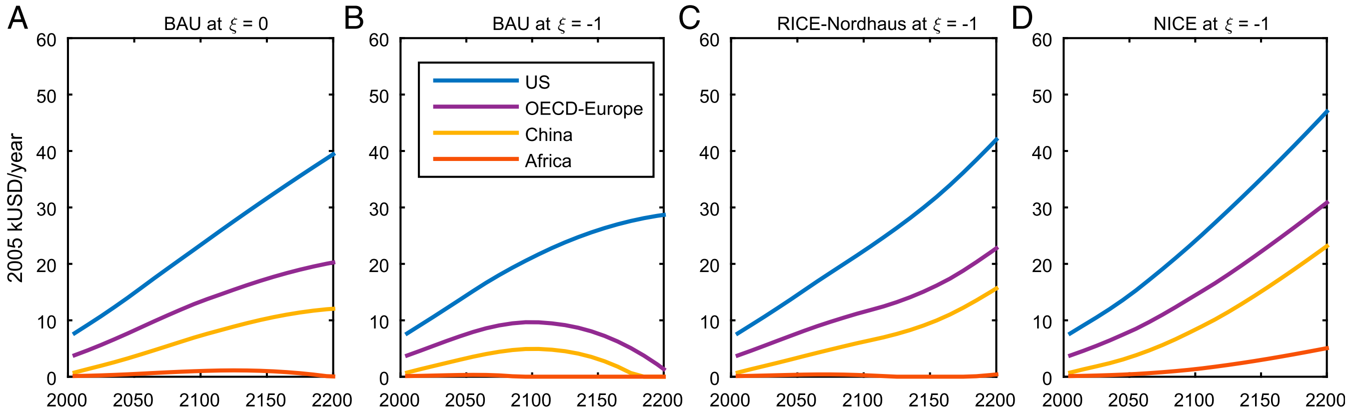

Fig. 2. Per capita consumption net of damage of the lowest quintile in four regions: United States, OECD-Europe, China, and Africa. In *A* there is no policy (BAU) and an equal distribution of damage. In *B* there is no policy (BAU) and inversely proportional distribution of damage. In *C* RICE-Nordhaus carbon price is applied in a world with inversely proportional damage. In *D* the optimal carbon price is applied in a world with inversely proportional damage.

be warranted if the distribution of damage across socioeconomic strata were skewed enough to the detriment of the poor. The case we make is also somewhat analogous to that of Weitzman (5), proposing to model the uncertain distribution of damages, rather than merely evaluating policy by calculating the average or expected damage that may occur. His argument is that if there is no way to hedge against very bad low-probability outcomes, and if society dislikes such bad outcomes disproportionately, one must model the whole probabilistic distribution, rather than gloss over the problem by averaging. Our argument is mathematically similar but bears on the distribution across individuals rather than states of the world. The distribution of future climate impacts on society could be so skewed, and unsharable across members of society (discussed in the next section), that significantly more mitigation effort would be optimal than is usually proposed under aggregate models.

The carbon prices we report are only optimal in a constrained sense. A fully unconstrained optimization would treat the world as a globe and adopt a globally uniform carbon price under the presumption of transfers equalizing consumption. In the absence of such equalizing transfers, the constrained optimum in a disaggregated model involves differentiated carbon prices requiring less effort from the less affluent (27, 28). Here we constrain the optimization even further, requiring a globally uniform carbon price despite the heterogeneity in income and constraint against redistribution. We require the same marginal effort from each region, despite the fact that regions are different in their ability to contribute. We adopt this constrained approach despite the welfare cost, seeing it as a likely focal point of the international bargain over mitigation effort.[##] Differentiated effort of the sort proposed in ref. 27 would lead to stronger optimal emission reductions than we propose here, but the strong sensitivity to the value of ξ would be unaffected.

At the subregional level we assume that mitigation cost is distributed across income groups in proportion to their income. Like the subregional damage distribution, which we parameterize by ξ above, this could take a different form—especially because the distribution of mitigation cost is a function of policy details.[***] For example, suppose the poor had to pay disproportionally for mitigation because their energy expenditures are a larger fraction of their total expenditures. In that case, optima for models such as NICE, which make explicit the burden of climate change on the poor, would entail less mitigation (a lower carbon price trajectory) than when mitigation effort is proportional to consumption—holding other assumptions the same. The opposite effect would follow if, due to different policies or lower involvement of the poor with energy markets, the abatement cost was less than proportional for the poor. We leave the determination of the exact quantitative effects to future work.

Fig. 2 shows per capita consumption paths for the lowest quintiles in four regions. We show these regions—and only the poorest quintile—to illustrate the effect that the distribution of damage can have on the development of the lowest income groups. The two left panels plot BAU under equal ($\xi=0$) and inversely proportional ($\xi=-1$) damage. Owing to a combination of relatively large regional damage and high income inequality, the poorest fifth in Africa hardly partake in growth, or grow and eventually lose those gains. This is true for $\xi=0$, but particularly stark if $\xi=-1$. The poorest fifth in China and Europe experience a slowdown in the former case, and also an eventual collapse in the latter. As shown in the third panel, if $\xi=-1$, the poorest fifth in Africa do not grow even under the mitigation policy that is optimal under the aggregated RICE model (RICE-Nordhaus policy in Fig. 1).[†††] In contrast, the poorest in all regions participate in growth under the optimal policy in NICE, even when $\xi=-1$, as can be seen in the fourth panel.[‡‡‡]

In existing IAMs, the absence of disaggregation of rich vs. poor individuals means that the fate of the poor is not represented. NICE demonstrates that the net consumption of the poor can exhibit a different pattern than average consumption. In particular, the consumption of the poorest in some regions could eventually decline, even under the policy that the aggregate model considers optimal (the RICE-Nordhaus policy).[§§§]

[##]Moreover, we find this a more consistent way of implementing the (in the IAM literature common) feature of equal marginal abatement costs. Other regionally disaggregated models do so by modifying the objective function with weights. See *Materials and Methods* for a brief discussion of the problems with that approach.

[***]A carbon tax that is rebated lump-sum has different distributional consequences than a carbon tax that is used to reduce capital or payroll taxes (see, e.g., refs. 29 and 30 for an analysis of this issue).

[†††]In light of the fact that the decline only begins in the 22nd century (except for BAU; $\xi=-1$), one could imagine that the results are driven primarily by the damages in the distant future. We have confirmed that the stark differences among the optimal carbon policies as a function of ξ shown in Fig. 1 are insensitive to the model's time horizon. That time horizon is 2595, but the policies to 2050 are nearly the same even when the horizon shrinks to 2105. Fig. S1 plots the same carbon prices as Fig. 1*A*, alongside the equivalent prices for model runs that are made to end in 2105 and 2155.

[‡‡‡]This can be verified for all regions in Fig. S4, where we show additional panels for different quintiles and elasticity assumptions in all 12 regions.

[§§§]This echoes the results from recent literature (surveyed in ref. 31) suggesting that climate change may have previously unappreciated impacts on the dynamics of poverty reduction by increasing the risk of nonpoor individuals falling into poverty and by reducing the ability of poor people to escape poverty. This would support the contention that unmitigated damage might impede the poor from sharing in economic growth.

This finding shows why ignoring inequality within regions may be unacceptable from the perspective of both justice and sustainability, if one understands justice as requiring that (current) benefits to the affluent should not stem from activities that harm the (future) poor, and sustainability as requiring that future generations be able to sustain their predecessors' level of living standards, not only on average but also in the most disadvantaged groups.

Redistribution by Other Means

It is well understood from the theoretical cost–benefit analysis literature that such attention to distributional issues would be unnecessary, and even inefficient, if first-best transfer policies were available to correct for inequalities.

To determine whether the additional mitigation effort we compute could be obviated by an exogenous level of income redistribution, we add to the model a revenue-neutral constant-proportion "flat" tax on the postdamage consumption levels. The tax revenue is distributed equally, as a lump-sum basic income.

Specifically, we investigate the magnitude of the tax that would bring the carbon price back to the RICE-Nordhaus level even when $\xi = 0$. That is, we calibrate the tax to generate the same optimal mitigation effort in two scenarios (both with Nordhaus's normative parameters): (*i*) NICE with the redistributive tax in the case of equal-damage distribution ($\xi = 0$) and (*ii*) RICE (which has no inequality within regions) without redistribution. To make the case as favorable as possible to redistributive taxation, it is assumed that the tax has no disincentive effects reducing gross domestic product (GDP). Therefore, this redistribution is maximally effective.

We examine two variants of such redistributive taxation. In the first variant, we assume that transfers will happen only within regions, with the same tax rate in all regions and at all times. We find that it would require a redistributive tax on consumption of 65% to make the two carbon price trajectories the same.[¶¶¶]

In the second variant, we examine the same pair of damage scenarios but assume there is a cross-regional transfer instead of within-region redistribution. More specifically, we consider a cross-regional transfer of assistance levied in equal proportion on all residents of the richest four regions, and distributed in equal quantity among all of the residents of the poorest eight regions. We find that there is in fact no sufficiently large amount of such a transfer, implemented in this way, that would bring the $\xi = 0$ carbon price trajectory with the transfer down to the RICE-Nordhaus level. Such a tool is simply too blunt to achieve the task.

Note that if redistribution were actually costless and if the values of society supported the unconstrained maximization of the utilitarian objective, the resulting policies would involve complete redistribution of income and complete compensation of damages across quintiles in addition to externality-correcting policies.

Such extreme sharing is most unlikely to happen (for many reasons: e.g., inequalities are often considered to be partly legitimate due to unequal individual efforts, and climate impacts cannot be distinguished from other sources of fluctuations). This is why we instead examine different options—a combination of flat tax and basic income or international transfers. These are more policy-relevant and show that the amount of redistribution that makes the usual RICE results an acceptable simplification would be very high indeed.

These results provide some indication that redistributive policy is not a good substitute for stronger mitigation policy. This is not to say that redistribution may not be an important complementary policy. Still further analysis is needed to understand how mitigation and redistribution can best interact in the protection of the future poor from climate impacts.

Conclusion

Our results demonstrate the importance of accounting for inequalities within regions. As we have shown in NICE the optimal mitigation effort under the discounting and inequality aversion assumptions of Nordhaus (2) when damages are distributed inversely proportionally to income is equivalent to optimal mitigation in the more aggregated RICE model under the lower discounting and inequality aversion assumptions of the Stern Review (1). Therefore, properly accounting for the distribution of consumption and damage within regions may be as important for climate change policy as the debate over discounting. Modeling the income distribution is also essential to incorporating concern for the vulnerability of the future poor: a concern shared by a wide range of ethical and religious perspectives[###] as well as the utilitarian objective that guides our optimization.

The recent IPCC AR5 WGII report (35) has highlighted the vulnerability of the poor to climate impacts. Still, the empirical estimates of the distribution of climate impacts among different socioeconomic strata are currently very limited. We show that improving these estimates and incorporating them into cost–benefit IAMs will increase the accuracy of the prescriptions of these models and thus help better inform policy making on global climate change. Representing subregional inequalities and the distribution of damage and mitigation cost should become new best practices in cost–benefit IAMs.

Materials and Methods

NICE is derived from the RICE2010 Excel spreadsheet.**** In this section we describe the modifications relating to the additional description of the subregional income distributions and the redistributive experiments, as well as the welfare function. The full details on the difference between NICE and RICE2010 are found in the sections below. As in RICE2010, we optimize for a carbon tax to maximize a social welfare function, which in our case takes the separable and constant elasticity form

$$W(c_{ijt}) = \sum_{ijt} \frac{L_{ijt}}{(1+\rho)^{10t}} \frac{c_{ijt}^{1-\eta}}{1-\eta}. \qquad [1]$$

Notice that this specification implies an aversion to inequality in consumption (parameterized by η) that is independent of whether the inequality is across contemporaries or across time.

As can be seen from Eq. **1**, unlike RICE2010 we do not use Negishi weights. They are not needed in our extension because we restrict redistribution between regions. That is, the social planner does not have the option to redistribute consumption across regions (or even across quintiles within regions) to maximize Eq. **1**. In the original (GAMS) RICE model, consumption is an instrument, and full equalization of consumptions across regions would be implemented with an objective like Eq. **1** without further restrictions. Negishi weights were introduced to restrict redistribution and ensure that it does not become a policy tool. In NICE and our version of RICE, we do not need Negishi weights because we restrict the possibility of redistribution directly. Moreover, Negishi weights distort the evaluation of the distribution of damages, making the incidence of damage on different regions (and income strata, if applied to those) unimportant to a Negishi-weighted objective. Furthermore, as in the RICE2010, we constrain the social planner to equalize marginal abatement cost across regions, which was another one of the desired implications of Negishi weights.

The main substantive extension from RICE2010 to NICE is the inclusion of subregional income quintiles for all of the 12 regions. Using the World Development Indicators' data on income distribution by country we compute the current quintile distributions for the RICE regions. Assuming that these remain constant, we create consumption quintiles for all regions using these distributions in all periods.

[¶¶¶]That is, if a 65% flat tax were implemented in every region and every period, and the revenue recycled lump sum within each region, the optimal carbon price trajectory at $\xi = 0$ would be equivalent to the optimal carbon price trajectory at $\xi = 1$ without redistribution. Given the model's savings rates and the assumption of no disincentive effects, this would be equivalent to an additional 48% marginal income tax rate.

[###]See ref. 32 on sustainability, ref. 33 on justice, and Pope Francis' Encyclical Letter of May 2015 (34) for a religious perspective.

****The spreadsheet can be found on William Nordhaus's website, www.econ.yale.edu/~nordhaus/homepage.

Denoting regional gross output, mitigation cost and damage by Q_{it}, Λ_{it}, and D_{it} respectively, net output is given by

$$Y_{it} = \frac{1-\Lambda_{it}}{1+D_{it}} Q_{it}. \quad [2]$$

Given population, L_{it}, and savings rate, s_{it}, average consumption in region i and period t is given by

$$\bar{c}_{it} = \frac{1-s_{it}}{L_{it}} Y_{it}. \quad [3]$$

The disaggregated predamage consumption quintiles are computed by

$$c_{ijt}^{\mathrm{pre}} = 5\bar{c}_{it}(1+D_{it})q_{ij}, \quad [4]$$

where q_{ij} is the income share of the jth quintile in region i. The postdamage consumptions are given by

$$c_{ijt} = c_{ijt}^{\mathrm{pre}} - 5\bar{c}_{it}D_{it}d_{ij}, \quad [5]$$

where d_{ij} is the damage share of the jth quintile in region i.

The damage shares are computed for different values of the elasticity ξ, such that, for all ξ and corresponding constants $k_{i\xi}$,[††††]

$$d_{ij} = k_{i\xi} q_{ij}^{\xi}. \quad [6]$$

This yields a constant elasticity relationship for the damage as a function of income.

The modifications for the *Redistribution by Other Means* section are implemented as follows. In both modifications, postdamage consumption is modified by revenue neutral transfers, in one case across quintiles within regions and in the other case across regions. For the within-region redistribution the same marginal tax rate τ is applied in each region to yield posttax consumptions:

$$c_{ijt}^{\mathrm{tax}} = (1-\tau)c_{ijt} + \theta_{it}, \quad [7]$$

where

$$\theta_{it} = \tau\bar{c}_{it}, \quad [8]$$

which results in a revenue-neutral reallocation within regions.

For the cross-regional transfer we levy a constant proportion α on the consumption of the four rich "donor" regions: United States, Japan, OECD Europe and "Other High Income" (OHI). Denote this group of regions by $\mathcal{D}$. Then for $i \in \mathcal{D}$,

$$c_{ijt}^{\mathrm{aid}} = (1-\alpha)c_{ijt}. \quad [9]$$

Denoting by $\Omega_t = \sum_{i\in\mathcal{D}} \alpha\bar{c}_{it}L_{it}$ the total amount of aid, the consumptions of the aid-receiving regions ($i \notin \mathcal{D}$) are given by

$$c_{ijt}^{\mathrm{aid}} = c_{ijt} + \frac{\Omega_t}{\sum_{i\notin\mathcal{D}} L_{it}}. \quad [10]$$

NICE deals with abatement cost following RICE2010, which distributes abatement cost across regions in such a manner that the marginal abatement cost to each region is always the same, with the additional constraint of zero transfers between regions. This amounts to an implementation in which each region implements the same carbon price and recycles the revenues internally.

Income and Damage Distributions

RICE2010 consists of 12 regions, with explicit regional parameters describing economic and climate variables as regional aggregates. Our analysis is based on the idea that subregional distribution is an important feature being masked by this level of aggregation. To get at a regional description of consumption inequality we break down the consumption part of regional output into quintile shares. These are computed by aggregation of the cumulative distribution functions given by the World Bank Development Indicators data on GDP, population, and quintile shares at the national level (20). We used 2005 data, when available, or the most recent available alternative.

When regions are not disaggregated, the Gini coefficient of the World is 0.55, but when each region is disaggregated into quintiles as described above the Gini coefficient is 0.65. The difference stems from the fact that much of global inequality is hidden at the subregional and subnational level. This is the inequality that is "hidden" at the level of aggregation of RICE that we are able to capture in NICE.

We plot the global Lorenz curves for the disaggregated and the aggregated regions as well as the regional Lorenz curves in Fig. S2. The Gini coefficients for the 12 regions range from a high of 0.57 for the Africa region to a low of 0.30 for Japan.

In Table S1 we present the income shares in percent of the regional quintiles that come out of the regional disaggregation. These are also the damage shares of the same quintiles when $\xi = 1$ (i.e., when damage is distributed proportionally to income).

In Table S2 we show the damage shares in percent for the case $\xi = -1$. When $\xi = 0$ damage is distributed evenly. That is, each entry would be 20 in the table for $\xi = 0$.

Modifications to RICE2010

NICE is based on a MATLAB implementation of the RICE2010 Excel spreadsheet. The spreadsheet model was implemented as is apart from the following modifications.

Savings Rate. We implement a fixed (Solow) savings rate of 25.8% in all regions and all time periods. This has the large benefit of simplifying the optimization algorithm. Furthermore, it can be also be interpreted as the optimal savings rate of private savers with a time-separable and discounted objective with a logarithmic utility function.[‡‡‡‡] Capital depreciation, which is 10% per annum in RICE2010, is decadized arithmetically (rather than geometrically as in the original model) to full depreciation. Combined with logarithmic utility (of the private savers, not the social planner), it can be shown (see ref. 36) that the resulting endogenous savings rate of an infinitely lived agent is given by

$$s_{it} = \frac{\gamma}{(1+\delta)^{10}}. \quad [11]$$

Here γ is the capital share in the Cobb–Douglas production function, and δ is the annual pure rate of time preference of the representative agent's objective. When $\gamma = 0.3$ and $\delta = 1.5\%$, $s_{it} = 25.8\%$.

Sea-Level Rise. RICE2010 implements sea-level rise (SLR)-related damages as an innovation over the previous version of RICE. In addition to the quadratic damages from temperature, it models an additional term based on a simple SLR module. For simplicity our version does not implement this exact specification. Instead, we estimate new coefficients for a quadratic function of temperature to get similar quantitative effects.

Denoting by D^{nonS} as the non-SLR component and by D^{S} the SLR component, the original specification consists of a damage function D such that

$$D_{it} = D_{it}^{\mathrm{nonS}} + D_{it}^{\mathrm{S}} \quad [12]$$

with

$$D_{it}^{\mathrm{nonS}} = \beta_{1i}T_t + \beta_{2i}T_t^2 \quad [13]$$

$$D_{it}^{\mathrm{S}} = \left(b_{1i}S(T_t) + b_{2i}S(T_t)^2\right)\left(G_{i,0,t-1}\right)^{\frac{1}{4}}. \quad [14]$$

Here T_t is the temperature increase above preindustrial levels, $S(T_t)$ is the amount of SLR as a function of temperature

††††The constant $k_{i\xi}$ is chosen so that $\sum_j d_{ij} = 1$.

‡‡‡‡This is different from the social planner's objective, with $\eta = 2$.

increase, and $G_{i,0,t-1}$ is the economic growth factor (one plus growth rate) of region i between period 0 and period $t-1$.

From this specification, we estimate a new specification:

$$\widetilde{D}_{it} = \lambda_{1i} T_t + \lambda_{2i} T_t^2. \quad [15]$$

This is done by computing D from the spreadsheet model for a couple of runs of the model (BAU and optimum). For every region, these terms are regressed by ordinary least squares against temperature by the specification (Eq. **15**). The result is an estimate of the total damage term, which only depends on temperature.

Table S3 shows the resulting estimated damage coefficients λ_{ni} alongside the coefficients of the original non-SLR component of damage β_{ni}. The resulting functions from temperature increase to proportional economic damage (for all 12 regions) are plotted in Fig. S3.

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