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Global unanimity agreement on the carbon budget

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Abstract: Carbon budgets are a useful way to frame the climate mitigation challenge and much easier to agree upon than the allocation of emissions. We propose a mechanism with countries agreeing on the global carbon budget, while the decision to emit is decentralized at the country level. The revenue is collected in a global fund and allocated according to endogenously defined weights proportional to the marginal cost of climate change. The proposal features a *unanimous agreement* of the national citizenries of the world and global Pareto efficiency. We run a simulation in the spirit of the Paris Agreement, with zero emissions after 2055. At the Global Unanimity Equilibrium, permits are priced at 90$/tC, yielding 1.3 trillion dollars annually. Africa, India and the less developed countries in Asia are the only net recipients, while the US and China are the largest net contributors.

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Introduction

The global emissions problem is one where non-cooperative (Nash) equilibrium among countries in the choice of their national emissions will suffer from the tragedy of the commons.[1] That name is simply a dramatic way of saying that in the emissions 'game,' the Nash equilibrium is (massively) Pareto inefficient. Countries must cooperate to avoid this bad equilibrium. The COP meetings are venues that should be understood as attempts to build trust and solidarity among nations, so a cooperative solution that is Pareto efficient can be achieved.[2]

However, a climate agreement to reduce emissions has been proved difficult to achieve. The global carbon budget, we argue, is a useful way of framing the climate mitigation challenge and perhaps a much easier issue to agree upon than the allocation of emission permits. We propose a method by which the decision on the level of carbon emissions can be decentralized to the regional or country level, where firms treat their emissions as a production input for which a price is charged. The revenues from these charges accumulate in a global fund, and are returned to global citizens according to national shares that are announced ex ante. We model the global economy as one with a single good, produced in all countries according to nationally specific production functions, which use labor and capital as inputs, and emit carbon according to nationally specific intensities with respect to output. We propose a global equilibrium in capital, output, and emissions. The markets for capital and output are standard. The market for carbon emissions is not. As mentioned, the *demands* for carbon emissions of countries are set by the profit-maximizing firms in each country, which must pay for standard inputs and proposed emissions. The *supply* of global emissions is *unanimously agreed upon* by country/regional citizenries. In choosing its desired global level of carbon emissions, each country maximizes the utility of its representative citizen, who benefits from consumption of the (unique consumption) good, and suffers damages from the global emissions level. In equilibrium, all markets clear: in particular, all countries agree upon the desired global carbon budget, which equals (in equilibrium) the sum total of the demands for carbon emissions of the world's firms.

The virtues of the proposal are the following: (1) the global emissions level is not set by negotiations but by *unanimous agreement* of the national citizenries of the world; (2) the demand to emit carbon is decentralized to the firm level; (3) the equilibrium is globally Pareto efficient – there is no feasible allocation of capital, the good, and emissions that could make all countries better off. The system can be viewed as one in which each country's firms demand permits to emit carbon, for which they pay a common price, and the vector of country shares for the distribution of the carbon fund assures country unanimity of agreement on what the number of carbon permits globally should be.

In our approach, decisions to emit are made at the firm level. Because firms decide upon their emissions as part of a profit-maximizing plan, no firm has an incentive to emit more than it demands. Substantial negotiations would be required to achieve agreement on the production and damage functions that characterize nations/regions. And the shares according to which the global carbon revenues are returned to nations must appear to be fair, for if they are not accepted, then unanimity on the global emissions level will dissolve. But once the mechanism is implemented, it will only be necessary to monitor that firms do pay for their profit-maximizing emissions to the global fund.

A global unanimity equilibrium

In this section, we model the above proposal and study its properties. There are n countries, each endowed with labor, capital, and a technology for producing a single good. Country j is represented by an agent with a quasi-linear utility function

$$u_j(x,E) = x - h_j(E), \tag{1}$$

where x represents the GDP per capita of the country, h_j is a convex damage function, and E is the global level of carbon emissions. Each country has a concave aggregate production function

$$y = G_j(K), \tag{2}$$

where y is output of the single good and K is capital. It is assumed that labor is immobile across countries, but capital is mobile. Therefore, the production function G_j assumes full employment of the country's labor supply, which is implicit in equation (2). Besides its labor supply, country j is endowed with capital in the amount $\bar{K}_j$.

Emissions are assumed to be proportional to production[3,4]

$$E_j = \eta_j y_j \ . \tag{3}$$

Definition 1. An allocation of output and emissions $((x_1,E_1),...,(x_n,E_n))$ is *globally feasible* if there is an allocation of capital $(K_1,....,K_n)$ and output $(y_1,...,y_n)$ such that:

$$y_j = G_j(K_j),\ E_j = \eta_j y_j,\ \sum x_j = \sum y_j \quad \sum K_j = \sum \bar{K}_j \quad . \tag{4}$$

Definition 2. A feasible allocation is *Pareto efficient* if there is no other feasible allocation that gives at least one country higher utility and no country lower utility.

We now describe how the economy works. There are three markets: for the produced good, whose price will be denoted p; for capital, whose interest rate is r; and for carbon emissions, whose price is c. The firm in each country will demand capital to maximize profits:

$$\Pi_j = pG_j(K_j) - c\eta_j G_j(K_j) - rK_j, \tag{5}$$

where it must pay the carbon cost of the emissions it creates. All profits, which here include wages because labor is implicit in the production function, are returned to the population of the country. The carbon payments are deposited in an international fund, and will be distributed to countries as demogrants, where country j will receive back a fraction a_j of total revenues. Thus, along with the price vector (p,c,r), global citizens observe a vector of shares $(a_1,...,a_n) \in \Delta^{n-1}$, where Δ^{n-1} is the unit simplex in $\Re^{n-1}$.

The income of country j will be:

$$I_j = \Pi_j + r\bar{K}_j + a_j cE, \tag{6}$$

where E is global emissions, and so cE is the value of the carbon fund. Each country supplies its entire capital endowment to the market.

It is clear there is a supply and demand for capital, and there is also a supply and demand for the good, because each country will demand the good in amount I_j/p.

The demand for emissions is determined by the firms' profit-maximizing choices, but we have yet to determine the supply of emissions, which we do as follows. Note that the utility of country j is given by:

$$V_j(E) = \frac{\Pi_j + r\bar{K}_j + a_j cE}{p} - h_j(E). \tag{7}$$

For the citizenry of country j, the optimal level of global emissions, E, is therefore given by the first-order condition:

$$(V_j)'(E)=0 \quad \text{or} \quad a_j\frac{c}{p}=(h_j)'(E). \tag{8}$$

We close the model by requiring that the citizenries of the n countries *unanimously agree* on the value of E. Thus, the global citizenry 'supplies' the emission permits *in toto* to firms.

We summarize the equilibrium of the economy as follows.

Definition 3 A *global unanimity equilibrium* is a price vector (p,c,r), a share vector $(a_1,...,a_n)\in\Delta^{n-1}$, an allocation $(x_1,...,x_n,K_1,...,K_n,E_1,...,E_n)$, and a global supply of emission permits E such that:

(a) for each country j, (K_j,E_j) maximizes firm profits $\Pi_j=pG_j(K_j)-cE_j-rK_j$, subject to the constraint $E_j=\eta_jG_j(K_j)$,

(b) for each country j, E maximizes its utility $V_j(E)=\dfrac{\Pi_j+r\bar{K}_j+a_jcE}{p}-h_j(E)$,

(c) country j's demand for the good is $x_j=\dfrac{\Pi_j+r\bar{K}_j+a_jcE}{p}$, and

(d) all markets clear: $\sum\bar{K}_j=\sum K_j,\ \sum E_j=E,\ \sum x_j=\sum G_j(K_j)$.

We have:

Proposition 2.

A. *Any global unanimity equilibrium satisfies the first-order conditions for Pareto efficiency.*

B. *In equilibrium, the share of the global carbon fund that country i receives is proportional to its marginal damages* $(h_j)'(E)$.

(Proved in Supplementary Note 1)

Economists will recognize that a global unanimity equilibrium is a species of Lindahl equilibrium. How would the equilibrium be achieved? An international team would collect the data (damage functions, production functions, capital endowments, carbon intensities of production) and compute the equilibrium, as we do in the next section. In particular, the share vector $a=(a_1,\ldots,a_n)$ would be computed, and as we see from equation (9), the country shares of the emissions fund are proportional to marginal damages at the solution. As we wrote, the virtues of the solution are global Pareto efficiency, unanimity of agreement on the global carbon budget, and decentralization of the demands for carbon permits.

Results

To illustrate the implications of a global unanimity equilibrium, we simulate a 12-region world that negotiate, in the spirit of the Paris Agreement, a climate agreement for 40 years (2016-2055), with the assumption of zero emissions afterwards. To approximate the dynamic situation, we endow each region with an annual stock of capital, an annual population, and a carbon intensity parameter that represent annual average values for the period in consideration. We also identify utility with the present value (in international $) of the average annual consumption, net of climate change damages. Climate change damages are computed as the monetized present value (also in international $) of warming costs to the end of the century associated to cumulative emissions. Details are provided in the Methods section.

Data come from the baseline run in the Regional Integrated model of Climate and the Economy (RICE), representing a business-as-usual scenario.[3,5] RICE is described in Nordhaus and Boyer[3] and is one of the leading climate-economic models.[6] The twelve regions correspond to United States (US), the European Union (EU), Japan, Russia, Eurasia, China, India, Middle East, Africa, Latin America, Other High Income countries (OHI), and Other Asian countries.

We solve for the Global Unanimity Equilibrium using Mathematica 11 (details in the supplementary notes). At equilibrium, emission permits are priced at 90$/tC, yielding an average total revenue of 1.3 trillion dollars per annum. Global average emissions are 14.4 GtC for the period 2016-2055, and zero afterwards. Therefore, total cumulative emissions amount to 575 GtC (approximately 2,100 $GtCO_2$), which, according to (12), would result in a temperature increase around 1.3ºC above pre-industrial levels. These values are fairly consistent with the latest Global Warming of 1.5ºC IPCC report (Figure SPM1 (a) and (c)).[12]

Results are summarized in Table 1 and Fig. 1. The following points are worth emphasizing:

1. Africa, China and India receive the largest shares of total revenue, being the regions with the highest marginal costs of increases in temperature according to RICE-2010. These three regions together receive over half of total revenue.
2. However, when we account for the contribution to the global fund, China becomes the second largest net contributor, with a net payment of 78 billion dollars, only after the 99 billion dollars of net contribution by the USA (Fig. 1 and last column in Table 1). The net contributions of these two regions alone amount for almost 60% of the total amount by net contributors.
3. Africa, India and the small less developed countries in Asia are the only net recipients from the global fund. Africa, with 193 billion dollars, is by far the largest net recipient, obtaining 2.75 times the amount received by India (70 billion \$). The *net* annual payment to India, Africa and Other Asia is \$371 billion per annum, virtually quadruple the \$100 billion commitment to the developing world agreed upon in Paris (COP-21).
4. Although the mechanism does not have any explicit built-in redistributive objective, inequality is reduced compared to 2015 values. For instance, while the US per capita income is 14 times that of Africa in 2015, it reduces to only 8.5 times on average for the period 2016-2055. This equalizing effect may originate in the negative relationship between income and climate change costs. Poorer regions are more intensively affected by climate change than richer regions, receiving a larger share of total revenue, hence reducing income differences.

Region	Share of total permits revenue a_j	$\frac{a_j}{\text{Pop. Share}}$	a_j per million person	Revenues		
				billion $	$ per capita	as %GDP
US	0.077	1.72	0.20	121.70	322.04	0.55
EU	0.112	1.65	0.19	177.61	309.20	0.77
Japan	0.015	1.14	0.13	23.62	214.23	0.50
Russia	0.007	0.45	0.05	10.38	84.75	0.39
Eurasia	0.010	0.44	0.05	16.05	82.75	0.61
China	0.181	1.07	0.13	287.53	201.23	1.47
India	0.131	0.74	0.09	207.27	139.04	1.94
Midd.East	0.057	1.57	0.18	89.85	293.75	1.48
Africa	0.220	1.11	0.13	348.59	208.52	3.06
LatAme	0.063	0.75	0.09	99.80	141.43	0.78
OHI	0.030	1.89	0.22	48.19	355.02	0.81
Oth.Asia	0.099	0.62	0.07	157.30	116.20	1.49

Table 1 Allocation of permits' claims and revenues. The shares of total revenue are endogenously determined in equilibrium according to $a_j = \frac{1-\rho}{\rho-\rho^N}\frac{p}{c}(h_j)'(E)$. Each country receives revenue equal to $a_j\left(c \times E\right)$, where $\left(c \times E\right)$ is total revenue from emission permits. GDP is the average value for the region in 2016-2055, the period under consideration.

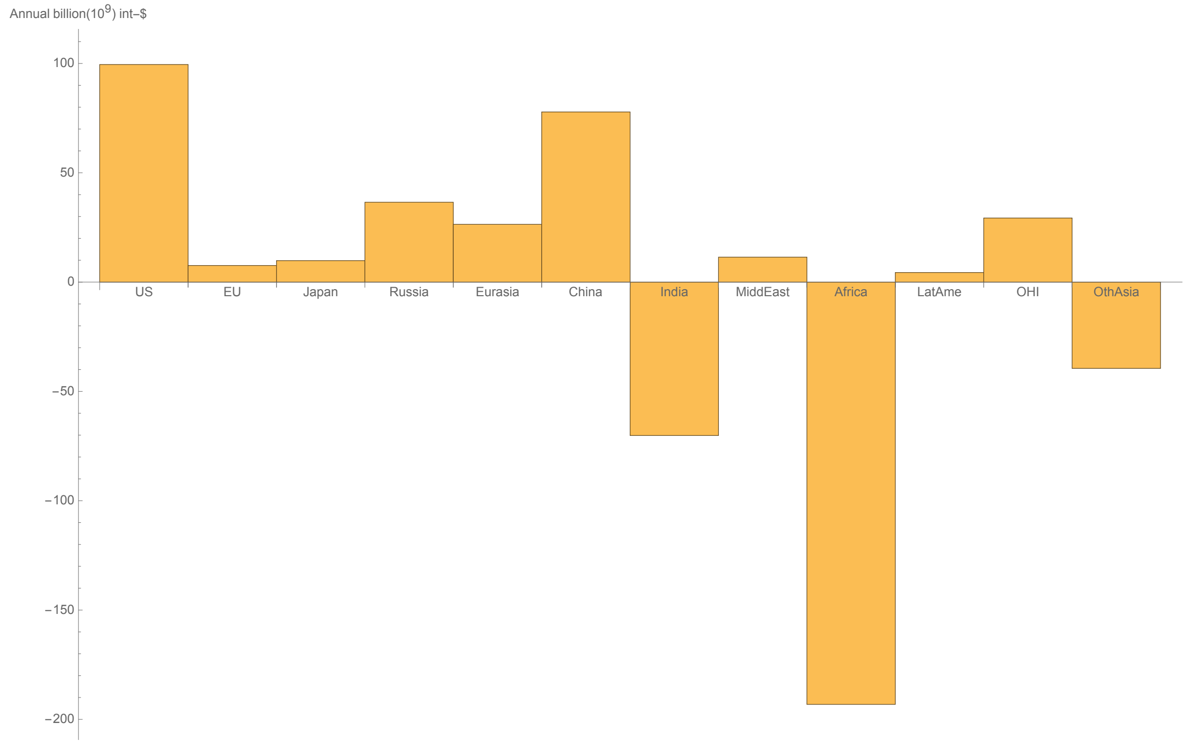

Fig.1 Net contributions to the global fund. Bars represent the difference between the amount contributed and the amount received by each region from the global fund. Only India, Africa and Other Asian (representing Asian small developing countries) are net recipients, they receive from the global fund more than what they contribute from buying pollution permits. USA, China and Russia are the main net contributors. Quantities are in billion (10^9) of international dollars.

Climate damages in RICE model are almost surely underestimated.[13,14] For a robustness check, we repeat the analysis for a range of much larger damages, finding a similar pattern in the allocation of net recipients, with magnitudes increasing with the cost of climate change (Supplementary Note 5).

The climate response of zero emissions is an important source of uncertainty in understanding the long-term climate response to a given quantity of cumulative emissions. We have followed the view that temperature tends to remain stable after zero emissions.[15-17] However, other models simulate temperature increases for a few decades after stabilizing,[18,19] or decreasing or slightly declining temperatures following zero emissions.[20-23] We deal with this uncertainty showing that results are robust to the current range of Transient Climate Response to Emissions (TCRE). The current range of TCRE is “larger than the uncertainty range derived from the observational record,” suggesting that “there is little evidence of missing major positive carbon cycle feedbacks that would significantly decrease the estimate of carbon budgets derived from model TCRE values”.[9] The robustness analysis finds that the effects of different values for the TCRE are equivalent to changing damages, scaling up or down magnitudes but keeping the same patterns (Fig. 2).

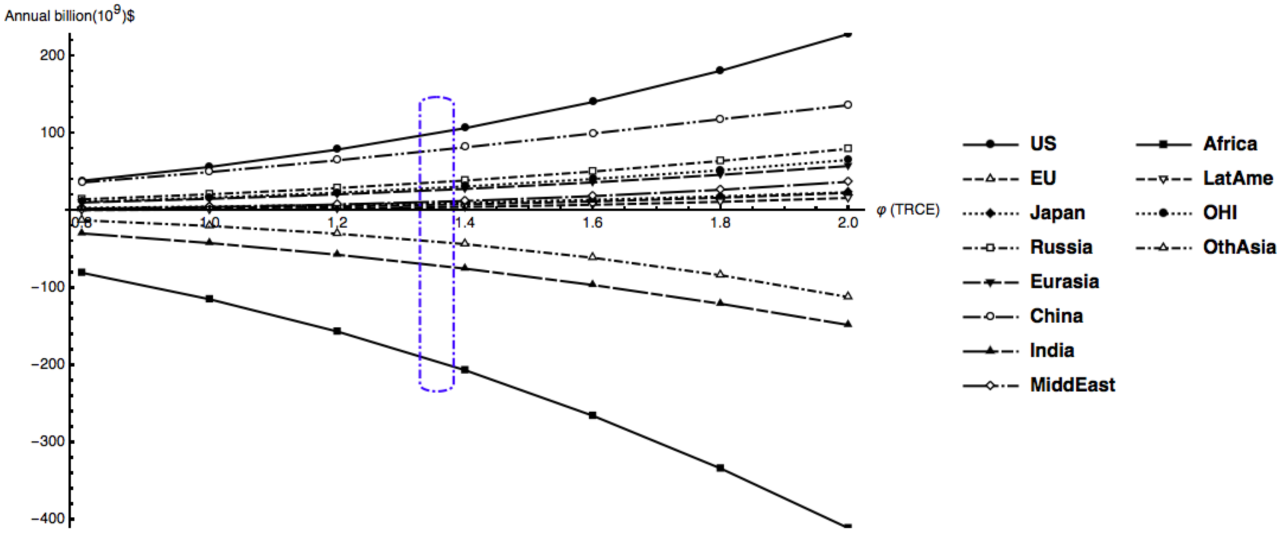

Fig. 2 Net contributions and recipients for different values of the TCRE. The blue rectangle represents the net contributions for $\varphi = 1.35$, the best estimate used in our analysis. The values of $\varphi \in [0.8, 2]$ belong to the observationally constrained 5%-95% range.[10]

Is the global unanimity equilibrium fair or just?

There is a literature, mainly authored by philosophers and political theorists, concerning the justice or fairness of proposals for addressing the climate-change challenge. Potier et al. provide a recent comprehensive survey.[24] It is not our task to review this literature here. We do, however, wish to comment somewhat further on the proposal's virtues.

We believe it is difficult if not impossible to define what a just solution to the climate-change challenge is, apart from providing a solution to the problem of the just global allocation of resources *tout court*. This point is forcefully made, in another area of discourse, by Murphy and Nagel.[25] Their project is to define 'just taxation,' and their salient point is that it's impossible to define just taxation apart from defining a just allocation of resources overall. If one had the solution to the larger problem, just taxation would be that taxation that would render after-tax incomes equal to the just distribution of income. Short of that, one could define second-best just taxation as taxation that would move a society in the direction of the just distribution of income. Surely any taxation that would not move a society towards its just distribution should not be considered just: and how would one be able to evaluate that movement without knowing what the just distribution is?

Similarly, one can argue that to be just, an allocation of permits to emit carbon among nations must necessarily produce a global distribution of income that moves in the direction of the globally just distribution of income. However, if we insisted on this criterion for evaluating proposals to address climate change, it is unlikely we would ever be able to design a politically acceptable agreement. We cannot make the solution of the climate-change challenge hostage to an agreement upon the rectification of the injustices committed by slavery, colonialism and imperialism, inter alia, but global justice surely requires the rectification of those historical harms. Both the libertarian Robert Nozick[26] and the egalitarian John Rawls[27] would agree on that point.

We base our advocacy of the proposal offered on its following attractive features:

- It decentralizes the achievement of a globally Pareto efficient allocation of capital, the good, and emissions; in particular, firms propose profit-maximizing levels of emissions, where the cost of emissions to them is determined by an equilibrium price that equates ‘supply’ and ‘demand’ for emissions.
- While the demand for emission (permits) is left to firms, the global supply of permits is determined by unanimous agreement among nations, concerning what global emissions level maximizes the country’s utility, given the prices of the good, capital and emissions, and the vector of shares $(a_1,...,a_n)$.
- No central authority sets the global supply of permits, nor is there any ex ante allocation of permits to individual firms or nations.
- In equilibrium, the share of the global revenues from emissions fees that a country/region receives is proportional to the marginal damages from global emissions that it sustains. Thus, countries with more severe marginal damages are compensated more.
- Our simulations indicate that, over a 40 year period, about $370 billion per annum would be transferred from the global North to the global South. The three regions that are net recipients of these transfers are Africa, India and Other Asian. This is almost four times to annual transfers agreed upon in Paris. Global income distribution would as well improve, in the sense of lowering inter-regional inequality, although that was not an explicit goal of the proposal.

We do not wish to attempt a stronger *ethical* defense of the shares $(a_1,...,a_n)$ according to which the emissions fund will be distributed. The main justification of the specific share vector is that it engenders Pareto efficiency and global unanimity of national/regional citizenries with regard to the global emissions budget. Because arriving at a cooperative solution to this massive challenge to our species at this time is so important, the achievement of those objectives, we propose, is sufficient justification.

Methods

Here we explain in detail the components of the model for our application and their calibration based on RICE-2010: utility function, production function, carbon intensity and endowments (stock of capital and population).

Utility is measured as the present value of average annual consumption $v(x_j)$, net of climate damages $h_j(E)$ related to annual emissions E,

$$u_j(x_j,E) = v(x_j) - h_j(E)\,. \tag{9}$$

Both consumption and damages are measured in trillions of international US dollars. For a discount factor ρ and a period of N years, the present value of consumption is simply

$$v(x_j) = \sum_{t=1}^{N} \rho^t x_j = \frac{\rho - \rho^{N+1}}{1-\rho} x_j\,. \tag{10}$$

Climate change damages are generated by the increase in temperature, which, ultimately, depends on cumulative emissions. We proceed in three steps: First, we calibrate annual climate change damages for region j as a function of the increase in temperature ΔT. Second, using TCRE, which relates global cumulative emissions until period t to temperature increases, we obtain annual damages as a function of cumulative emissions. Finally, we compute the present value of climate change damages.

Annual climate damages for region j as a function of temperature increase $d_j(\Delta T)$ can be nicely fit to the baseline run data of RICE-2010 for the period 2005-2215 using an exponential function[7]:

$$d_j(\Delta T) = \alpha_{1j}\, e^{\alpha_{2j}\,\Delta T} \tag{11}$$

Damages are measured in annual trillions of international dollars, and temperature change in degree Celsius from pre-industrial levels. The parameters α_{1j} and α_{2j} are estimated to best fit each region's damages to the data (Table S4; Supplementary Note 2 shows the goodness of the fit).

Using the finding that temperature change is approximately linearly proportional to cumulative carbon emissions E_t^{cum} in GtC,[8,9] we write

$$\Delta T_t = \varphi\ 10^{-3} E_t^{cum} \tag{12}$$

where φ is the ratio of warming to cumulative CO_2 in ºC/TtC, known as the Transient Climate Response to Emissions (TCRE). We take $\varphi = 1.35$ºC per TtC as the best estimate of an observationally constrained estimation.[9,10] Combining (11) and (12), region j climate damages in year t from global cumulative emissions E_t^{cum} can be written as

$$\hat{D}_j(E_t^{cum}) = \alpha_{1j}\, e^{\alpha_{2j}\varphi 10^{-3} E_t^{cum}} \tag{13}$$

Let E_0^c represent historical cumulative CO_2 emissions from 1850 to 2015, amounting to 309GtC.[11] Considering a stream of average annual emissions E during N years with zero emissions afterward, the present value of total climate damages for $\hat{N} > N$ years is represented by (Supplementary Note 3)

$$h_j(E) = \sum_{t=1}^{\hat{N}} \rho^t \, D_j\left(E,t\right) = \sum_{t=1}^{N} \rho^t \, e^{\alpha_{2j}\varphi 10^{-3}(E_0 + t\,E)} + \sum_{t=N+1}^{\hat{N}} \rho^t \, e^{\alpha_{2j}\varphi 10^{-3}(E_0 + N\,E)} \qquad (14)$$

.

The **utility function** of region j for the next N years results from (9), (10), and (14):

$$u_j(x_j, E) = \frac{\rho - \rho^{N+1}}{1-\rho} x_j - \sum_{t=1}^{N} \rho^t \, e^{\alpha_{2j}\varphi 10^{-3}(E_0 + t\,E)} - \sum_{t=N+1}^{\hat{N}} \rho^t \, e^{\alpha_{2j}\varphi 10^{-3}(E_0 + N\,E)} \qquad (15)$$

.

The utility level represents the present discounted value of consumption net of medium- and long-term costs from climate change.

Production is a function of labor and capital, and, as in RICE-2010, of the Cobb-Douglas type:

$$G_j(K) = A_j \left(L_j\right)^{1-\gamma} \left(K\right)^{\gamma}, \qquad (16)$$

with $\gamma = 0.33$ representing the elasticity of output with respect to capital. Total factor productivity (TFP) A_j is calibrated to the average values of output, capital and population in the baseline run of RICE-2010 for the period 2006-2055 (Table S3, Fig. S2).

Letting $\kappa_j = A_j (L_j)^{1-\gamma}$, the production function can be expressed as

$$G_j(K) = \kappa_j \; K^{\gamma} \qquad (17)$$

The values of κ_j are presented in column 2 of Table S4 in the supplementary notes.

Finally, average annual capital stock $\bar{K}_j$ (in trillions of int-\$) and carbon intensity η_j (in GtC/trillion \$) are obtained as the average values in the baseline run of RICE2010 for the period 2006-2055 (Table S4).

Summarizing, each region is characterized by a utility function (15) with region specific damages from climate change, a production function (17) with region specific TFP and population, an average annual stock of capital, and a carbon intensity parameter. All calibrated values are provided in Table S4 in the supplementary notes.

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Supplementary Material

Supplementary Note 1

Proposition 1

A. *Any global unanimity equilibrium satisfies the first-order conditions for Pareto efficiency.*
B. *In equilibrium, the share of the global carbon fund that country i receives is proportional to its marginal damages* $(h_j)'(E)$.

Before proving the proposition, we provide the necessary conditions for Pareto efficiency.

Lemma 1 *The necessary first-order conditions for an allocation to be Pareto efficient are:*

$$
\begin{aligned}
&(i)(\forall j)(1>\eta_j \sum_l (h_l)'(E))\\
&(ii)(\forall i,j)\left(\frac{(G_i)'(K_i)}{(G_j)'(K_j)} = \frac{1-\eta_j \sum_l (h_l)'(E)}{1-\eta_j \sum_l (h_l)'(E)} \right)
\end{aligned}
\tag{S1}
$$

where $E=\sum_j E_j$.

Proof: The conditions for Pareto efficiency are given by solving the following program:

$$
\begin{aligned}
&\max x_j - h_j(E)\\
&s.t.\\
&\forall i \neq j \quad x_i - h_i(E) \geq k_i \quad (\lambda_i)\\
&\sum G_i(K_i) \geq \sum x_i \quad (\alpha) \qquad\qquad \text{Program (PE)}\\
&\sum \bar{K}_i \geq \sum K_i \quad (\beta)\\
&E \geq \sum \eta_i G_i(K_i) \quad (\gamma)
\end{aligned}
$$

The program is not convex, because of the last constraint (the $\{G_i\}$ are concave functions). Therefore the Kuhn-Tucker conditions are necessary but not sufficient for the solution of (PE).

Define $\lambda^1 = 1$. Then the K-T conditions are:

$$
\begin{aligned}
&(\partial x_i) \quad \lambda_i = \alpha \text{ for all i}\\
&(\partial K_i) \quad \alpha(G_i)' - \beta - \gamma\eta_i(G_i)' = 0\\
&(\partial E) \quad -\sum_i \lambda_i (h_i)' + \gamma = 0
\end{aligned}
$$

We deduce that $\lambda_i = 1 = \alpha$ for all i; $\gamma = \sum_l (h_l)'(E)$; and

$$\beta = (G_i)'\left(1 - \eta_i \sum_l (h_l)'\right).$$

From this last equation we have the conditions:

$$1 \geq \eta_i \sum_l (h_l)'(E) \text{ for all i} \qquad \text{(PEa)}$$

$$(\forall i, j)\left(\frac{(G_i)'}{(G_j)'} = \frac{1 - \eta_j \sum_l (h_l)'(E)}{1 - \eta_i \sum_l (h_l)'(E)}\right) \qquad \text{(PEb)}$$

These are the stated conditions in proposition. ■

Proof of Proposition 1

The f.o.c.s for profit-maximization are :

for all j , $(G_j)'(K_j)(p - c\eta_j) = r$ or $(G_j)'(K_j)(1 - \frac{c}{p}\eta_j) = \frac{r}{p}$. (S2)

The f.o.c.s for the unanimous agreement on the level of global emissions E are:

for all j, $(h_j)'(E) = a_j \frac{c}{p}$, (S3)

from which it follows that $\sum (h^l)'(E) = \frac{c}{p}$. Substituting this into equation (S1) gives:

for all j, $(G_j)'(K_j)\left(1 - \eta_j \sum (h_l)'(E)\right) = \frac{r}{p}$. Conditions (i) and (ii) of the Proposition follow immediately, proving claim *A*.

Claim *B* follows immediately from equation (S3). ■

Supplementary Note 2: Calibration of regional damage cost functions

Climate damages for region j are defined as a function of temperature increase ($d_j(\Delta T)$) and calibrated to the baseline run data of RICE2010 (Table S1) for the period 2005-2215 using an exponential function:

$$d_j(\Delta T) = \alpha_{1j}\, e^{\alpha_{2j}\,\Delta T} \tag{S4}$$

Damages are measured in annual trillions of international dollars, and temperature change in degree Celsius from pre-industrial levels. The parameters α_{1j} and α_{2j} are estimated to best fit each region's damages to the data. Estimations for each of the 12 regions exhibit R^2 and adjusted-R^2 above 99% (Table S2). Figure S1 shows the fit of the calibration.

Supplementary Note 3: Climate damages in year t

Let E_0^c represent historical cumulative emissions. Consider a stream of average annual emissions E during N years with zero emissions afterward. Cumulative emissions until year t are $E_t^{cum} = E_0^c + t\,E$ for $t \le N$, and $E_t^{cum} = E_0^c + NE$ for $t \ge N$. Since damage costs as a function of cumulative emissions are $\hat{D}_j(E_t^{cum}) = \alpha_{1j}\, e^{\alpha_{2j}\varphi 10^{-3} E_t^{cum}}$, it follows that climate damages in year t are

$$D_j(E,t) = \alpha_{1j}\, e^{\alpha_{2j}\varphi 10^{-3}\left(E_0^{cum}+t\,E\right)} \text{ for } t \le N\text{, and} \tag{S5}$$

$$D_j(E,t) = \alpha_{1j}\, e^{\alpha_{2j}\varphi 10^{-3}\left(E_0^{cum}+N\,E\right)} \text{ for } t \ge N\,. \tag{S6}$$

Therefore,

$$h_j(E) = \sum_{t=1}^{\hat{N}} \rho^t\, D_j\left(E,t\right) = \sum_{t=1}^{N} \rho^t\, e^{\alpha_{2j}\varphi 10^{-3}(E_0+t\,E)} + \sum_{t=N+1}^{\hat{N}} \rho^t\, e^{\alpha_{2j}\varphi 10^{-3}(E_0+N\,E)}\,. \tag{S7}$$

Supplementary Note 4: *Computing the unanimity equilibrium*

We restrict the price vector (p,c,r) to the unit simplex Δ^2. Thus, we write $r = 1-p-c$. Then the first-order conditions for profit maximization of the firms can be written:

$$K_j = (G_j)^{-1}\left(\frac{1-p-c}{p-c\eta_j}\right). \tag{S8}$$

Now consider the three equations:

$$\sum_j \bar{K}_j = \sum_j K_j \tag{S9}$$

$$\sum_j (h_j)'(E)\frac{p}{c} = 1 \tag{S10}$$

$$E = \sum_j \eta_j G_j(K_j) \tag{S11}$$

Equation (S9) says the capital market clears; equation (S10) follows from the fact that E is the unanimous choice by citizenries of the global emissions level; and equation (S11) says that the emissions market clears. Walras's Law assures us that the goods market clears. Using equation (S8) we eliminate the variables $\{K_j\}$ from equations (S9)-(S11), which now become three simultaneous equations in (p,c,E). Solving these equations gives the equilibrium.

The Mathematica© program solves equations (S8)—(S11) for (p,c), E and K as follows.

1. First, define $K_j(p,c)$ from the FOC of profit maximization

$$K_j(p,c) := \left(\frac{\gamma}{\text{1-c-p}}\left(p-c\eta_j\right)\kappa_j\right)^{\frac{1}{1-\gamma}} \tag{S12}$$

2. Use (S12) in the capital market clearing condition:

$$\left(\frac{\gamma}{\text{1-c-p}}\right)^{\frac{1}{1-\gamma}} \sum_{j=1}^{12}\left(\kappa_j\eta_j\left(p-c\eta_j\right)\right)^{\frac{1}{1-\gamma}} = \sum_{j=1}^{12}\bar{K}_j \tag{S13}$$

3. The clearing condition for the market for emissions and (S12) imply

$$\left(\frac{\gamma}{\text{1-c-p}}\right)^{\frac{\gamma}{1-\gamma}} \sum_{j=1}^{12}\eta_j\kappa_j\left(\left(p-c\eta_j\right)\kappa_j\right)^{\frac{\gamma}{1-\gamma}} = E \tag{S14}$$

4. Finally, from the FOC of the unanimity equilibrium

$$\begin{aligned} &p\sum_{j=1}^{12}\alpha_{1j}\hat{\alpha}_{2j}\theta_{0j}\left(\frac{N\left(\rho\text{-}\rho^{-N+\hat{N}+1}\right)\left(\theta_{1j}(E)\right)^N}{1\text{-}\rho} + \left(\frac{\theta_{1j}(E)}{1\text{-}\theta_{1j}(E)}\right)^2\left(1\text{-}\left(\theta_{1j}(E)\right)^N\right)\right) \\ &+\sum_{j=1}^{12}\alpha_{1j}\hat{\alpha}_{2j}\theta_{0j}\frac{\theta_{1j}(E)\left(1-\left(N-1\right)\left(\theta_{1j}(E)\right)^N\right)}{1\text{-}\theta_{1j}(E)} = \frac{c\left(\rho-\rho^N\right)}{1-\rho} \end{aligned} \tag{S15}$$

where $\hat{\alpha}_{2j} := \frac{\varphi \times \alpha_{2j}}{10^3}$, $\theta_{0j} := e^{E_0 \hat{\alpha}_{2j}}$, and $\theta_{1j}(E) := \rho e^{\hat{\alpha}_{2j} E}$.

From equations (S13)—(S15) the program finds the price of output and emissions permits, and the total level of emissions: (p^*, c^*, E^*). Then it computes

- K_j^*: the stock of capital for each region, using (S12);
- the price of capital: $r^* = 1 - p^* - c^*$;
- total revenue: $c^* \times E^*$;
- the share of total revenue for region j: $\frac{1-\rho}{\rho-\rho^N} \frac{p^*}{c^*} (h_j)'(E^*)$;
- emissions of region j: $E_j(p,c) = \eta_j \kappa_j \left(K_j^*\right)^\gamma$;
- the income of region j: $p^* \kappa_j \left(K_j^*\right)^\gamma + r\left(\bar{K}_j - K_j^*\right) - c^* E_j(p^*, c^*) + a_j c^* E^*$; and
- the net contribution of region j as $c^* E_j(p^*, c^*) - a_j c^* E^*$.

Supplementary Note 5: *Robustness check*

The magnitude of climate damages in DICE and RICE models are most likely underestimated. For a robustness check we repeat the analysis for a range of much larger damages. In particular, we study allocations for damages 2, 5 and 10-fold those used in RICE2010 (that is, we consider $2 \times \alpha_{1j}, 5 \times \alpha_{1j}$, and $10 \times \alpha_{1j}$ in (S4)). We find that the allocation of net recipients shows similar patterns. If anything, differences between net recipient and net contributors exacerbate with the increase in damages. Results are found in Fig. S3.

Figures and Tables

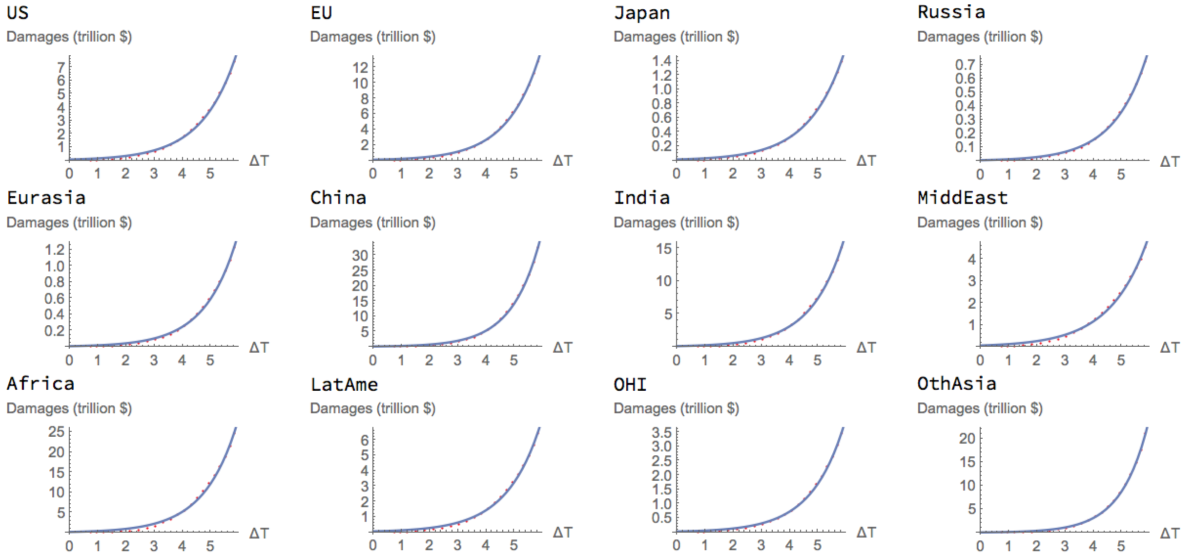
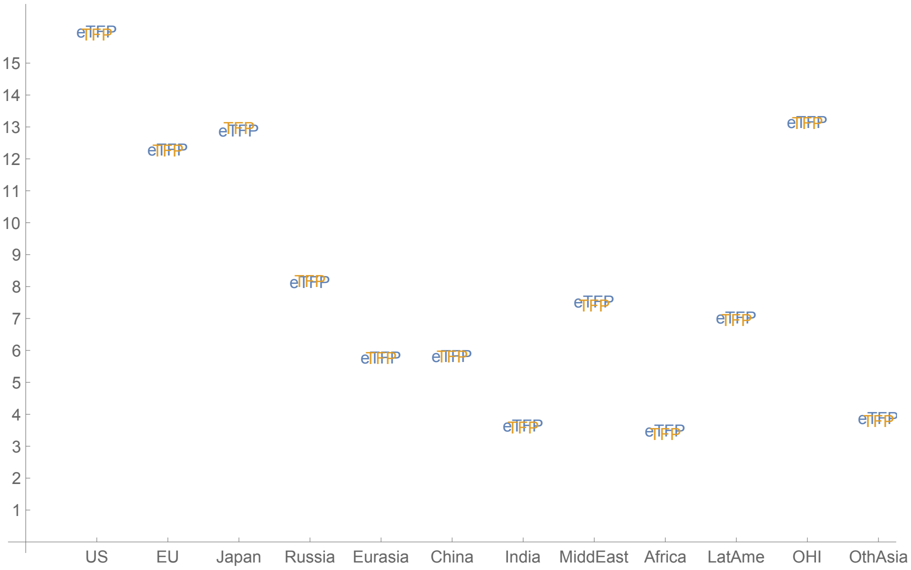


Fig. S1. Estimated annual damage functions (blue solid line) and actual point data from RICE2010 baseline run (red dots). Damages measured in trillions of annual international-dollars.



REGIONS	US	EU	Japan	Russia	Eurasia	China	India	MiddEast	Africa	LatAme	OHI	OthAsia
eTFP	15.9928	12.2985	12.8935	8.1464	5.7806	5.8292	3.6537	7.5341	3.5003	7.0330	13.1651	3.8831
Avg. TFP	15.9011	12.2715	12.9671	8.1820	5.7673	5.8109	3.5881	7.4153	3.3848	6.9627	13.1237	3.7896

Fig. S2. Average 2006-2055 total factor productivity in RICE2010 (TFP), and estimated total factor productivity (eTFP).

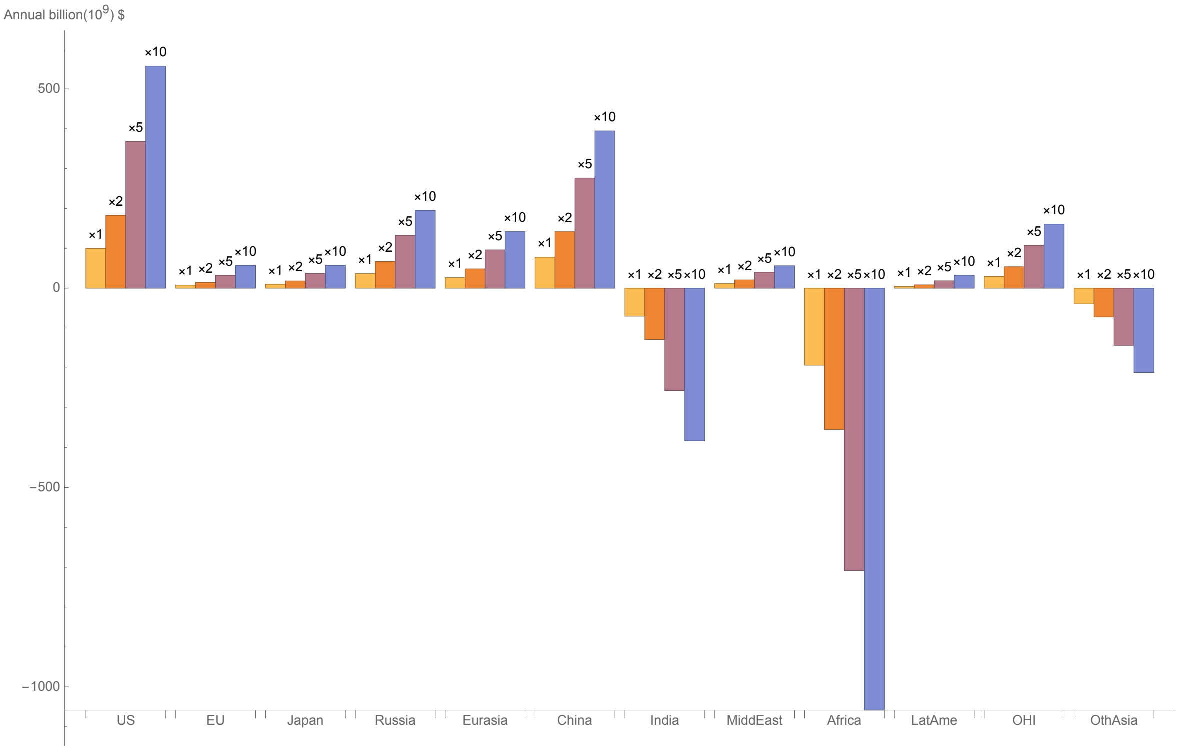


Fig. S3. Net contributions and recipients as increases in temperature entail larger damages. The bars shown correspond to the net contribution of each region for damages that are $\times 2$, $\times 5$, and $\times 10$ those in RICE2010 baseline run data. A negative value means that the region receives more from the global fund than it contributes.

	Tempt.	Annual climate change damages (trillions of int-$ per annum)											
year	Change (°C)	US	EU	Japan	Russia	Eurasia	China	India	MiddEast	Africa	LatAme	OHI	OthAsia
2005	0.73070	0.00935	0.01173	0.00334	0.00104	0.00086	0.00663	0.00994	0.00554	0.00746	0.00529	0.00278	0.00571
2015	0.94387	0.02021	0.04350	0.00694	0.00230	0.00198	0.05589	0.02590	0.01397	0.02321	0.01262	0.01269	0.01340
2025	1.20613	0.04275	0.08144	0.01310	0.00461	0.00443	0.11603	0.05726	0.02905	0.05599	0.02786	0.02381	0.03226
2035	1.49926	0.08173	0.14601	0.02251	0.00835	0.00886	0.21457	0.11373	0.05521	0.12313	0.05556	0.04273	0.07008
2045	1.80860	0.14257	0.24230	0.03468	0.01394	0.01609	0.36262	0.20658	0.09644	0.24630	0.10035	0.07029	0.13798
2055	2.12340	0.22888	0.37414	0.05178	0.02174	0.02681	0.56957	0.34241	0.15431	0.43964	0.16554	0.10706	0.24547
2065	2.43529	0.34364	0.54447	0.07454	0.03195	0.04173	0.85110	0.52974	0.23210	0.71822	0.25557	0.15344	0.40420
2075	2.73901	0.49175	0.75753	0.10223	0.04455	0.06139	1.21812	0.78225	0.33548	1.11831	0.37518	0.21066	0.63192
2085	3.03226	0.67684	1.01552	0.13472	0.05954	0.08622	1.67934	1.11025	0.46909	1.67328	0.52815	0.27922	0.94567
2095	3.31449	0.90387	1.33649	0.17220	0.07684	0.11661	2.29977	1.52496	0.64049	2.44189	0.71828	0.36502	1.37078
2105	3.58611	1.17354	1.73935	0.21926	0.09920	0.15535	3.11989	2.03508	0.83575	3.37014	0.95002	0.47306	1.91334
2115	3.84052	1.48180	2.24197	0.27819	0.12807	0.20397	4.20694	2.64044	1.04171	4.39468	1.22266	0.60890	2.57415
2125	4.08099	1.82910	2.82489	0.34466	0.16105	0.26050	5.54053	3.34469	1.27361	5.57047	1.53693	0.76794	3.38989
2135	4.30983	2.24344	3.51536	0.42419	0.20161	0.32873	7.13854	4.16637	1.52997	6.95919	1.89814	0.95238	4.34411
2145	4.52899	2.69988	4.29612	0.51156	0.24680	0.40564	9.03139	5.09463	1.81019	8.52319	2.30084	1.16177	5.48729
2155	4.73957	3.20350	5.17183	0.60746	0.29706	0.49174	11.24380	6.13336	2.11460	10.26080	2.74639	1.39769	6.84170
2165	4.94229	3.75892	6.14886	0.71250	0.35278	0.58736	13.79650	7.28525	2.44322	12.17060	3.23556	1.66184	8.42941
2175	5.13764	4.37029	7.23282	0.82715	0.41424	0.69272	16.70780	8.55200	2.79579	14.24810	3.76866	1.95579	10.27340
2185	5.32595	5.04153	8.42873	0.95179	0.48172	0.80796	19.99370	9.93456	3.17187	16.48650	4.34563	2.28099	12.39750
2195	5.50748	5.77645	9.74115	1.08672	0.55541	0.93309	23.66830	11.43330	3.57083	18.87690	4.96610	2.63881	14.82580
2205	5.68233	6.57305	11.18160	1.23266	0.63481	1.07006	27.79340	13.12190	4.01303	21.53380	5.65569	3.03141	17.67680
2215	5.85083	7.43195	12.76010	1.39022	0.71966	1.22012	32.42670	15.05060	4.51102	24.53710	6.43059	3.46086	21.05990

Table S1. This table reproduces climate change damages (in trillions of international-$) and temperature change (in ºC with respect to 1850) in Nordhaus' RICE-2010 model. (Source: RICE-2010 Excel spreadsheet version 4.012510-baselina run.)

US

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.0671706	0.00487152	13.7884	1.1253×10^{-11}
alpha2	0.808006	0.0134174	60.2208	4.35076×10^{-24}

AdjustedRSquared 0.998792

RSquared 0.998902

EU

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.0866663	0.00538869	16.083	6.60945×10^{-13}
alpha2	0.856373	0.0114501	74.7917	5.81344×10^{-26}

AdjustedRSquared 0.999209

RSquared 0.999281

Eurasia

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.0074742	0.000620131	12.0526	1.25835×10^{-10}
alpha2	0.875017	0.0152537	57.3642	1.14381×10^{-23}

AdjustedRSquared 0.998651

RSquared 0.998774

China

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.101928	0.00628593	16.2152	5.67397×10^{-13}
alpha2	0.987606	0.0112386	87.8761	2.33431×10^{-27}

AdjustedRSquared 0.999414

RSquared 0.999468

Africa

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.171745	0.0174427	9.84626	4.10277×10^{-9}
alpha2	0.85253	0.0187093	45.5672	1.10537×10^{-21}

AdjustedRSquared 0.997872

RSquared 0.998066

LatAme

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.0527673	0.00446195	11.8261	1.75894×10^{-10}
alpha2	0.824709	0.015618	52.805	5.93151×10^{-23}

AdjustedRSquared 0.998424

RSquared 0.998567

Japan

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.0134138	0.000887388	15.1161	2.08742×10^{-12}
alpha2	0.797017	0.0122526	65.0487	9.37525×10^{-25}

AdjustedRSquared 0.998967

RSquared 0.999061

Russia

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.00518722	0.000355474	14.5924	3.99521×10^{-12}
alpha2	0.847028	0.0126305	67.0621	5.10934×10^{-25}

AdjustedRSquared 0.999018

RSquared 0.999107

India

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.100338	0.00787059	12.7485	4.63325×10^{-11}
alpha2	0.859527	0.0144409	59.5205	5.49076×10^{-24}

AdjustedRSquared 0.99875

RSquared 0.998864

MiddEast

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.0579984	0.00539895	10.7425	9.36232×10^{-10}
alpha2	0.748439	0.0173325	43.1813	3.20745×10^{-21}

AdjustedRSquared 0.997686

RSquared 0.997896

OHI

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.0235396	0.00135142	17.4185	1.48398×10^{-13}
alpha2	0.855916	0.0105727	80.9555	1.19877×10^{-26}

AdjustedRSquared 0.999325

RSquared 0.999386

OthAsia

	Estimate	Standard Error	t-Statistic	P-Value
alpha1	0.050104	0.00244678	20.4775	6.87985×10^{-15}
alpha2	1.03329	0.00887209	116.465	8.43865×10^{-30}

AdjustedRSquared 0.999664

RSquared 0.999695

Table S2. Estimation of regional damage functions parameters.

Region	TFP A_j	GDP Y_j (trillion int-$)	Stock of Capital $\bar{K}_j$ (trillion int-$)	Population L_j (millions)
US	15.993	28.1160	63.5154	377.904
EU	12.299	29.3408	66.1483	574.429
Japan	12.894	6.0218	13.5586	110.259
Russia	8.146	3.4653	7.7646	122.517
Eurasia	5.781	3.3683	7.5898	193.942
China	5.829	24.9943	55.6930	1428.870
India	3.654	13.4476	30.3280	1490.660
MiddEast	7.534	7.7420	17.3715	305.861
Africa	3.500	14.1933	32.0531	1671.710
LatAme	7.033	16.2705	36.9398	705.643
OHI	13.165	7.6236	17.0958	135.729
OthAsia	3.883	13.3611	30.3416	1353.650

Table S3. Estimated TFP, and average annual output, capital and population values from RICE-2010 baseline run (2006-2055).

Region	Parameter Production	Stock of Capital	Carbon Intensity	Parameters in the damage function	
	κ_j	$\bar{K}_j$ (trillion \$)	η_j (GtC/trillion \$)	α_{1j}	α_{2j}
US	8.0926	63.5154	0.0789	0.0672	0.8080
EU	8.3429	66.1483	0.0578	0.0867	0.8564
Japan	2.7546	13.5586	0.0539	0.0134	0.7970
Russia	1.8737	7.7646	0.1441	0.0052	0.8470
Eurasia	1.8338	7.5898	0.1304	0.0075	0.8750
China	7.4834	55.6930	0.1369	0.1019	0.9876
India	4.8316	30.3280	0.0822	0.1003	0.8595
MiddEast	3.2878	17.3715	0.1234	0.0580	0.7484
Africa	5.0156	32.0531	0.0726	0.1717	0.8525
LatAme	5.5100	36.9398	0.0591	0.0528	0.8247
OHI	3.2531	17.0958	0.0999	0.0235	0.8559
OthAsia	4.7999	30.3416	0.0719	0.0501	1.0333

Table S4. Calibrated values based on the baseline run of RICE2010

	ANNUAL INCOME			ANNUAL NET PAYMENT
Regions	Initial per capita (2015) thousand $	Per capita thousand $	Average trillion $	billion(10^9) $
US	48.97	58.16	21.98	123.113
EU	31.04	40.14	23.06	10.066
Japan	35.05	42.82	4.72	12.322
Russia	16.27	21.87	2.68	44.715
Eurasia	8.46	13.49	2.62	32.333
China	8.59	13.69	19.56	90.989
India	3.66	7.15	10.66	-85.143
Midd.East	14.20	19.85	6.07	15.609
Africa	3.51	6.81	11.39	-234.817
LatAme	11.51	18.12	12.78	6.224
OHI	35.15	43.89	5.96	36.051
Oth.Asia	3.83	7.80	10.55	-51.462

Table S5. Annual Income (GDP) and annual net payment from emission permits. Income is measured as gross firm revenues plus net income from capital minus the net payment for emission permits:

$$Income_j = \left[p\,\kappa_j \left(K_j(p,c) \right)^{\gamma} \right] + \left[r\left(\bar{K}_j - K_j(p,c) \right) \right] - \left[c\,E_j(p,c) - a_j\,c\,E \right]$$

Population is the average population in 2016-2055.