

Compensation for “Meaningful Participation” in Climate Change Control: A Modest Proposal and Empirical Analysis¹

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The debate over an international climate change regime has thus far focused primarily on efficiency concerns in developed countries. This paper suggests a means by which equity concerns may be addressed in the ongoing negotiations. A system of transfers is developed that is motivated by the difference between the damage caused by a country and the damage suffered by that country as a result of climate change. Illustrative calculations of the magnitude and direction of these transfers are made. We find that in general transfers flow from temperate to tropical countries but that the degree of uncertainty associated with these calculations is very large. © 2001 Elsevier Science (USA)

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I. INTRODUCTION

In the international negotiations over the control of climate change, the developing countries so far have assumed few obligations. In the Kyoto Protocol on limiting greenhouse gas (GHG) emissions, only a subset of the world's economies, the so-called Annex I countries (the highly developed economies plus Russia, Ukraine, and parts of Eastern Europe), initially agreed to treaty-based limits on GHG emissions. Developing countries enter the treaty obliquely, mainly through the so-called clean development mechanism, which aims to foster investments linking the developed and developing countries in emissions control.³

The United States is calling for a more active role for the developing world, including binding commitments to GHG emissions ceilings by several of the large developing countries. In general, the developing world has resisted such entreaties, arguing that their highest priority is to grow and that growth requires increased emissions of GHGs. Language in support of this position can be found in the United Nations Framework Convention on Climate Change (UNFCCC). Developing countries stress that per capita emissions in the advanced economies are several times those in the poorer countries, so that limiting the emissions of poorer countries would be unfair. The United States counters with the argument that cost-effective reduction of global GHGs necessarily requires efforts by all countries that contribute to the GHGs. Moreover, emissions from the developing world are growing faster than those from rich countries. Reductions on the scale called for by Kyoto will have little effect on climate change in isolation.

At present, this dialogue—or debate—has not progressed very far. There are several reasons for this impasse. First, there is a distinction between cost effectiveness (where in the world should the control be undertaken in order to minimize the global costs of control) and equity (who should bear the costs of mitigation and abatement resulting from climate change) that has not been adequately clarified and agreed upon by the parties to the Protocol. Second, the global control of anthropogenic climate change will require a complex cooperative effort among a large number of individual nations. This cooperative effort will have to be based on a thorough understanding of how the various participating nations contribute to the process of global climate change, and how that process affects them.

On both dimensions—contributions to climate change and effects from climate change—there are huge uncertainties. The scientific understanding of climate change is itself at a very early stage. There are large disagreements among scientists about the effects of changes in greenhouse gas concentrations on the global climate.⁴ Moreover, there are even larger unknowns about how individual countries and regions might be affected by global climate changes, since the implications of rising GHGs for climate patterns (e.g., temperature, precipitation, storm patterns) and for material well-being (e.g., agricultural production, public health, physical comfort) are poorly understood at the regional, national, and global scales. Finally, there are important quantitative uncertainties about how countries have, in the past, contributed to changes in stocks of GHGs, and how they are likely to do so in the future [22].

³ For a discussion of the Kyoto agreement itself, see, among others, Cooper [3].

⁴ For an overview of the skeptical position, see Lindzen [20].

This paper aims to advance our understanding of the relatively neglected equity dimension of this complicated problem. We propose here a system of compensatory transfers from those who contribute to climate change more than they suffer from it to those countries whose damages outweigh their responsibility for the problem. We make this calculation under a “business-as-usual” scenario in which no mitigation is undertaken as the result of a treaty such as the Kyoto Protocol. The transfer system we develop can be thought of as a means of operationalizing the “Marshall plan for developing countries” that Schelling [31] has alluded to as a partial solution to the climate change problem. But where Schelling suggested that developing countries decide among themselves how to allocate such transfers, we suggest that the nature of the climate change problem itself suggests an equitable division and the appropriate level of the transfer. We suggest that these transfers may be a means by which equity concerns can be addressed, and thus, developing countries can be induced to participate in climate change control.

Our main conclusion can be put simply. For the temperate-zone economies, the contribution to rising carbon concentrations is much larger than their share of global damages, while the reverse is true for the tropics. In effect, the temperate-zone economies are likely to impose severe net costs on the tropical regions. Since the temperate-zone economies tend to be rich, and the tropical-zone economies tend to be poor, global climate change represents a burden imposed on the poorer countries by the richer countries (this point was stressed earlier by Schelling [30], but without detailed quantitative estimates). Equitable solutions to the control of global climate change should take this interregional pattern into account, subject to the significant uncertainties associated with this problem.

We proceed as follows. Section II develops one potential method for addressing international equity concerns in the context of a climate change regime. Section III presents empirical evidence on past trends of GHG emissions, both from fossil fuels and land-use change (i.e., deforestation). In Section IV we use econometric estimation to model emissions. These estimates are used to make baseline forecasts for future emissions so that the implications of the methodology developed in Section II can be explored. We are able to rely on a reduced-form model of emissions from fossil fuels that has been estimated by Schmalensee, Stoker, and Judson (SSJ) [32], but we must ourselves estimate a model of emissions from land-use change. Section V reviews some of the evidence, sketchy as it is, about the relevant damages from climate change, again disaggregated among the developed and developing countries. We apply the methodology developed in Section II. Section VI offers some concluding observations.

II. EQUITY IN CLIMATE CHANGE CONTROL

At a basic theoretical level (abstracting from uncertainty and dynamics among other things), the problem of anthropogenic climate change may be treated like any other environmental externality. If the socially optimal level of emissions can be identified, it can be secured in two ways. The first is the Pigouvian or corrective tax on energy use [28]. The second is a quantity limit. The government would mandate the level of total emissions and might distribute tradable emissions permits in the total amount of the efficient emissions level. The debate around developing country participation in climate change control has focused to a

considerable extent on an international tradable permit regime because the distribution of permits could potentially be used to address the equity concerns of developing countries. Claussen and McNeilly [4] propose that a weighted consideration of “responsibility, standard of living, and opportunity” should be used to assign emissions permits to developing countries. Frankel [9] and Baumert *et al.* [2] suggest that developing countries select emissions targets that are indexed to their rate of economic growth to ensure that an emissions ceiling does not inhibit economic development. Larsen and Shah [19] and Rose [29] suggest a distribution of permits that gives developing countries the right to emit a “business-as-usual” level of CO₂. One proposal that has been offered, particularly by developing country signatories to the protocol, is that emissions property rights be allocated to countries on a per-capita basis. In each of these scenarios, the permit distribution need not affect the efficiency of the final emissions allocation if trading occurs with low transaction costs. The proposals differ in the amount of implied wealth transfer to the developing world. This transfer is intended to address equity concerns regarding the allocations of mitigation costs and to induce participation in a climate change treaty by poor countries.

A per-capita allocation of emissions rights would likely result in the largest wealth transfer to developing countries of any of these proposals since that is where the majority of the world’s population is found. However, we propose that this is only a partial solution to the equity dilemma because all individuals in all countries will not feel the damages from climate change equally. Most research suggests that tropical developing countries will be relatively severely impacted. A complete solution to the equity problem must consider contributions of countries to the stock of CO₂ and the differential damages experienced by each country, not only the fact that there are vast differences in wealth and population among countries.

We propose that equity concerns require that victims of the behavior of others be compensated. We suggest here a means of addressing equity concerns regarding damages that is independent of a permit allocation and is based on differential expected damages rather than damages experienced. This reflects the fact that it is expected damages that must determine climate change policy to a large extent; long lags in research and development and capital formation mean that emissions cannot be easily avoided over the short run. Resources from ex ante transfers can be used to make investments in clean technology. Moreover, ex ante compensation for expected damages in return for participation in climate change control addresses Schelling’s [31] paradox that investment in climate change mitigation helps future citizens of developing countries that will likely be richer than citizens of those countries who are alive today. Finally, apart from the fact that ex ante compensation is intended to encourage participation in a treaty, it avoids the potential moral hazard that might be introduced by ex post compensation.

In a world in which every country’s actions affect all other countries, we recognize that international regimes are not easy to design. In particular, we abstract from many mechanism design concerns in this presentation and acknowledge that no polluter can be forced to pay in the international context [36]. Nonetheless, the polluters in the case of climate change do have some incentive to pay because developing country participation is necessary for cost-effective mitigation. The proposal here is a means of choosing the amount of payment and a basis for its disbursement. That being said, we remain silent about many practical concerns as to the application and timing of this or any other transfer scheme.

Besides the Marshall plan analogy made by Schelling [31], Parikh *et al.* [27] have proposed a system of transfers like the one we develop here. These authors suggest that transfers should be made to poor countries as “liability payments for damages and excess past concentrations,” which corresponds closely to the method we propose. We offer quantitative estimates of such transfers and are initially agnostic about whether such a method will result in transfers from rich countries to poor ones.

We propose the following standards for compensation. Suppose that the total atmospheric carbon concentration is T , which has a known relationship to the earth’s surface temperature of the form specified in Nordhaus [23]. Damages result from the deviation of the earth’s average temperature from its average preindustrial level. Thus, responsibilities for changes in temperature are equivalent to responsibilities for changes in the carbon stock. First, we allocate the total carbon stock into the contributions of each country i , by tracking the historical evolution of T according to the emissions of individual economies. Thus, $T = \sum_i T_i$. Let $\sigma_i = T_i/T$ be the share of the global carbon stock due to country i . Next, we define worldwide damages caused by T , as well as indirect damages resulting from abatement and mitigation efforts. The damages in an individual country are thus the sum of two components: the damages due to T , given by $D_i(T)$, where $D' > 0, D'' > 0$, plus the loss of gross domestic product (GDP) resulting from mitigation efforts, which we designate as ΔY_i .⁵ Thus, total damages are $D_i(T) + \Delta Y_i$. Worldwide damages are therefore

$$(1) \quad \text{WD} = \sum_i [D_i(T) + \Delta Y_i].$$

Let

$$(2) \quad \lambda_i = (D_i + \Delta Y_i) / \text{WD}$$

be the share of worldwide damages accounted for by country i . In the calculation of λ_i that is presented in this paper, we assume that $\Delta Y_i = 0$. This follows from our assumption of a business-as-usual scenario.⁶

Our proposal is based on the premise that victims of climate change should be fully compensated for the damages that they incur. This would follow from a philosophical position in which each person owns the “right” to an unchanged environment and therefore must be compensated in full when the environment changes due to human causes. Thus, global compensation would be $C = \text{WD}$. This is the central idea behind our conceptualization of equity concerning damages; each country would receive a share of global transfers equal to $\lambda_i \text{WD}$. Each country would make a transfer equal to the share in which it *caused* the global damages, $\sigma_i \text{WD}$. If in fact all countries suffered damages equally, λ_i would be equal to a country’s share of the world population. In this case, if a country’s share of emissions equaled its share of world population, its net transfer payment (NTP) would be zero. If countries experience differential impacts, λ_i may be greater or less than the country’s population share. The NTP that each country makes would

⁵ There are also indirect damages such as those due to trade and production effects. However, these damages are technological externalities that flow through the production function and that are reflected in prices.

⁶ We thank a reviewer for pointing out that weighting by marginal utility may be even more correct as a means of addressing the question of whether one dollar in a rich country is equal to one dollar in a poor country.

therefore equal the damages caused minus the damages received:

$$(3) \quad NTP_i = \sigma_i WD - \lambda_i WD = (\sigma_i - \lambda_i) WD.$$

By construction, of course, $\sum_i NTP_i = 0$. That is, net positive transfers by some countries exactly balance the net negative transfers (i.e., the compensation for net damages). The net contributors to the global damage (i.e., those countries that cause more damage to the world than they experience) pay the net victims (i.e., those countries that experience more damages than they cause).⁷

In the empirical discussion that follows, we make illustrative calculations of σ_i , λ_i , and NTP_i for 13 groups of countries that we call the “Nordhaus regions” since the groups have been created by Nordhaus [23, 24]. Our results suggest that the temperate-zone economies cause more damage than they sustain. Thus, *the direction of global compensation should be from the temperate-zone to the tropical-zone economies.*

III. EMPIRICAL EVIDENCE ON CO₂ EMISSIONS

In this section, we introduce some scientific background and review the historical contributions from rising atmospheric carbon, first from fossil fuels and then from land use on an annual basis from 1860. We summarize these data and then forecast emissions using a panel data econometric model for fossil fuel emissions estimated by SSJ and a cross-sectional model for land-use change emissions that we estimate. These models serve as the means of predicting stocks and damages so that illustrative calculations of the transfer scheme can be made, as explained in Sections IV and V.

Scientific Background

The main sources of anthropogenic CO₂ emissions are energy use and land-use change, particularly deforestation. In 1996, emissions from fossil fuel use totaled 6.18 billion tons of carbon [21]. Emissions from land-use change in the tropical world, including nonreplacement timber harvesting, shifting and sedentary agriculture, and cattle ranching, have been estimated to be 1.6 billion tons in 1990 [14, 16]. There is a great deal more uncertainty surrounding the measurement of emissions from land use relative to fossil fuels, and even greater uncertainty regarding other sources of CO₂, particularly livestock and solid waste. Because of this uncertainty, we consider only CO₂ from fossil fuels and land-use change.⁸

⁷ The calculations made here are at the country level, rather than the individual level. One might imagine making these calculations to take into account that individuals within countries suffer differential damages and contribute to the stock of carbon differentially, just as individuals across countries do. Data limitations preclude making these calculations at this level of detail, even if it were desirable.

⁸ This reasoning follows Nordhaus [25], who limits his analysis to CO₂ only, assuming a constant exogenous level of emissions from land-use change. Other GHGs contribute to global warming besides CO₂, including N₂O and CH₄, but global time series for these emissions are not available. Chlorofluorocarbons may also contribute to global warming but their emissions have largely been controlled as a result of the Montreal Protocol.

To model the process by which emissions are translated into atmospheric CO₂ concentrations, we follow Nordhaus [23] closely. A system of equations describes the “mixing” process by which the global stock of CO₂ cycles between the atmosphere, the upper reservoirs, and the deep oceans. At any point in time, atmospheric concentrations above the preindustrial level, approximately 590 gigatons of carbon (GtC), lead to increased global surface warming through increased radiative forcing. Increased radiative forcing leads to temperature increases of the global surface, the upper oceans, and the lower oceans with lags resulting from thermal inertia.⁹ Increases in the global surface temperature cause damage. Using these equations, we track the stock of CO₂ created by the regions for which Nordhaus has estimated damage equations. These regions are Japan, the United States, the European Union (EU), other high-income countries, the high-income Organization of Petroleum Exporting Countries (OPEC), middle-income countries, Russia, lower-middle-income countries, Eastern Europe, low-income countries, China, India, and Africa.¹⁰ We also calculate damages experienced by each of these regions, again following Nordhaus [24]. The damage function is presented in Section V.

Historical Contributions to Atmospheric Carbon from Fossil Fuels

Marland *et al.* have estimated the global CO₂ emissions from fossil fuel use on a country basis beginning in 1751 [21]. Non-OPEC high-income countries contributed 46% of combustion emissions in 1996. Developing countries (non-Annex 1), accounting for 77% of the world population and 37% of the world income in 1994, were relatively insignificant contributors of CO₂ emissions until 1960.

We calculated the annual stock associated with these flows since 1870 for the Nordhaus regions.¹¹ Annex 1 countries contributed more than 85% of the atmospheric concentrations of CO₂ from fossil fuels over the past 100 years. While China has contributed about one-third of the balance, it has done so mostly during the past 30 years.

To estimate future emissions from fossil fuels, and thus responsibilities of the Nordhaus regions for the stock of CO₂ in 2045, we rely on the estimates made by SSJ. Using annual data for the period 1950–1990 they estimate a simple relationship between per capita CO₂ emissions (c_{it}), expressed as thousands of metric tons of carbon, and per capita income (y_{it}), expressed as 1985 purchasing power parity (PPP) dollars per person. In 1990 the dataset covers 141 countries. The equation estimated is of the form

$$(4) \quad \ln(c_{it}) = a_i + \beta_t + F[\ln(y_{it})] + \varepsilon_{it}.$$

The index i refers to countries and t refers to time in years. The set of parameters a_i reflects country fixed effects. The set of parameters β_t reflect time

⁹ Due to space limitations, these equations are not reproduced here. A complete discussion is in Nordhaus [23, 24].

¹⁰ A listing of the countries in each group is in Nordhaus [23].

¹¹ As national boundaries change, so do the sources of CO₂. The following adjustments are made: for 1960–1972, the Ryukyu Islands are added to Japan; for 1960–1969, Tanganyika and Zanzibar are combined; for 1960–1979, the Panama Canal Zone is added to Panama; for 1960–1969, Sabah and Sarawak are added to Malaysia; and for 1960–1969, North and South Vietnam are combined.

fixed effects such as changes in world oil prices, technologies, and environmental policies, as well as in preferences unrelated to income levels. The $F(\cdot)$ is a piecewise linear spline which allows for distinct elasticities of emissions with respect to output in each segment of the spline function. For all spline segments, the estimated income elasticity was statistically significantly different from zero at the 95% level. The income elasticities of emissions are positive for income levels above \$629 and below \$9800 and take values between 0.07 and 1.10 in this range. The elasticity estimates show a clear inverted-U shape. The coefficient estimates were also significantly different from the previous coefficients, except in the case of three middle-income splines. The elasticity estimate for the final spline (incomes between \$9799 and \$19,627) is negative and significant, with a point estimate of -0.30 . We use these elasticities as a basis upon which to project the flows of CO_2 from fossil fuel use for each of the Nordhaus regions.

Historical Contributions of Atmospheric Carbon from Land-Use Change

The burning of fossil fuels for energy is the main but not the only source of CO_2 emissions. Land-use changes, mainly in the form of deforestation, currently contribute about 20% of the global CO_2 emissions from anthropogenic sources. As mentioned in the introduction to Section III, emissions from land-use change are poorly understood and have been estimated with a high degree of variance. Further, the main determinant of land-use emissions, deforestation, has also been poorly tracked over the past century. For our purposes, however, including land-use change emissions in this investigation is important. Deforestation is primarily a tropical phenomenon, and there is reforestation in temperate countries.¹² Failure to include the emissions from this activity would be misleading because, as discussed in the Introduction, damages are likely to be greatest in tropical regions. For an accurate picture of the direction of the compensation flows implied by our scheme, we need a rough estimate of responsibility for land-use emissions.

1. *The data.* Houghton and Hackler [16] provide an estimate of regional land-use change emissions from 1860–1980 for North America, Europe, the Soviet Union, and Japan, and from 1860–1990 for China, India, Tropical South and Southeast Asia, Latin America, and Africa. For the 1990s, we supplement these data with Annex 1 emissions estimates from the UNFCCC [34].

Again using Nordhaus's equations, we calculated the stock of CO_2 as of 1990 for each of the Nordhaus regions as a result of land-use change emissions since 1870.¹³

¹² According to WRI [37], almost 75% of all land-use emissions come from nine countries in Latin America and tropical Asia. The problem, while of uncertain magnitude, is almost certainly localized.

¹³ To use the Nordhaus damage equation, we must estimate emissions for the regions for which the equation has been calibrated. As such, the Houghton and Hackler [16] data by geographic region must be allocated to the Nordhaus categories. This was done on the basis of annual deforestation data. That is, if Houghton and Hackler report that emissions from Africa were equal to 0.10 GtC in 1960, we allocate this amount to the countries in that region on the basis of deforestation levels. Then we can recombine the emissions data for the Nordhaus regions. The deforestation data is from FAOSTAT [6] for 1961–1990 and Zon and Sparhawk [38] for 1900–1960. Like Houghton and Hackler [15], we assume that deforestation begins in 1750 in all countries in which it was recorded in 1900 and increases linearly until 1900.

Land-use emissions account for a relatively small amount of the current stock of CO₂, and responsibility for this stock is more evenly divided among the regions. In fact, developed countries have been sequestering carbon through reforestation at least since 1980 [16].

In order to project CO₂ emissions into the future we must understand the factors behind the dramatic shift in rates of deforestation (and hence forest cover) between regions and over time. Unfortunately, reliable time series on deforestation and forest area are not available. FAO [7, 8] report data on forest area for 1960, 1980, 1990, and 1995, but they are not strictly comparable except for the last two years. These data are also not consistent with the annual deforestation data supplied by the FAO as part of FAOSTAT [6]. Emissions at the country level are not available on an annual time-series basis either, though they are estimated by WRI [37] for 1991, for developing countries only. We have, therefore, limited ourselves to cross-sectional analysis of the 1991 emissions.

2. *The model.* Previous cross-country econometric analyses of deforestation have found that population density plays an important part in this phenomenon in developing countries [1, 5] because, in the absence of technical change in traditional agriculture, households must increase land under cultivation to maintain consumption levels as their numbers rise. On that basis, we specify the following regression equation to explain land-use change emissions, controlling for whether countries have forest to clear:

$$\begin{aligned}
 (5) \quad & \ln(\text{emissions/ha})_i \\
 & = a_0 + a_1 \ln(\text{population density})_i + a_2 (\ln(\text{population density}))_i^2 \\
 & \quad + a_3 (\% \text{ change in population density})_i \\
 & \quad + a_4 \ln(\text{forest cover/ha})_i \\
 & \quad + a_3 (\text{dummies for climate and regions}) + \varepsilon_i.
 \end{aligned}$$

Equation (5) was estimated using ordinary least squares allowing for heteroskedasticity. Population by climatic zone data is based on the Köppen–Geiger–Pohl [11, 12] system of classification, using population data from Tobler *et al.* [33]. Forest cover per hectare is from FAO [7, 8]. The regression results are reported in Table I. As expected, higher population density results in higher emissions, though at a decreasing rate.¹⁴ Among climatic variables, the percentage of land in temperate zones had a significantly negative effect on forest cover,

¹⁴ Perhaps because this sample is for developing countries only, income per capita does not have a coefficient estimate that is significantly different from zero. This is not consistent with historical evidence, which has shown developed countries to be afforesting as their incomes increased.

¹⁵ Despite these shortcomings, there is a limit to the amount of error we are introducing into the forecasts of long-term carbon concentrations, because there is an upper limit to the amount of emissions that may occur as a result of land-use change (i.e., the emissions that would result from total deforestation). While it is certainly not a policy prescription (!), we have estimated the effect of cutting down the entire tropical forest at a linear annual rate by 2050. We estimate the additional carbon stock above the 1990 level to be approximately 85 GtC [26] if this were to occur.

TABLE I
1991 Land-Use Change Emissions Cross-Sectional Regression

Explanatory variables	1991 Land-use change emissions
Log of population density	1.103 (3.37)
Log of pop. density squared	-0.131 (2.79)
Annual percentage change in pop. density	7.80 (2.20)
Log of 1990 forest cover per hectare	0.740 (9.42)
% of land in temperate climate zone	-1.089 (2.69)
% of people in rainforest climate zone	1.066 (2.90)
Constant	-6.225 (10.94)
Number of observations	63
R^2	0.819

Note. Asymptotic, heteroskedasticity-consistent t values in parentheses. Sample is developing countries only.

reflecting the fact that these regions are less well endowed with forest cover to begin with. The percentage of people in rainforest zones is estimated to increase emissions from land-use change, possibly because of the low productivity of soils in these regions. We employ the results of this estimation in our projections of future CO₂ emissions from land-use change.

It is clear from the preceding discussion that the prediction of emissions from land-use change used here is extremely imprecise. The data used for prediction are cross-sectional, so there is a potential for the residual error term to be correlated with the independent variables. The data are also for developing countries only, so that the likely effect of income growth on deforestation cannot be captured. We proceed with projections using (5) and the data we have discussed, with the caveat that the land-use emissions estimates are subject to a higher proportionate range of uncertainty than those for fossil fuels are.¹⁵

IV. PROJECTIONS OF CO₂ EMISSIONS AND STOCK TO 2050

Having modeled historical emissions, we use the econometric estimates to project annual emissions to 2050. With these forecasts we can estimate the stock of CO₂ in 2045 and regional responsibilities for this stock.

In the case of fossil fuels, we cannot use the emissions projections presented by SSJ because those are for the world as a whole, while we are interested in the emissions paths of the Nordhaus regions separately. This means that we must have a means of projecting national income per capita. To forecast population, we use the average of the low and medium United Nations (UN) projections [35]. To

forecast income, we make the following simple assumption: we assume that the U.S. economy grows at a rate of 1.5% annually. For other countries, we construct growth projections based on the following partial convergence equation along the lines suggested by Gallup *et al.* [10]:

$$(6) \quad \text{gap}_t = 0.98\text{gap}_{t-1}, \quad \text{where } \text{gap}_{t-1} = \ln(y_{i,t-1}/A_i y_{US,t-1}).$$

We assume that the GDP per capita of country i converges to a long-run level equal to $(A_i y_{US,t})$, where y_{it} is the per-capita income level of country i . The parameter A_i is introduced to take into account those fundamental considerations (e.g., physical geography) that may limit full convergence between country i and the United States, and it takes the value of one for all industrialized countries. It is defined in the following manner for nonindustrialized countries:

$$(7) \quad \ln(A_i) = -0.5(\text{Tr}_i) - 0.5(L_i) + \ln(0.7).$$

The parameter Tr_i is the percentage of a country's land in tropical ecozones and L_i is a dummy variable for non-European landlocked countries. According to this specification, developing countries attain at most 70% of the U.S. income level, with non-European landlocked and tropical countries falling further below that level.

The income projections calculated from (6) and (7), population forecasts from the UN, and the coefficient estimates from SSJ are sufficient to project fossil fuel emissions by country assuming that the income elasticity of emissions estimated for the last spline within our sample applies to all higher income levels.¹⁶ Figure 1 shows the projected path of the stock of CO₂ from fossil fuels from 1870 to 2050 for the Nordhaus regions.

We project CO₂ emissions from land-use sources using (5) and the UN population forecast (we assume that the percentage of the population in any climate zone in a country remains constant), but we must add an additional calculation to make this forecast. We cannot simple-mindedly predict land-use change emissions from this equation because this would not take into account the fact that a country's forest cover declines with land-use change emissions and thus provides an upper bound on the level of emissions possible. For forecasting purposes, we must use emissions in period t to determine forest cover in period $t + 1$. We have used a simple transformation method between carbon emissions and forest loss that

¹⁶ For forecasting purposes, we require a time trend that will capture energy productivity gains that lower emissions per unit of GDP at a given level of income. The time fixed effects in SSJ's basic equation contain both changes in productivity and real price energy changes since the real price of energy is not included as an independent variable in the equation. We need to separate the price and productivity trends in the fixed effects, but we are unable to do so for the entire sample because of a lack of energy price data. We do have energy price data for the Organisations for Economic Co-operation and Development (OECD) and so can obtain a pure productivity effect for this subsample as the coefficient on a time variable. When the equation is run for the OECD alone, including energy prices and a time variable rather than fixed effects, the coefficient on time is negative (-0.01) and significant. This represents productivity changes. We use this coefficient from the OECD-only regression to supplement the income spline coefficients in order to forecast emissions for the entire sample. Since prices are excluded from the forecast, we make the implicit assumption that the real price of energy is constant for the period under consideration.

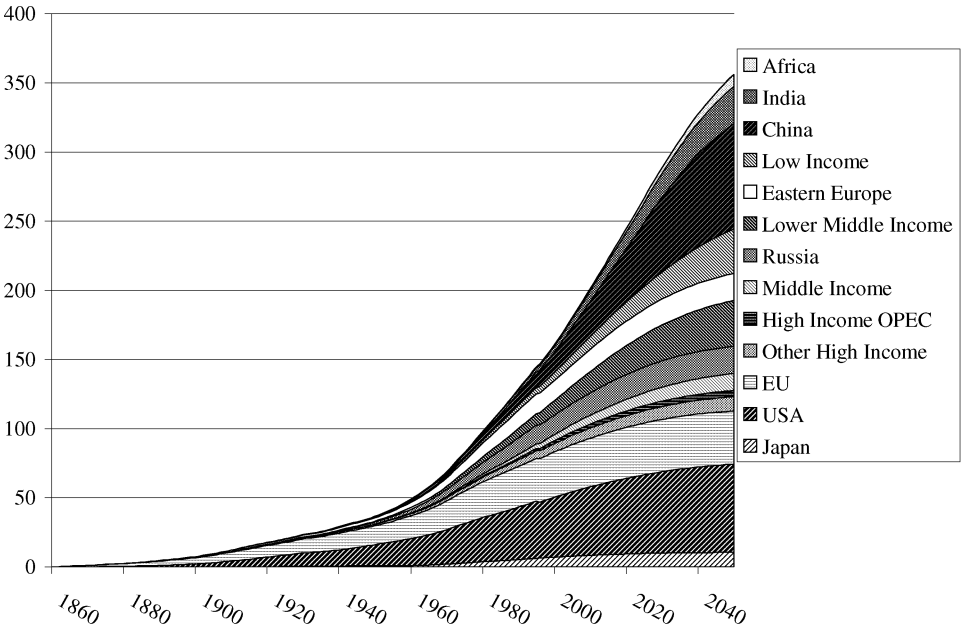


FIG. 1. Projected stock of CO₂ from fossil fuels by region 1860–2050 (billion tons of C).

follows WRI [37] closely.¹⁷ Figure 2 shows the projected atmospheric stock from land-use change emissions for each of the Nordhaus regions.

Figure 3 shows the sum of fossil fuel and land-use change atmospheric CO₂ stocks. The emissions projections that are the basis for this stock calculation suggest that total U.S. emissions decline steadily from 1.5 GtC in 1996 to 0.85 GtC by 2050, while total Chinese emissions increase from 0.92 to 1.79 GtC in the same period (we use actual fossil-fuel emissions from 1990–1996, and so account for the recent upturn in U.S. emissions). Developed countries continue to sequester carbon through reforestation at the rate of about 200 million tons per year while the rest of the world reduces its land-use emissions from about 1.5 billion tons in 1990 to less than 1 billion tons annually by 2050.

For the world as a whole, Figs. 1 and 2 show that the time paths of land-use and fossil fuel atmospheric stocks are very different. First, fossil fuel stocks continue to rise rapidly, while land-use stocks rise modestly. Second, the magnitudes of the two stocks are very different. The total stock of carbon from land-use change is around 73 GtC in 2050, while the total atmospheric stock from fossil fuels in 2050 is 356 GtC. This means that for the world as a whole, Figs. 1 and 3 are virtually indistinguishable. The total atmospheric stock of CO₂ for the world (including the

¹⁷ Methodologies for making this transformation are complicated and have arrived at very different results because calculating emissions from land-use change requires assumptions regarding the use and type of the wood deforested and the treatment of the land in question after deforestation occurs [14]. The WRI methodology begins by classifying each country's forests as tropical, temperate, or boreal. A measure of average biomass per hectare of forest is assigned on the basis of this specification: 140, 120, and 53 tons of biomass per hectare, respectively. For each type of forest, it is assumed that the carbon content of the biomass is 45%. Seventy-five percent of this carbon is immediately emitted when forest is cleared.

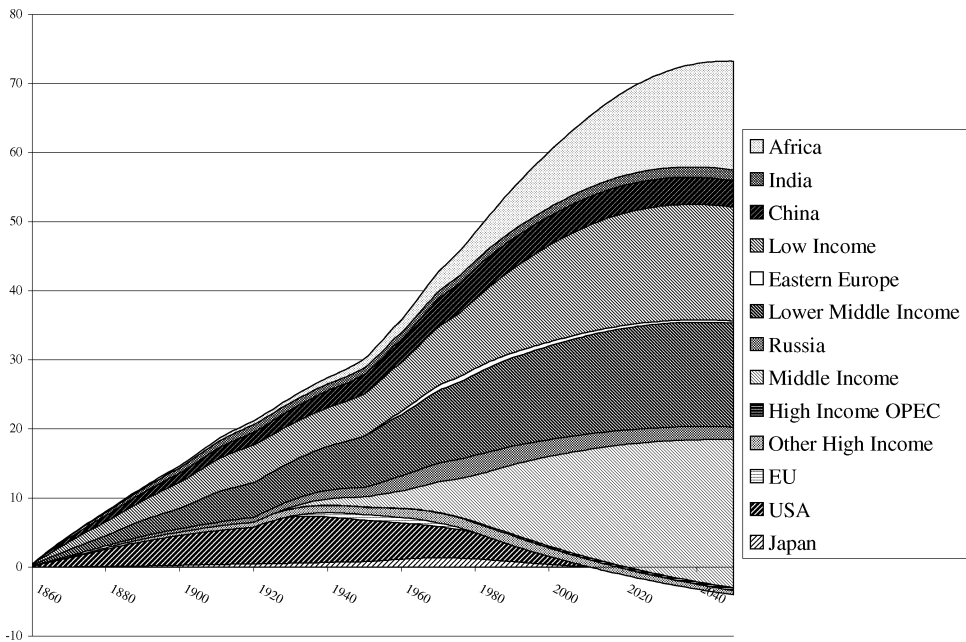


FIG. 2. Projected stock of CO₂ from land use by region 1860–2050 (billion tons of C).

natural stock of 590 GtC) at 2050 is projected to reach approximately one trillion tons of carbon. Inserting this stock forecast into Nordhaus' temperature calculation discussed in Section II, we predict a 1.3-degree Celsius increase in temperature relative to 1990 by 2045. This suggests that in 1990, the global mean temperature had increased by approximately 0.43 degree Celsius relative to 1900.¹⁸

V. DAMAGES FROM CLIMATE CHANGE

We did not carry out any original research in this paper regarding the damages from rising GHG concentrations. We use the quadratic damage function developed by Nordhaus [24, 25]. Ultimately, damages result from the level of κ_{UP} , the global surface temperature, at any time t . Nordhaus posits a relationship between $\kappa_{UP}(t)$ and income loss (DJ) of the form

$$(8) \quad DJ(t) = \theta_{1,j}\kappa_{UP}(t) + \theta_{3,j}\kappa_{UP}(t)^2,$$

where $\theta_{i,j}$ are region-specific parameters reflecting differential impacts of climate change. The regions for which this equation has been calibrated in 2045 form the units of our own analysis. The specific values of these parameters by region are given in Nordhaus [24.]

¹⁸ This forecast is driven almost entirely by the spline function specification of fossil fuel emissions that we take from SSJ. The prediction of the total stock of CO₂ calculated here and the forecast developed by SSJ are both higher than that of Nordhaus [23]. They are also higher than the main scenario of the IPCC [17]. SSJ provide confidence intervals and a complete discussion of the implications of an environmental Kuznets curve [13, 18] for emissions forecasting. For our purposes, a simple baseline is sufficient.

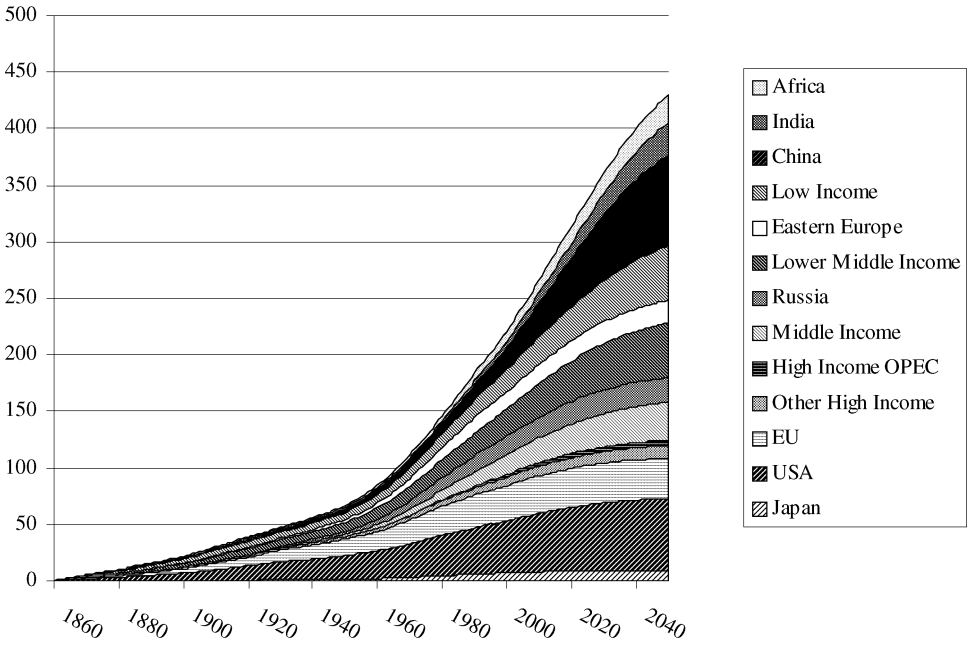


FIG. 3. Projected stock of CO₂ from fossil fuels and land use by region 1860–2050 (billion tons of C).

Nordhaus estimates $\theta_{i,j}$ by distinguishing between noncatastrophic and catastrophic impacts, where the latter are measured as “insurance premiums” on the avoidance of catastrophic outcomes. Among the noncatastrophic damages, Nordhaus includes estimates of the costs of climate change on health, amenities (e.g., recreation), coastal flooding, and agricultural productivity. In general, the risks to the tropics exceed the risks to the temperate zones, most clearly in the effects on agriculture and on disease burdens. The result of applying our projections of a 1.3-degree Celsius global temperature increase over 1990 levels by 2045 to the Nordhaus damage functions show that the big losers as a result of climate change, clearly, are the poorer countries.

On the basis of the methodology developed in Section II, we can use our forecast of CO₂ emissions and Nordhaus’ regional damage equations to obtain an estimate of the likely contributions of each region to the global damages and their share of these damages under a business-as-usual scenario. The balance between the two will provide an indication of the direction of compensation flows. For each Nordhaus region, Table II shows income and population levels in 2045. Using our estimate of the stock of CO₂ in 2045, we calculate columns 4 and 5 using (8). Column 5 is equivalent to the parameter λ_i defined in (2), where $\Delta Y_i = 0$. Column 6 is calculated from the historic and projected emissions calculations described in Sections III and IV. This column corresponds to the parameter σ_i , the share of the global CO₂ stock due to each region’s activities.

Recall that we defined a region’s net transfer payment as $NTP_i = (\sigma_i - \lambda_i)WD$, where WD is total world damages. These transfers, expressed as percentages of world and own GDP, respectively, are shown in the columns 7 and 8 of Table II.

TABLE II
 Interregional Transfers Implied by Proposed Compensation Scheme

(1) Nordhaus [23] regions	(2) 2045 UN forecast population (thousands)	(3) 2045 Forecast PPP GDP (millions)	(4) Damages as percentage of own GDP	(5) Damages as percentage of world damage "λ"	(6) Contribution to stock of CO ₂ as percentage of total stock "σ"	(7) Net transfer as percentage of world GDP	(8) Net transfer as percentage of own GDP
Japan	106,391	4,011,585	0.01	0.0	3.1	-0.04	-1.19
United States	312,983	12,815,233	0.06	0.5	18.4	-0.25	-2.20
EU	332,417	11,596,737	1.62	11.9	11.2	0.01	0.09
Other high income	78,474	2,619,915	-1.00	-1.7	3.0	-0.07	-2.79
High income OPEC	16,980	370,618	1.47	0.3	1.3	-0.01	-3.95
Middle income	355,720	5,440,169	1.35	4.7	3.5	0.02	0.35
Russia	109,934	2,092,953	-1.15	-1.5	5.7	-0.10	-5.48
Lower middle income	936,978	14,663,390	1.46	13.6	9.3	0.06	0.47
Eastern Europe	161,521	2,832,811	-0.44	-0.8	5.7	-0.09	-3.60
Low income	1,719,230	15,239,445	2.33	22.5	8.5	0.20	1.45
China	1,385,457	17,751,105	-0.16	-1.8	21.0	-0.32	-2.03
India	1,375,622	14,052,243	3.47	30.9	7.3	0.33	2.65
Africa	1,427,028	8,740,153	3.85	21.3	2.1	0.27	3.46
Total	8,318,733	112,226,358	1.41				

Under a business-as-usual scenario, this methodology results in flows from the temperate zone to the tropical zone and, in general, from rich countries to poor ones. Since these transfers do not reflect mitigation and adaptation efforts (ΔY_i), it must be emphasized that the damages shown here exceed those that occur if a climate change mitigation strategy is introduced. However, given the vulnerability of the tropics, it is likely that transfers in the context of a mitigation strategy would still flow from temperate to tropic and rich to poor.

Rough calculations suggest that even if the United States or China *alone* were to reduce its annual emissions level to zero, in 2045 net damages to other regions caused by either country would still be positive. Acting independently, neither country could “balance its books” with the rest of the world by ceasing to emit CO₂. This is largely a result of the fact that CO₂ is a stock pollutant and any year’s emissions flow has only a marginal effect on total damages.

VI. SUMMARY AND CONCLUSIONS

Even with the profound uncertainties surrounding the causes and effects of climate change, our empirical discussion suggests several general conclusions. It appears that temperate-zone countries will be disproportionately responsible for the projected increase in GHG atmospheric concentrations, while bearing few of the costs. On the other hand, tropical countries, by and large, bear heavier costs of climate change and have a disproportionately lower role in the increase of CO₂. Under our transfer scheme India and Africa in particular would receive compensation, while the United States causes far more damage than it suffers and would make payments to other countries. A major exception to the conclusion that poor countries should be compensated is China. China bears few projected costs of climate change, but is a projected large contributor to CO₂ emissions. This would also imply compensation from China to other developing countries. This is largely a result of the fact that China is a temperate country and is not projected to suffer damages on the same scale as, say, India.

While the case for including the developing countries in climate change agreements is sound, the appropriate methods for their inclusion remain to be agreed upon. The developing countries should be included according to criteria both of cost effectiveness and equity. This paper suggests one definition of equity, based on differential net damages, which might serve to induce developing country participation in a climate change regime. Illustrative calculations of the transfers implied by this definition of equity suggest that resources would flow from temperate to tropical countries, which in most cases also means from rich to poor.

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