Requiem for Kyoto:
An Economic Analysis of the Kyoto Protocol

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Abstract

This paper uses the newly developed RICE-98 model to analyze the economics of the Kyoto Protocol. It analyzes versions of the Kyoto Protocol that have different approaches to trading emissions rights and compares these with efficient approaches. The major conclusions are: (a) the net global cost of the Kyoto Protocol is $716 billion in present value, (b) the United States bears almost two-thirds of the global cost; and (c) the benefit-cost ratio of the Kyoto Protocol is 1/7. Additionally, the emissions strategy is highly cost-ineffective, with the global temperature reduction achieved at a cost almost 8 times the cost of a strategy which is cost-effective in terms of "where" and "when" efficiency. These conclusions assume that trading in carbon permits is allowed among Annex I countries.

1. Climate-Change Policy and The Kyoto Protocol

Governments have struggled to find policies that can at the same time satisfy the demands of electoral politics and meet the needs for responsible stewardship of the globe. The initial response of nations to the threat of global warming was the Framework Convention on Climate Change (FCCC), which issued from the Rio Summit of 1992.

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Under the FCCC, Annex I countries (high-income nations plus the former Soviet Union and Eastern European countries) committed on a voluntary basis to limit their concentrations of GHGs to 1990 levels. This commitment left open almost all the important questions, such as the environmental, economic, and political components of such a commitment.[2]

It soon became apparent that the voluntary approach under the FCCC was producing next to nothing in actual policy measures. Moreover, some countries, particularly the U.S., were experiencing rapid growth in CO_2 emissions. This led the advocates of strong policy measures to pursue binding commitments, which led to the Kyoto Protocol of December 1997. The key provision of the Kyoto Protocol is Article 3, which states: "The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases ... do not exceed their assigned amounts, ... with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012." In other words, Annex I countries will on average reduce their emissions of greenhouse gases by 5 percent relative to 1990 levels by the budget period 2008-2012.

Both economic theory and the broad array of economic experience has shown that allowing economic agents to trade — in this case, trade national emissions-reduction permits — can substantially reduce the cost of meeting an aggregate quantitative reduction target. The U.S. therefore proposed international emissions trading. The trading provision is contained in Article 6, which reads: "For the purpose of meeting its

[2] A full discussion of the FCCC can be found at the website http:// www.unfccc.de/. The text and discussion of the Kyoto Protocol can also be found at site.

commitments under Article 3, any Party included in Annex I may transfer to, or acquire from, any other such Party emission reduction units ... provided that: ...[t]he acquisition of emission reduction units shall be supplemental to domestic actions for the purposes of meeting commitments under Article 3." This provision gives Annex I nations the right to trade emissions units. However, it is haunted by the vague and troubling provision that the acquired permits shall be supplemental to domestic actions. In other words, nations can buy only part of their emissions reductions — although the allowable amounts are unspecified.

An additional provision introduces the possibility of offsets from developing countries. Article 12 defines a *clean development mechanism*, under which "(a) Parties not included in Annex I will benefit from project activities resulting in certified emission reductions; and (b) Parties included in Annex I may use the certified emission reductions accruing from such project activities to contribute to compliance with part of their quantified emission limitation and reduction commitments... Emission reductions resulting from each project activity shall be certified ... on the basis of ...real, measurable, and long-term benefits related to the mitigation of climate change [and] reductions in emissions that are additional to any that would occur in the absence of the certified project activity."[3] Some have interpreted this as a green light to include trading with developing countries,[4] but the need to ensure additionality and to certify each transaction probably means it will lead to only a small fraction of potential trades.

A further complication involves GHG emissions other than those from energy use. The Kyoto Protocol has provision for five other gases as well as for the potential for enhancing sinks. Specialists are working to understand the potential offsets that might

[3] All citations to the Protocol have omitted provisions that are not relevant to the present analysis, such as the need for consent and the monitoring by international bodies.

[4] A substantial but unspecified use of the clean development initiative is assumed in the administration's economic analysis of the Kyoto Protocol. See section III.E below.

come from these additional actions, and we incorporate current assumptions used in the Energy Modeling Forum's runs of July 1998.

2. Economic Analysis of the Kyoto Protocol

1. The RICE-98 model

This analysis uses a newly developed integrated-assessment model of the global economy and global warming.[5] The present model, the RICE-98 model, is a revised and updated version of earlier work by the author and collaborators. Earlier versions of the DICE and RICE models (these being acronyms for the *D*ynamic *I*ntegrated Model of *C*limate and the *E*conomy and a *R*egional *I*ntegrated Model of *C*limate and the *E*conomy) have been widely applied in climate-change studies.[6] We begin with a description of the RICE-98 model, with a fuller account to be available shortly on the Internet.

The approach taken in the RICE model views climate change in the framework of optimal economic growth theory. This approach was developed by Frank Ramsey in the 1920s (see Ramsey [1928]) and made rigorous by Tjalling Koopmans and others in the 1960s (see especially Koopmans [1967]). In this framework, society invests in reproducible and human capital, along with investments to slow harmful climate change, in order to increase consumption in the future. Emissions reductions in the extended model are analogous to investment in the mainstream model. Society must take steps today, reducing consumption by devoting resources to reducing greenhouse-gas emissions, in order to prevent economically harmful climate change and thereby increasing consumption possibilities in the future.

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[5] The discussion here presents the results of RICE-98.09.

[6] The earlier models are the DICE model (see especially Nordhaus [1992, 1993, 1994]) and the RICE model (see Nordhaus and Yang [1996]).

In the RICE model, the world is divided into thirteen regions — both large sovereign countries (such as the U.S. and India) and large regions (such as the European Union or Africa). The regional definition is provided in the appendix B. Each country is assumed to have a well-defined set of preferences by which it chooses its path for consumption over time. The preferences are increasing in per capita consumption, with diminishing marginal utility of consumption. The welfare of different generations is combined using a time-separable function that applies a pure rate of time preference to different generations. Each nation is assumed to maximize its social welfare function subject to a number of economic and geophysical constraints. The key decisions faced by each country or region are the levels in each period of consumption, investment in tangible capital, and carbon-energy use. The carbon-energy use produces CO_2 emissions which lead to future climate change.

The model contains both a traditional economic sector and a novel climate sector designed for climate-change modeling. In the economic sector, each country or region is assumed to produce a single commodity which can be used for either consumption or investment. In the baseline model, there is no trade in goods or capital, but countries sometimes trade rights for carbon emissions and receive consumption goods in return. Each country is endowed with an initial stock of capital and labor and an initial and different level of technology. Population growth and technological change are exogenous in the baseline model, while capital accumulation is determined by optimizing the flow of consumption over time.

In the revised RICE-98 model, energy is treated by defining a new input into production called "carbon-energy." Carbon-energy is the carbon equivalent of energy consumption and is measured in carbon units. Output is produced with a Cobb-Douglas production function in capital, labor, and carbon-energy inputs. CO_2 emissions and output are therefore a joint product of using inputs of carbon-energy. Technological change takes two forms: economy-wide technological change and energy-saving technological change. Economy-wide technological change is Hicks neutral, while energy-saving technological change is modeled as reducing the output-carbon elasticity (or the amount of carbon emissions per unit output at given input prices). There is also a non-carbon backstop technology that is available at $500 per ton of carbon-energy (approximately $700 per ton of coal or $ $120 per barrel of oil).

On the supply side, a long-run carbon supply curve is introduced. The supply curve allows for limited (albeit huge) long-run supplies of carbon-energy at rising costs. The shape of the cost curve is drawn from estimates of the long-run cost curve for coal because the preponderance of recoverable fossil fuels are coal-based. In the optimal-growth framework, fossil fuels are efficiently allocated over time, which implies that low-cost resources have scarcity (Hotelling) rents and that carbon-energy prices rise over time. There is a world market for carbon-energy, and the wholesale price of carbon-energy is equalized in all regions. The retail price in each region is the sum of the world wholesale price and a region-specific markup. Each country is assumed to supply its carbon-energy domestically, so there is no trade in carbon-energy.

We calibrate the production function and the markups using existing cross-country evidence on energy use, energy prices, and energy-use price elasticities.

The environmental sector of the model contains a number of geophysical relationships that link together the different factors affecting climate change. This part contains a carbon cycle, a climate-change equation, and a climate-damage relationship. In the earlier RICE model, endogenous emissions included all GHG emissions, although CO_2 was quantitatively the most important. In RICE-98, endogenous emissions are limited to industrial CO_2. A major change in environmental policy over the last decade is that the chlorofluorocarbons (CFCs) are now strictly controlled outside the framework of the climate-change agreements under different protocols. It is not generally appreciated that control of CFCs has had a significant impact on projected global warming. CFCs are fairly potent greenhouse gases, with 100-year GWPs (global warming potential -- a measure of the climatic effect of a greenhouse gas over a given time period) thousands of times that of carbon dioxide. Industrial emissions are, as noted above, treated as a joint product of carbon-energy in the new models. Other contributions to global warming are taken as exogenous. These include CO_2 emissions from land-use changes as well as the non-CO_2 greenhouse gases.

The original DICE and RICE models used an empirical approach to estimating the carbon flows, deriving the parameters of the emissions-concentrations equation from data on emissions and concentrations. RICE-98 replaces the earlier treatment with a structural approach that uses a three-reservoir model calibrated to existing carbon-cycle models. Climate change is represented by global mean surface temperature, and the relationship uses the consensus of climate modelers and a lag suggested by coupled ocean-atmospheric models.

Understanding the economic impacts of climate change continues to be the thorniest issue in climate-change economics. The present study follows first-generation approaches by analyzing impacts on a sectoral basis. There are three major differences from many earlier studies. First, the approach here is focused on developing estimates for all major countries and regions rather than for the U.S. This focus is obviously necessary both because global warming is a global problem and because the impacts are likely to be larger in poorer countries. Second, this study focuses more heavily on the non-market aspects of climate change with particular importance given to the potential for catastrophic risk; this approach is taken because of the finding of the first-generation studies that the “best-guess” impacts on market sectors are likely to be relatively limited. Third, we estimate that impacts are likely to differ sharply by region — Russia and other high-latitude countries (principally Canada) are likely to benefit slightly from a 3 degree C benchmark warming . At the other extreme, low-income regions — particularly Africa and India — and Europe appear to be quite vulnerable to climate change. The United States appears to be relatively less vulnerable to climate change than many countries.

A final important revision in the RICE-98 model is different treatment of the discount rate. Two important changes have been made. First, the new model allows for different discount rates in different regions. The pure rate of social time preference appears to be higher in low-income countries than in high-income countries. Based on the observed relationship between measured capital stock and GDP, we take the initial pure rate of time preference to be 3 percent per year in high-income countries and up to 6 percent per year in low-income countries. The second difference builds in a decline in the pure rate of social time preference in the coming decades. This can either be interpreted as reflecting a likely decline in the discount rate or as reflecting uncertainty in underlying factors which would lead to a decline in the certainty-equivalent discount rate even if the underlying discount rate were unchanged. (For more explanation, see Nordhaus 1998b.) In the modeling results presented here, the pure rate of social time preference rate in high-income countries declines to 2.3 percent per year by 2100 and about 1.4 percent per year by 2300. The major effect of the changing treatment of the discount rate is to lower current optimal carbon taxes and control rates and to raise long-run optimal carbon taxes and control rates.

The equations of the RICE-98 model are provided in Appendix A. A more thorough discussion of the model can be found in Nordhaus 1998b. (The version of the model described in that source has been updated since the writing of this paper.)

2. Assumptions for the analysis of the Kyoto Protocol

In the current analysis, we analyze a number of different runs to determine the effect of different climate-change policies on the global and regional economies as well as on the major environmental variables related to climate change. Table 1 shows the major runs analyzed in the present paper. Most of them require no discussion, but a few details need elaboration.

The reference case (Run 1) assumes that the energy and economic systems evolve with no carbon-emissions constraints or carbon taxes. In the "optimal" case (run 2), carbon abatement is optimized over space and time — the optimization balances the costs of substituting other inputs for carbon energy with the benefits of reduced climate change. It will be useful to provide a word of interpretation of the optimal case. This is not presented in the belief that an environmental pope will suddenly appear to provide the infallible canons of policy that should and will be scrupulously followed by all. Rather, the optimal policy is provided as a benchmark for policies to determine how efficient or inefficient alternative approaches may be.

The cases denoted "Kyoto emissions limitations" take the emissions limitations agreed upon in the Kyoto Protocol and extend them indefinitely for Annex I countries — this might be called "Kyoto forever." There are four variants of the Kyoto Protocol analyzed here. Under the "no-trade" run 3a, no trading of emissions permits is allowed among the six major blocs of Annex I countries and there are no offsets with the non-Annex I countries. Under the "OECD-trade" runs (run 3b), emissions trading is allowed only among the OECD regions.[7] The "Annex I-trade" case (run 3c) allows full trading allowed among all Annex I regions. The global trading case (3d) extends the umbrella of trading to all countries. In this case, the non-Annex I regions receive emissions permits equal to their no-control emissions in run 1, but regions are then allowed to sell any

[7] Strictly speaking, the "OECD" here includes the OECD less Mexico and South Korea and includes Hong Kong. It is essentially all the high-income countries.

emissions rights that exceed their actual emissions. Each of these runs has serious implementation issues, but these are ignored in this analysis.

It should be emphasized that global trading in case 3d is actually a radical extension of the Kyoto Protocol and contains crucial and questionable assumptions about the behavior of non-Annex I countries. In principle, each region will be better off by agreeing to this limit-and-trade procedure — it can do no worse than simply consuming its permits and can do better by reducing its low marginal-cost sources and selling the permits at the world price. This assumption is highly questionable in practice, however, because of the difficulty of estimating and assigning the appropriate baseline emissions, because of the need to ensure compliance among countries with weak governance structures, and because of the potential for countries repudiating their commitments in the future.[8]

In addition to the Kyoto runs, we present two alternative cases which are useful for assessing the efficiency of different approaches. The emissions objectives of the Kyoto Protocol are not based on any ultimate environmental objective — they are instead simple and easily understood guidelines of holding emissions constant. We can translate the emissions objectives into more meaningful environmental objectives by examining the consequences of the Kyoto Protocol for CO_2 concentrations and for global temperature. Run 4a determines a program that minimizes the cost of meeting the concentrations target implicit in the Kyoto emissions limitations; in this policy, concentrations are constrained to be at the same level implied by the Kyoto Protocol after 2050. Run 4b takes the same approach for global temperature, finding the path that minimizes the cost of attaining the temperature trajectory implicit in the Kyoto Protocol after 2100. (These dates are selected to take account of the lags between emissions and the two other objectives.) The idea

[8] Some of the issues raised by a quantitative approach to climate-change policy are discussed in the companion paper to this one Nordhaus [1998a].

behind runs 4a and 4b is that we can ask how cost-effective the different approaches are in attaining the environmental objectives embodied in the Kyoto Protocol.

This point can be put in a different way. It is desirable to design policies that are economically efficient so that the environmental objectives can be attained in a least cost manner. There are four kinds of standards that we can examine — how-efficiency, where-efficiency, when-efficiency, and why-efficiency. *How-efficiency* denotes the use of efficient ways of achieving the actual emissions in a given year and country; in the current study, we assume that countries attain how-efficiency by either using uniform carbon taxes or by auctioning off emissions permits. *Where-efficiency* denotes allocating emissions reductions across countries to minimize the costs of attaining the global emissions target for a given year. As we move from the no-trade to the global-trade case, we are assured to attain where-efficiency. *When-efficiency* refers to efficient allocation of emissions over time. There is no reason to believe the Kyoto Protocol satisfies the criterion of when-efficiency because the emissions targets were arbitrarily chosen. Cases 4a and 4b examine the efficient pattern of emissions reductions to achieve when efficiency when the targets are the concentrations and global temperature associated with the Kyoto Protocol. Finally, *why-efficiency* refers to the question of the ultimate goal of the environmental program and denotes a plan which balances costs of abatement and benefits of damage reduction. Again, the Kyoto Protocol is unlikely to satisfy the criterion of why-efficiency because the emissions targets were arbitrarily chosen; moreover, one of the major findings of the present study is that the Kyoto Protocol is extremely far from a why-efficiency policy. The optimal program in run 2 satisfies why-efficiency (given the parameters of the RICE model) and can therefore be used as a benchmark for why-efficiency comparisons with other proposals.

Table 1. Runs for Analysis of Kyoto Protocol

This list shows the runs examined in the analysis of the Kyoto Protocol.

1. *Reference*: no controls

2. Optimal: sets emissions by region and period to balance the costs and benefits of emissions reductions

3. *Kyoto emissions limitations:*
   a. No trade: no trade among 6 major Annex I blocs
   b. OECD trade: emissions trading limited to OECD countries
   c. Annex I trade: emissions trading limited to Annex I countries
   d. Global trade: emissions trade among all regions
4. *Cost effectiveness benchmarks:*
   a. Limit atmospheric concentrations to those resulting from the Kyoto Protocol case 3c (for the period after 2050)
   b. Limit global mean temperature to that resulting from the Kyoto Protocol case 3c (for the period after 2100)

3. Major Results

In this section we present the major results of the current set of runs. It should be emphasized that these projections from the RICE-98 model are subject to major uncertainties and are constantly being revised as new data and models are developed. The sections review in order the results for the climate variables, the economic variables, the costs and damages, the comparisons among the different runs, and finally compares these results with other studies.

1. Environmental variables

The first set of results pertains to the major environmental variables — emissions, concentrations, and global temperature increases. Figure 1 and Table 2 show the level of global industrial CO_2 emissions for the major cases, while Figure 2 shows the difference in cumulative emissions reductions from the uncontrolled base. The RICE-98 model foresees a strong continuation of the growth of CO_2 emissions, primarily because of the projection of significant economic growth over the coming decades. In the reference (uncontrolled) run, emissions rise from 5.9 GtC (gigatons or billions of tons of carbon) in the 1990-99 period to about 23 GtC tons around 2100.

The controlled runs show an interesting feature. One important result is that the global emissions in the Kyoto Protocol are close to our estimate of the optimal emissions over the next century. Indeed, cumulative emissions reductions are virtually identical over the period until 2100. The different Kyoto cases have similar reductions.

Figure 1

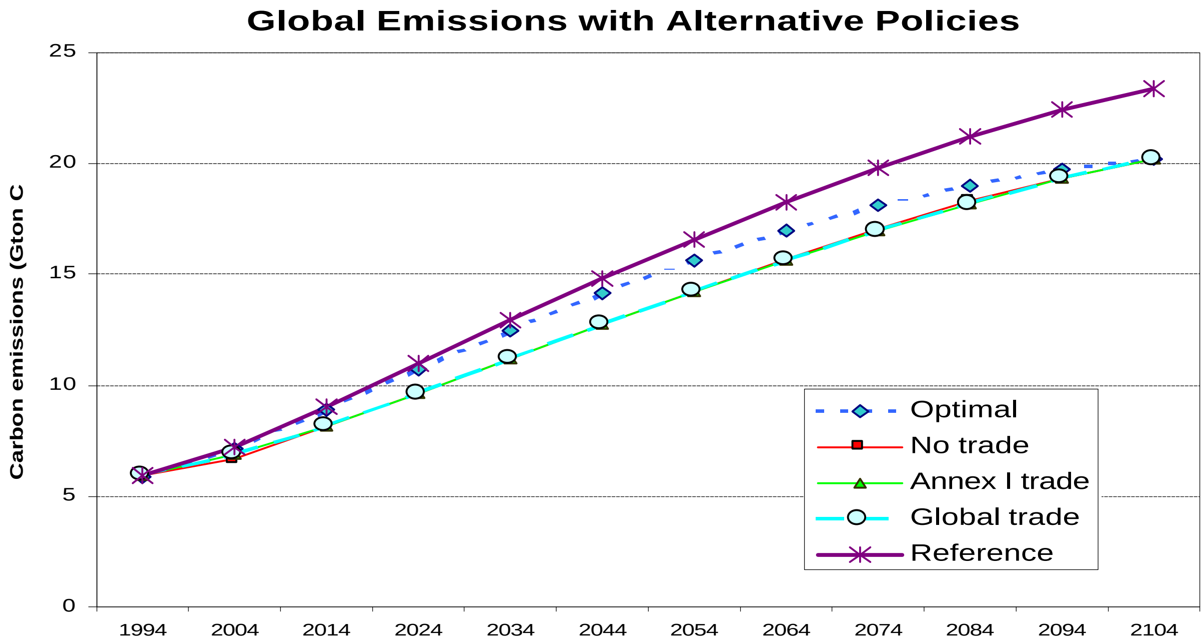


Figure 2

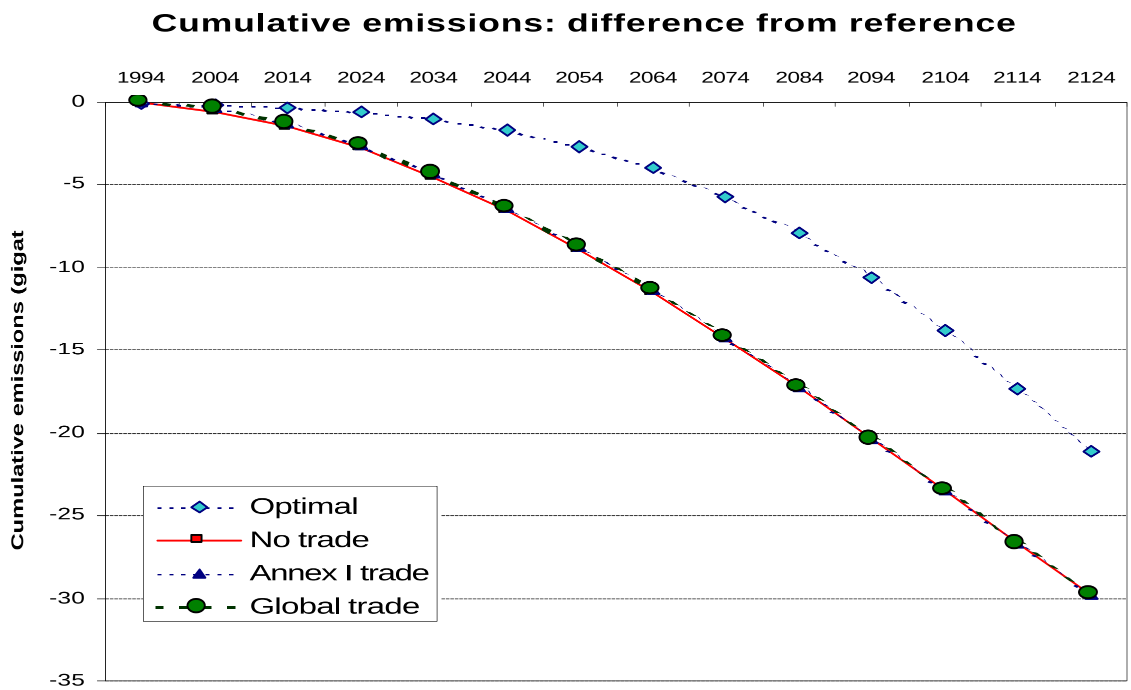


Table 2. Global Carbon Emissions for Different Policies

[Billions of tons per year, carbon weight, industrial emissions only]

Policy	***2010***	***2050***	***2100***
Reference	8.1	15.7	22.9
Optimal	8.0	14.9	20.0
Global trade	7.5	13.5	19.8
Annex I trade	7.5	13.5	19.8
OECD trade	7.4	13.5	19.8
No trade	7.4	13.5	19.8

The buildup of CO_2 concentrations projected in the RICE-98 model is shown in Figure 3. The buildup is slightly less rapid than in standard scenarios. In the uncontrolled run of RICE-98, CO_2 concentrations in 2100 are about 642 ppm (1357 GtC) as compared to 710 ppm (1500 GtC) in the IPCC IS92a scenario.[9] The lower buildup of concentrations is due to both lower emissions and a slightly lower fraction of CO_2 concentrations retained in the atmosphere than in standard calculations.

The impact on globally averaged temperature is shown in Figure 4 and Table 3. The trend in the reference RICE-98 run is close to the conventional IPCC scenarios. The baseline temperature increase is 0.43 ºC in 1995 and rises to 2.3 ºC by 2100, for an increase of 1.9 degrees. This increase compares with a baseline warming used in IPCC [1996a] of 2.0 ºC in 2100 relative to 1990 for the baseline with a climate sensitivity of 2.5 ºC.

[9] The IPCC 92a scenario is shown in IPCC [1996a], p. 23.

Figure 3

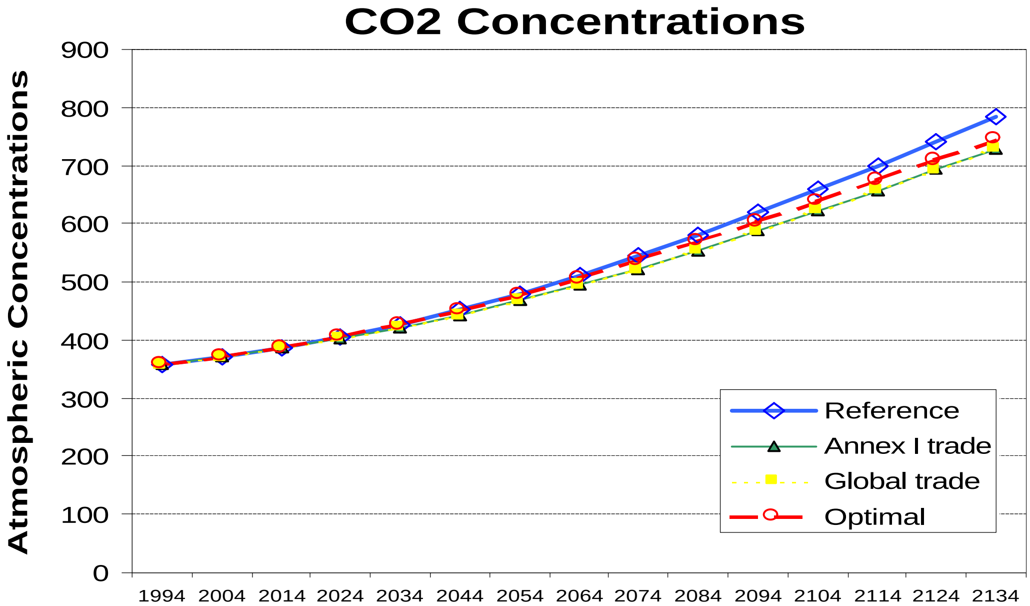


Figure 4

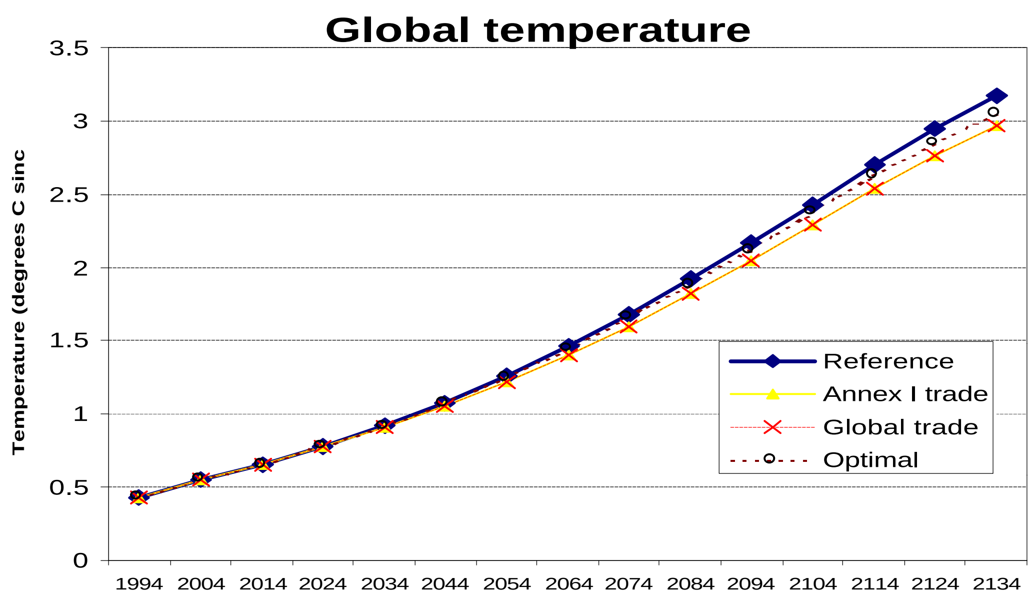


Table 3.

Global Temperature Increase for Different Policies

[Increase from 1800, globally averaged, degrees C]

Policy	*2000*	*2100*	*2200*
Reference	0.49	2.30	4.23
Optimal	0.49	2.25	3.99
Global trade	0.49	2.17	3.97
OECD trade	0.49	2.17	3.97
Annex I trade	0.49	2.17	3.97

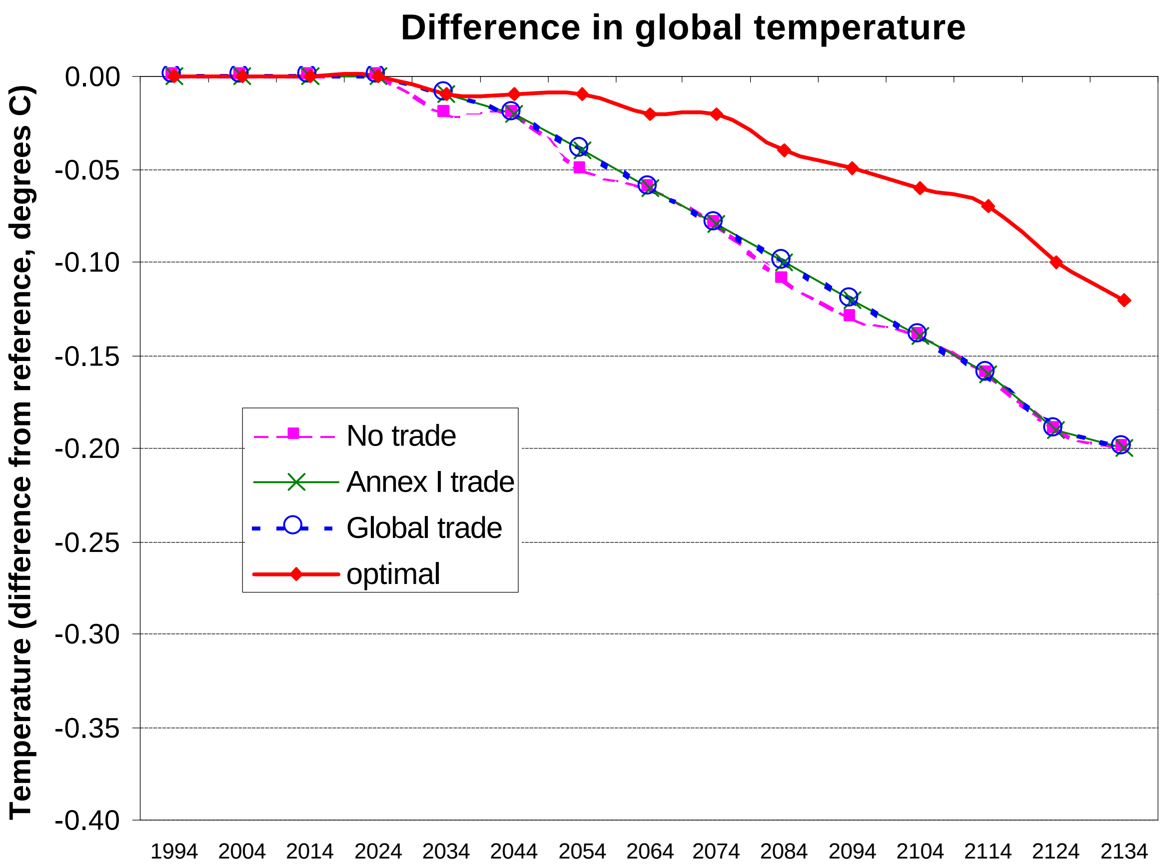
Figure 5 shows the difference in temperature from the reference for different scenarios. These impacts mirror the numbers on cumulative emissions with a lag. Note that the impact of the Kyoto Protocol on global temperature is quite modest, especially for the first century. The reduction in global mean temperature in the Annex I case relative to the reference in 2100 is 0.13 ºC; this compares with a difference of 0.17 ºC from the Kyoto Protocol calculated by Wigley [1998]. The temperature reduction in the optimal run is essentially the same as the Kyoto runs by the 22nd century.

The key results here are the following:

•Emissions trends in this analysis are close to the standard estimates considered in climate-change policies.

•The Kyoto Protocol will have a modest impact on global warming. Because the Kyoto Protocol policy does not succeed in capping the

Figure 5



emissions of non-Annex I countries, the long-run impact of the Kyoto Protocol on carbon emissions and global temperature is extremely small.

•In the short run, the emissions, concentrations, and warming under the Kyoto Protocol are more stringent than the optimal policy; by the 22nd century the optimal and Kyoto policies have essentially the same environmental impacts.

2. Economic variables

1. Carbon prices

One of the most useful measures of the stringency of climate-change policy is the level of carbon prices that would be generated by the policies. “Carbon prices” are the prices of rights to emit CO_2. In a tradable-emissions regime, they would be the prices of emissions permits; in a fiscal regime, they would be carbon taxes or emissions fees. Table 4 and Figures 6 and 7 show the carbon prices for the major cases. The optimal and global-trading cases have relatively modest carbon prices. The carbon tax in the global-trading case is $17 per ton in 2010, then rises to $46 per ton in 2100. (All these are in 1990 prices per ton of carbon; 1998 prices would be about 20 percent higher using the U.S. GDP deflator.)

Policies which restrict trade would have extremely large and potentially damaging carbon prices. The Annex I-trading case has sharply rising carbon prices in the Annex I region, starting at $57 per ton in 2010 and rising to around $300 per ton in the second half of the next century. (These are for Annex I countries; carbon prices in non-Annex I countries are by assumption zero.)

Russia and Eastern Europe play a crucial role in the base Kyoto Protocol case. The existence of large baseline emissions in these countries represents an enormous pool of reducible emissions that keeps the carbon prices in the OECD region down in the Annex I case. As shown in Figures 6 and 7, the prices for the no-trade or OECD-only trading versions of the Kyoto Protocol are significantly higher than the Annex I case. For example, the U.S. 2010 prices are $144 and $127 per ton for the OECD and no-trading cases. In the U.S. carbon prices are estimated to rise to $350 to $314 per ton carbon by the middle of the next century. These numbers are so large that they cast a fairy-tale (or perhaps horror-story) quality to the analysis. For example, by the middle of the next century, annual U.S. carbon tax revenues are between $70 and $400 billion dollars depending upon the version of the Kyoto Protocol. In the Annex I case, the U.S. is transferring $10 to $70 billion annually to other countries through carbon emissions permits in the next century. It seems unlikely that the our models can adequately represent the impacts on the overall economy, on trade flows, or on the political response of such enormous changes.

2. Overall Abatement Costs

The next set of issues concerns the economic impact of alternative policies. The present value of total abatement costs is shown in Table 5. The present value of abatement (which excludes damages) ranges from a low of $173 billion in the global-trading case; to $828 billion in the Annex I-trading case; to a high of $1,488 billion in the no-trade case. Clearly, there are enormous stakes involved in global warming.

It is interesting to compare the costs of different regimes with the minimum global cost of meeting the Kyoto temperature trajectory. We estimate that the trajectory can be attained at a minimum cost of $109 billion. The global trading scenario is relatively efficient, with costs only 1.6 times the minimum cost. The other scenarios have a cost of between 8 and 14 times the minimum cost. Note that there is relatively little gain from trading within the OECD countries alone; most of the gain from Annex I trade arises from the inclusion of Russia and other Eastern European countries under the trading bubble.

Figure 9 shows the impact of different strategies on the time path of world output, while Table 6 and Figures 10 and 11 show the impact on different regions. The measures here are the gross domestic outputs of different countries aggregated at market prices and

Figure 6

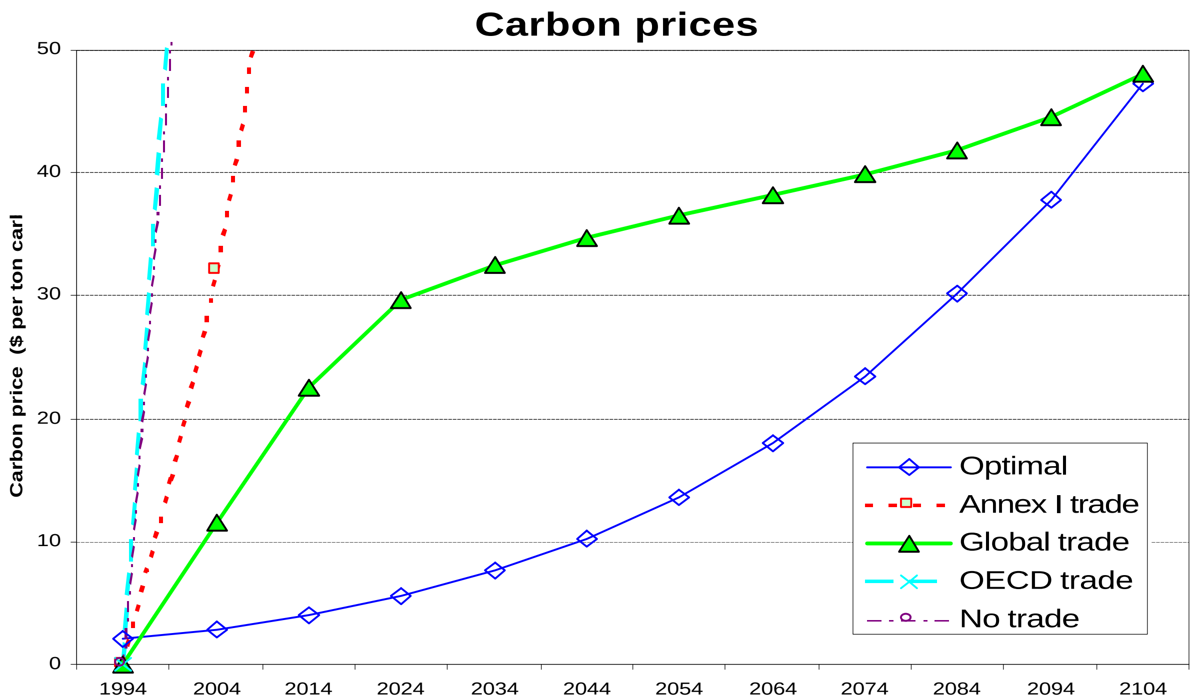


Figure 7

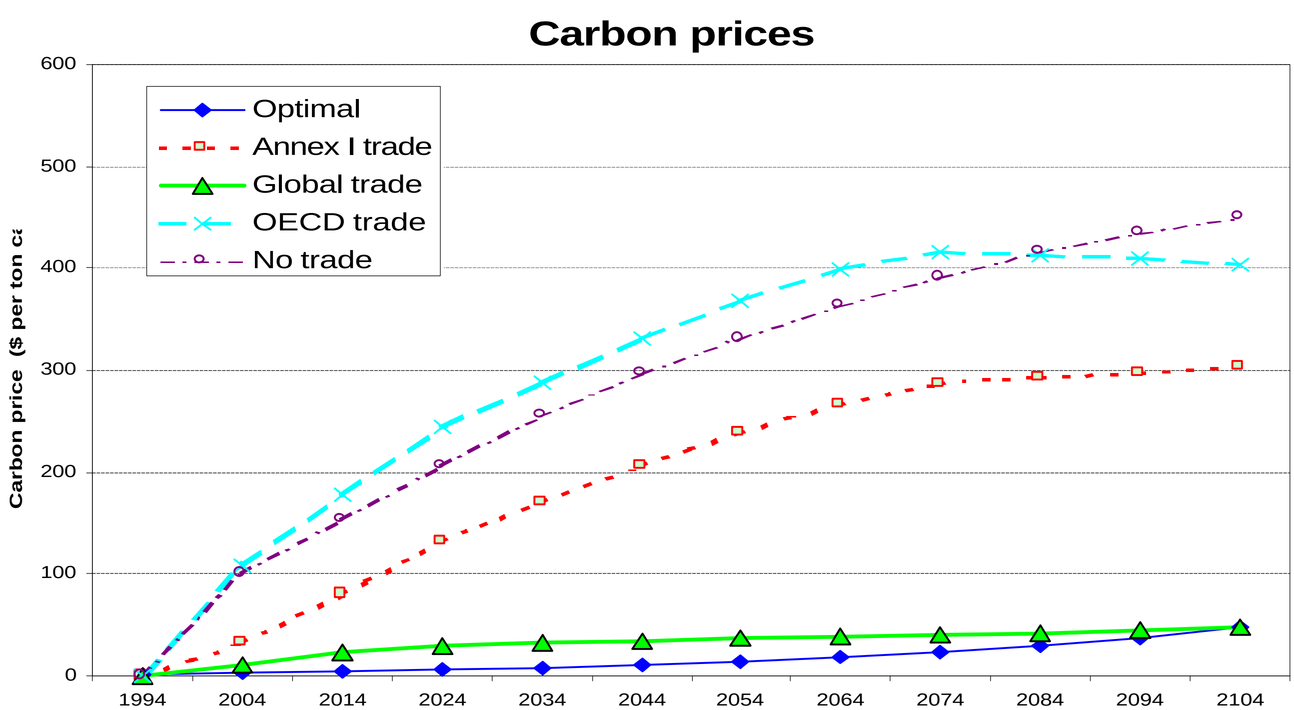


Table 4. Carbon Prices for Different Policies

[Price of emissions permits in dollars per ton carbon]

	[1990 prices]			
Policy	***1995***	***2010***	***2050***	***2100***
Reference	0	0	0	0
Optimal	2	3	12	43
Global trade	0	17	36	46
Annex I trade	0	57	222	300
OECD trade	0	144	350	406
No trade	0	127	314	442
	[1998 prices (a)]			
Policy	1995	2010	2050	2100
Reference	0	0	0	0
Optimal	2	4	15	52
Global trade	0	21	43	56
Annex I trade	0	69	270	365
OECD trade	0	175	425	494
No trade	0	154	382	538

Note: Prices are the market-clearing prices of carbon emissions permits. For global trading and optimal case, prices are equalized in all regions. For other cases, carbon prices are zero in regions with no controls and differ across controlled regions in "no trade" case

(a)1990 prices are converted into 1990 prices using the U.S. GDP deflator,

Strategy	***Discounted Costs***
Reference (no controls)	0
Optimum	49
Kyoto Protocol:	
Global trade	173
Annex I trade	828
OECD trade	1,463
No trade	1,488
Limit to Kyoto concentrations	171
Limit to Kyoto temperature	109

Table 5. **Discounted Abatement Costs in Different Strategies**

Table shows the discounted global costs of different targets and control strategies. The estimates are calculated as the difference between the discounted value of consumption in the case considered relative to the reference case. The figures are in 1990 U.S. dollars and exclude damages from climate change.

Figure 9

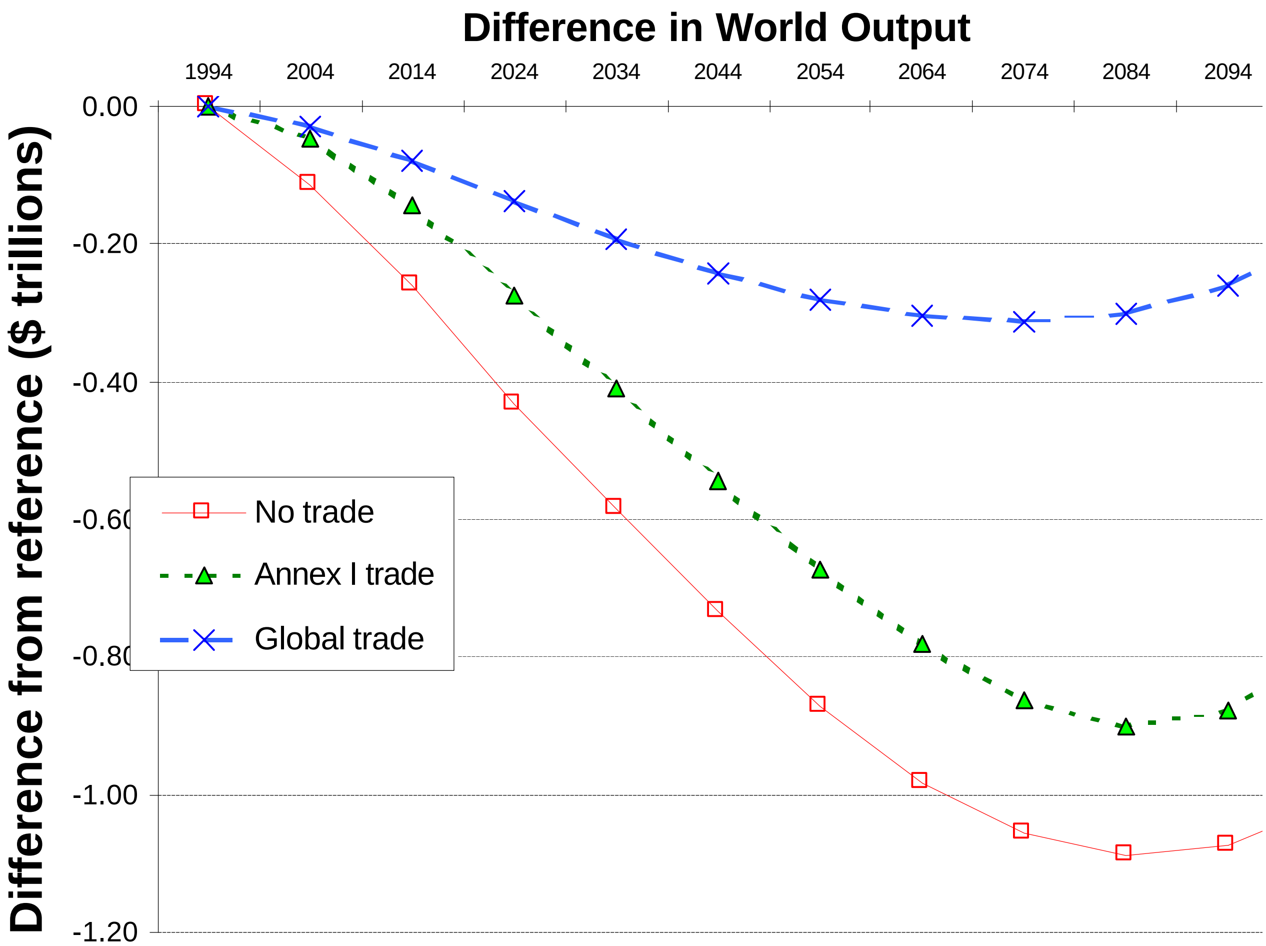


Figure 10

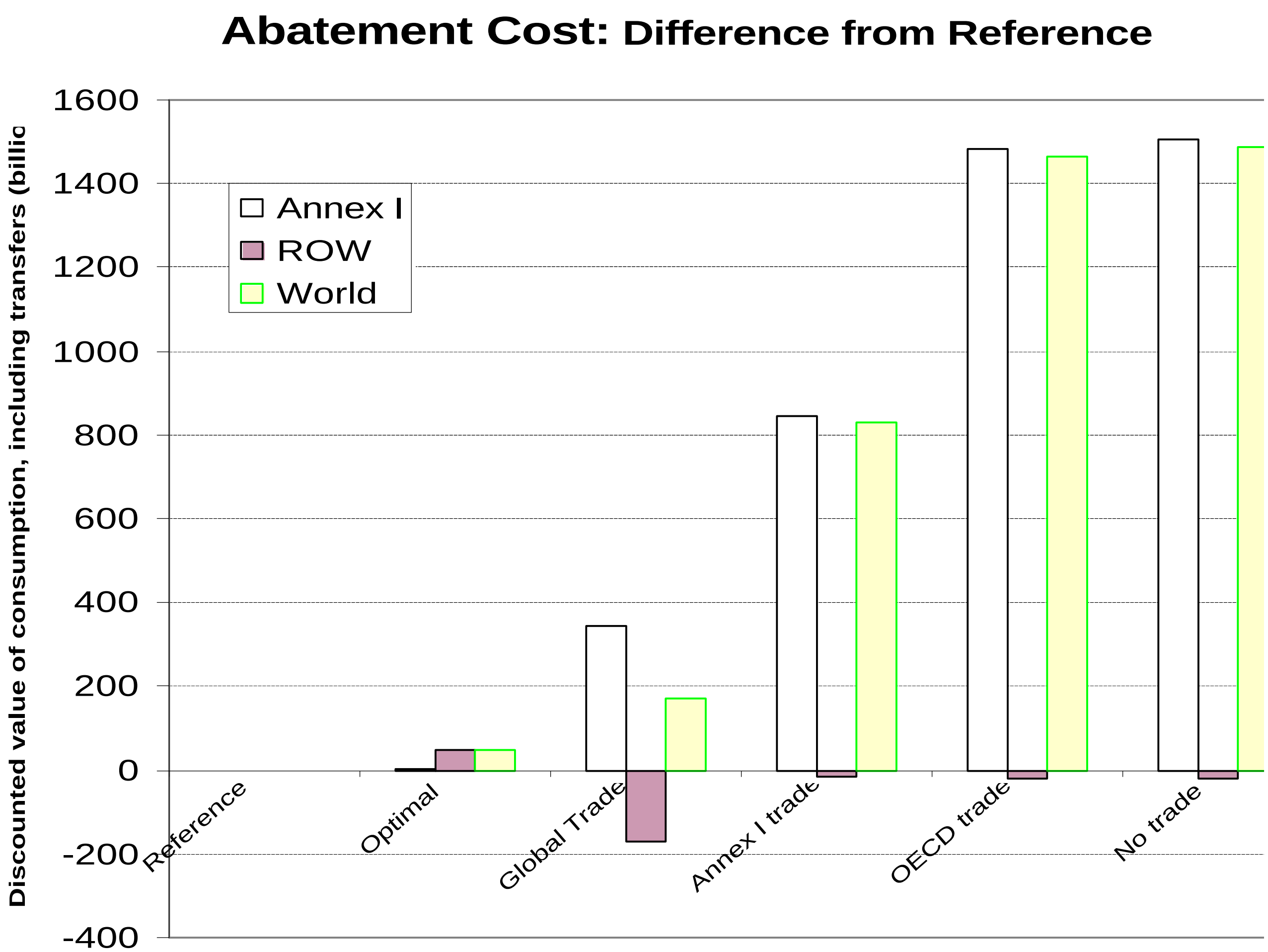
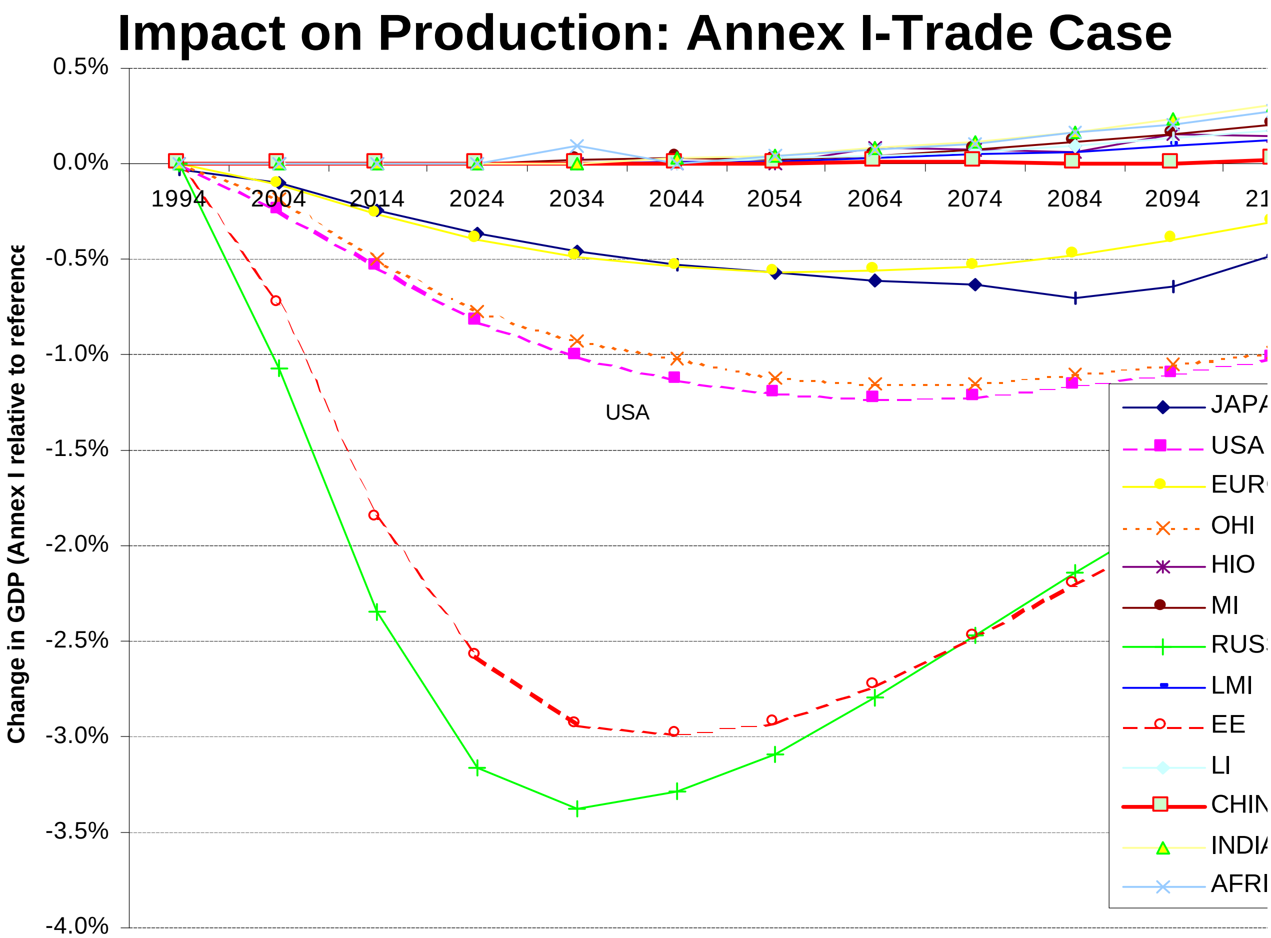

Abatement Cost: Difference from Reference
Discounted value of consumption, including transfers (billio
1600
1400
1200
1000
800
600
400
200
0
-200
-400
Annex I
ROW
World
Reference
Optimal
Global Trade
Annex I trade
OECD trade
No trade

Figure 11



Impact on Production: Annex I-Trade Case
Change in GDP (Annex I relative to reference
0.5%
0.0%
-0.5%
-1.0%
-1.5%
-2.0%
-2.5%
-3.0%
-3.5%
-4.0%
1994
2004
2014
2024
2034
2044
2054
2064
2074
2084
2094
USA
USA
OHI
HIO
MI
LMI
EE
LI

Table 6A. Economic Impact of Different Policies:

Excluding Climate Damages

[Difference from no-control base; billions of 1990 U.S. dollars]

With transfers	*Annex I*	*ROW*	*World Total*
Reference	*0*	*0*	*0*
Optimal	*-3*	*-46*	*-49*
Global Trade	*-344*	*171*	*-173*
Annex I trade	*-846*	*18*	*-828*
OECD trade	*-1483*	*19*	*-1463*
No trade	*-1507*	*20*	*-1488*
Limit to Kyoto Concentrations	*-49*	*-122*	*-171*
Limit to Kyoto Temperature	*-14*	*-95*	*-109*

Note: Cost is equal to the discounted value of consumption for 30 decades, discounted at the consumption discount rate. Transfers are calculated as the present value of the purchases (sales being negative) valued at the U.S. discount rate. Runs exclude climate damage.

Table 6B. Economic Impact of Different Policies:

Including Climate Damages

[Difference from no-control base; billions of 1990 U.S. dollars]

With transfers	*Annex I*	*ROW*	*World Total*
Reference	*0*	*0*	*0*
Optimal	*23*	*-13*	*10*
Global Trade	*-291*	*232*	*-59*
Annex I trade	*-790*	*74*	*-716*
OECD trade	*-1406*	*77*	*-1329*
No trade	*-1454*	*77*	*-1377*
Limit to Kyoto Concentrations	*2*	*-60*	*-58*
Limit to Kyoto Temperature	*9*	*-24*	*-15*

Note: Cost is equal to the discounted value of consumption for 30 decades, discounted at the consumption discount rate. Transfers are calculated as the present value of the purchases (sales being negative) valued at the U.S. discount rate. Runs include climate damage.

market exchange rates. The major and not surprising result is that the economic burden of the Kyoto Protocol lies completely on Annex I countries. The countries whose outputs are most seriously affected are Russia and Eastern Europe. Their outputs are reduced because of the need to reduce energy use to sell permits; their levels of income as opposed to output are actually higher.

3. Costs by Region

It is important to understand the distribution of costs by region. The following table shows the impact on discounted consumption (including trading transfers):

Total Increase in Production Costs for Annex I Case

[billions of dollars, present value to 1990 in 1990 U.S. prices, difference from no controls, excluding damages but inclusive of permit purchases]

Japan	166
USA	517
Europe	325
Rest of World	-180
World	828

This table gives some idea of why the U.S. might be unhappy about the Kyoto Protocol: it bears two-thirds of the burden.

4. Trading and transfers

Figure 12 shows the impact of the Kyoto Protocol — assuming Annex I trading — on incomes of different countries. In these figures, “gross domestic income” equals gross domestic product including the net revenues from sale of emissions permits. Both the United States and Europe are losers, although the time paths are different. Russia is a winner.

Figure 13 and Table 7 show the permit trading in the Annex I-trade version of the Kyoto Protocol. The Annex I case shows the near-term advantage gained by Russia and Eastern Europe and the major losses suffered by the U.S. The U. S. increases its permit purchase from about $40 billion annually in 2050 to $73 billion at the end of the next century. Sales of permits would probably be Russia's major export.

Figure 12

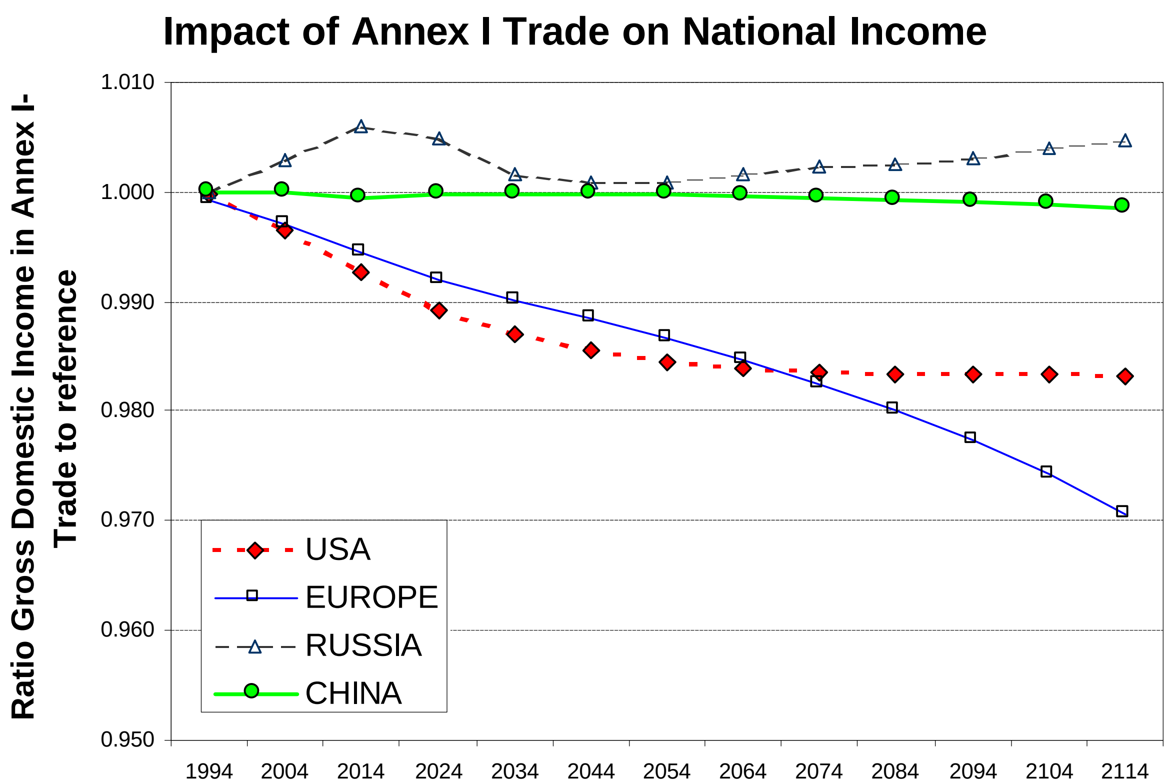


Figure 13

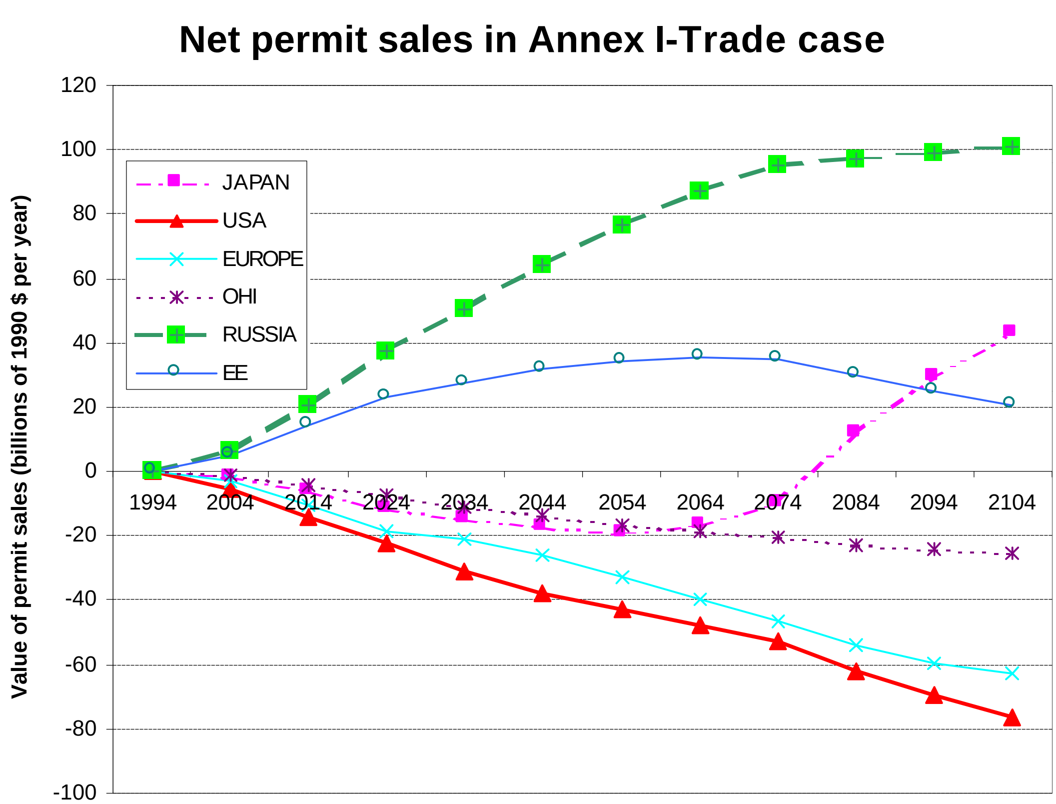


Table 7. Permit Purchases with Annex I trade

[Billions of 1990 U.S.dollars per year; sales are (+) and purchases are (-)]

	2010	*2050*	*2100*
JAPAN	*-4*	*-18*	*36*
USA	*-10*	*-40*	*-73*
EUROPE	*-7*	*-29*	*-61*
OHI	*-3*	*-15*	*-25*
HIO	*0*	*0*	*0*
MI	*0*	*0*	*0*
RUSSIA	*13*	*70*	*100*
EE	*10*	*33*	*23*
LI	*0*	*0*	*0*
CHINA	*0*	*0*	*0*
INDIA	*0*	*0*	*0*
AFRICA	*0*	*0*	*0*

Note: Transfers are the sales (+) or purchases (-) of carbon emissions permits
under the Kyoto Protocol with trading only among Annex I countries.

The results on flows of permit revenues reveal two major flaws in the design of the Kyoto Protocol. First, the Protocol caps the emissions of one group of countries at historical levels but does not do so for the non-Annex I countries. Bringing non-Annex I countries in under the additionality criterion assigns *reference* emissions to non-Annex I countries, thus giving them substantially different treatment from Annex I countries. A second and related major design flaw is assigning historical emissions. This gives a major windfall to those countries which had inefficient energy systems (particularly Russia, Eastern Europe, and Germany after its purchase of East Germany). A better procedure would be a rolling emissions base, which would remove the advantages of inefficiency and also remove the difference of treatment of non-Annex I and Annex I countries.

5. Summary of economic impacts

The overall impacts of the Kyoto Protocol and variants are complex, but the major points to emphasize are the following:

- There are big impacts of virtually all variants of the Kyoto Protocol on Annex I countries. The discounted value of production costs (exclusive of transfers and climate damages) for Annex I countries range from a low of $50 billion in the global-trading case to a high of $1,507 billion in the no-trading case.

- However, these number are impacts on output. Even though the global cost in the global trading case is significantly reduced by emissions trading, the impacts on national income continue to be extremely large in all cases. If transfers are included, the overall cost to Annex I nations of the Kyoto Protocol ranges from $344 to $1,507 billion.

- Non-Annex I countries, Russia, and Eastern Europe are the major beneficiaries of the Kyoto Protocol, even if damages are excluded. The benefits for non-Annex I countries are around $20 billion in lower production costs, exclusive of lower damages.

- Trading significantly reduces the aggregate cost of abatement — particularly trading with Russia and low-income countries like China. But the cost of these efficiency gains are large transfers — particularly from the United States.

2. Costs and damages

The comparisons up to now exclude the damages from global warming. It is always important to keep in mind that the point of reducing emissions is to reduce future damages. The impact of different policies on both costs and damages is shown in Figure 14. The first set of bars shows the discounted value of damages. Our estimates indicate that there are likely to be substantial costs of global warming in any of the cases examined here; the costs total approximately $1.8 trillion in present value in the reference case.[10]

As shown in Figure 15, the different policies reduce damages by only a modest amount. Indeed, one of the surprises is how little the policies affect the damages from global warming. The reasons are that, because there is so much inertia in the climate system and because the Protocol does not limit the emissions of developing countries, the Kyoto Protocol reduces the global temperature increase by only a fraction of a degree over the next century. The other point that is shown in Figure 14 is that inefficient policies, such as OECD trading or no trading, raise the costs of abatement substantially with little or no improvement in benefits. For example, moving from no controls to the Kyoto Protocol plan with Annex I trading incurs discounted abatement cost of $0.83 trillion; however, the discounted value of damages decreases only from $1.83 to 1.72 trillion. The benefit cost ratio of moving to the optimal plan is 1.2. By contrast, the benefit-cost ratios are 0.14 for Annex I trading and 0.07 for no trading. All these ratios make the optimistic assumption that the policies are efficiently implemented in each region.

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[10] The damage function in the version of the RICE-98 model used for this analysis is undergoing revision and will change in the final version.

Figure 14

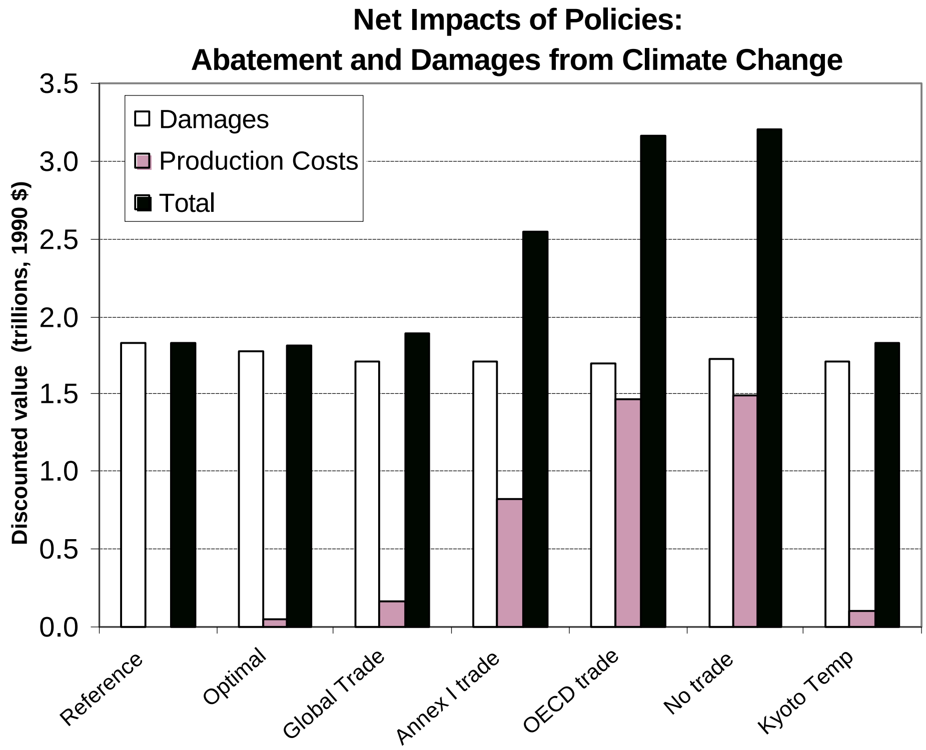
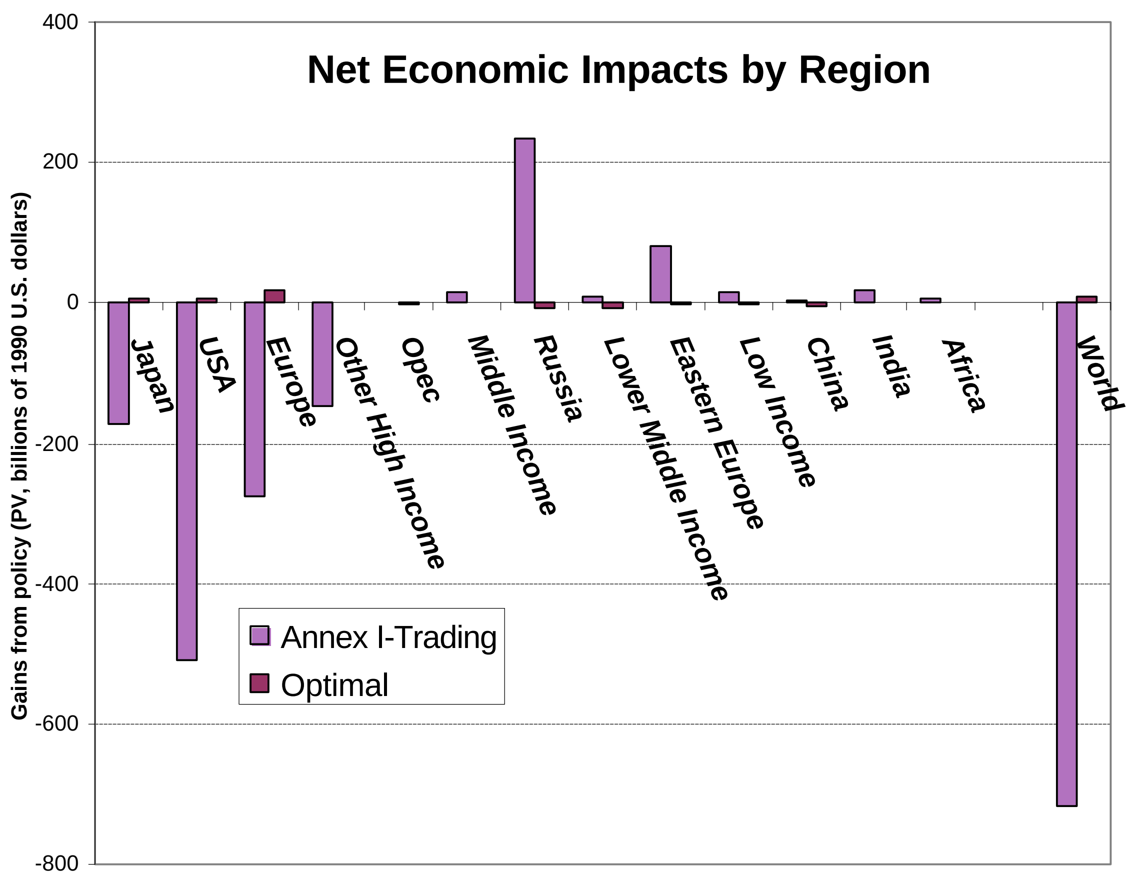


Figure 15



Finally, Figure 15 shows the distribution of net impacts (including transfers and climate damages) of the three major policies considered here.

The main conclusions that come from an examination of damages are that there are likely to be substantial damages from climate change, but that the Kyoto Protocol captures essentially the same damage reduction as the optimal program at a substantial increase in costs.

3. The Gains from Trade

Much has been made about the gains from trade. Table 8 shows the improvements in cost-effectiveness under different trading options. In this comparison, we have taken the temperature path associated with meeting the Kyoto Protocol as the standard of a cost-effective policy; the "no-trading" plan has zero cost-effectiveness. We then calculate the costs of attaining that trajectory under different trading plans.

One major surprise is that trading within the OECD only attains relatively little — 2 percent — of the potential gains from trade. This low fraction comes because the energy efficiencies are relatively similar within the large OECD blocs. The other surprise is how much of the gains are obtained by global trading — 95 percent. Moreover, targeting concentrations rather than temperature gets about 96 percent of the way to a cost-effective strategy.

Table 8. Cost-effectiveness of Different Policies

Policy	*Cost-effectiveness [percent]*
Temperature Target	100.0
Concentrations target	95.5
Global trade	95.4
Annex I trade	47.8
OECD trade	1.8
No trade	0.0

Note: "Cost-effectiveness" is defined as the fraction of the total gains from trading, different timing, or different targets that is achieved by a given policy. The standard is relative to the "temperature target," which is the trajectory of global mean temperature after 2100 that is implicit in the Kyoto Protocol.

4 Findings and Conclusions

The present paper examines the implications of the Kyoto Protocol and variants of that policy in a new integrated-assessment model of climate change and the world economy. Before moving to the major conclusions, it must be emphasized that these results should be taken with suitable reservations reflecting the difficulties inherent in the subject and the fact that this is but one of many models that can be used to estimate the impacts of the Kyoto Protocol.

First, it appears that the strategy behind the Kyoto Protocol has no grounding in economics or environmental policy. The approach of freezing emissions at a given level for a group of countries is not related to a particular goal for concentrations, temperature, or damages. Nor does it bear any relation to an economically oriented strategy that would balance the costs and benefits of greenhouse-gas reductions. The best way of comparing runs is probably the stringency of policy as indicated by the carbon prices. The emissions and concentrations implicit in the Kyoto Protocol are close to those in the optimal policy over the next century. However, because the emissions reductions are targeted to Annex I countries, the costs of achieving these emission reductions are 8 to 14 times more costly (these being the full Annex I-trading and the no-trading variants).

Second, while the environmental damages from climate change do not differ markedly among the different Kyoto Protocol variants, the costs of implementation vary enormously. The cost of the no-trade variant of the Kyoto Protocol is about 9 times the cost of the global-trade variant. Most of the gains from trade come from including non-OECD countries such as Russia, China, and India. The costs of an efficiently designed Kyoto Protocol range between $0.8 to $1.5 trillion in discounted costs, while the benefits of the emissions reduction from the Kyoto Protocol are around $0.12 trillion. This emphasizes the point that efficient design of the policy should be the major concern of policymakers.

Third, carbon prices in the realistic versions of the Kyoto Protocol are projected to be extremely high and to grow rapidly in the coming decades. The model suggests that prices exceeding $250 per ton of carbon in the controlled regions are likely to occur if the Protocol is effectively enforced through the middle of next century. The implications of such high prices for fiscal, macroeconomic, and trade policy are daunting.

Fourth, the Kyoto Protocol has significant distributional consequences. Annex I countries pay the costs of Protocol. These costs will come either through abatement activities or through purchase of permits. The lion's share of these costs are borne by the United States — the U.S. pays almost two-thirds of the global cost in the central Annex I case.

Appendix

4. Equations of RICE-98

Market equilibrium

(1) $\max_{\{c_J(t)\}} \sum_J phi^J W^J$

Utility function for region J

(2) $W^J = \sum_t U^J[c_J(t),L_J(t)](1+rho_J(t))^{-t} = \sum_t L_J(t)\{\log[c_J(t)]\}(1+rho_J(t))^{-t}$

*Production function for region J

(3) $Q_J(t) = omega_J(t)A_J(t)K_J(t)^{gamma} L_J(t)^{1-gamma-beta_J(t)}EC_J(t)^{beta_J(t)}$

(4)

*Output plus income from permit sales equals investment and consumption plus energy costs:

(4) $Q_J(t) + tau_J(t)[EC_J(t) - pi_J(t)] = C_J(t) + I_J(t) + p^E{}_J(t)\ EC_J(t) + p^B(t)\ B_J(t)$

Per capita consumption

(5) $c_J(t) = C_J(t)/L_J(t)$

Capital accumulation

(6) $K_J(t) = (1-delta_K)K_J(t-1) + I_J(t-1)$

*Retail price of carbon-energy

(7) $p^E{}_J(t)= q(t) + markup^E{}_J(t) + tau_J(t)$

*Cumulative world extraction of carbon-energy

(8) $CumC(t) =CumC(t-1) + EC(t)$

* Energy supply

(9a) $q(t) = xi_1 + xi_2[CumC(t)/CumC^*]^{xi_3}$

(9b) $E_J(t) = EC_J(t) + B_J(t)$

*Carbon cycle

(10a) $M_{UP}(t) = E(t-1) + (1- alpha_{UP,LO})\ M_{UP}(t-1) + alpha_{LO,UP}\ M_{LO}(t-1)$

(10b) $M_{LO}(t) = alpha_{UP,LO}\ M_{UP}(t-1) + (1- alpha_{LO,UP})\ M_{LO}(t-1)$

(10c) $M_{AT}(t) = alpha_{AT}\ M_{UP}(t)$

Radiative forcings

(11) $F(t) = eta\{\log[M_{AT}(t)/M_{AT}(0)]/\log(2)\} + O(t)$

Climate equations

(12a) $T_{UP}(t) = T_{UP}(t-1) +sigma_1\{F(t) - lambda T_{UP}(t-1) - sigma_2[T_{UP}(t-1) -T_{LO}(t-1)]\}$

(12b) $T_{LO}(t) = T_{LO}(t-1) +sigma_3[T_{UP}(t-1) -T_{LO}(t-1)]$

*Damage equation

(13) $D_J(t)/Q_J(t) = theta_{1,J}\ T(t)^{theta2} + theta_{3,J}\ T(t)^{theta4}$

Damage parameter

(14) $omega_J(t) = 1-D_J(t)/Q_J(t)$

Note: Equations with asterisks (*) are for equations that are substantially revised since the original DICE and RICE models.

5. Variable definitions in RICE-98

$A_J(t)$= total factor productivity of region J

$B_J(t)$ = backstop energy supplied in region J

$c_J(t)$ = per capita consumption of region J

CumC(t) = cumulative world extraction of carbon energy

CumC* = total recoverable world resources of carbon-energy

$D_J(t)$ = damage from climate change of region J

$EC_J(t)$ = carbon-energy consumption = CO_2 emissions of region J

EC(t) = $EC_J(t)$ = total consumption of carbon-energy = CO_2 emissions

F(t) = total radiative forcings

$I_J(t)$ = gross investment of region J

$K_J(t)$ = capital stock of region J

$L_J(t)$ = population, proportional to employment of region J

$markup^E_J(t)$ = markup of carbon energy of region J (exclusive of carbon prices)

$M_{AT}(t)$ = mass of carbon in atmosphere

$M_{LO}(t)$ = mass of carbon in lower reservoir (lower ocean)

$M_{UP}(t)$ = mass of carbon in upper reservoir (atmosphere, biosphere, upper ocean)

$omega_J(t)$ = damage factor of region J

O(t) = other radiative forcings

$p^B(t)$ = price of backstop substitute for carbon-energy

$p^E_J(t)$ = price of carbon-energy of region J

$pi_J(t)$ = allocation of carbon emissions permits of region J

phi^J = welfare weights of region J

q(t) = world wholesale price of carbon-energy (including Hotelling rent)

$Q_J(t)$ = gross output of region J

$rho_J(t)$ = pure rate of social time preference for country J and time period t

t = periods [t=1 for 1990-99, t=2 for 2000-09, and so forth]

$tau_J(t)$ = carbon tax

$T_{LO}(t)$ = global mean temperature of lower oceans

$T_{UP}(t)$ = global mean surface temperature

U^J = utility function per period of region J

W^J = social welfare function of region J

6. Regional definition in RICE-98

Region	Abbreviation in tables and graphs
1. USA	USA
2. Japan	Japan
3. European Union plus	Europe
4. China	China
5. Russia	Russia
6. India	India
7. High-income OPEC (Saudi Arabia, Libya, UAE, ...)	HIO
8. Other high income (Canada, Australia, Hong Kong, ...)	OHI
9. Eastern Europe (Poland, Ukraine, ...)	EE
10. Middle income (Brazil, Korea, Taiwan, ...)	MI
11. Lower middle income (Mexico, Turkey, Iran, ...)	LMI
12. Low income (Indonesia, Pakistan, ...)	LI
13. Sub-Saharan Africa (Nigeria, Zaire, ...)	Africa

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