Multi-Gas Assessment of the Kyoto Protocol

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Abstract

The Kyoto Protocol is an international agreement aimed at limiting emissions of several greenhouse gases (GHGs; specifically: CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6), and allows credit for approved sinks for CO_2. It does not include consideration of several other trace atmospheric constituents that have important indirect effects on the radiative budget of the atmosphere. Here we show that inclusion of other GHGs and CO_2 sinks greatly reduces the cost of achieving CO_2 emissions reductions specified under the agreement. The Kyoto Protocol extrapolated to 2100 reduces predicted warming by only about 17%. The errors caused by simulating other GHGs with scaled amounts of CO_2 on atmospheric composition, climate, and ecosystems are small. Larger errors come from failure to account for interactive and climatic effects of gases that affect atmospheric composition but are not included in the protocol (CO, NO_x, and SO_x). Over the period to 2100, the Global Warming Potential (GWP) indices based on a 100-year time horizon as specified in the protocol appear to be an adequate representation of trace gas climatic effects. The principal reason for the success of this simplified GWP approach in our calculations is that the mix of gas emissions resulting from a carbon-only rather than a multi-gas control strategy does not change by a large amount.

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Many trace atmospheric constituents affect the radiative budget of the atmosphere.[1] In addition to carbon dioxide (CO_2) the Kyoto Protocol includes five other greenhouse gases (GHGs).[2] The Protocol also allows credit for approved carbon sinks. Most analyses of the economic and climatic implications of the Kyoto Protocol have focused on CO_2 emissions from fossil fuel combustion[3,4] or have given only limited consideration to other gases and sinks.[5,6] Yet one main reason for including sinks and other GHGs in the agreement was to possibly reduce the cost of control. A variety of studies suggest the potential carbon sinks may be low-cost[7,8] and identify opportunities for reductions of other GHGs.[9,10,11] They also point to the risks of failing to control gases whose lifetimes are on the order of 1000 years.[9,12,13] Few studies have yet considered an integrated evaluation of the costs of multi-gas control strategies, or the implications of reductions in different mixes of GHGs for atmospheric composition, climate, and ecosystem effects.

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Assessment of multi-gas strategies also raises questions regarding the adequacy of the Kyoto Protocol requirement that GHGs be credited toward commitments using 100-year Global Warming Potentials (GWPs).[14] Unfortunately, GWPs hide complex feedbacks among ecosystems, atmosphere, and oceans and omit responses that are nonlinear with changing levels of different gases. They also ignore chemical interactions among the GHGs and other gases, including processes of formation and destruction that depend on climate itself.[15] Patterns of forecast climate change may differ under alternative combinations of gas controls, and ecosystem response may vary depending on the balance of control between CO_2 and other gases such as methane (CH_4) and perfluorocarbons (PFCs).

Using the MIT Integrated Global System Model (IGSM)[16] we examine these questions of multi-gas control as envisioned by the Kyoto protocol, exploring the costs of emissions reduction, the adequacy of GWPs, and the consequences for the atmosphere, climate, and ecosystems.

Multi-Gas Control and the Kyoto Agreement

Under the Kyoto Protocol, parties listed in its Annex B agree to limit anthropogenic emissions of the aforementioned greenhouse gases, measured in terms of equivalent amounts of CO_2 (Article 3).[2] The Protocol establishes maximum allowable emissions levels for the period 2008 to 2012 for each party as a percentage of base year emissions. The Protocol also allows credit toward these allowable emissions levels for carbon sinks resulting from direct, human-induced afforestation and reforestation measures occurring after 1990. The references to forestry and to "direct human-induced change" appear to rule out natural re-growth of forests. At present, soil carbon sequestration that might occur if agricultural practices were changed or land were abandoned is ruled out until agreed methods of measurement and verification are determined and, even then, these action would have to be in addition to what might have occurred otherwise. The Protocol also seems to rule out credit for indirect sink enhancement from increased growth of plants due to elevated atmospheric CO_2 itself or from deposition of nitrogen emitted from industrial processes. Thus although the role of terrestrial ecosystems in balancing the carbon budget is important in understanding the carbon cycle,[17,18] the magnitude of a natural land sink is irrelevant to Kyoto accounting.

Our analysis is focused on the multi-gas provisions of the agreement and is limited to provisions directed at Annex B countries. Emissions and control costs are analyzed using the MIT Emissions Prediction and Policy Assessment (EPPA) model,[19] which is the economic component of the IGSM. Forecast CO_2 emissions include fossil fuel sources and cement production plus estimated emissions from tropical deforestation. (Kyoto-approved carbon sinks and natural terrestrial and ocean sinks are discussed below.) We develop a reference forecast of greenhouse gas emissions, $E_i(t)$, for the trace gases i identified in the Kyoto protocol, where $i = 1,\ldots, 6$ refers to CO_2, CH_4, nitrous oxide (N_2O), PFCs, hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) respectively. Emissions of these gases are converted into carbon equivalent units by means of their individual GWP values g_i, where $g_1 = 1.0$ for the reference gas, CO_2.[20] We also forecast carbon monoxide (CO), nitrous oxides (NO_x), and sulfur oxides (SO_x) emissions. These are

necessary for calculating the chemical interactions that determine atmospheric levels of radiatively active gases. Also SO_x is the major anthropogenic source of aerosols that cause regional cooling.

Within the EPPA framework, emissions controls on fossil CO_2 are modeled differently from those on the other greenhouse gases, and from carbon sinks. Carbon controls are introduced by means of a constraint on "allowed" CO_2 emissions, $AE_1(t)$, and the costs of the restriction are calculated within the model. However, the economic effects of reductions in emissions of the other gases are not yet included in EPPA. These costs are calculated external to the model in the form of marginal abatement curves relating the marginal cost to the amount of abatement, drawing on independent studies of reduction possibilities through modifications of production processes that emit these gases.[9,10,11,12,21,22] Forest sinks offer potential for carbon reduction, though care must be taken to account for limits on available land, biological growth, and costs.[7,8,23]

For the non-CO_2 gases, marginal abatement curves are developed for each region of the form:

$$P_i(t) = F[g_i R_i(t)] \qquad i = 2, \ldots, 6, \tag{1}$$

where $R_i(t)$ is the level of reduction in period t below the EPPA baseline forecast, and $P_i(t)$ is the shadow price of reduction in carbon-equivalent units. A similar function can be calculated for CO_2 using the EPPA model directly:

$$P_1(t) = G[E_1(t) - AE_1(t)] \tag{2}$$

where $[E_1(t) - AE_1(t)] \equiv R_1(t)$. Similar marginal abatement curves are derived for Kyoto-defined carbon sinks, $S(t)$:

$$P_S(t) = H[S(t)]. \tag{3}$$

The Protocol includes net changes in sinks from activities "since 1990."

Using these definitions we consider three different representations of the policy constraint implied by the Kyoto Protocol. Comparison of results for these cases will allow assessment of the economic and climatic implications of the multi-gas form of the agreement.

Case 1: Fossil CO_2 Target and Control. This case is representative of much previous work on the costs of limiting the greenhouse effect. It includes only CO_2 in determining allowable emissions, unlike the requirements in the Kyoto protocol that require consideration of multiple gases.

Case 2: Multi-gas Target with Control on CO_2 Emissions Only. This case is constructed with the multi-gas target as described in the Kyoto protocol, but only carbon emissions from fossil fuel consumption are controlled.

Case 3: Multi-gas Target and Controls. The multi-gas Kyoto target applies and parties seek the least cost control across all gases and carbon sinks.

The Protocol defines different baselines, B_i, for the controlled gases: B_i = 1990 for CO_2, CH_4 and N_2O, with some exceptions for economies in transition (areas of the Former Soviet Union and Eastern Europe), which can choose a later baseline; and B_i = 1995 for PFCs, HFCs and SF_6. Under the Kyoto Protocol, reductions must be met for a commitment period of 2008 to 2012.

The EPPA model is solved on a 5-year time step, and this Kyoto constraint is represented by the middle year of the period, $t = 2010$.

Case 1, the carbon-only example, thus treats the Kyoto policy as determining allowable emissions, as:

$$AE^C(t) = E_1(t) \le kE_1(B_1), \tag{4}$$

where k is the Kyoto fraction (0.93 for the United States for example), $E_1(B_1)$ is the actual fossil fuel emissions level for the region for $B_1 = 1990$, and the superscript C indicates accounting for carbon only. Cases 2 and 3 include all gases under the Kyoto accounting procedure, where the allowed future emissions are:

$$AE^M(t) = k\sum_i g_i E_i(B_i), \tag{5}$$

where the supercript M indicates multi-gas accounting. Case 2 considers controls only on CO_2, so that:

$$AE_1(t) \le AE^M(t) - \sum_2^6 g_i\left[E_i(t) - E_i(B_i)\right]. \tag{6}$$

That is, the carbon emissions must be reduced by enough to cover the growth in the other gases between the base year and the commitment period. In Case 3 account is taken of the potential for reducing each non-fossil GHG source, and increases in carbon sinks, using the marginal abatement curves defined above. Given specified levels of reduction in other gases, $R_i(t)$, and provision of sinks $S(t)$, the allowed emissions of CO_2 are the following:

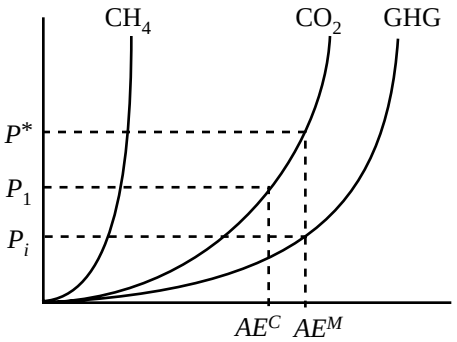
$$AE_1(t) \le AE^M(t) - \sum_2^6 g_i\left[E_i(t) - E_i(B_i) - R_i(t)\right] + S(t). \tag{7}$$

Combining the reference scenario with the Kyoto target for each region thus allows computation of the level of reduction of carbon-equivalent emissions required to satisfy the Kyoto target (AE). Efficient markets for reductions will yield a trading price, expressed in carbon equivalent units, that will be equal across gases:

$$P = P_i = P_S \qquad \text{for all } i. \tag{8}$$

This system, including the EPPA model and the externally generated marginal abatement curves, can be solved for the cost-minimizing set of emissions reductions, subject to the Kyoto constraint. An iterative procedure is used. Given the required level of GHG emissions control, an initial shadow price $P_1(t)$ for carbon equivalent emissions and abatement levels for all gases and sinks are computed using marginal abatement curves. These quantities are used in forming the policy constraint for EPPA as in equation 7. The EPPA model produces a new shadow price of carbon. New quantities of abatement for GHGs and sinks are computed using marginal abatement curves based on this new shadow price. EPPA is rerun with a policy constraint based on these new quantities. The procedure is repeated until the shadow price converges. **Figure 1** illustrates schematically the resulting equilibrium condition and how our 3 policy cases generate different abatement costs.

Figure 1. *Abatement costs*. Marginal abatement curves for CO_2 and for CH_4 in carbon-equivalent units relate the marginal cost of reducing emissions to the amount of reduction achievable at that cost, ordering reductions from lowest to highest cost. The curve GHG is the sum of the two. If the required reduction is AE^M, then the equilibrium price is P_i (our Case 3). If all GHG reduction is taken from emissions of CO_2 from fossil fuels only then the required shadow price increases to P^*. If only CO_2 emissions are included in setting allowable emissions then the constraint is lower (AE^C) and the shadow price is P_1.



The baseline and allowable emissions under the Kyoto protocol are presented in **Table 1**. Within the 12-region EPPA model the regions comprising Annex B are the United States (USA), 12 countries of the European Union as of 1990 (EEC), Japan (JPN), the remainder of the OECD (OOE), the regions of the former Soviet Union (FSU) and Central and Eastern Europe (EET). Fossil fuel carbon emissions are those from EPPA. The trace gas emissions coefficients for CH_4 and N_2O were set to produce the Annex B FCCC-reported emissions for 1990. All emissions are reported in tons of carbon equivalent using GWPs with 100-year horizons. Allowable emissions are higher in Policy Cases 2 and 3 than in Case 1 because of the inclusion of other gases (equation 6).

Without controls, trace gas emissions are projected to increase substantially in the reference scenario in all regions except the FSU by 2010 (**Table 2**). The increases from the base year range

Table 1. *Kyoto Baseline Anthropogenic Emissions (Mtce/yr*[*]*)*

Gas	USA	EEC	OOE	EET	JPN	FSU
CO_2	1362	822	318	266	298	891
CH_4	170	129	69.9	64.5	9.0	154.6
N_2O	92.3	71.7	23.4	8.9	9.3	11.3
SF_6	10.5	6.2	3.3	1.0	3.5	3.2
HFC	12.3	7.6	2.5	0.5	4.6	1.6
PFC	7.4	4.1	7.2	1.1	1.3	6.2
Total	1654	1042	425	342	326	1068
Kyoto Percentage	0.93	0.92	0.945	0.93	0.94	0.98
Allowable Emissions: Case 1	1267	757	301	248	280	873
Allowable Emissions: Cases 2 & 3	1539	958	401	318	306	1047

[*] megatons of carbon equivalent per year

Table 2. *Reference Anthropogenic Emissions at year 2010 (Mtce/yr)*

Gas	USA	EEC	OOE	EET	JPN	FSU
CO_2	1838	1064	472.0	394.8	424.2	763
CH_4	184	143.3	84.8	82.1	10.9	209
N_2O	121	92.3	31.9	10.6	13.7	14.2
SF_6	12.7	7.65	4.2	1.6	4.9	3.5
HFC	27.6	17.7	6.1	1.7	11.6	4.6
PFC	5.0	2.8	5.1	0.9	0.3	5.3
Total	2188.3	1327.7	604.1	491.7	465.6	999.6
Required Reduction: Case 1	571.3	307.5	171.3	147.3	144.2	(-110)
Required Reduction: Cases 2 & 3	649.6	369.4	202.9	173.7	159.5	(-47)

from 29% (EEC) and 33% (USA) to 42% (OOE and JPN) and 46% (EET). Aggregate emissions in the FSU are projected to be 7.5% less in 2010 than in1990, most of this reduction having already occurred prior to 1998. The change in emissions by the 2008-2012 commitment period is one of the more important factors in determining the total cost of the agreement, and the permit price. The FSU's allowable emissions exceed reference emissions in 2010, giving the FSU so called "hot air" that can be traded or banked against future increases in emissions. Including the non-carbon gases in calculating reference emissions reduces this "hot air" by nearly 60% reflecting the fact than non-carbon gases in the FSU are projected to grow in the reference scenario.

We developed marginal abatement curves for 2010 for sinks and gases other than CO_2 from detailed evaluations of the economic potential for reduction by combining existing literature, recent studies, and cost estimates from industry experts. Curves for sinks were developed based on a US study of forest carbon sequestration on agricultural land.[7] Quantities of forest carbon sequestration for different regions available in 2010 were based on a study that considered tree growth potential on currently idle or underused land.[23] We phased in the tree-planting program as if it started in the year 2000.

Emissions reduction potential for CH_4 was based on assessment of the costs of recovery from landfills, livestock waste, coal seams, and oil and gas production conducted for the United States.[21,22] Other EPPA regions were assumed to face similar costs. No abatement potential is included for CH_4 from ruminant animals or rice production. Existing economic studies show the marginal cost to be very high for animals and rice[7] although these studies do not consider some of the possible technological options that have been suggested more recently.[24] The reduction potential for N_2O from fertilized soils was based on econometric studies of the price response of fertilizer demand.[25,26] Abatement from adipic and nitric acid production was based on experts' estimates. A reduction in vehicle emissions was projected in the reference scenario, and no further abatement opportunities were assumed.

Estimates of the reduction potential and cost for other gases was based on information from the published literature and industry experts. Two main sources of HFCs such as CHF_3 and CH_2FCF_3 are as a by-product of hydrochlorofluorocarbon (HCFC) manufacture[27] and release from mobile air conditioning.[28] Stationary cooling, foam blowing, and solvents and aerosols are also sources. We considered recovery and thermal oxidation of by-products of HCFC production and replacement of HFCs with CO_2 in mobile air conditioners,[29] and recovery and replacement options for the remaining sources as abatement options. PFCs such as $CF_4$are emitted during production of primary aluminum[11] and semiconductors, and through their use as a replacement for ozone-depleting substances phased out under the Montreal protocol. We estimated reduction rates and costs for the aluminum industry.[11] Also, costs of recovery from gas streams and subsequent combustion and of substitute chemicals were assumed to be available to the semiconductor sector and to other miscellaneous uses were estimated.

SF_6 is emitted from magnesium and semiconductor production, manufacture and use of electrical switchgear,[10] and a broad category of other miscellaneous sources.[30] For switchgear manufacturing losses we account for the fact that recycling of SF_6 is economical at current prices,

and assume rates of post-installation control at higher prices. Similarly, it is assumed that, at increased prices, magnesium producers will be able to cut specific emissions to values already achieved by Norwegian manufacturers.[30]

Our economic analysis is focused on 2010. To extend the analysis to 2100, for purposes of the climatic analysis, we assume that the Kyoto commitment remains unchanged. **Figure 2** shows the GHG emissions for the years 1990 to 2100 for the reference and Kyoto Case 2 (multi-gas target with CO_2 control only) and Case 3 (multi-gas target and multi-gas controls). The left panel shows that the difference between anthropogenic CO_2 emissions and total natural CO_2 sinks (predicted for the ocean and prescribed for the land[16]) grows with time in all runs. Stabilization of atmospheric CO_2 at a constant level requires the sources to equal the sinks so even with the Kyoto policies the CO_2 concentrations rise at accelerating rates. For all non-CO_2 gases we base contributions beyond 2010 on the reduction percentage below baseline as calculated for 2010 (Fig. 2, right panel). The contribution from sinks was assumed to remain unchanged from the computed 2010 level through 2100.

Reference emissions of carbon reach 17.4 gigatons (Gt) by 2100 (Fig. 2). Previous EPPA reference cases projected fossil CO_2 emissions of 20.6 Gt.[16] The lower level of global emissions in this paper result from (1) updating the benchmark to reflect history through 1995, (2) matching near-term projections in EPPA to more detailed short-term forecasts, and (3) delaying entry of backstop technologies from 2010 to 2025. This paper also includes emissions of other GHGs. When combined using 100-year GWPs total emissions reach about 25 Gt carbon equivalent (Gtce) by 2100. Maintenance of the Kyoto protocol through 2100 reduces combined annual emissions by about 7 Gtce in 2100. Even with the Kyoto protocol the gap between emissions and sinks increases. Stabilization of atmospheric CO_2 at a constant level requires the emissions to equal the sink so even with the Kyoto policies the CO_2 concentrations rise at accelerating rates.

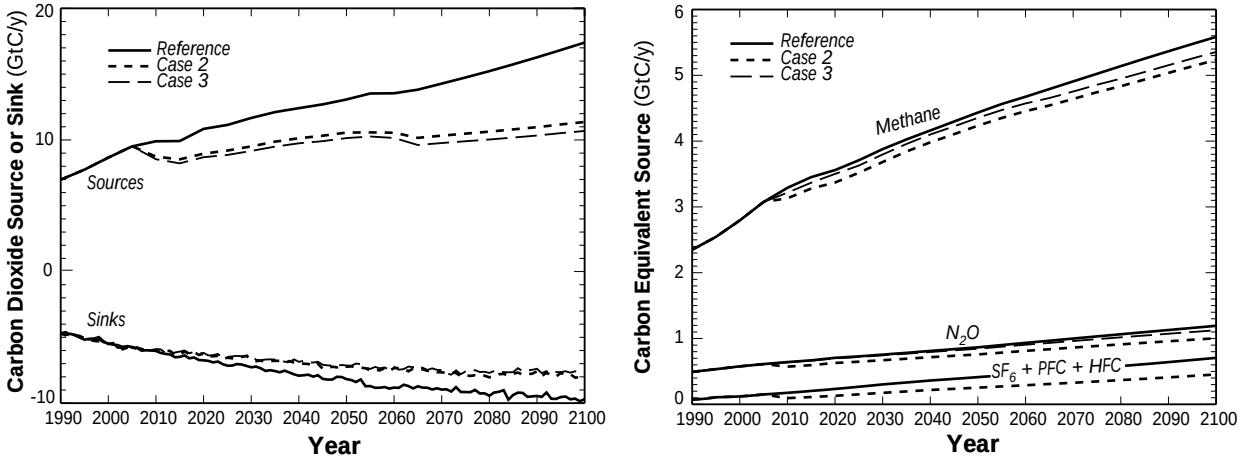


Figure 2. *Future GHG emissions*. The left panel shows CO_2 sources (positive) and total CO_2 sinks for the reference and Policy Cases 2 and 3. The right panel shows non-CO_2 sources expressed as equivalent amounts of CO_2 emissions using GWPs with 100 year horizons.

Costs of Meeting the Kyoto Protocol

Omitting other trace gases leads to an overestimate of the carbon price (comparing Case 1 and Case 3) from about 8% in the EET ($11, in 1985 US$) to 153% in the OOE ($158). Much of the difference comes from variation in the carbon sink potential among the regions. For example, there is relatively small sink potential in EET and Japan and a very large sink potential relative to carbon emissions in OOE. Cases 2 and 3 differ in the ways the Kyoto protocol is implemented. We find that if countries fail to find mechanisms to enhance sinks and encourage opportunities to reduce GHGs other than CO_2 the carbon-equivalent price is over $100 per ton higher for the USA, EEC, OEE and JPN. The multi-gas strategy in the Kyoto protocol thus creates an opportunity for lower abatement costs, but introduces a risk of higher costs if reductions in these other gases are not made.

A useful economic measure of these differences is the total cost of the agreement computed as the integral under our marginal abatement curves (**Table 3**). The OOE, USA and EEC stand to benefit substantially by inclusion of sinks and other gases. For Annex B as a whole, the error of leaving out other trace gases is about a $27 billion/year (1985 US$) overestimate of costs in 2010 (Case 3 *vs*. Case 1). Case 3 also achieves a greater reduction in greenhouse gases. For Annex B the reduction in Case 1 is 1.34 Gtce/year compared with 1.55 Gtce/year in Cases 2 and 3. To achieve the 1.55 Gtce reduction only through fossil energy carbon emissions would cost nearly $62 billion/year more (Case 2 *vs*. Case 3), increasing the cost of the agreement by over 60 percent. The EET is the only region that ends up with higher costs when other GHGs and sinks are included. This happens because of their limited potential for sinks and the fact that emissions of other greenhouse gases are growing rapidly in the EPPA reference case.

We also evaluated the effects of multi-gas control on permit trading among Annex B regions which is an important feature of the Kyoto protocol but only summarize the results here. “Hot air” (used to describe the situation where actual emissions fall below allowable emissions) in the FSU is significantly reduced as a result of inclusion of other gases. This “hot air” is important in analyses of trading because other regions can purchase these emissions permits from the FSU. Less “hot air” lowers the value of trading, and the overall volume of trade is reduced in Case 3 compared with Case 1. Of interest is that trading is of almost no benefit to the USA in the multi-gas case because the trading price coincidentally settles down very close to the USA price without trade.

Table 3. *Total Annual Cost in 2010 of Abatement (in 1985 US$ $\times 10^9$)*

	USA	EEC	OOE	EET	JPN	FSU
Case 1: CO_2 target and control	37.5	30.0	15.6	8.9	34.0	0
Case 2: Multi-gas target, CO_2 control	45.6	44.2	18.2	11.4	42.2	0
Case 3: Multi-gas target and control	27.8	23.7	8.0	9.2	30.8	0

Atmospheric Composition, Climate, And Ecosystem Implications

To analyze the effects of the Kyoto agreement on atmospheric composition, climate, and terrestrial ecosystems we use other components of the MIT Integrated Global System Model (IGSM).[16] EPPA emissions predictions are combined with estimates from a Natural Emissions Model, which takes account of changes of both climate and ecosystems. These combined emissions then drive a Coupled Atmospheric Chemistry and Climate Model.[15,16,31] This coupled model takes account of the roles of the ocean and atmosphere in climate and chemical cycles (including the carbon cycle). Outputs of climate variables and CO_2 concentrations from the coupled model then drive a Terrestrial Ecosystems Model[32] which predicts among other variables the uptake of CO_2 by natural land ecosystems and the levels of organic carbon and nitrogen in soils (which help drive natural emissions).

Along with the enhancements to EPPA discussed above, the version of the IGSM used in this paper also has certain improvements in its chemical and radiative components over the previous published version.[15,16] First, the aforementioned three additional classes of anthropogenic gases, specifically, HFCs, PFCs, and SF_6, are now included. Concentrations of these gases are calculated from their prescribed emissions discussed above (assumed to be distributed by latitude in the same way as emissions of chlorofluorocarbon $CFCl_3$) and calculated loss rates taking into account the effects of transport and chemistry (primarily the reactions of HFCs with OH radicals). Radiative forcing is then computed from these concentrations by converting them into radiatively equivalent augmentations to the concentration of $CFCl_3$ using the ratios of their instantaneous specific radiative forcing to that for $CFCl_3$.

Second, the radiative forcing due to tropospheric ozone is computed from the predicted ozone concentrations in the model (whereas previously it was kept constant). Third, stratospheric ozone concentrations (while still prescribed as before) are updated each month to simulate their known annual cycle. Finally, the scaling of the total solar irradiance (computed in the climate submodel) to obtain the ultraviolet solar irradiance (which drives photochemistry) has been improved using the World Meteorological Organization's recipe.[33] The new IGSM chemistry-radiation submodel, given the new EPPA predictions for emissions outlined earlier, yields a reference run (used in this paper) with a predicted temperature increase from 1990 to 2100 of 2.4˚C. This increase may be compared to 2.6˚C for the reference run with the old IGSM version.[16] Despite several changes in EPPA and chemistry-radiation submodels, the reference run in this paper and the previous reference are very similar. This happens because the effects of the lower CO_2 emissions predicted by EPPA are offset approximately by the additional emissions of the three new classes of gases, while effects of the inclusion of the (predicted) increases in tropospheric ozone are offset approximately by the higher EPPA SO_x emissions.

The effects of Kyoto Cases 2 and 3 on predicted temperatures (**Figure 3**) are not large.Predicted warming (and predicted sea level rise) by 2100 is lowered by only about 17% in both cases. Differences between predicted climate variables in Case 2 and Case 3 are anticipated due to two causes. First, we expect differences in the predicted climatic effects of the non-CO_2 gases if we use GWPs to convert emissions of these gases to equivalent emissions of CO_2 because GWPs only approximate the effects of these gases on climate. Emissions, aggregated by GWPs, were identical in Cases 2 and 3. To the extent the GWP aggregation is inconsistent with the complex interactions among gases as modeled in the IGSM the climatic effects will differ between the two cases. Second, natural variability as simulated by the climate model, should lead to year-to-year (but not substantial decade-to-decade) differences between the two cases. Despite these expectations, the differences on the 110–year time frame illustrated here between Cases 2 and 3 are small. This is not entirely unexpected since GWPs based on a 100-year time horizon are used. Also, there is a time lag (induced by oceanic heat uptake) between an increase in radiative forcing by greenhouse gases and the full warming response in the climate system. A more direct measure of the differences (GWPs versus specific calculations) is provided by examining the radiative forcing. Specifically, the carbon-only approach (Case 2) has 3% higher radiative forcing in 2100 than the multigas approach (Case 3) and this small difference illustrates the effects of interactions (chemical and radiative) between the non–CO_2 gases not captured by GWPs, *e.g*. the effects of added CO and CH_4 on their principal sink (OH radicals) and hence on the lifetimes of these two gases.[34]

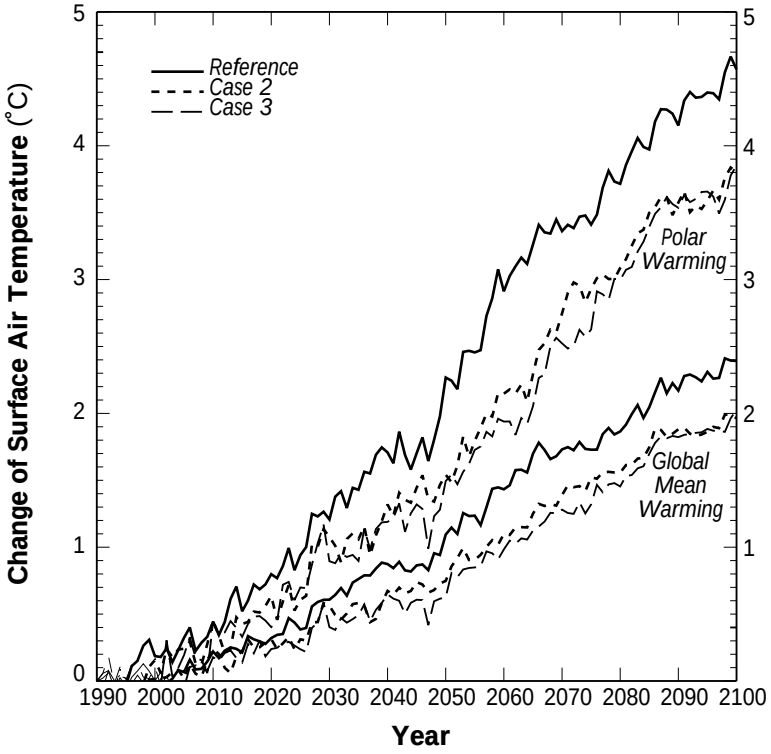


Figure 3. Average global and polar regional warming trends in the reference and Policy Cases 2 and 3 runs.

While the absolute and percentage lowering of predicted global average warming is modest, the effect on absolute warming at the polar regions is more substantial (Fig. 3). Specifically the average polar warming is lowered from about 4.6˚C in the reference run to about 3.8˚C in the Case 2 and 3 runs (polar region defined as latitudes higher than 51˚N and 51˚S and warming defined as difference between 2100 and 1990 temperatures). Such a lowering in polar warming may be important for stability of terrestrial boreal and tundra ecosystems and of the Greenland and Antarctic ice sheets.

Patterns of emissions control may have an influence on how terrestrial ecosystems respond to future climate change. Their response generally depends on two compensating factors: (1) the influence of atmospheric CO_2 concentration on the uptake of carbon by plants (CO_2 fertilization); and (2) the influence of global climate on key ecosystem processes such as photosynthesis, plant respiration, transpiration and decomposition. Current understanding suggests that changes in climate (warming and precipitation changes) alone will reduce both plant production and carbon storage in natural ecosystems as a result of increased plant respiration and decomposition. Also increases in atmospheric CO_2 should compensate for at least some of these climate-induced reductions in plant production and ecosystem storage. This compensation should hold until the atmospheric CO_2 concentration reaches a critical (saturation) level, after which there would be no additional beneficial effects. However, the magnitude of the CO_2-caused compensation and the saturation level of atmospheric CO_2 is uncertain. Some ecological models, including ours, predict that the CO_2 fertilization effect will be large enough to more than compensate for climate-induced reductions in plant production and ecosystem carbon storage throughout the 21st century. Other models predict that the climate-induced effects will dominate the ecosystem response and any CO_2 fertilization compensation will disappear during the first half of the 21st century.[35]

Net Primary Production (NPP) defined as the difference between plant carbon uptake by photosynthesis and loss by respiration is an important ecosystem variable. The three IGSM runs all show NPP increases but the two policy scenarios show smaller increases (**Figure 4**). As a result, about 33 Gt (Pg) less carbon will be stored in natural terrestrial ecosystems by 2100 in the two runs simulating the Kyoto protocol than in the reference case. However, we find relatively little difference (4 Gt C) in the storage capacity of natural terrestrial ecosystems between the two policy cases.

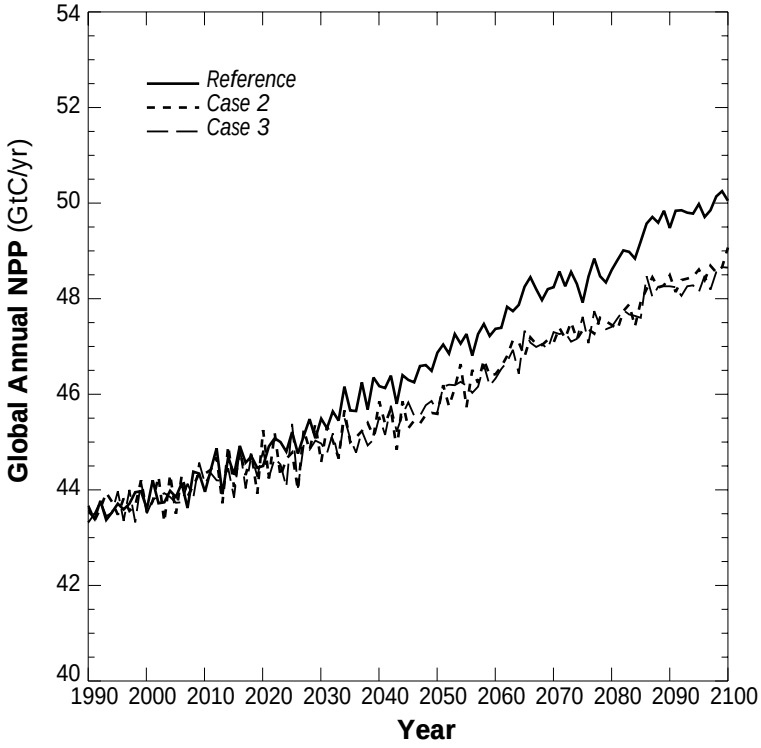


Figure 4. Globally averaged Net Primary Production (NPP) of natural ecosystems in the reference and Policy Case 2 and 3 runs. NPP increases in all scenarios but the two policy runs have 22% less increase than the reference run.

The TEM does not allow for redistribution of ecosystem boundaries. Based on extensive studies of species' responses to climate changes in the past, climate changes should lead to the natural redistribution of major plant groups. However, the details of the redistribution

such as how fast redistribution will occur or the areal extent of the dieback-reorganization sequence are uncertain. One reason for this uncertainty is incomplete understanding of the biological mechanisms involved in the redistribution process. Another reason is the inaccuracy in the predicted rate of climate change that is in turn dependent on a combination of economic decisions and feedbacks from the land to the climate system.

Concluding Remarks

Much current analysis and policy discussion narrows the climate issue to a debate about carbon emissions from fossil fuels. In contrast, we have analysed climate policy as negotiated under the Kyoto agreement including critical issues like forest sinks and the non-CO_2 greenhouse gases. The analysis also considers atmospheric interactions among these gases, climate feedbacks, the role of CO and NO_x, and the cooling effect of aerosols.

Economic analyses that leave out other trace gases err in several ways: reference emissions are understated, allowable emissions in the commitment period are too low, and opportunities to reduce emissions of other gases are not considered in abatement options. These effects are partially offsetting, so it is not possible to predict the direction of the error *a priori*. We find, however, that omitting non-CO_2 gases and sinks leads to an overestimate of cost in most countries on the order of 14%. More important, however, is that achieving approximately the same reduction in warming by control of fossil CO_2 only, ignoring other gases and sinks, would cost over 60% more. Failure to consider other trace gases and sinks also affects the value of permit trading. The most striking effect is that consideration of these gases reduces “hot air” in the FSU by nearly 60%. Further, the OOE becomes one of the lower emissions control cost regions, whereas with only carbon from fossil fuels it is high cost. The overall volume of trading falls, and the USA gains little from a trading system that involves all of Annex B regions.

The effects of expressing non-CO_2 GHGs in terms of equivalent amounts of CO_2 on atmospheric composition, climate, and ecosystems are relatively small. Instead, our analysis shows that the larger errors come from failure to account for interactive and climate effects of gases that affect atmospheric composition but are not included in the protocol (CO, NO_x, SO_x). Over the period to 2100, GWPs appear to be an adequate representation of trace gas climatic effects provided there are defined with a 100 year time horizon. The principal reason for the success of this simplified GWP approach in our calculations is that the mix of gas emissions resulting from a carbon-only rather than a multi-gas control strategy does not change by a large amount. There are other possible feedbacks and interactions that may be important that we were unable to consider. Also, effects may become more pronounced over longer periods, and inclusion of developing countries (or generally more stringent controls than contained in the Kyoto protocol) could show that simplified GWPs create larger errors.

Our analysis is subject to many uncertainties. Our reference scenario is merely a plausible picture of the future rather than a most-likely prediction. This initial look at the addition of other gases and sinks in the Kyoto protocol indicates that they could be quite important and, at a minimum, more research is warranted to understand the role of these gases in mitigating potential climate change.

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