Discussion Paper

Research Department, Central Bureau of Statistics, Norway

No. 97 July 1993

Coalitions and Side Payments in International CO_2 Treaties

by

Snorre Kverndokk

Coalitions and Side Payments in International CO_2 Treaties

by

Snorre Kverndokk

Abstract

Most numerical studies analysing the costs and benefits of international CO_2 emissions abatement assume full cooperation by all countries and regions in the world. Based on the experience from the 1992 Rio conference on the one side, and the theory of self-enforcing agreements to restrict pollution among sovereign countries on the other, full cooperation will probably not be the outcome of an international treaty on reducing CO_2 emissions. In this study we focus on coalitions and side payments in international CO_2 treaties by answering questions such as: Given the commitment of cooperation by a defined group of countries, what is the optimal policy of the group? What is the global loss of partial cooperation compared to full cooperation (social optimum), and how is the optimal abatement level affected by the number of countries committed to cooperate? The framework of the analysis is as follows. A group of OECD countries have committed themselves to cooperate on the global warming problem. The coalition (or the cooperating countries) chooses emission levels and offer the non-cooperating countries transfers if they restrict their emissions. The abatement and side payments made by the coalition are chosen so that its intertemporal utility function is maximised. Compared to the social optimum, limited participation implies a significant global loss. However, compared to doing nothing, a treaty signed by a group of countries may be important. Side payments are an effective policy instrument for making a limited treaty significant.

***Keywords:** Constrained CO_2 treaties, Coalations, Side payments*

Acknowledgement: I am grateful to Asbjørn Torvanger and Michael Hoel for helping me develop the model and for valuable comments, to Kjell Arne Brekke, Samuel Fankhauser, Jan Fuglestvedt, Rolf Golombek, and Haakon Vennemo for comments on earlier drafts, to J. Oliveira Martins (OECD) for providing me with data, and to Ted Gartner for editing assistance.

1. INTRODUCTION

Abating CO_2 emissions has two aspects. First, CO_2 emissions are a by-product of production activities that create goods for final demand. Thus, emitting CO_2 creates income. Second, accumulation of CO_2 and other greenhouse gases (GHGs) in the atmosphere may have negative effects in the future in the form of climate change. The negative external effects from CO_2 accumulation may harm all countries in the world and not only the emitting country. Thus, while the *benefits* from CO_2 emissions are immediate and directed towards the emitting country, the *costs* will be worldwide and continue as long as the CO_2 remains in the atmosphere.

The two aspects of CO_2 emissions abatement, i.e., the costs and the benefits, have been studied numerically in several papers (see Nordhaus (1991a,b, 1992), Peck and Teisberg (1992), Fankhauser and Kverndokk (1992), Eyckmans et al. (1992), and Cline (1992a,b)). However, these studies assume full cooperation by all countries in the world in an international CO_2 treaty, which means that they calculate the socially efficient abatement of CO_2 emissions.

Another strand of the literature concentrates on the possibility of limited participation in the future CO_2 treaty (see Barrett (1990, 1991) and Carraro and Siniscalco (1991, 1992)). These papers discuss, among other things, whether self-enforcing agreements to restrict pollution among sovereign countries are possible, which means whether a coalition of cooperating countries can be stable. A coalition is stable if no country, whether it is a part of the coalition or not, wants to change its action given the actions of the other countries. According to numerical and theoretical analyses, only a small number of countries are likely to join a stable coalition. However, it is possible that the cooperating countries can expand the stable coalition through self-financed utility transfers. They are interested in providing incentives for emissions reductions in the non-cooperating countries, and side payments may be the right instrument to create this. The side payments could be carried out by linking environmental policy to other economic policies such as financial aid, trade policy, technology transfers, etc. Hence, such actions will make the treaty broader by compensating the gains from "free riding" (enjoying the benefits of reduced emissions without contributing to the reduction).

Full cooperation, as analysed by the first group of papers, may therefore not be the outcome of an international CO_2 treaty without introducing side payments. Fankhauser and Kverndokk (1992) argue that a socially optimal treaty may only be achieved if side payments are offered to at least China and the countries of the former Soviet Union. They also conclude that the OECD countries are the only countries with an incentive for internal cooperation and unilateral reductions. The 1992 conference in Rio confirms the latter conclusion, and it also was the opening for side payments from the developed to the developing world as part of a future CO_2 treaty.

In this paper we want to combine the two strands of literature by a numerical analysis of costs and benefits under constrained CO_2 treaties. By analysing different regimes of coalitions and side payments, we want to study problems such as:

- Given the commitment of cooperation by a defined group of countries, what is the optimal policy of the group (e.g., what are the side payments to other countries)?
- What is the global loss of partial cooperation compared to full cooperation (defined as the social optimum)?
- How is the optimal abatement level affected by the number of countries committed to cooperate?

The framework of such an analysis can be as follows. Following the arguments of Fankhauser and Kverndokk (1992), a group of OECD countries has committed itself to cooperation on the global warming problem. The problem is to find the optimal policy for this group. We assume that the group is fixed throughout the analysis, although we do not analyse the problem of stability (see above). Henceforth, the concept coalition is used only for this original group of cooperating countries.

The cooperating countries (the coalition) choose their emissions and offer the non-cooperating countries transfers if they restrict emissions to certain levels. The abatement in the non-cooperating countries will reduce accumulation of CO_2 in the atmosphere and therefore reduce the global warming problem. The cooperating countries face two trade-offs: (1) increasing current emissions increases current consumption possibilities but reduces prospective consumption due to future climate change; (2) emissions reductions by non-cooperating countries reduce climate change, which means higher prospective consumption for the cooperating countries, while giving side payments in itself reduces their current consumption possibilities. The abatement and side payments made by the coalition are chosen so that its intertemporal utility function is maximised. The constrained agreement is also compared to a treaty with full cooperation (the social optimum).

The paper is organised in the following way. In Section 2, the model is outlined. Section 3 describes the specific functions and data, while the simulation results are given in Section 4. Some sensitivity analyses are provided in Section 5, and conclusions are summarised in Section 6.

2. THE MODEL

I is the set of cooperating countries (the coalition) and N is the set of all countries. The aim of the coalition is to find the *optimal time path of consumption* over the planning horizon of τ years. Thus, they trade off income against damage from CO_2 emissions, as well as offer side payments to non-cooperating countries, to find the optimal path of consumption over time. The *intertemporal utility* function, W, is formalised in equation (1), where C(t) is the consumption of the coalition at time t, U[.] is the total utility of the coalition, and ρ is a discount rate representing pure time preferences.

$$W = \sum_{t=0}^{\tau}(1+\rho)^{-t}U[C(t)] \tag{1}$$

This intertemporal utility function will be maximised subject to several constraints. Consider first the *production* of country n at time t, $P_n(t)$, defined in the following way:

$$P_n(t) = D_n[T(t)]\cdot F_n[e_n(t),z_n(t)] \tag{2}$$

$F_n[.]$ is production in the absence of the climate-feedback effect. It is a function of domestic CO_2 emissions, $e_n(t)$, and a vector of exogenous technology variables at time t, $z_n(t)$. This income function is increasing and concave in CO_2 emissions, *ceteris paribus,* and expresses the income to a country under different CO_2 emission levels. For further characteristics of this function, see

Kverndokk (1993) and Hoel (1992a).

The feedback from climate to production in country i, which is the damage from global warming, is represented multiplicatively by $D_n[.]$:

$$\begin{gathered} 0 \leq D_n[T(t)] \leq 1 \\ D_n[T(0)] = 1 \\ \frac{\partial D_n[T(t)]}{\partial T(t)} < 0 \\ \frac{\partial^2 D_n[T(t)]}{\partial T(t)^2} \leq 0 \end{gathered}$$

The multiplicative damage function is decreasing and concave in T(t), where T(t) is the increase in the global mean temperature between preindustrial time (taken to be 1765) and time t. Hence we assume convexity of damages with respect to temperature, where $1 - D_n[T(t)]$ is the relative loss in income in country n at temperature increase T(t). Thus, as a simplification, the various aspects of climate change are represented by this single variable. We set $T(t) \leq \bar{T}$, where the value of $\bar{T}$ is specified to avoid negative production, i.e., $D_n[.] \geq 0$, and therefore $P_n(t) \geq 0$ for $T(t) \leq \bar{T}$. The model is specified such that there is no loss at time 0 (defined as 1990).

The relation between *temperature increase* and emissions of CO_2 can, in general, be described in the following way:

$$\begin{aligned} T(t) &= f[e(0),\ldots,e(t);t] \\ e(s) &= \sum_{n\in N} e_n(s), \quad s = 0,\ldots,t \end{aligned} \tag{3}$$

which gives the temperature increase as a function of aggregated CO_2 emissions in previous and current periods.

To restrict the global CO_2 emissions, the coalition offers transfers to the non-cooperating countries if they are willing to limit their emissions. Based on Hoel (1992b), the transfers offered are such that the non-cooperating countries obtain the same production with their imposed emissions and the side payments as they would with the right to choose emissions optimally. Thus, the optimal *side payment* to the non-cooperating country j is defined as follows:

$$\begin{aligned} D_j[T(t)]\cdot g_j[e_j(t),z_j(t)] &\equiv \{\max_x D_j[T(t)]\cdot F_j[x,z_j(t)]\} - D_j[T(t)]\cdot F_j[e_j,z_j(t)] \\ &= D_j[T(t)]\cdot(\{\max_x F_j[x,z_j(t)]\} - F_j[e_j(t),z_j(t)]) \end{aligned} \tag{4}$$

In the absence of the greenhouse effect, $g_j[.]$ is the production loss in country j from choosing $e_j(t)$ instead of the optimal emissions. $D_j[.]g_j[.]$ is hence the side payment, which must be offered to country j at time t, $j \notin I$, to make it indifferent (in the sense of equal production) between choosing e_j (and receiving the side payment) and the emissions maximising production. Implicitly, country j is assumed to be small in the sense that it considers T(t) and therefore $D_j[T(t)]$ as exogenously given.

Assuming that there is a constant ratio between consumption and production, the aggregated *consumption* for the coalition is specified in the following way[1]:

$$C(t) = \sum_{i \in I} P_i(t) - \sum_{j \notin I} D_j[T(t)]\cdot g_j[e_j(t),z_j(t)] \tag{5}$$

The object of the coalition is to maximise the present value of utility over the planning horizon. Hence, the maximisation problem in equation (1), subject to equations (2) through (5), gives the optimal path of emissions and therefore consumption for this group of countries.

The first order conditions for this maximisation problem, i.e., $\partial W/\partial e_l(s) = 0$ and $\partial W/\partial e_k(s) = 0$, where $l \in I$, $k \notin I$ and $0 \le s \le \tau$, can be presented in the following way:

The first part on the left side of equation (6) is the discounted marginal utility from an increase

---

[1] The factor of proportionality between consumption and production, ζ, is in this study set equal to 1. However, this is irrelevant in this respect, since the assumption means that we can specify the utility as a function of production, P, i.e., $u[C] = u[\zeta P] = \hat{u}[P]$.

$$
\begin{aligned}
(1+\rho)^{-s}\cdot\frac{\partial U[.]}{\partial C(s)}\cdot\frac{\partial F[.]}{\partial e_l(s)}\cdot D_l[.] - \sum_{t=s}^{\tau}\left[(1+\rho)^{-t}\cdot\frac{\partial U[.]}{C(t)}\cdot\sum_{j\notin I}\left(\frac{\partial D_j[.]}{\partial T(t)}\cdot\frac{\partial T(t)}{\partial e_l(s)}\cdot g_j[.]\right)\right] = \\
-\sum_{t=s}^{\tau}\left[(1+\rho)^{-t}\cdot\frac{\partial U[.]}{\partial C(t)}\cdot\sum_{i\in I}\left(\frac{\partial D_i[.]}{\partial T(t)}\cdot\frac{\partial T(t)}{\partial e_l(s)}\cdot F_i[.]\right)\right]
\end{aligned}
\qquad \textbf{(6)}
$$

in the emissions from a country within the coalition due to higher production in period s. The second part shows the discounted utility gain over the planning horizon due to lower side payments. The increase in emissions involves higher damage and therefore lower side payments to the non-cooperating countries. The right side gives the discounted utility loss in the coalition over the planning horizon due to damage from the increased emissions. Thus, in the optimal state, the gains from higher production and lower side payments from emissions within the coalition should be balanced against the current and future damage directed toward the coalition.

From the above optimality condition, we see that the emissions from the countries within the coalition are higher when side payments are given to other countries than they would be in the absence of side payments (the second part on the left side is zero). This is because the damage from global warming in the non-cooperating countries involves a gain for the coalition in terms of lower side payments, an irrelevant effect under unilateral actions.

Equation (7) gives the condition to determine the emissions from the non-cooperating countries. At the optimal solution, the discounted utility loss in the coalition due to damage from these emissions should be balanced against the utility gains from lower side payments. The first part on the right side of the equation represents the impacts from side payments due to higher production in the emitting country in period s, while the last part is the discounted utility gains from lower side payments due to higher damage in all non-cooperating countries caused by increased emissions.

$$
\begin{aligned}
\sum_{t=s}^{\tau}\left[(1+\rho)^{-t}\cdot\frac{\partial U[.]}{C(t)}\cdot\sum_{i\in I}\left(\frac{\partial D_i[.]}{\partial T(t)}\cdot\frac{\partial T(t)}{\partial e_k(s)}\cdot F_i[.]\right)\right] = \\
(1+\rho)^{-s}\cdot\frac{\partial U[.]}{\partial C(s)}\cdot\frac{\partial g_k[.]}{\partial e_k(s)}\cdot D_k[.] + \sum_{t=s}^{\tau}\left[(1+\rho)^{-t}\cdot\frac{\partial U[.]}{\partial C(t)}\cdot\sum_{j\notin I}\left(\frac{\partial D_j[.]}{\partial T(t)}\cdot\frac{\partial T(t)}{\partial e_k(s)}\cdot g_j[.]\right)\right]
\end{aligned}
\qquad \textbf{(7)}
$$

The *social optimum*, which is the optimal solution under full cooperation, is defined as the maximum of the global intertemporal utility function (1) subject to (2), (3), and $C(t) = \Sigma_n P_n(t)$, $n,l \in N$. This gives the following optimum condition:

$$(1+\rho)^{-s}\cdot\frac{\partial U[.]}{\partial C(s)}\cdot\frac{\partial F[.]}{\partial e_l(s)}\cdot D_l[.] = -\sum_{t=s}^{\tau}\left[(1+\rho)^{-t}\cdot\frac{\partial U[.]}{\partial C(t)}\cdot\sum_{n\in N}\left(\frac{\partial D_n[.]}{\partial T(t)}\cdot\frac{\partial T(t)}{\partial e_l(s)}\cdot F_n[.]\right)\right] \qquad \textbf{(8)}$$

Thus, in the optimal state, the utility gain from increased production in one country at time s should be balanced against the discounted utility loss from global warming in all countries over the rest of the planning horizon.

3. FUNCTIONAL FORMS AND DATA

Time periods and regions

According to Cline (1992a), the atmospheric buildup of carbon content is likely to continue over the next three centuries due to the massive reserves of fossil fuels. Thus, the appropriate time horizon for greenhouse analysis is in the order of 250-300 years. A long planning horizon is also justified by long-term impacts, which are a characteristic of global warming. Impacts are only felt after some 30 to 50 years, but may then persist for as much as two or three centuries. Following these arguments, the model is simulated for the period 1990 to 2230, giving a planning horizon of 240 years, where $t = 0$ refers to 1990. However, we do not report results for the last 50 years to avoid extreme end effects caused by the relatively arbitrary time horizon.

We divide the world into seven blocks of countries based on the OECD GREEN model (Burniaux et al. (1992a,b)).[2]

---

[2] The GREEN model is divided into 12 sectors. Therefore, in our model, ROECD consists of the GREEN regions Japan and OOECD (Other OECD), while REST consists of CEECs (Central and Eastern Europe), EE-LDCs (Energy-Exporting LDCs), DAEs (Dynamic Asian Economies), Brazil, and ROW (Rest of the World). The calibration of the parameters is based on the original 12-sector version, and the parameters of ROECD and REST are weighted averages of the parameters in the above mentioned groups with CO_2 emissions as weights.

1. USA
2. EEC
3. Rest of OECD (ROECD)
4. The former Soviet Union (EX-USSR)
5. China
6. India
7. Rest of the World (REST)

According to this list, the OECD countries consist of the three first regions while regions 1 to 4 are industrialised countries. The last group is a mixture of both industrialised and developing countries.

The production module

In the present analysis, the production in a country is defined as its gross domestic product (GDP). The *income function* in equation (2), the F[.] function, is taken from Kverndokk (1993):

$$\begin{aligned} F_n[e_n(t), z_n(t)] &= Y_n[e_n(t); t] = \hat{Y}_n(t) - G_n[e_n(t); t] \\ G_n[e_n(t); t] &= \frac{q_n(t)\hat{e}_n(t)}{b_n(t)} \left(\frac{\hat{e}_n(t) - e_n(t)}{\hat{e}_n(t)} \right)^{b_n(t)}, \quad e_n(t) \leq \hat{e}_n(t) \end{aligned} \tag{9}$$

where (the subscript is left out for simplicity):

$z = \{b, q, \hat{Y}, \hat{e}\}$,
b = the constant elasticity of abatement costs with respect to abatement ($\hat{e} - e$),
q = the shadow price of CO_2 when $e = 0$, i.e. the tax on CO_2 emissions which leads to a total substitution away from fossil fuels to non-fossil backstop technologies (the switch price of CO_2),
Y = GDP in the absence of climate change,
$\hat{Y}$ = GDP in the absence of climate change and emissions constraints (BAU GDP without climate change),
$\hat{e}$ = CO_2 emissions from energy use in the absence of any emissions constraints (BAU CO_2), and

G = abatement costs for abatement equal to $\hat{e} - e$.

The income function is concave in CO_2 emissions for $b > 1$ and $q > 0$. The condition $b \geq q\hat{e}/\hat{Y}$ ensures that GDP is non-negative. For further characteristics of the function, see Kverndokk (1993).

The exogenous BAU scenario ($\hat{e}$ and $\hat{Y}$) is defined so that the emissions maximise the production in the absence of global warming, i.e., $G_n[.] = 0$.

The data are taken from the OECD's GREEN model (see Burniaux et al. (1992a,b)) and the parameter specifications for the income function as well as for the other functions are given in Appendix 1. In 1990, the *q-values* are set equal to the high arbitrage tax levels for gas vs carbon-free fuel in 2050 in the GREEN reference scenario,[3] while they decrease linearly to the high arbitrage tax levels for carbon-free fuel vs synthetic fuel[4] by the year 2090 and remain constant from this time onwards. The decline in the switch prices is due to an expected increase in fossil fuel prices, as well as the possibilities of falling costs of backstop technologies.

The *b-values* are calibrated using data for carbon taxes in 2015 under the GREEN Toronto scenario, since 2015 was the first year with positive carbon taxes in all regions in the GREEN simulations. This means that the carbon taxes in the GREEN model equal the respective shadow prices of carbon in our model in 2015 at the specific emission levels. The exogenous paths of the b-parameters follow the paths for the autonomous energy-efficiency parameter (AEEI) in the GREEN model, which is a growth of 1% p.a. in all regions from 1990 to 2050. We assume a uniform growth of 0.5% p.a. until 2100 and zero growth in the parameter thereafter.

The time series of BAU variables are also based on exogenous growth rates. The annual *growth rates for BAU GDP* in the absence of climate change from 1990 to 2050 are based on Burniaux et al. (1992a). From 2051 onward, the growth rates build on the long-run growth rates in Manne and Richels (1992) and Cline (1992a), leading to an almost 21-fold multiple of gross world

---

[3] The high arbitrage tax levels correspond to taxes at which the conventional fuel still accounts for 30% of total energy demand (see the Appendix, Table A2, in Burniaux et al. (1992a)).

[4] This corresponds to the long-term equilibrium tax level in Manne and Richels (1992).

product (GWP) by 2230 if there are no feedbacks from global warming.[5]

The *BAU CO_2 growth rates* from fossil fuel use are based on GREEN to the middle of the next century and build on the long-run growth rates from Manne and Richels (1992) and Cline (1992a) thereafter. This gives an average annual growth rate of 0.4% for the period 2100-2230, which corresponds relatively well to the long-term growth rates of CO_2 emissions of 0.5% annually assumed in Cline (1992a).

Under these assumptions, BAU CO_2 emissions from energy use increase to almost 60 billion ton carbon by 2230. The relative share of total emissions for different regions is shown in Figure 1. The share of OECD countries declines from 47% in 1990 to only 3% in 2230. This is due to a decline in emissions from 2111 onward derived from technology changes and backstop technologies, as well as a high increase in emissions from developing countries. The share of Chinese emissions increases from 10% in 1990 to 60% in 2230.

To illustrate the abatement possibilities in the model, abatement costs and taxes are calculated under a reduction scenario where each region stabilises its emissions to 1990 levels. This is shown in Appendix 2.

The *damage function* in equation (2) is specified in the following way, involving no damage in 1990 (period 0):

$$D_n[T(t)] = 1 - k_n \cdot \left(\frac{T(t) - T(0)}{\Lambda - T(0)}\right)^{\gamma}, \quad \gamma \geq 1 \tag{10}$$

Thus, k_n is the relative GDP loss in region n due to the climate-feedback effect at temperature

---

[5] To compare our estimate to other studies, Cline (1992a,b) assumes that the global production multiples 26-fold from 1990 to 2275 in the absence of global warming, while Nordhaus (1992) assumes a 7 1/2-fold multiple over the same period. A high growth as assumed in this study may raise serious doubts of feasibility due to limits of the global resource and environmental base. The possibility of such a growth has, however, been supported although not recommended by Cline (1992a), p. 287. Cline argues that lower per capita growth than in the past may be difficult to avoid, and that the per capita income projections do not seem high at least on the basis of the experience over the past century.

increase Λ, where Λ is set to 2.5 °C[6], i.e., $1 - D_n[.] = k_n$ when $T(t) = \Lambda$. For a similar additive specification of the damages, see Fankhauser and Kverndokk (1992).

A multiplicative damage function like the one above may be a good description if most of the damage related to global warming comes from activity losses in GDP-producing activities like agriculture, while an additive damage function may best represent the damage if it reduces amenities not usually included in the GDP measure, like loss of wetlands due to rising sea levels, loss of bio-diversity, and so on. However, willingness to pay for such amenities increases with income or GDP, involving higher valuations in richer countries. Thus, damage should in some way be related to GDP.[7]

Several studies, see, e.g., Nordhaus (1991a,b), Cline (1992a), and Fankhauser (1992), estimate that a temperature increase of 2.5 °C since preindustrial time will cause a global damage in the interval of 1-2% of GWP. Thus, in this study we work with three different scenarios for total damage at 2.5 °C actual global temperature increase: 1%, 2%, and 3% of GWP, named *Scenario 1, 2,* and *3,* respectively (see Table 1).

Table 1: The damage scenarios

SCENARIO 1:	SCENARIO 2:	SCENARIO 3:
Total damage at T(t) = 2.5 °C is 1% of Gross World Product	Total damage at T(t) = 2.5 °C is 2% of Gross World Product	Total damage at T(t) = 2.5 °C is 3% of Gross World Product

For parameter calibration of the *k-values*, we use the damage distribution pattern in Fankhauser (1992). *T(0)*, the global temperature increase from preindustrial time to 1990, is set equal to 0.6 °C, based on Houghton et al. (1992), while γ is set equal to 1.3, which is the estimate of Cline (1992a).

---

[6] This is IPCC's best guess for an equilibrium temperature change at a doubling of CO_2 equivalents in the atmosphere (see Houghton et al. (1990, 1992)).

[7] Fankhauser and Kverndokk (1992) solve this problem by employing an additive damage function, where the annual damage is assumed to grow proportionally with income.

The climate module

Our model represents the 17 major GHGs, where only the CO_2 emissions from energy use (see the production module above) are specified endogenously. Thus, we assume that the international agreement only concerns these emissions and that other emissions, including CO_2 emissions due to changes in land-use patterns, are not affected.

The climate module of the model consists of a stock equation, (11), and several temperature equations, (12) and (13).

The *stock equation* gives the atmospheric concentration of CO_2 at different emission levels. Emissions of GHGs increase the corresponding concentrations in the atmosphere. However, the observed concentrations are less than they would have been if all emissions since preindustrial time had been added to a constant preindustrial stock. For example, the observed increase in atmospheric CO_2 concentration since the industrial revolution is only one-half of what it would have been if all CO_2 emissions were added to the preindustrial stock. This is due to the removal of carbon from the atmosphere into the oceans and the terrestrial biosphere. As a simplification in economic studies, the complex process of atmospheric GHG accumulation has been modeled in three different ways (see e.g., Peck and Teisberg (1992)): As a depreciation model assuming a constant annual depreciation of the stock of GHGs based on the lifetime of the actual GHG (lifetime is defined as the time required for one unit of the GHG to depreciate to 1/e units), as an atmospheric fraction model, where a certain fraction (airborne fraction) of the GHGs reaches the atmosphere each year (e.g., one-half for CO_2), or as a combination of depreciation of the existing stock and a fraction of current emissions immediately removed from the atmosphere.

We have chosen the depreciation model for the accumulation of CO_2 (for both endogenous and exogenous emissions) in the atmosphere, where the preindustrial stock is assumed to be the equilibrium stock. This means that if all anthropogenic emissions were eliminated, the atmospheric concentration would approach the preindustrial level. However, we do not apply a constant depreciation rate. The lifetime of CO_2 is assumed to increase linearly from 120 to 300 years over a time interval of 250 years starting in 1990, due to saturation of the carbon-sink capacity of the oceans (see Houghton et al. (1990, 1992)). This is shown in equation (11), where $Q(t)$ is the atmospheric concentration of CO_2 at time t, Q^P is the preindustrial concentration, $Z(t)$

is the difference between concentration at time t and preindustrial time, L(t) is the lifetime of CO_2, and X(t) is the global emissions (in PPM) at time t.

$$\begin{aligned} Q(t) &= Q^{P} + Z(t), \\ Z(t) &= Z(t-1)\cdot(1 - \frac{1}{L(t)}) + X(t), \quad t > 0 \end{aligned} \tag{11}$$

The parameters are set according to Houghton et al. (1990, 1992) and Peck and Teisberg (1992), and are specified in Appendix 1.

The *temperature equations* describe the reaction of temperature to changes in atmospheric GHG concentrations or radiative forcing, i.e., heating in watt per square metre (W m^{-2}), and consist of functions for potential and actual temperature increase. Potential temperature increase is the increase in the geophysical equilibrium. Before fully warming the earth's surface, the greenhouse effect must first heat up the oceans (ocean terminal lag). This may take as long as three decades or more, and the potential temperature increase is therefore the increase in temperature after full adjustment. Potential temperature increase due to CO_2 emissions, T_{CO2}^{P}, is specified according to Peck and Teisberg (1992). The A and B parameters in equation (12) are fit so that the increase is zero at the preindustrial concentration and 2.5 °C for twice the preindustrial concentration of CO_2.[8]

The potential temperature increase due to emissions of the 16 other GHGs, T_{OGHG}^{P}, is the product of the total warming coefficient, θ (measured in °C/W m^{-2}),[9] and the radiative forcing above preindustrial level, R(t) (measured in W m^{-2}).[10] The time series for radiative forcing, where CFCs are assumed to be phased out by 2020, are taken from the calculations of Hoel and Isaksen (1993).

---

[8] Peck and Teisberg (1992) assume a temperature increase of 3 °C for twice the preindustrial concentration of CO_2. However, 2.5 °C corresponds to IPCC's best guess (Houghton et al. (1990, 1992)).

[9] Usually potential temperature increase is specified as the product of radiative forcing, R, the warming to be expected as the direct impact of radiative forcing before taking account of feedback, λ, and the feedback multiplier, β, i.e., $T^{P} = R\lambda\beta$ (see, e.g., Cline (1991, 1992a)). In our model, θ represents both the direct and indirect impact of radiative forcing, i.e., the product of λ and β.

[10] This is of course also true for CO_2 and is implicitly included in our specifications (11) and (12). The relation between radiative forcing and atmospheric concentration of CO_2 is usually assumed to be $R_{CO2} = 6.3 \ln [Q(t)/Q^{P}]$.

$$\begin{aligned} T^P_{CO2}(t) &= A\ln Q(t) - B, \\ T^P_{OGHG}(t) &= \theta R(t), \\ T^P(t) &= T^P_{CO2}(t) + T^P_{OGHG}(t) \end{aligned} \qquad (12)$$

Based on Nordhaus (1991a,b), the increase in actual temperature (T) in each period is governed by a lagged adjustment process due to the thermal inertia of oceans as mentioned above, where the speed of adjustment is determined by the delay parameter α, which is set equal to 0.025.

$$T(t) = \alpha T^P(t) + (1 - \alpha)T(t - 1) \qquad (13)$$

The parameter specifications are given in Appendix 1. The development in endogenous CO_2 emissions, atmospheric CO_2 concentration, and actual temperature increase under the BAU scenario are shown in Figure 2. For a comparison to other studies, see Cline (1992a) for analysis in the very long term (2275), and Houghton et al. (1992) for analysis to the year 2100. Based on these comparisons, our estimates seem to be in the upper end.

To illustrate the importance of global warming in the long run, the development of GWP with feedbacks from the warmer climate, i.e., $\Sigma_n D_n[.]\hat{Y}_n(.)$, is shown in Figure 3. Global warming affects GDP relatively little until 2050. The effects in the 22nd century are high however. By 2300, more than 13% of potential GDP is lost under Scenario 1, and 40% is lost under Scenario 3.

The consumption module

The *utility function* for the coalition is specified in the following way:

$$\begin{aligned} U[C(t)] &= \frac{1}{1 - \mu}[C(t)^{1-\mu} - 1], \quad \mu \neq 1, \mu > 0 \\ U[C(t)] &= \ln C(t), \quad \mu = 1 \end{aligned} \qquad (14)$$

This is an isoelastic utility function where $1/\mu$ is the elasticity of substitution between consumption at two points in time.

Compared to other studies, Nordhaus (1991a,b, 1992) uses a μ value equal to 1, while Cline (1992a) proposes a value of 1.5 for USA. In this model μ is set equal to 1.

The rate of pure time preference, ρ, is set equal to zero to avoid discrimination of future generations. See, e.g., Cline (1992a) and Hoel and Isaksen (1993). This is discussed further in Section 5.

The simulations of the optimal CO_2 emissions and hence consumption paths are provided in the next section.

4. RESULTS

Following the arguments from Fankhauser and Kverndokk (1992), the only regions with incentives for unilateral emission reductions are EEC, ROECD, and under certain conditions, USA. Thus, in addition to the social optimum, simulations are run with two different coalitions. First, we assume that an agreement to reduce CO_2 emissions is signed by EEC and ROECD. Thus, the first coalition consists of all OECD countries apart from USA. Then, USA is included, which means that in the second coalition all OECD countries are assumed to sign the treaty.

Assuming that there are no transaction costs related to side payments, the coalition calculates and offers optimal side payments to all other countries. If the side payments do not gain the coalition, the transfers calculated under the optimisation problem would be zero. However, in the real world there would probably be *transaction costs* related to side payments, which means that the coalition may concentrate on compensating a limited group of countries consisting of the main emitters of CO_2 outside the coalition. Thus to represent this, under a regime with transaction costs, the coalition of EEC and ROECD will offer side payments to USA, the countries of the former Soviet Union, China, and India, which are all among the top 10 emitters in the world, considering the former Soviet Union as one region.

Table 2: The different coalition regimes

	REGIME 1	REGIME 2	REGIME 3	SOCIAL OPTIMUM
REGIONS IN THE COALITION	EEC ROECD	USA EEC ROECD	EEC ROECD	USA EEC ROECD EX-USSR China India REST
REGIONS OUTSIDE THE COALITION	USA EX-USSR China India REST	EX-USSR China India REST	USA EX-USSR China India	

We can now specify the four different coalition regimes. In Regime 1, the reference regime, the coalition of EEC and ROECD offers side payments to all other regions. The coalition is extended to all OECD countries in Regime 2, while in Regime 3 the original coalition (EEC and ROECD) does not offer side payments to REST due to transaction costs. The last regime is the social optimum. The different coalition regimes are summarised in Table 2.

The simulations are run for periods of 10 years, and we therefore assume that the treaty is signed every 10 years, specifying the same percentage-reduction level from BAU emissions within the 10-year interval. This means that the optimal emissions grow with the BAU CO_2 growth rates.[11] Further, as mentioned in the introduction, we assume a constant coalition within the planning horizon of 230 years. The results are presented for the time period 1990 to 2180, and the simulations were carried out using the GAMS/MINOS system; see Brooke et al. (1992). However, due to the great uncertainties in analysis dealing with such a long time horizon, the results should only be considered illustrative estimates. We also concentrate on the relative differences between the coalition regimes, due to the sensitivity of the actual levels of the

---

[11] Using 10-year instead of 1 year periods also requires new assumptions about the parameter α and the lifetime of CO_2. We have set $\alpha = 0.224$ (calculated from $(1\text{-}0.025)^{10} = 1\text{-}\alpha$) and assume a constant lifetime of CO_2 within the intervals.

optimal variables (see the sensitivity analysis below).

The optimal policy

Figures 4 and 5 show the *optimal emission levels* under the different coalition regimes. In the graphs we only report the results for the "best guess" scenario, Scenario 2 (see Table 1); however we comment on all scenarios.

Consider the results for Regime 1 and the social optimum; the results for Regimes 2 and 3 will be presented below. The total emissions reductions compared to the BAU scenario are substantial, especially from the middle of the next century (see Figure 4), reaching 100% under the social optimum and 60-85% under Regime 1. The high abatement levels are, among other things, due to low abatement costs[12] and high damage costs over time, as well as a low discount rate. This will be further commented on in Section 5. The socially optimal abatement paths are high compared to the studies of Peck and Teisberg (1992) and Nordhaus (1992). However, Nordhaus sets the rate of pure time preference equal to 3%, while we use a zero rate. Simulations with Nordhaus's DICE model employing lower rates of time preference give abatement paths within the range of this study (see Cline (1992b)). The optimal abatement levels are, however, quite modest in the beginning (year 2000), less than 10% under Regime 1, Scenario 1.

The emission reductions in the regions outside the coalition are actually higher than the corresponding abatement in the coalition. Under Regime 1, Scenario 2, abatement is up to 72% in the coalition and 78% outside the coalition. The bulk of emission reductions are taken in China and India (84% and 82%) due to, among other things, the relatively low marginal abatement costs in these countries using the GREEN data.

While the emissions reductions seem high compared to BAU emissions, this is not the impression comparing them to 1990 emissions, as shown in Figure 5. With limited participation, the

---

[12] To illustrate this, in the model the abatement costs at 100% abatement, i.e. $G_n[0,t]$, are about 15% of BAU GDP in the absence of climate change ($\hat{Y}$) for the OECD countries in 1990. These costs are decreasing over time due to technological progress, and amount to about 1% within 2080 under the assumptions of the model. The corresponding abatement costs in the non-OECD countries are significantly higher; e.g., 85% in EX-USSR and 47% in China in 1990; however they also decrease over time to 7% and 5% respectively in 2080.

emissions will increase compared to the 1990 level, which is not in accordance with recommendations from international conferences such as Toronto and Hamburg 1988. The first calling for emission reductions of 20% of 1990 levels from the year 2005 onwards and the second recommending reductions of 30% by the year 2000. Reductions within this recommended range correspond however to the socially optimal emissions under Scenarios 2 and 3.

The *optimal side payments* in per cent of GDP before action is taken (BAU GDP) are shown in Figures 6 and 7. The hump shape of the graphs can be explained by the abatement paths in Figures 4 and 5, with increasing abatement to about 2100 and lower abatement thereafter, as well as lower abatement costs and higher damage costs over time. The transfers are quite modest in most years, with the peak at 1.7% of the coalition GDP by 2100 under Regime 1, Scenario 3. Under the "best guess" scenario, Scenario 2, the peak is however 0.95%. In comparison, this is just above the development assistance disbursement target of 0.7% established by the United Nations, which however is not met by most industrialised countries. The transfers to the non-cooperating countries in terms of their GDP under Regime 1 are relatively smaller, owing to larger total GDP in this group.

Figure 8 shows the *actual temperature increase* under the different regimes. The abatement strategies have a minor effect on the temperature in the first decades of agreements. However, from the middle of the next century the differences are significant. To illustrate, under Scenario 3, the temperature increase is about 64% lower than BAU by 2180 under the socially optimal regime (2.8 °C) and 40% lower under Regime 1 (4.6 °C). Thus, even if the decline in prospective temperature increase is high under limited participation, there are big differences compared to the socially optimal paths.

Gains from CO_2 abatement

Figure 9 shows the *global GDP gains* compared to BAU GDP under the different coalition regimes. Until the middle/end of the next century, the global gains are negative — a loss of more than 3.5% at the most — with the highest losses under the socially optimal policies. The gains however are positive from the second half of the century onward, up to 31% by 2180 under the social optimum and 22% under Regime 1 (Scenario 3). The results are due to the long-term impacts of global warming - impacts are only felt after some 30 to 50 years - the long planning horizon and the low discount rate.[13] The problem can be compared to one of investment; the costs are immediate while the gains will come later. Here, the policy makers are willing to trade off lower GDP in the near future against benefits in later periods.

The differences in the gains for the coalition and the non-cooperating regions are substantial under the social optimum as well as under limited participation. The non-cooperating countries will gain most at the end of the planning horizon, an increase in GDP of 37% by 2180 compared to 15% in the coalition. However, the non-cooperating countries will have the highest losses in the beginning of the planning horizon from the abatement strategies before side payments are taken into account, as much as 4.4% of the potential GDP under the social optimum. The high losses in the beginning are among other things due to high potential economic growth; while the high gains from cooperation in the long term are due to significant damage from climate change. This may indicate one difference between the regions inside and outside the coalition: Even if the regions outside the coalition gain substantially over the total planning horizon, they may be reluctant to cooperation due to high initial costs. This means that they employ a higher discount rate than the coalition.

Extending the coalition

To see how the optimal policy is affected by the number of countries committed to cooperation, we compare the results from the coalition of EEC and ROECD to the corresponding results for a coalition of all OECD countries, i.e., Regimes 1 and 2. The results for Regime 2 under Scenario 2 are also shown in Figures 4 through 9.

The main impression is that the optimal solutions are still somewhat far from the social optimum. However, under Scenario 3, including USA in the coalition actually means a stabilising of total emissions just below 1990 levels in the first part of the next century (see Figure 5). A stabilising of emissions at 1990 levels has been mentioned as a goal for international negotiations, for example, under the Rio conference in 1992. In the other scenarios, the emissions are higher than 1990 levels. The differences when it comes to actual temperature increase and total GDP gains seem relatively marginal as well. However, the total side payments from the coalition to the non-

---

[13] We set the rate of pure time preferences equal to zero; however, using a concave utility function results in an implicit discounting of future consumption (see Section 5 below).

cooperating countries have increased since this regime involves higher reductions, and hence higher abatement costs in the non-cooperating region. The increase in abatement can be explained from equation (7): Including USA in the coalition implies an increase in the damage costs taken into account by the coalition (see the left side of the equation), while it means lower gains from reduced side payments due to the damage in the non-cooperating countries (see the last part of the right side) since there are fewer countries to compensate. Thus, to attain an optimal solution, the first part of the right side has to increase, giving higher abatement in the non-cooperating countries.

Limited compensation

Under Regime 3, the REST region is not compensated for emissions reductions due to transaction costs related to side payments. We assume that the emissions from REST follow the BAU path, which means that we ignore carbon leakages from actions taken by the other countries (see e.g., Burniaux et al. (1992a) and Manne and Rutherford (1992)).

The emissions from the REST region accounts for about 17% in 1990 and 22% in 2230. Thus, ignoring this region under an international treaty means that still more than 75% of emissions have been accounted for. This seems like a high portion; however, as seen from the results under Regime 3 in Figures 4 through 9, the negative impacts of limited compensation are relatively more important than the positive impacts of including USA in the coalition. For instance the difference between Regimes 1 and 3 is larger than the difference between Regimes 1 and 2 with respect to temperature change: The temperature increase under Regime 3 by 2180 will be almost 5.9 °C compared to 5.1 °C under Regime 1. In comparison, the corresponding reduction in temperature when moving from Regime 1 to Regime 2 is only 0.5 °C (see Figure 8).

5 SENSITIVITY ANALYSIS

Most of the functional forms and parameter values used in the analysis are subject for discussion, and the results will of course depend of the data employed. Sensitivity analysis is therefore essential.

The data for the *income function* are taken from the GREEN model (Burniaux et al. (1992a,b)). This study is rather optimistic in terms of abatement costs. Calibrating the income function using data from Manne and Richels (1992) will give lower abatement in all scenarios and regimes. For sensitivity analyses on the income function, see Fankhauser and Kverndokk (1992) and Kverndokk (1993).

The studies of Peck and Teisberg (1992) and Fankhauser and Kverndokk (1992) concluded that the optimal reduction levels are very sensitive to the form of the *damage function* (the value of γ). To see the effect on the main variables in this study, we have run simulations with a linear damage function ($\gamma = 1$). Even the little reduction in the parameter value of γ has impacts on the main variables, involving for example reduced abatement and higher temperature increase. However the abatement is still high with the linear damage function. The most sensitive variable to changes in this parameter is the side payments. These have been reduced by about 50% compared to the original levels, indicating lower gains from free riding with a linear damage function. Even if the total gains under the social optimum are higher, the higher the damage is, the total gains with limited participation seem not to be equally sensitive.

As discussed in, e.g., Cline (1992a,b) the *social discount rate* is composed of two elements: A component for pure time preference, and a component for utility-based discounting, where the latter follows from the assumption that future consumption will be higher than the current level, which means that the marginal utility from an additional unit of consumption will be lower in the future than today.

Following the arguments of Cline (1992a,b), we have set the rate of pure time preference, ρ, equal to 0. However, this component has been the subject of long discussion (see, e.g., Lind (1982) for a survey), and is for example set equal to 3% in the study of Nordhaus (1992). Sensitivity analysis on the component of pure time preference confirms the conclusions in Cline (1992b); a high rate of pure time preference reduces the optimal abatement quite drastically in the beginning of the time horizon, but abatement rises quickly, giving high-percentage cutbacks by the end of the planning period. Increasing the rate of pure time preference to 1% reduces the social optimal abatement in 2000 under Scenario 2 by more than 40%, and delays the stage of no CO_2 emissions by two decades. A rate of 3% will correspondingly reduce the social optimal abatement by more than 70% in 2000 and give a peak of reductions at about 85% by the end of the next century.

Changing the optimisation problem to maximise the discounted sum of utility over time, where per capita utility is a logarithmic function of per capita consumption, actually puts more weight on future consumption compared to the original optimisation problem. Thus, this is similar to a reduction in the pure rate of time preferences, giving higher abatement in the beginning of the time period.[14]

Reducing the elasticity of substitution in the utility function by setting μ equal to 1.5, which is the value applied by Cline (1992a), actually increases the utility-based discounting (see above). Thus, this will reduce abatement in the beginning of the planning horizon, and the optimal abatement is actually in the same range as when employing a rate of pure time preferences equal to 1%.

To sum up, even if the optimal abatement paths are very sensitive to the various parameters employed, the main characteristics of limited participation under international CO_2 treaties seems robust.

6. CONCLUSIONS

In this paper, we have run simulations for a planning horizon of more than 200 years. Due to the great uncertainties of such a long time period, our results should be taken only as illustrative estimates. Nevertheless, we hope this exercise may show some of the main characteristics of limited participation under international CO_2 treaties.

The analysis shows that even if limited participation may have a significant influence on the climate and therefore the economy in the long run, it will not meet the recommendations from international conferences. Compared to the social optimum, there is a significant global loss of limited participation. However, the most likely alternative to coalition formation seems to be a

---

[14] To see this, let $U(C/N) = \ln(C/N)$. We then have $\Sigma_t(1+\rho)^{-t}N\ln(C/N) = \Sigma_t(1+\rho)^{-t}(N\ln C - N\ln N)$. The latter part of this expression ($N\ln N$) is exogenous and does not influence the optimal paths of emissions. Assuming that population, N, is increasing over time actually puts more weight on future rather than current consumption.

"laissez-faire" regime, involving great damage in the long run. A treaty signed by only a group of countries may therefore be important.

Unilateral actions to tackle the global warming issue have been criticized because of carbon leakages (see, e.g., Pezzey (1992)). The importance of the leakages has been analyzed in several studies but the conclusions differ (see, e.g., Burniaux et al. (1992a) and Manne and Rutherford (1992)). However, as shown in this analysis, side payments may be an effective policy instrument to avoid or reduce the problem of leakages and to make a limited agreement significant. Side payments to countries outside the coalition may be within politically acceptable levels, making such a policy instrument more likely. This study also emphasises the importance of compensating as many countries as possible even in the absence of carbon leakages.

Including USA in the coalition has a relatively marginal impact on the development of the climate in the long run, even if the current emissions of USA amount to almost 25% of global emissions. This is due to the potential increase in emissions from developing countries, especially China. Thus, even if limited participation by a group of OECD countries is an important alternative to no agreements, this stresses the importance of future emissions abatement in the major developing countries.

REFERENCES

Barrett, S. (1990): "The problem of global environmental protection", in Oxford Review of Economic Policy, 6(1): 68-79.

Barrett, S. (1991):"The Paradox of International Environmental Agreements", mimeo, London Business School.

Brooke, A., D. Kendrick and A. Meeraus (1992): GAMS: A User's Guide - Release 2.25, Redwood City: The Scientific Press.

Burniaux, J. M., J. P. Martin, G. Nicoletti and J. Oliveira Martins (1992a): "The Costs of Reducing CO_2 Emissions: Evidence from GREEN". OECD, Department of Economics and Statistics, Working Paper No. 115. Paris: OECD.

Burniaux, J. M., J. P. Martin, G. Nicoletti and J. Oliveira Martins (1992b): "GREEN -- A multi-sector, multi-region dynamic general equilibrium model for quantifying the costs of curbing CO_2 emissions: A technical manual". OECD, Department of Economics and Statistics, Working Paper No. 116. Paris: OECD.

Carraro, C. and D. Siniscalco (1991): "The international protection of the environment: Voluntary agreements among sovereign countries", in: P. Dasgupta, K. G. Mäler and A. Vercelli (eds.) The protection of transnational commons, Oxford: Clarendon.

Carraro, C. and D. Siniscalco (1992): "The international dimension of environmental policy", in European Economic Review, 36(2/3): 379-387.

Cline, W. R. (1991): "Scientific basis for the greenhouse effect", in The Economic Journal, 101: 904-919.

Cline, W. R. (1992a): The Economics of Global Warming, Institute for International Economics, Washington DC.

Cline, W. R. (1992b): "Socially Efficient Abatement of Carbon Emissions", Institute for International Economics, Washington DC. Paper presented at the Second CICERO Seminar on Climate Change, Oslo.

Dean, A. and P. Hoeller (1992): "Costs of reducing CO_2 emissions: Evidence from six global models". OECD, Department of Economics and Statistics, Working Paper No. 122. Paris OECD.

Eyckmans, J., S. Proost and E. Schokkaert (1992): "Efficiency and Distribution in Greenhouse Negotiations". Paper presented at the 3rd Annual EAERE Meeting, Krakow, June 1992.

Fankhauser, S. (1992): "Global Warming Damage Costs: Some Monetary Estimates", GEC Working Paper 92-29, Centre for Social and Economic Research on the Global Environment (CSERGE), University College London and University of East Anglia.

Fankhauser, S. and S. Kverndokk (1992):"The Global Warming Game - Simulations of a CO_2 Reduction Agreement". Memorandum No 13 from the Department of Economics, University of Oslo, and GEC Working Paper 92-10, Centre for Social and Economic Research on the Global Environment (CSERGE), University College London and University of East Anglia.

Hoel, M. (1992a): "Stabilizing CO_2 Emissions in Europe: Individual Stabilization versus Harmonization of Carbon Taxes", mimeo, Center for International Climate and Energy Research, Oslo (CICERO).

Hoel, M. (1992b): "Efficient international climate agreements in the presence of free riders", CICERO Working paper 92:7, Center for International Climate and Energy Research, Oslo.

Hoel, M. and I. Isaksen (1993): "Efficient abatement of different greenhouse gases", Memorandum No 5 from the Department of Economics, University of Oslo.

*Houghton, J. T., G. J. Jenkins and J. Ephraums (eds.) (1990):*Climate Change - the IPCC Scientific Assessment, (Report from Working Group I, The Intergovernmental Panel on Climate Change). WMO, UNEP, IPCC. Cambridge: Cambridge University Press.

Houghton, J. T., B. A. Callander and S. K. Varney (eds.) (1992): Climate Change 1992 - the supplementary report to the IPCC Scientific Assessment, (Report from Working Group I, The Intergovernmental Panel on Climate Change). WMO, UNEP, IPCC. Cambridge: Cambridge University Press.

Kverndokk, S. (1993):"Global CO_2 Agreements: A Cost-Effective Approach", in: The Energy Journal, 14(2): 91-112.

Lind, R., ed. (1982): Discounting for Time and Risk in Energy Policy, Baltimore: John Hopkins University Press.

Manne, A. S. and R. G. Richels (1992): Buying Greenhouse Insurance - the Economic Costs of CO_2 Emission Limits. Cambridge, MA: MIT-Press.

Manne, A. S. and T. Rutherford (1992): "International Trade in Oil, Gas and Carbon Emission Rights: An Intertemporal Equilibrium Model". Paper presented at the International Institute for Applied Systems Analysis, Laxemburg, Austria, September.

Nordhaus, W. D. (1991a): "To Slow or not to Slow: the Economics of the Greenhouse Effect", in: Economic Journal, 101(407): 920-937.

Nordhaus, W. D. (1991b): "A sketch of the economics of the greenhouse effect", in: American Economic Review, Papers and Proceedings, 81(2): 146-150.

Nordhaus, W. D. (1992): "The 'DICE' Model: Background and Structure of A Dynamic Integrated Climate-Economy Model of the Economics of Global Warming", New Haven: Yale University.

Peck, S. C. and T. J. Teisberg (1992): "CETA: a Model for Carbon Emissions Trajectory Assessment", in: The Energy Journal, 13(1): 55-77.

Pezzey, J. (1992): "Analysis of unilateral CO_2 control in the European Community", in The Energy Journal, 13(3): 159-171.

APPENDIX 1

Table 1: Value of production parameters

	b (2015)	q^a (1990)	q^a (2090-)	$\hat{Y}^b$ (1990)	$\hat{e}^c$ (1990)
USA	2.804999	1107	299	4536.6	1338.7
EEC	2.548641	1056	276	2740.3	812.6
ROECD	3.338589	1317	331	2594.6	606.6
EX-USSR	3.080579	2069	454	1024.2	1010.1
China	5.518024	1755	443	533.2	608.2
India	5.422125	2147	482	239.2	148.9
REST	3.033441	1644	400	2913.5	1289.5

a US$ (1985) per ton of carbon
b billions US$ (1985)
c GtC

Table 2: Annual growth rates in BAU GDP without feedback effects

	1990-2000	2001-2020	2021-2050	2051-2080	2081-2110	2111-2140	2141-2230
USA	2.6	2.2	1.6	1.0	1.0	0.8	0.5
EEC	2.2	1.7	1.3	1.0	1.0	0.8	0.5
ROECD	3.2	2.4	2.0	1.0	1.0	0.8	0.5
EX-USSR	2.6	2.1	1.6	1.0	1.0	0.8	0.5
China	4.6	4.4	3.4	2.5	2.0	1.5	1.0
India	4.6	4.5	3.4	2.5	2.0	1.5	1.0
REST	3.7	3.4	2.7	1.5	1.0	0.8	0.5
WORLD	3.0	2.6	2.1	1.4	1.2	1.0	0.7

Table 3: Annual growth rates in BAU CO_2 emissions

	1990-2000	2001-2020	2021-2050	2051-2080	2081-2110	2111-2140	2141-2230
USA	1.1	0.8	0.6	0.5	0	-1.0	-1.0
EEC	0.8	0.7	0.6	0.5	0	-1.0	-1.0
ROECD	2.0	1.5	1.3	0.5	0	-1.0	-1.0
EX-USSR	1.9	1.3	1.0	0.5	0	-1.0	-1.0
China	3.7	3.5	3.2	2.5	2.0	1.0	0.5
India	3.7	3.7	3.7	2.5	2.0	1.0	0.5
REST	2.5	2.4	2.0	1.5	1.0	0	0
WORLD	2.0	1.8	1.8	1.5	1.2	0.4	0.3

Table 4: Per cent GDP loss due to 2.5 °C actual temperature increase

	Total damage: 1 % of GWP	Total damage: 2 % of GWP	Total damage: 3 % of GWP
USA	0.867	1.733	2.6
ROECD	0.933	1.867	2.8
EEC	1.0	2.0	3.0
EX-USSR	0.467	0.933	1.4
China	4.067	8.133	12.2
India and REST	1.533	3.067	4.6

Table 5: Value of stock parameters

Parameter	Value	Meaning
$X_{Exog\text{-}CO2}$	0.61^{a} 0.35^{b}	exogenous emissions of CO_2 (ppm)
Q^{P}	280	preindustrial CO_2 concentration (ppm)
Z(0)	73	additional concentration of CO_2 (ppm) from preindustrial time to 1990
$L_{CO2}(0)$	120	lifetime of CO_2 (years) in 1990

a emissions in 1990
b annual rate of increase

Table 6: Value of temperature parameters

Parameter	Value	Meaning
A	3.607	Parameter in potential temperature function
B	20.328	Constant in potential temperature function
λ	0.75	Total warming coefficient (°C/W m^{-2})
α	0.025	Lag parameter

APPENDIX 2

To illustrate the abatement possibilities in the model, abatement costs and taxes are calculated under a reduction scenario where each region stabilises its emissions at 1990 levels from the year 2000 onwards. This is shown in Figures A1 through A4. Compared to other models, see, e.g., Dean and Hoeller (1992), Charts 7 and 8, our estimates seem to be within the same range for the next century for most regions. However, our abatement costs are mainly falling over time, a characteristic not supported by the studies reported in Dean and Hoeller (1992). This may partly be explained by lower emission growth rates at the end of the next century in our model. The low costs or taxes in the 22nd and 23rd centuries are mainly due to decreases in emissions for most countries; for example by 2170, stabilisation is already achieved in USA and no abatement is necessary therefore. The large differences in the constant elasticity of abatement costs, b, in the long run can also be justified by the relatively small abatement costs in all regions by the end of the planning horizon.

Figure A1

Abatement costs at stabilisation, OECD

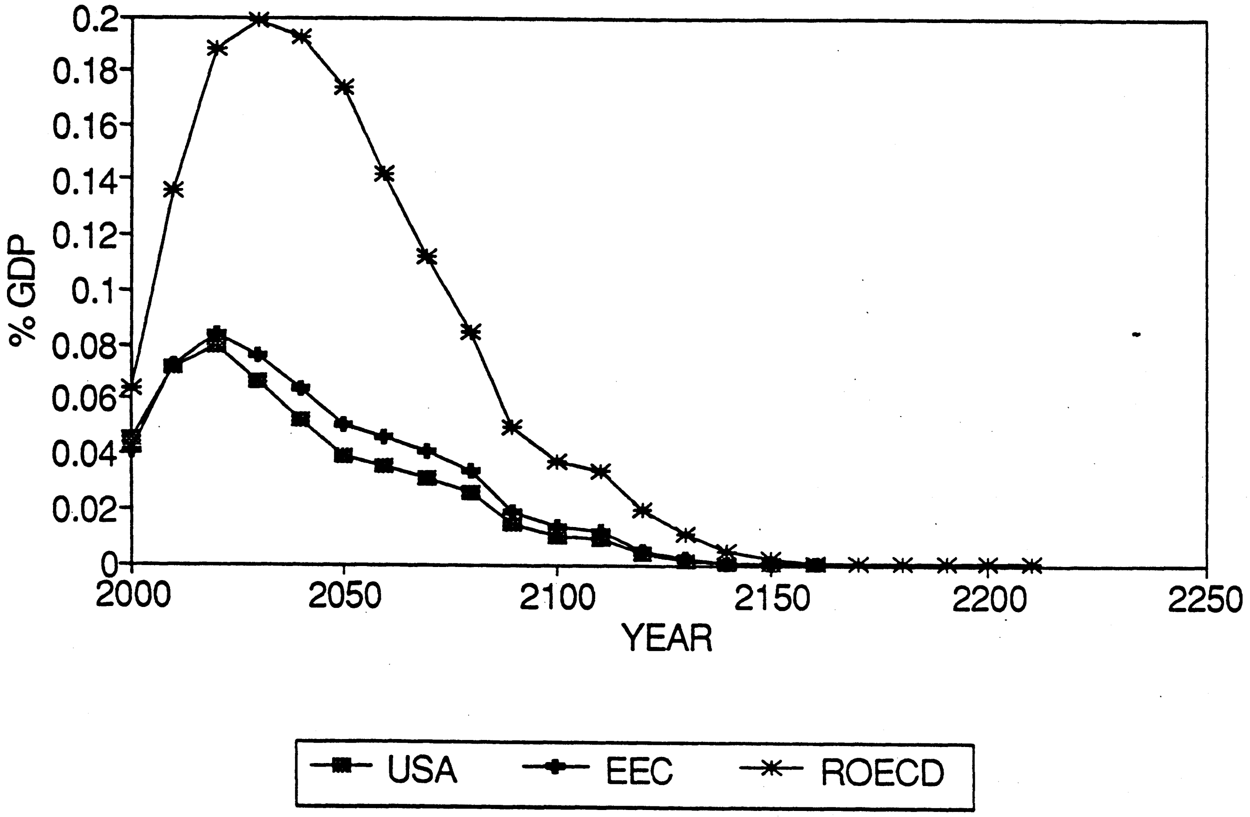


Figure A2

Abatement costs at stabilis., Non-OECD

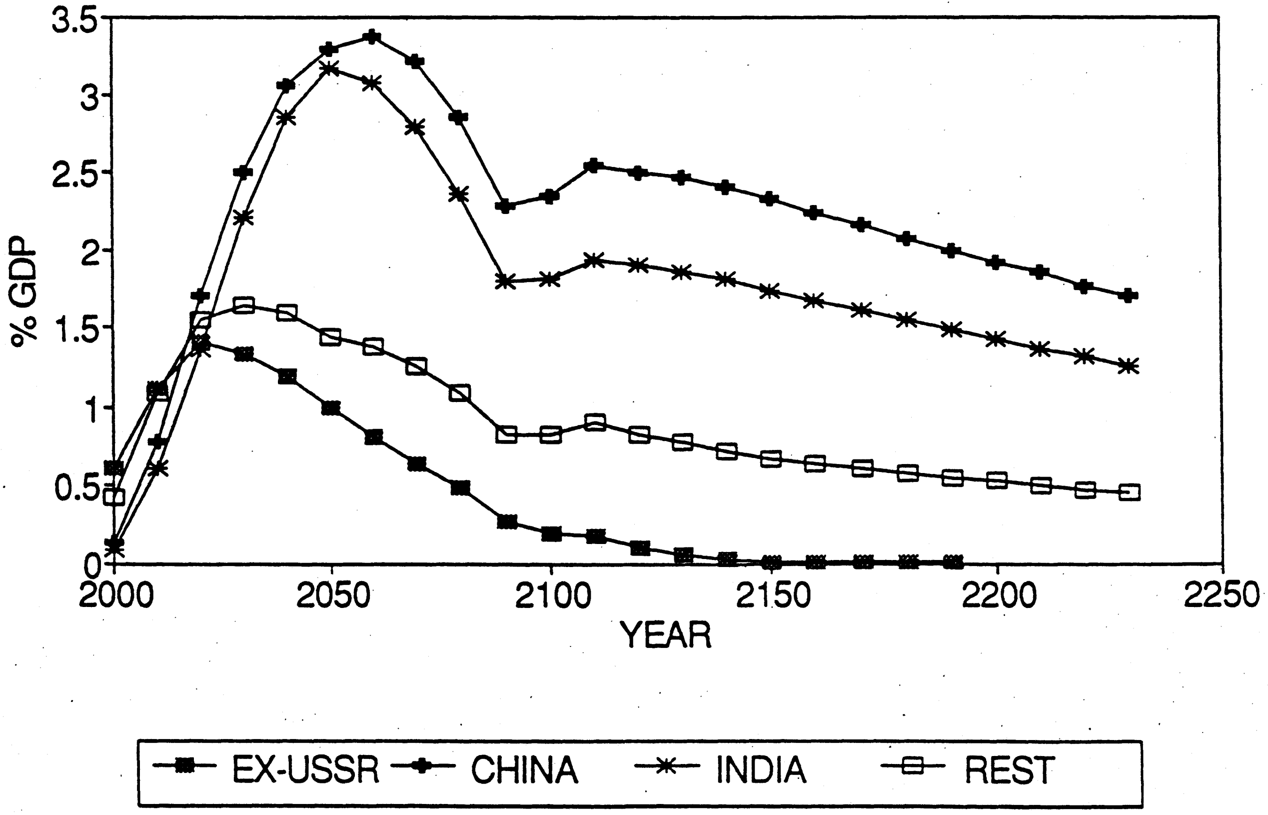


Figure A3

Carbon taxes at stabilisation, OECD

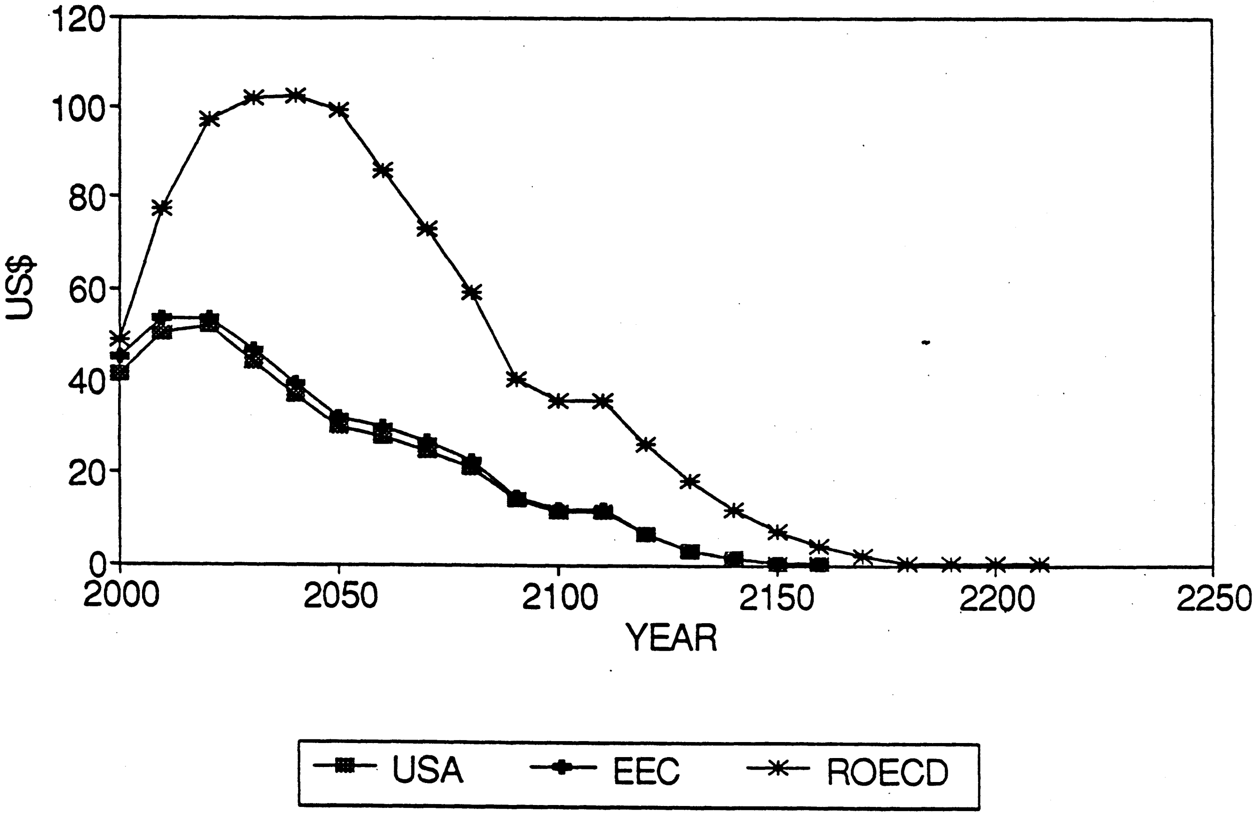


Figure A4

Carbon taxes at stabilisation, Non-OECD

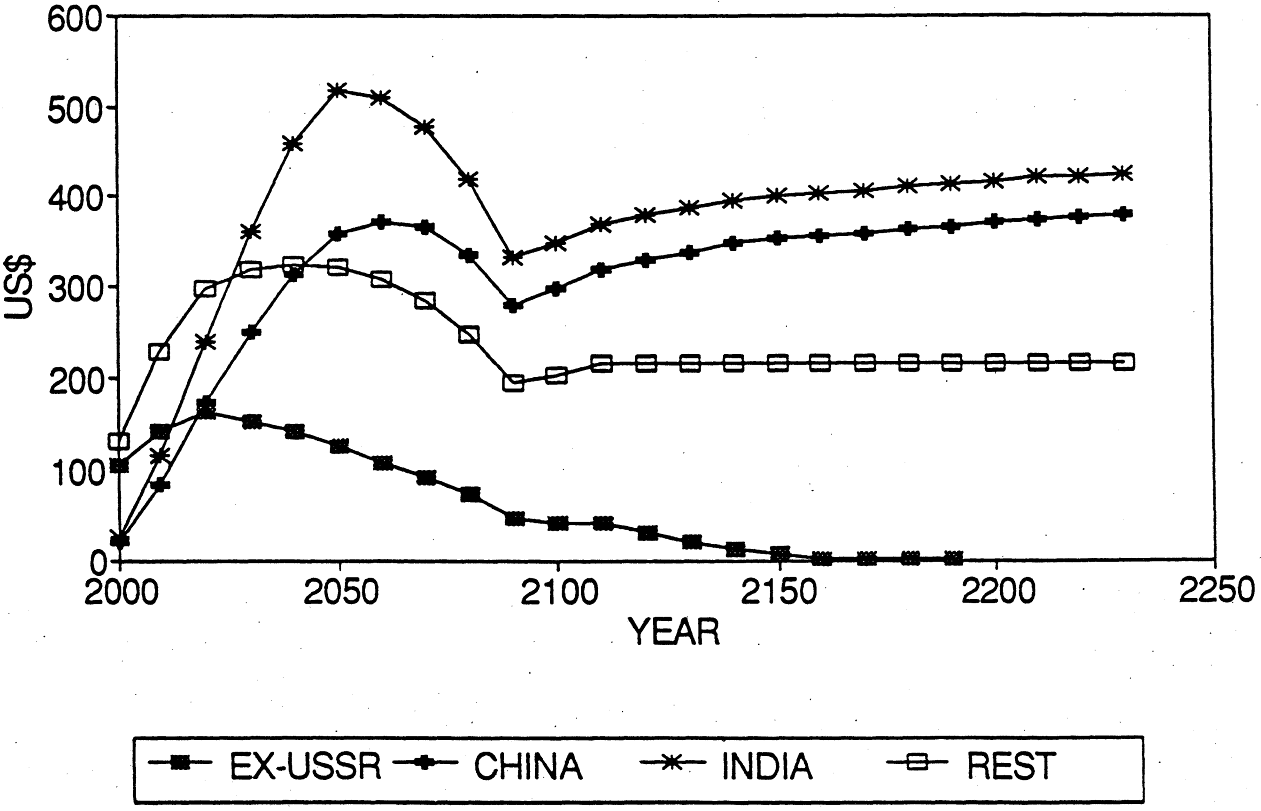


Figure 1

Relative CO2 emissions in BAU scenario

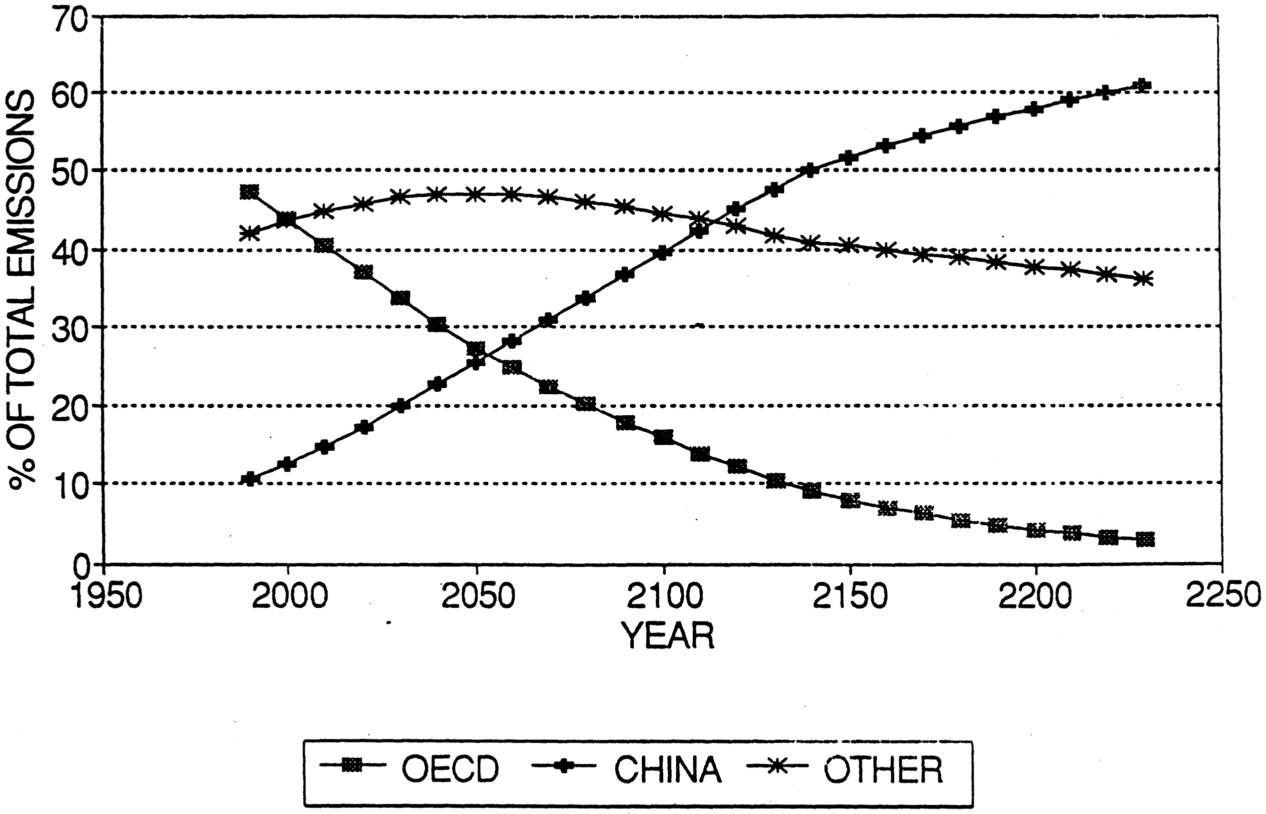


Figure 2
BAU paths: CO_2 emissions from energy use, atmospheric CO_2 concentration, and actual temperature increase

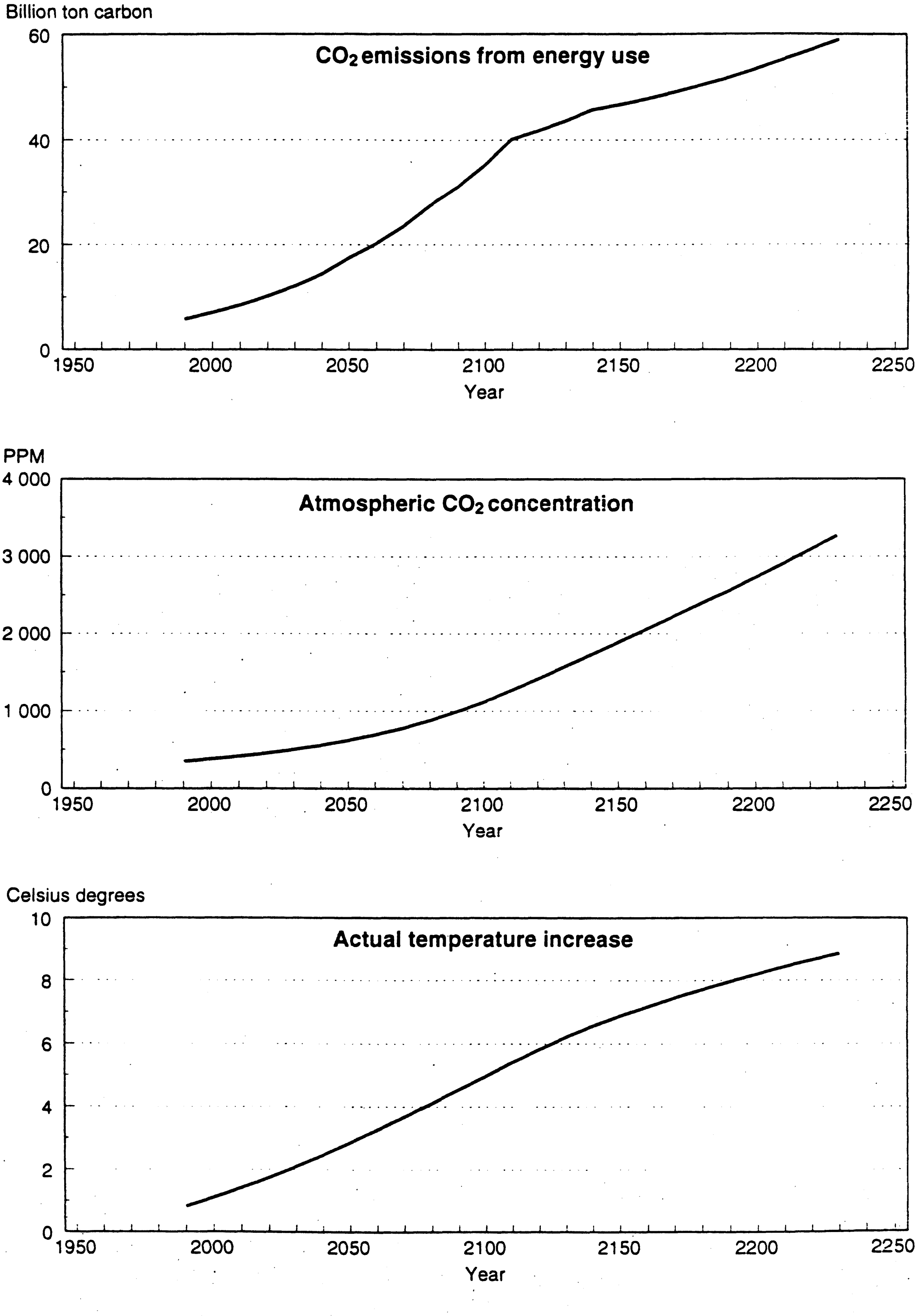


Figure 3

BAU GWP with feedback from global warm.

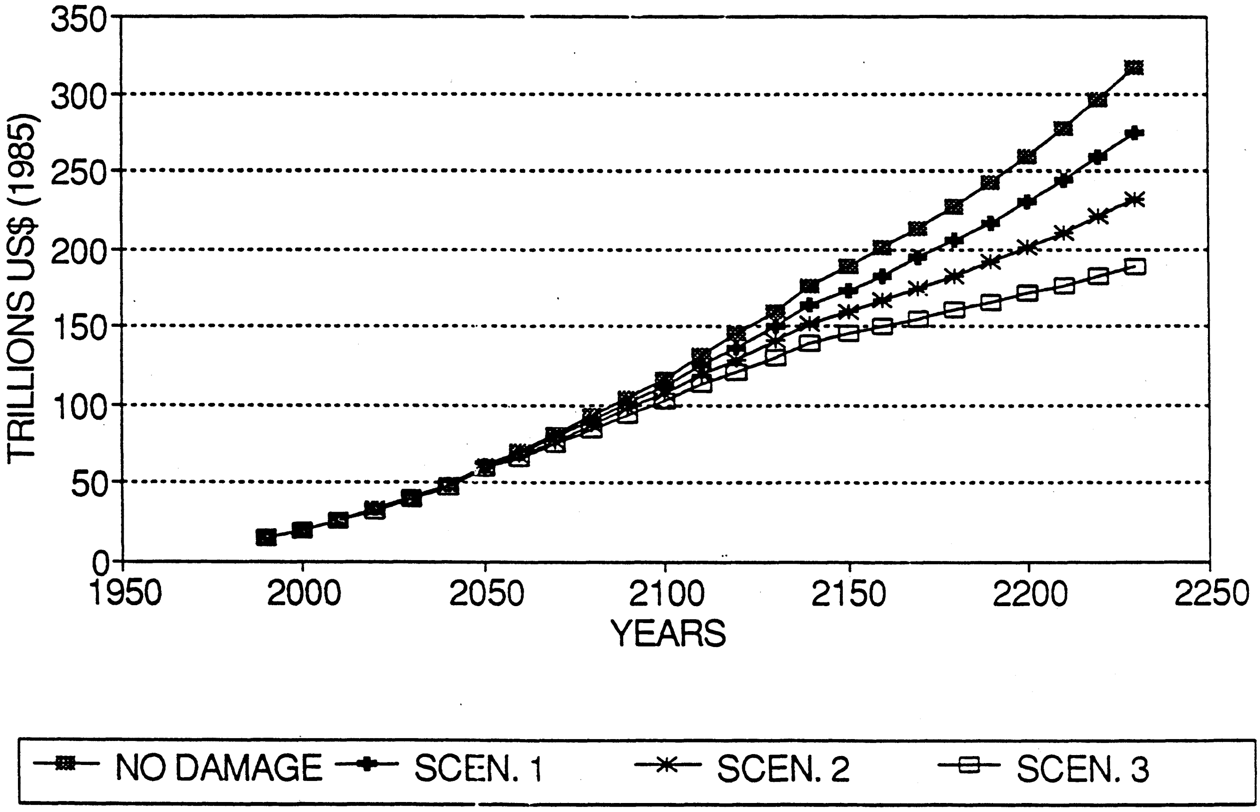


Figure 4

Global CO2 reductions rel. to BAU, S2

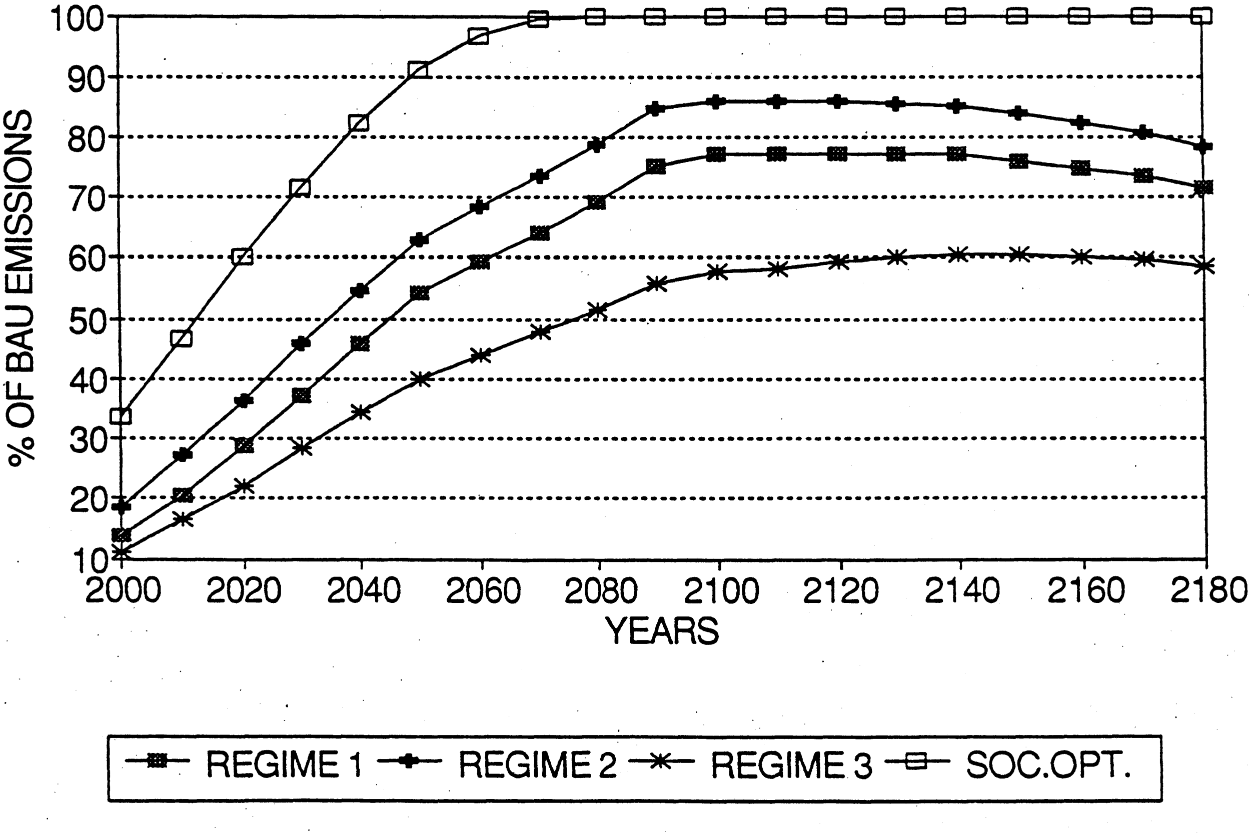


Figure 5

Global CO2 em. rel. to 1990 level, S2

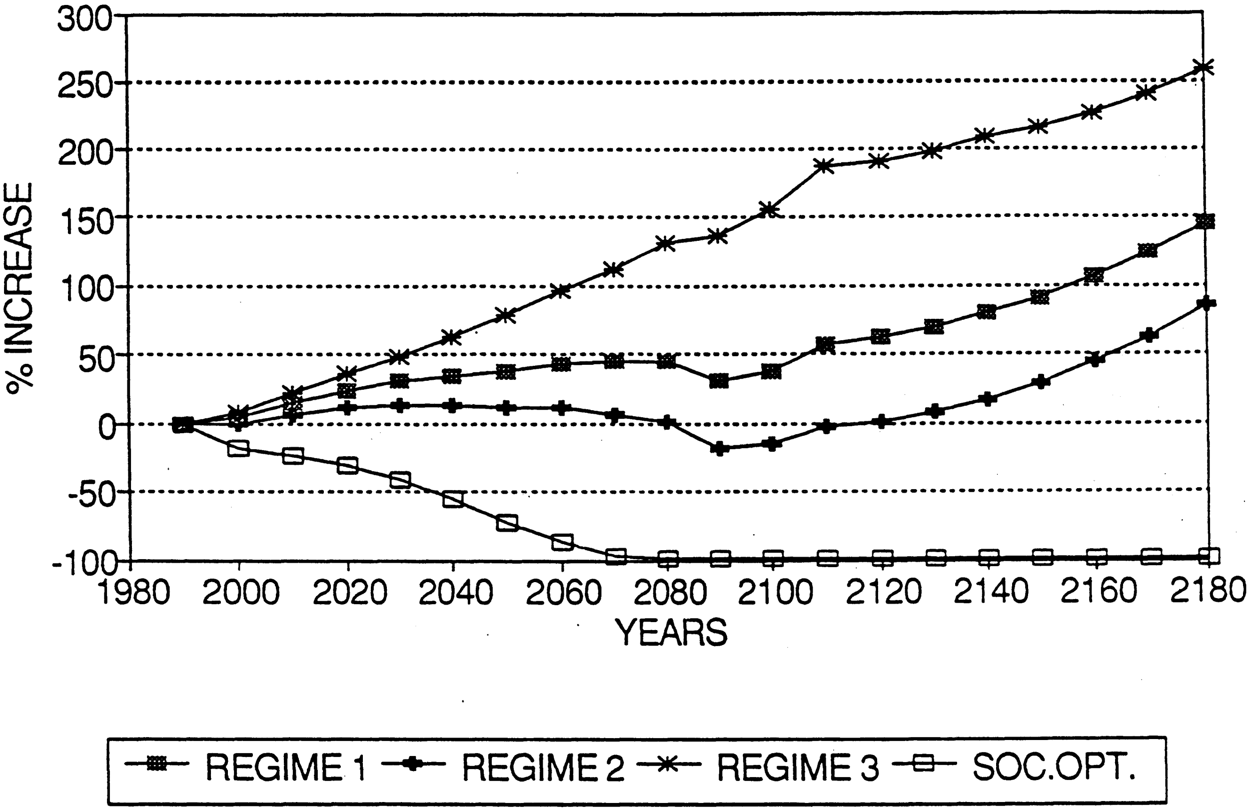


Figure 6

Compensation in % of GDP of coalit., S2

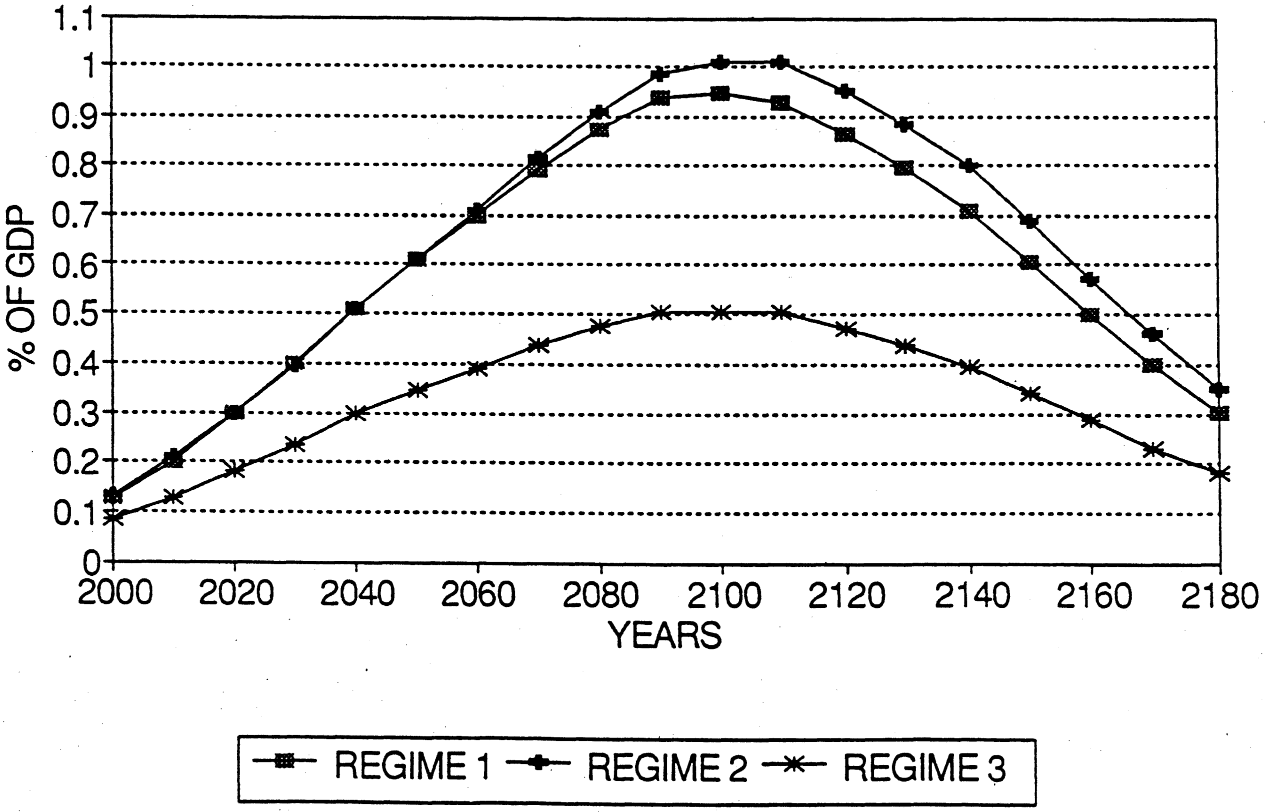


Figure 7

Compens. in % of GDP outs. coalit., S2

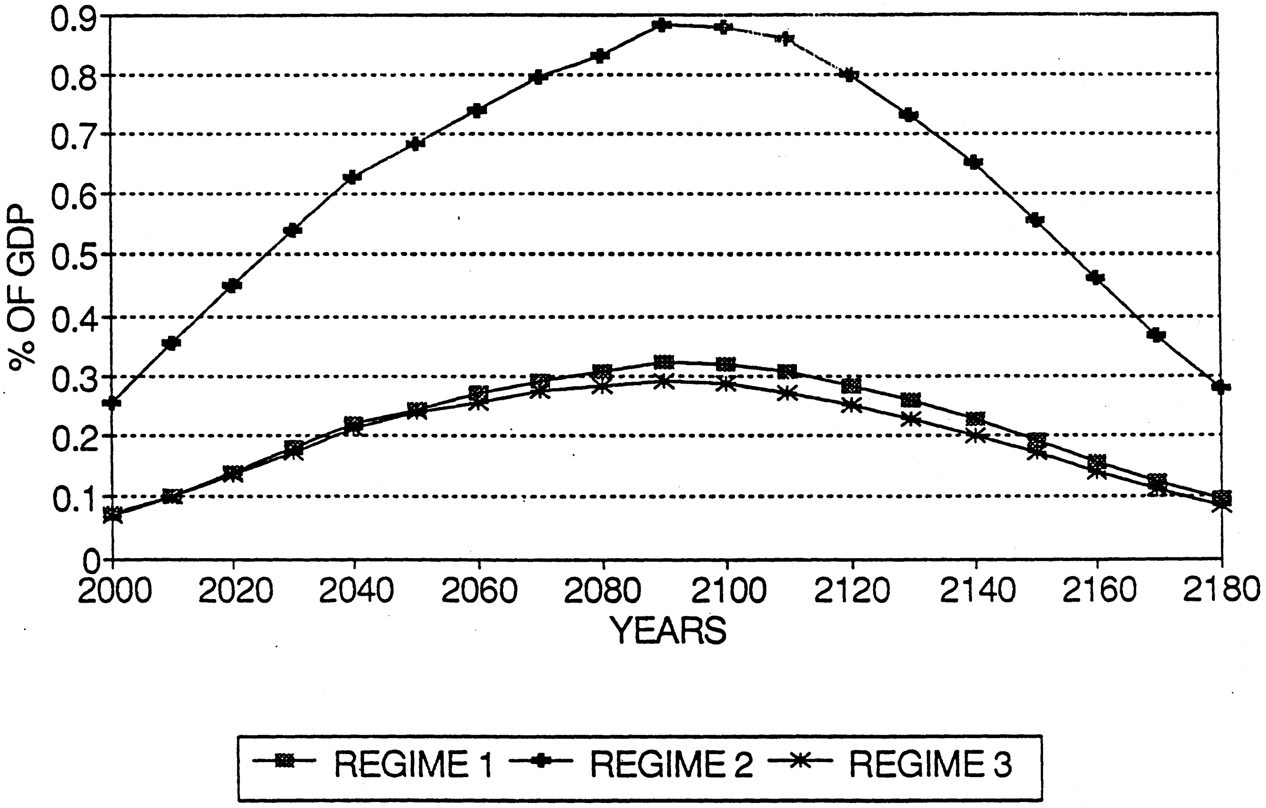


Figure 8

Actual temperature increase, S2

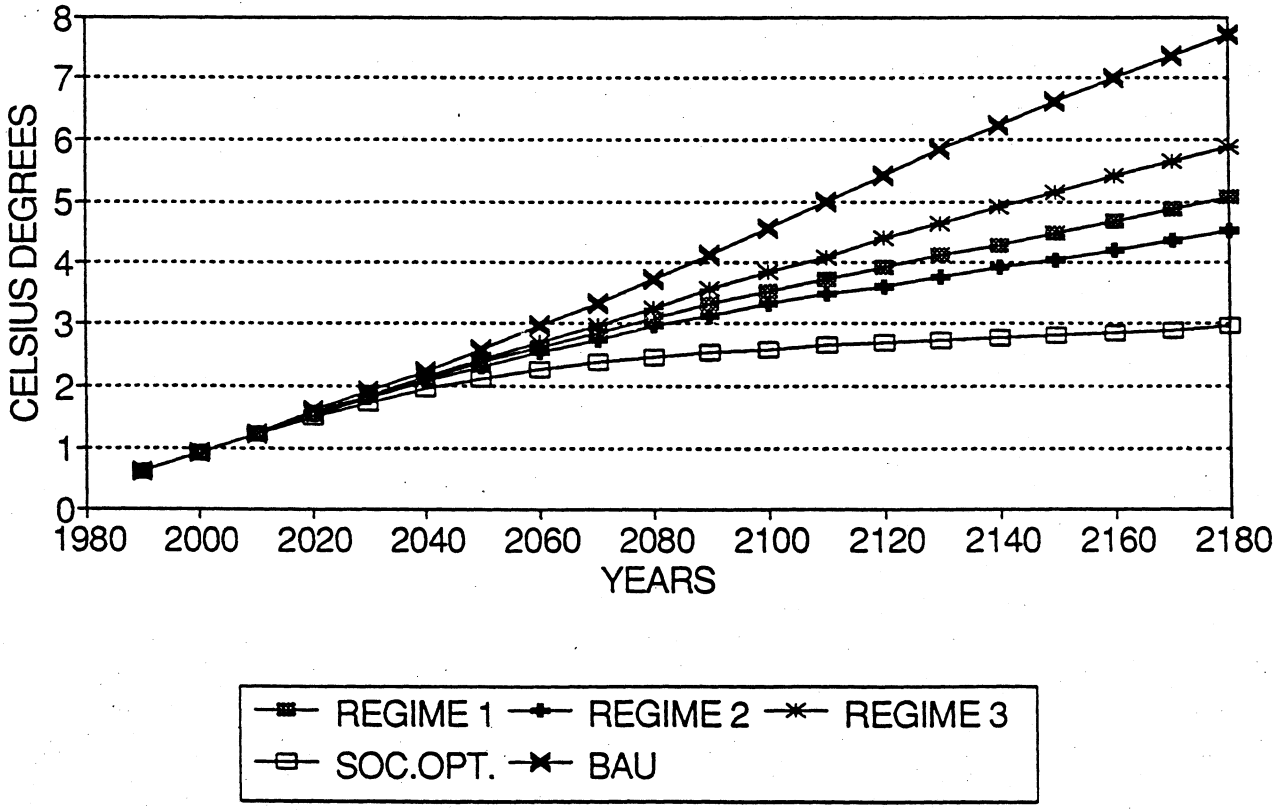
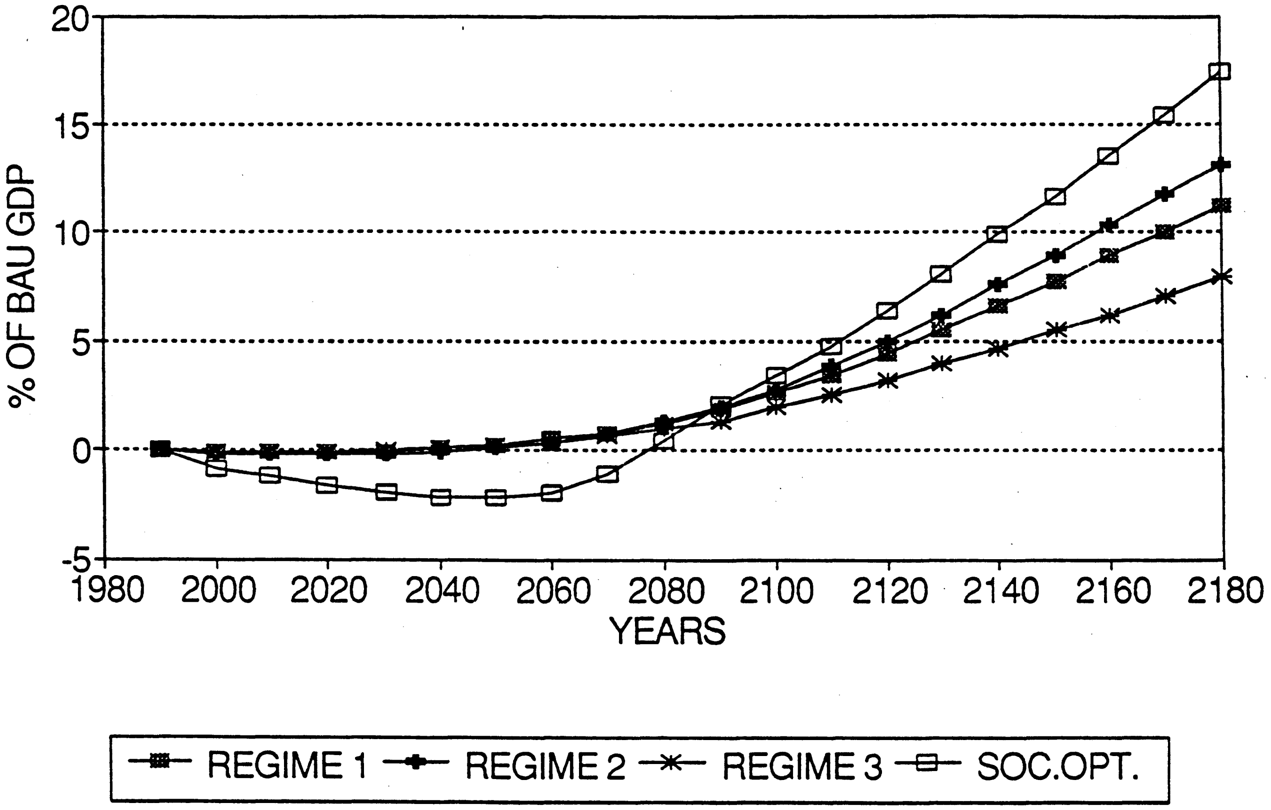


Figure 9

Global GDP gains compared to BAU, S2



ISSUED IN THE SERIES DISCUSSION PAPER

No. 1 *I. Aslaksen and O. Bjerkholt (1985)*: Certainty Equivalence Procedures in the Macroeconomic Planning of an Oil Economy.

No. 3 *E. Biørn (1985)*: On the Prediction of Population Totals from Sample surveys Based on Rotating Panels.

No. 4 *P. Frenger (1985)*: A Short Run Dynamic Equilibrium Model of the Norwegian Production Sectors.

No. 5 *I. Aslaksen and O. Bjerkholt (1985)*: Certainty Equivalence Procedures in Decision-Making under Uncertainty: An Empirical Application.

No. 6 *E. Biørn (1985)*: Depreciation Profiles and the User Cost of Capital.

No. 7 *P. Frenger (1985)*: A Directional Shadow Elasticity of Substitution.

No. 8 *S. Longva, L. Lorentsen and Ø. Olsen (1985)*: The Multi-Sectoral Model MSG-4, Formal Structure and Empirical Characteristics.

No. 9 *J. Fagerberg and G. Sollie (1985)*: The Method of Constant Market Shares Revisited.

No. 10 *E. Biørn (1985)*: Specification of Consumer Demand Models with Stochastic Elements in the Utility Function and the first Order Conditions.

No. 11 *E. Biørn, E. Holmøy and Ø. Olsen (1985)*: Gross and Net Capital, Productivity and the form of the Survival Function. Some Norwegian Evidence.

No. 12 *J.K. Dagsvik (1985)*: Markov Chains Generated by Maximizing Components of Multidimensional Extremal Processes.

No. 13 *E. Biørn, M. Jensen and M. Reymert (1985)*: KVARTS - A Quarterly Model of the Norwegian Economy.

No. 14 *R. Aaberge (1986)*: On the Problem of Measuring Inequality.

No. 15 *A.-M. Jensen and T. Schweder (1986)*: The Engine of Fertility - Influenced by Interbirth Employment.

No. 16 *E. Biørn (1986)*: Energy Price Changes, and Induced Scrapping and Revaluation of Capital - A Putty-Clay Model.

No. 17 *E. Biørn and P. Frenger (1986)*: Expectations, Substitution, and Scrapping in a Putty-Clay Model.

No. 18 *R. Bergan, Å. Cappelen, S. Longva and N.M. Stølen (1986)*: MODAG A - A Medium Term Annual Macroeconomic Model of the Norwegian Economy.

No. 19 *E. Biørn and H. Olsen (1986)*: A Generalized Single Equation Error Correction Model and its Application to Quarterly Data.

No. 20 *K.H. Alfsen, D.A. Hanson and S. Glomsrød (1986)*: Direct and Indirect Effects of reducing SO_2 Emissions: Experimental Calculations of the MSG-4E Model.

No. 21 *J.K. Dagsvik (1987)*: Econometric Analysis of Labor Supply in a Life Cycle Context with Uncertainty.

No. 22 *K.A. Brekke, E. Gjelsvik and B.H. Vatne (1987)*: A Dynamic Supply Side Game Applied to the European Gas Market.

No. 23 *S. Bartlett, J.K. Dagsvik, Ø. Olsen and S. Strøm (1987)*: Fuel Choice and the Demand for Natural Gas in Western European Households.

No. 24 *J.K. Dagsvik and R. Aaberge (1987)*: Stochastic Properties and Functional Forms of Life Cycle Models for Transitions into and out of Employment.

No. 25 *T.J. Klette (1987)*: Taxing or Subsidising an Exporting Industry.

No. 26 *K.J. Berger, O. Bjerkholt and Ø. Olsen (1987)*: What are the Options for non-OPEC Countries.

No. 27 *A. Aaheim (1987)*: Depletion of Large Gas Fields with Thin Oil Layers and Uncertain Stocks.

No. 28 *J.K. Dagsvik (1987)*: A Modification of Heckman's Two Stage Estimation Procedure that is Applicable when the Budget Set is Convex.

No. 29 *K. Berger, Å. Cappelen and I. Svendsen (1988)*: Investment Booms in an Oil Economy -The Norwegian Case.

No. 30 *A. Rygh Swensen (1988)*: Estimating Change in a Proportion by Combining Measurements from a True and a Fallible Classifier.

No. 31 *J.K. Dagsvik (1988)*: The Continuous Generalized Extreme Value Model with Special Reference to Static Models of Labor Supply.

No. 32 *K. Berger, M. Hoel, S. Holden and Ø. Olsen (1988)*: The Oil Market as an Oligopoly.

No. 33 *I.A.K. Anderson, J.K. Dagsvik, S. Strøm and T. Wennemo (1988)*: Non-Convex Budget Set, Hours Restrictions and Labor Supply in Sweden.

No. 34 *E. Holmøy and Ø. Olsen (1988)*: A Note on Myopic Decision Rules in the Neoclassical Theory of Producer Behaviour, 1988.

No. 35 *E. Biørn and H. Olsen (1988)*: Production - Demand Adjustment in Norwegian Manufacturing: A Quarterly Error Correction Model, 1988.

No. 36 *J.K. Dagsvik and S. Strøm (1988)*: A Labor Supply Model for Married Couples with Non-Convex Budget Sets and Latent Rationing, 1988.

No. 37 *T. Skoglund and A. Stokka (1988)*: Problems of Linking Single-Region and Multiregional Economic Models, 1988.

No. 38 *T.J. Klette (1988)*: The Norwegian Aluminium Industry, Electricity prices and Welfare, 1988.

No. 39 *I. Aslaksen, O. Bjerkholt and K.A. Brekke (1988)*: Optimal Sequencing of Hydroelectric and Thermal Power Generation under Energy Price Uncertainty and Demand Fluctuations, 1988.

No. 40 *O. Bjerkholt and K.A. Brekke (1988)*: Optimal Starting and Stopping Rules for Resource Depletion when Price is Exogenous and Stochastic, 1988.

No. 41 *J. Aasness, E. Biørn and T. Skjerpen (1988)*: Engel Functions, Panel Data and Latent Variables, 1988.

No. 42 *R. Aaberge, Ø. Kravdal and T. Wennemo (1989)*: Unobserved Heterogeneity in Models of Marriage Dissolution, 1989.

No. 43 *K.A. Mork, H.T. Mysen and Ø. Olsen (1989)*: Business Cycles and Oil Price Fluctuations: Some evidence for six OECD countries. 1989.

No. 44 *B. Bye, T. Bye and L. Lorentsen (1989)*: SIMEN. Studies of Industry, Environment and Energy towards 2000, 1989.

No. 45 *O. Bjerkholt, E. Gjelsvik and Ø. Olsen (1989)*: Gas Trade and Demand in Northwest Europe: Regulation, Bargaining and Competition.

No. 46 *L.S. Stambøl and K.Ø. Sørensen (1989)*: Migration Analysis and Regional Population Projections, 1989.

No. 47 *V. Christiansen (1990)*: A Note on the Short Run Versus Long Run Welfare Gain from a Tax Reform, 1990.

No. 48 *S. Glomsrød, H. Vennemo and T. Johnsen (1990)*: Stabilization of Emissions of CO_2: A Computable General Equilibrium Assessment, 1990.

No. 49 *J. Aasness (1990)*: Properties of Demand Functions for Linear Consumption Aggregates, 1990.

No. 50 *J.G. de Leon (1990)*: Empirical EDA Models to Fit and Project Time Series of Age-Specific Mortality Rates, 1990.

No. 51 *J.G. de Leon (1990)*: Recent Developments in Parity Progression Intensities in Norway. An Analysis Based on Population Register Data.

No. 52 *R. Aaberge and T. Wennemo (1990)*: Non-Stationary Inflow and Duration of Unemployment.

No. 53 *R. Aaberge, J.K. Dagsvik and S. Strøm (1990)*: Labor Supply, Income Distribution and Excess Burden of Personal Income Taxation in Sweden.

No. 54 *R. Aaberge, J.K. Dagsvik and S. Strøm (1990)*: Labor Supply, Income Distribution and Excess Burden of Personal Income Taxation in Norway.

No. 55 *H. Vennemo (1990)*: Optimal Taxation in Applied General Equilibrium Models Adopting the Armington Assumption.

No. 56 *N.M. Stølen (1990)*: Is there a NAIRU in Norway?

No. 57 *Å. Cappelen (1991)*: Macroeconomic Modelling: The Norwegian Experience.

No. 58 *J. Dagsvik and R. Aaberge (1991)*: Household Production, Consumption and Time Allocation in Peru.

No. 59 *R. Aaberge and J. Dagsvik (1991)*: Inequality in Distribution of Hours of Work and Consumption in Peru.

No. 60 *T.J. Klette (1991)*: On the Importance of R&D and Ownership for Productivity Growth. Evidence from Norwegian Micro-Data 1976-85.

No. 61 *K.H. Alfsen (1991)*: Use of Macroeconomic Models in Analysis of Environmental Problems in Norway and Consequences for Environmental Statistics.

No. 62 *H. Vennemo (1991)*: An Applied General Equilibrium Assessment of the Marginal Cost of Public Funds in Norway.

No. 63 *H. Vennemo (1991)*: The Marginal Cost of Public Funds: A Comment on the Literature.

No. 64 *A. Brendemoen and H. Vennemo (1991)*: A climate convention and the Norwegian economy: A CGE assessment.

No. 65 *K. A. Brekke (1991)*: Net National Product as a Welfare Indicator.

No. 66 *E. Bowitz and E. Storm (1991)*: Will Restrictive Demand Policy Improve Public Sector Balance?

No. 67 *Å. Cappelen (1991)*: MODAG. A Medium Term Macroeconomic Model of the Norwegian Economy.

No. 68 *B. Bye (1992)*: Modelling Consumers' Energy Demand.

No. 69 *K. H. Alfsen, A. Brendemoen and S. Glomsrød (1992)*: Benefits of Climate Policies: Some Tentative Calculations.

No. 70 *R. Aaberge, Xiaojie Chen, Jing Li and Xuezeng Li (1992)*: The Structure of Economic Inequality among Households Living in Urban Sichuan and Liaoning, 1990.

No. 71 *K.H. Alfsen, K.A. Brekke, F. Brunvoll, H. Lurås, K. Nyborg and H.W. Sæbø (1992)*: Environmental Indicators.

No. 72 *B. Bye and E. Holmøy (1992)*: Dynamic Equilibrium Adjustments to a Terms of Trade Disturbance

No. 73 *O. Aukrust (1992):* The Scandinavian Contribution to National Accounting

No. 74 *J. Aasness, E, Eide and T. Skjerpen (1992):* A Criminometric Study Using Panel Data and Latent Variables

No. 75 *R. Aaberge and Xuezeng Li (1992):* The Trend in Income Inequality in Urban Sichuan and Liaoning, 1986-1990

No. 76 *J.K. Dagsvik and Steinar Strøm (1992):* Labor Supply with Non-convex Budget Sets, Hours Restriction and Non-pecuniary Job-attributes

No. 77 *J.K. Dagsvik (1992)*: Intertemporal Discrete Choice, Random Tastes and Functional Form

No. 78 *H. Vennemo (1993)*: Tax Reforms when Utility is Composed of Additive Functions.

No. 79 *J. K. Dagsvik (1993):* Discrete and Continuous Choice, Max-stable Processes and Independence from Irrelevant Attributes.

No. 80 *J. K. Dagsvik (1993):* How Large is the Class of Generalized Extreme Value Random Utility Models?

No. 81 *H. Birkelund, E. Gjelsvik, M. Aaserud (1993):* Carbon/energy Taxes and the Energy Market in Western Europe

No. 82 *E. Bowitz (1993):* Unemployment and the Growth in the Number of Recipients of Disability Benefits in Norway

No. 83 *L. Andreassen (1993):* Theoretical and Econometric Modeling of Disequilibrium

No. 84 *K.A. Brekke (1993):* Do Cost-Benefit Analyses favour Environmentalists?

No. 85 *L. Andreassen (1993):* Demographic Forecasting with a Dynamic Stochastic Microsimulation Model

No. 86 *G.B. Asheim and K.A. Brekke (1993):* Sustainability when Resource Management has Stochastic Consequences

No. 87 *O. Bjerkholt and Yu Zhu (1993):* Living Conditions of Urban Chinese Households around 1990

No. 88 *R. Aaberge (1993):* Theoretical Foundations of Lorenz Curve Orderings

No. 89 *J. Aasness, E. Biørn and T. Skjerpen (1993):* Engel Functions, Panel Data, and Latent Variables - with Detailed Results

No. 90 *Ingvild Svendsen (1993):* Testing the REH. Using Norwegian Microeconomic Data (Will be issued later)

No. 91 *Einar Bowitz, Asbjørn Rødseth and Erik Storm (1993):* Fiscal Expansion, the Budget Deficit and the Economy: Norway 1988-91 (Will be issued later)

No. 92 *Rolf Aaberge, Ugo Colombino and Steinar Strøm (1993):* Labor Supply in Italy

No. 93 *Tor Jakob Klette (1993):* Is Price Equal to Marginal Costs? An Integrated Study of Price-Cost Margins and Scale Economies among Norwegian Manufacturing Establishments 1975-90.

No. 94 *John K. Dagsvik (1993):* Choice Probabilities and Equilibrium Conditions in a matching Market with flexible Contracts

No. 95 *Tom Kornstad (1993):* Empirical Approaches for Analysing Consumption and Labour Supply in a Life Cycle Perspective

No. 96 *Tom Kornstad (1993):* An Empirical Life Cycle Model of Savings, Labour Supply and Consumption without Intertemporal Separability

Natural Resources Division, P.B. 8131 Dep, 0033 Oslo 1, Norway
Tel: (47) 22 86 48 32,
Fax: (47) 22 11 12 38, Telex: 11 202 SSB N