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An Empirical Investigation of Dynamic Cooperative and Noncooperative Solutions for Global Warming

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SUMMARY

Empirical investigation of global warming models in economics have started basically with simple calibrations of control models where the whole world was represented by a single agent. Theoretical advances in disaggregated game theoretic models have also motivated the analysis of disaggregated empirical models which have been extended to computable dynamic general equilibrium models or explicit solution of games related to global warming. The present paper is an empirical investigation of co-operative and noncooperative solutions in global warming using a dynamic disaggregated model of five groups of countries. This paper differs from previous empirical analysis by econometrically estimating benefit functions for each group of countries using cointegration techniques and by explicitly solving an optimal control model for the co-operative solution and a differential game model with linear Markov strategies for the noncooperative solution. The Markov strategies assumption is more realistic since it allows for the emissions of the groups to be affected by the actions of the other groups through the accumulation of CO_2.

NON TECHNICAL SUMMARY

The investigation of issues related to CO_2 accumulation and the appropriate policies in order for sovereign countries to reach some agreed upon solution have received extensive attention in the environmental economics literature both at the theoretical and the applied level. At the applied level the investigation started basically with numerical solutions of relatively simple control models of global warming where the whole world was regarded as a simple country. Theoretical advances in multi country models of global warming have also motivated the analysis of multi country empirical models which have been extended to include computable dynamic general equilibrium models or explicit solutions of games related to global warming.

The purpose of the present paper is to conduct an empirical investigation of the global warming problem using a dynamic disaggregated model of five groups of countries. Our paper differs from previous empirical analyses of the topic in its methodological approach to the problem regarding two main issues.

First, the benefit function expressing benefits in terms of output from using fossil fuels and thus emitting CO_2 is estimated by econometric methods for each group of countries, as long-run equilibrium relationships using cointegration techniques.

Second, in assuming cooperative and noncooperative behaviour among the groups of countries we try to keep as close as possible to the spirit of the theoretical models of global warming by explicitly solving an infinite horizon optimal control problem for the cooperative solution and infinite horizon differential game problems for the noncooperative solution.

We believe that this approach can provide a link between theoretical models of global warming and empirical analysis so that it can be used to test theoretical results. Another advantage of the optimal control formulation of the problem is that since the model is disaggregated, the time paths of the optimal emission taxes can be determined. Furthermore the comparison of the value of the countries' welfare at the cooperative solution and the noncooperative solution can be used to calculate gains or losses from cooperation and thus determine whether side payments are required in order to sustain the cooperative solution.

CONTENTS

1 Introduction

The investigation of issues related to CO_2 accumulation and the appropriate policies in order to reach some desired solution have received extensive attention in the environmental economics literature both at the theoretical and the applied level. At the applied level the investigation started basically with simple calibrations of control models of global warming (e.g. Nordhaus 1982) where the whole world was represented by a single agent. Theoretical advances in disaggregated game theoretic models of global warming have also motivated the analysis of disaggregated empirical models which have been extended to include computable dynamic general equilibrium models or explicit solution of games related to global warming. Closely associated with the disaggregated analysis is the question of whether the social optimum or cooperative solution can be supported by policy instruments or agreements between countries.

Recently Fankhauser and Kverndokk (1996) have provided a solution for a static game of CO_2 emissions, where the players are groups of countries. The authors calculate illustrative estimates of the Nash equilibrium and the social optimum. They conclude that the cooperative solution can be supported by an international agreement that includes side payments to groups of countries that experience a reduction in welfare from moving from the noncooperative to the cooperative equilibrium with respect to CO_2 emissions.

In the same spirit Nordhaus and Yang (1996) have solved a disaggregated regional dynamic general equilibrium model that incorporates climate change (RICE, or regional integrated model of climate and economy). Using the RICE model, dynamic solutions for market, cooperative and noncooperative equilibrium are provided. In the noncooperative equilibrium it is assumed that the emissions of each country or group of countries is invariant to the emission policies of other countries.

The purpose of the present paper is to conduct an empirical investigation of cooperative and noncooperative solutions of global warming using a dynamic disaggregated model of five groups of countries. Our paper differs from previous empirical analyses of the topic in its methodological approach to the problem regarding two main issues.

First, the benefit function expressing benefits in terms of output from using fossil fuels and thus emitting CO_2 is estimated by econometric methods for each group of countries. The advantage of using the econometric approach and not relying on calibration of production functions, is that it is based on objective data which allows therefore a more realistic discrimination of the technological parameters and rates of technical change among the groups as well as the detection of structural breaks in the benefit functions. The benefit functions in our model are estimated as long-run equilibrium relationships using cointegration techniques.

Second, in solving for the cooperative and the noncooperative solution we try to keep as close as possible to the spirit of the theoretical models of global warming by explicitly solving an infinite horizon optimal control problem for the cooperative solution and infinite horizon differential games problems for the noncooperative solution.[1] The importance of using the differential game approach is that it allows us to employ Markov strategies according to which the emissions of each group depend on the actions of the rest of the groups through its dependence on the observed accumulation of CO_2. In this way a more realistic behavior for the groups can be introduced as compared to the case where groups take the actions of the other groups as given, since the assumption that the emissions of a group is invariant to the emissions of the rest can be justified in cases of small countries. However it certainly does not seem realistic when countries are aggregated as groups that are assumed to have the political will to act as a single agent regarding their emissions. In this case it is more realistic to assume that they condition their actions on the actions of the rest. Since the actions of the rest are reflected in the observed accumulation of CO_2 the assumption of Markov strategies employed in this paper seems to be a realistic representation.

The attempt to solve a differential game problem with Markov strategies undoubtedly creates a number of computational problems, furthermore our approach does not take explicitly into account the interrelations in the world economy. We believe however that this approach can provide a link between theoretical models of global warming and empirical analysis so that it can be used to test theoretical results. Another advantage of the optimal control formulation of the problem is that since the model is disaggregated, the costate variables of the differential game can be used together with the costate variable of the cooperative problem to determine the time paths of the optimal emission taxes. Furthermore the comparison of the value of the countries' welfare at the cooperative solution and the noncooperative solution can be used to calculate gains or losses from cooperation and thus determine whether side payments are required in order to sustain the cooperative solution.

2 Estimating Benefit and Damage Functions

The concept of the benefit function is used to estimate the benefits associated with CO_2 emissions which are generated by the combustion of fossil fuels used

[1] See for example van der Ploeg and de Zeeuw (1992), Hoel (1992), Xepapadeas (1995), Farzin and Tahvonen (1995).

in production activities. This function is regarded as a long-run equilibrium relationship and relates the total product produced in a country during a certain time period - the Gross Domestic Product (GDP) - with the emissions of CO_2 which are generated during the production of the aggregate output, as a by-product of production.

The following form is assumed for the benefit function:

$$Y_i(t) = B_i(E_i(t), t) \tag{1}$$

where Y_i denotes GDP and accounts for the benefits, E_i denotes CO_2 emissions, and t is assumed to reflect technical change.

The above benefit function is defined on the assumption that CO_2 emissions can be treated as a generalized input in the production of aggregate output, which is an assumption common in analyzing global pollution problems (Welsch 1993; Dockner and Van Long 1993; Hoel and Isaksen 1995; Petrakis and Xepapadeas 1996), and is also justified by the fact that CO_2 emissions are closely connected to the combustion of fossil fuels, which is closely connected to economic activity (Halvorsen et al. 1989).

According to standard economic theory assumptions, the benefit function should have the following properties:

$$\frac{\partial B_i}{\partial E_i} > 0, \quad \frac{\partial B_i}{\partial t} > 0, \quad \frac{\partial^2 B_i}{\partial E_i^2} < 0, \quad \lim_{E_i \longrightarrow 0} \frac{\partial B_i}{\partial E_i} = \infty$$

The benefit function as defined above is used for the estimation of benefits from CO_2 emissions for five groups of countries which represent different world regions. The five groups are defined below.

Group 1: Western Europe. This group includes the following countries: Austria, Belgium, Luxembourg, Denmark, Finland, France, Federal Republic of Germany, West Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Malta, Spain, Netherlands, Norway, Portugal, Sweden, Switzerland, United Kingdom.

Group 2: Latin America & Caribbean.

Group 3: United States & Canada.

Group 4: India.

Group 5: China.

The rest of the world is considered exogenous.

The data series for GDP and CO_2 cover the period 1952-1992 for the first three groups and the period 1960-1992 for the last two. The GDP time series are expressed in millions of international dollars while the CO_2 time series in thousand tons of carbon. The analytical description of the formulation of the two series is presented in Xepapadeas and Yiannaka (1997).

As has been mentioned above, equation (1) should be regarded as a long-run equilibrium benefit function. We believe that this is a more appropriate way to analyze problems with a large time horizon, like the global warming problem, given the inefficiency of a short run benefit function which would reflect only short-term adjustments towards equilibrium. To estimate such a long-run equilibrium relationship, the concept of cointegration is used (Phillips and Loretan 1991; Banerjee et al. 1993). Cointegration can be regarded as the empirical manifestation of a long-run relationship between variables that are known to be non-stationary. Since many, if not most, economic series are not stationary but integrated, tests for the order of integration must be conducted. But when integrated series are concerned conventional test statistics are a poor guide as to whether relationships exist among them. It is only if variables are cointegrated that regressions of one series on another will not be spurious. Thus when dealing with economic series that are known to be integrated, tests for cointegration must also be conducted.

Two conditions must hold in order for cointegration to exist. The first is that the series have to be integrated of the same order, and the second is that there must be some linear combination of the data series which is stationary, that is, integrated of order zero $I(0)$. This linear combination is the residual from a static ordinary least squares regression of one series on another. This regression is known as the cointegrating regression.

In order to describe the long-run benefit function in our model, and for the sake of simplicity, we let y_t denote $\ln(\text{GDP})_t$, and E_t denote $\ln(\text{CO2})_t$. The functional form for the equilibrium relationship expressing the benefit function for any group of countries is thus assumed to be linear in logarithms, and is given by the following functional form:

$$y_t = a + bE_t + gt + \varepsilon_t, \ t = 1, ..., T \tag{2}$$

where (y_t, e_t) are assumed to be integrated processes of order one, $I(1)$, and the error term is assumed to be integrated of order zero, $I(0)$. In this model the parameters a and b describe a hyperplane towards which the vector process (y_t, e_t) tends over time. The linear trend can be interpreted as reflecting technical change.

Following the standard approach the Augmented Dickey Fuller (ADF) unit root test is used, to check for the stationarity and the order of integration of the two series, ln(GDP) and $\ln(CO_2)$, of all five groups. It was found that all series are integrated of order one $I(1)$. The results of the test are presented in table 1.

Table 1. ADF test for a unit root on the levels and on the first differences of the series ln(GDP) and ln(CO_2)

GROUPS	ln(GDP)		ln(CO_2)	
	ADF stat. lev.	ADF stat.1st diff.	ADF stat.lev.	ADF stat.1st diff.
1	-0.209471 **	-4.770107 *	-2.542745 **	-4.129486 *
2	-0.198574 **	-3.634017 **	-1.209400 **	-5.712381 *
3	-1.150617 **	-4.750704 *	-1.031687 **	-4.661005 *
3	-1.280352 **	-5.397248 *	-1.14170 **	-5.90103 *
3	-0.710693 **	-3.916989 **	-3.430098 **	-5.890066 *

Large negative values of the statistic reject the null hypothesis

* refers to 1% critical level using MacKinnon critical values for rejection of hypothesis of a unit root

** refers to 5% critical level using MacKinnon critical values for rejection of hypothesis of a unit root

The first condition for cointegration is fulfilled, so in testing for the existence of a cointegrating relationship of the form (2), the error term should be integrated of order zero. The standard methods are residual based and test the null hypothesis of no cointegration against the alternative, that the variables are cointegrated. Thus the standard ADF unit root test is performed on the errors obtained by ordinary least squares (OLS) estimation of relationship (2), which tests the null hypothesis of no cointegration against the alternative of cointegration. According to the above analysis though, the cointegrating vector that results from the estimation of (2) is assumed to be time invariant. However there is a probability that there is structural variance or a structural break in the model. Gregory et al. (1996) have shown that in the presence of a structural break the power of the conventional ADF test falls sharply. So a case exists where the model is indeed cointegrated but the standard ADF test may not reject the null hypothesis due to a structural break in the cointegrating vector. In this case the researcher will falsely conclude that there is no long-run relationship, while in fact one exists (Gregory and Hansen 1996).

Considering the above we consider a test for parameter stability useful. For this reason the ADF* test of Gregory and Hansen (1996) is applied, which tests the null hypothesis of no cointegration against the alternative of cointegration which allows for a one-time regime shift of unknown timing. This must be considered as a pre-test for cointegration which can contribute to a correct model specification since rejection of the null hypothesis provides evidence in favor of the specification of the model with a regime shift. The structural break can be reflected in changes in the intercept, the slope of the cointegrating equation or in both. In this case cointegration can be taken as holding for some fairly long period of time and then shifting to a new long-run relationship. We consider the case where the structural break, if it takes place, can be analyzed in a model that allows for a change in the intercept, which is interpreted as the efficiency parameter of the benefit function, while the slope coefficient indicating the elasticity of CO_2 emissions is held constant. This is a level shift model with a trend which is given as follows:

$$y_{ti} = \alpha_i + \alpha^*_{1_i} D_{it} + b^*_i e_{it} + g^*_i t + \varepsilon_t \ , \ t = 1, ..., t_T \text{, for all groups } i \qquad (3)$$

where D_{it} is a dummy variable which takes the following values depending on the timing of the break:

$$D_{it} = \begin{cases} = 0 \text{ if } t \leq \tau_1 \\ = 1 \text{ if } t > \tau_1 \end{cases}$$

The ADF* statistics indicated that the null of no cointegration should be rejected for groups 1, 2, and 4, in favor of the alternative which allows for a break in the cointegrating vector. The ADF* statistic did not provide evidence in favor of the specification (3) for the groups 3 and 5, which means that there is no indication that a structural break took place in those groups during the period under analysis. The results of the ADF* test are presented in table 2.

Table 2. Structural breaks according to the ADF* test

GROUP	TIMING OF THE BREAK
1	1986
2	1973
3	no break detected
4	1987
5	no break detected

Given the above results and using model (2) to describe the benefit function for groups 3 and 5, and model (3) for groups 1, 2 and 4, we applied the standard ADF unit root test on the errors obtained by OLS estimation of relationships (2) and (3). The results indicated that all series in all groups are cointegrated, and they are presented in table 3.

Table 3. Test for cointegration using ADF test on the residuals of relationships (2) and (3

GROUPS	ADF test statistic
1 (W. Europe)	-4.591976 (-2.6211)*
2 (Latin America)	-3.935791 (-2.6211)*
3 (USA & Canada)	-3.355060 (-2.6261)*
4 (India)	-4.654328 (-2.6369)*
5 (China)	-2.255748 (-1.9521)**

MacKinnon critical values for rejection of hypothesis of a unit root are given in parenthesis

* refers to 1% critical level

** refers to 5% critical level

The results of the ADF test indicated that there is a long-run relationship between variables ln(GDP) and ln(CO2) in all groups, either of the form (2) or (3). So the next step is to estimate the cointegrating vector for every group. For this reason Parks' (1992) Canonical Cointegrating Regression Estimators (CCR) are used in addition to the OLS estimators due to the known problems associated with the latter (Phillips and Durlauf 1986). The results are given in table 4.

Table 4. Estimates of the benefit function using OLS and CCR estimators

GROUP	a_i	b_i	D_i	g_i
Group 1				
OLS	5.992243 (12.387)	0.600406 (16.141)	-0.082305 (-7.732)	0.029765 (33.875)
CCR	5.9405 (10.880)	0.6045 (14.376)	-0.0780 (-5.771)	0.02955 (27.934)
Group 2				
OLS	6.413852 (7.212)	0.583946 (7.098)	0.094387 (2.822)	0.016013 (3.988)
CCR	5.6588 (7.041)	0.6519 (8.806)	0.0143 (4.2213)	0.01434 (4.2213)
Group 3				
OLS	8.901171 (24.992)	0.395697 (15.014)	(–)	0.023673 (36.306)
CCR	8.9011 (24.9926)	0.3956 (15.0143)	(–)	0.0236 (36.3064)
Group 4				
OLS	10.92681 (20.606)	0.116398 (2.323)	0.090349 (4.082)	0.033367 (15.924)
CCR	10.954 (19.455)	0.1132 (2.1358)	0.07731 (2.766)	0.03381 (16.94)
Group 5				
OLS	10.668 (7.995)	0.231 (2.213)	(–)	0.0792 (19.291)
CCR	11.028 (13.347)	0.204 (3.176)	(–)	0.0788 (23.087)

t-statistic is given in parentheses

The results in table 4 support the existence of a structural break in groups 1, 2 and 4, since the dummy variables are proven to be significant. In addition the results indicate that exogenous technical change was significant in determining GDP. Moreover the elasticity of CO_2 emissions is less than one, indicating strictly concave benefit functions, which is in accordance with the theoretical models. Given the above results the benefit function for each group, using CCR estimators, is defined as:

- Group1: $Y(t) = (351.602)E(t)^{0.6045}\exp(0.02955t)$
- Group2: $Y(t) = (290.935)E(t)^{0.6519}\exp(0.01434t)$

- Group3: $Y(t) = (7340.56)E(t)^{0.395697}\exp(0.023673t)$
- Group4: $Y(t) = (61778.45)E(t)^{0.113214}\exp(0.03381t)$
- Group5: $Y(t) = (61574.309)E(t)^{0.201}\exp(0.0788t)$

In order to specify damages from global warming, we use the form of the damage function specified in Xepapadeas and Yiannaka (1997).[2] This damage function is a function of the climatic change, which is in turn a function of the concentration of CO_2, and takes the form:

$$D_i = D_i(T(t), t)\ ,\ \frac{\partial D}{\partial T} > 0\ ,\ T(t) = T(M(t))$$

where $T(t)$ is the increase in the average global temperature due to greenhouse warming above its preindustrial level, and $M(t)$ is anthropogenic atmospheric concentration of CO_2, above its preindustrial level.

The estimation of such a damage function requires the description of a relationship between CO_2 emissions and the climate development. We follow Nordhaus (1991) and take into account the temperature adjustment process, because the average climate responds slowly to the increase in radiative inputs. A simplified two-box diffusion model is used.

$$\begin{aligned} \dot{T}(t) &= \sigma\left[\lambda h(M(t) - T(t)\right] & (4)\\ \dot{M}(t) &= \beta E(t) - \delta M(t) & (5) \end{aligned}$$

where $E(t)$ is anthropogenic emissions of CO_2, $E(t) = \sum_{i=1}^{n} E_i(t)$, for the $i = 1, ..., n$ groups of countries, σ is the delay parameter of temperature in response to radiative increase (per year) ($\sigma = 0.025$), β is the fraction of CO_2 equivalent emissions that enter the atmosphere ($\beta = 0.64$), δ is the rate of removal of CO_2 equivalent emissions from the atmosphere (per year) ($\delta = 0.0083$ representing residence time of 120 years) and λ is a factor of proportionality between radiative forcing and the long-run temperature response, δ is set at 0.75 which means that an increase in radiative forcing of 1W/m2 gives a long-run temperature increase equal to 0.75 degrees (Celsius). This relation is based on the "best estimate" of climate sensitivity to radiative forcing as given in Houghton et al. (1992),[3] $h(M)$ is the increase in radiative forcing from CO_2 since its preindustrial level (measured in W/m2). The h function for CO_2 takes the form $6.3\ln\left(\frac{M}{M_p}\right)$, where M_p is

[2]For the definition of this type of damage function see Hoel and Isaksen (1995).
[3]For the values of these parameters see also Nordhaus (1992), Hoel and Isaksen (1995).

the atmospheric concentration of CO_2 in pre-industrial time (Wigley 1987, IPCC-I 1990). For the present time the ratio $\frac{M}{M_p}$ is set to 1.25 (Cline 1991).

Following Hoel and Isaksen (1995), the damage can be specified as:

$$D_i\left(T(t),t\right) = A_i\left(T(t)\right)^{\alpha}\exp(\theta t) \tag{6}$$

where α is the curvature of the damage function for climate change, which is set to 1.5 across all groups to allow for convexity in the damage function, θ expresses how the monetary damage of a climatic change develops over time for a constant climate in a specific country. The value of A_i , in global models of greenhouse damages, taken together with α=1.5 means that a temperature increase of 3 degrees is assumed to account for damages of x% of the world GDP. So to find the value A will take we first need to specify the value of x. There have been different estimates of the value of x starting with 0.25% (Nordhaus 1991) and reaching values in excess of 2.4% (Ayres and Walter 1991). We use the assumption of an intermediate value of $x = 1\%$. We then determine group A_i by taking the ratio A_i/A to be the same as the group's GDP to the world GDP.

Solution of differential equation (4) determines the evolution of emissions as a function of the CO_2 concentration as:

$$T(t) = T(0) = e^{-\sigma\tau} + \sigma\lambda\int_0^t e^{-\sigma(t-\tau)}h\left(M(\tau)\right)d\tau \tag{7}$$

Then the damage function can be written as a function of the CO_2 concentration alone.

The benefit and the damage functions defined in this section can be used to determine time paths for the evolution of the CO_2 concentration and the temperature corresponding to cooperative and noncooperative solutions.

3 Cooperative Solution

As is well known, the cooperative solution in the dynamic context corresponds to the solution of an optimal control problem where the objective is to maximize the sum of benefits less the sum of damages subject to the constraints imposed by the evolution of the CO_2 concentration and the temperature. Since however the temperature can be expressed as a function of the CO_2 concentration, only one state variable, M, needs to be included in the model. At this stage we consider an autonomous optimal control problem where the cooperative solution corresponds to the problem:

$$\max_{\{E_i(t)\ldots E_i(t)\}} \int_0^{\infty} e^{-rt} \sum_{i=1}^{n} \left[B_i\left(E_i(t)\right) - D_i\left(T(t)\right)\right] dt,\ n = 5 \tag{8}$$

subject to

$$\dot{M}(t) = \beta E(t) - \delta M(t)\ ,\ M(0) = M_o \tag{8.1}$$

$$T(t) = T(0) = e^{-\sigma\tau} + \sigma\lambda \int_0^t e^{-\sigma(t-\tau)} h\left(M(\tau)\right) d\tau\ ,\ T(0) = T_o \tag{8.2}$$

The above problem can be solved using the maximum principle as is common in this type of problem. The current value Hamiltonian function is defined as:

$$H = \sum_{i=1}^{n} \left[B_i\left(E_i(t)\right) - D_i\left(T(t)\right)\right] + \phi\left[\beta E(t) - \delta M(t)\right] \tag{9}$$

The conditions of the maximum principle imply that along the optimal path $\{E_i^*(t), M^*(t)\}$ the following conditions hold:

$$\frac{\partial H(t)}{\partial E_i} = B_i'\left(E_i^*(t)\right) + \phi\beta = 0\ ,\ E_i^*(t) > 0 \tag{10.1}$$

$$\dot{\phi}(t) = r\phi(t) - \frac{\partial H(t)}{\partial M} \text{ at } \{E_i^*(t), M^*(t)\} \tag{10.2}$$

$$\dot{M}(t) = \beta E^*(t) - \delta M^*(t)\ ,\ M(0) = M_o \tag{10.3}$$

$$\lim_{t\to\infty} e^{-rt}\phi(t) = 0\ ,\ \text{transversality condition} \tag{10.4}$$

The optimality conditions (10.1)-(10.4) can be used as a basis for the numerical solution for the cooperative path in the next section.

In order to be able to use an autonomous control problem though which the steady state long-run equilibrium values for the CO_2 accumulation and the temperature can be studied, the benefit functions estimated in the previous section should be modified appropriately. Thus we consider a common rate of technical change, g, for all groups defined as a weighted average of the individual rates which weights the proportion of each group GDP in the total GDP. Furthermore we assume that the parameter θ, expressing how the monetary damage of a climatic change develops over time for a constant climate in a specific country, can be approximated by g. Thus net benefits can be defined, omitting t to simplify notation, as:

$$e^{gt} \sum_{i=1}^{n} \left[a_i E_i^{b_i} - A_i T^{\alpha}\right]$$

Two more simplifications are undertaken in order to make sure that the solution to the optimal control problem can be obtained in a way that will provide useful information about the steady state of the system its stability properties and the properties' time paths towards the steady state. First the damage function is substituted by its linear approximation around the initial average global temperature $T_o = 15$ so that

$$D_i(t) = A_i T_o + \alpha A_i T_o^{\alpha-1} (T(t) - T_o)$$

with $T(t)$ given by (8.2).

Second in order to ensure the concavity of the problem the $h(M)$ function, which is concave as a logarithmic function, needs to be substituted by a convex approximation around the current concentration of CO_2. Otherwise the net befit function for the control problem is not concave. Thus $h(M)$ is substituted by

$$h(M) \approx 6.3 \left[\ln \left(\frac{M_o}{M_p} \right) + \frac{1}{M_o} (M(t) - M_o) + \frac{1}{2M_o^2} (M(t) - M_o)^2 \right]$$

where $M_p = 6\text{GtCarbon} \times 10^2$ and $M_o = 7.5\text{GtCarbon} \times 10^2$.

Given the above specifications, optimal short-run emissions along the cooperative path are determined through (10.1) as:

$$E_i^c(t) = \left(\frac{-\phi(t)\beta}{b_i a_i} \right)^{\frac{1}{b_i - 1}} \tag{11}$$

The evolution of the CO_2 concentration, M, and its shadow cost, ϕ, are now determined by the system of differential equations

$$\begin{aligned} \dot{\phi} &= (\omega + \delta)\phi + \left(\alpha A T_o^{\alpha-1} \right) \left(6.3\sigma\lambda \left[\frac{1}{M_o} + \frac{1}{M_o^2} (M - M_o) \right] \right) && (12.1) \\ \omega &= r - g \,,\; r = 0.05 \,,\; g = 0.035 && \\ \dot{M} &= \beta \sum_{i=1}^{n} E_i^c - \delta M && (12.2) \end{aligned}$$

Differential equations (12.1), (12.2) determine the Modified Hamiltonian Dynamic System. The steady state long-run equilibrium for M and ϕ is determined by the solution of the system (12.1) and (12.2) for $\dot{\phi} = \dot{M} = 0$. The solution of this system is:

$$\phi_\infty = -215555 \,,\; M_\infty^c = 6.60005$$

This solution corresponds to concentration of CO_2 at an intermediate value between the preindustrial and the current concentration and a steady state cost of approximately 215$/ton of Carbon. The steady state equilibrium has the saddle point property since the eigenvalues of the linearized Jacobian of the MHDS around the equilibrium point are: $\{v_1 = 0.0295009, v_2 = -0.0145009\}$.[4] Thus a one-dimensional manifold exists along which the system converges to the long-run steady state equilibrium.[5] The time paths for M and λ along the stable manifold are determined as:[6]

$$
\begin{aligned}
M(t) &= 0.900049e^{-0.0145009} + 6.6005 \\
\phi(t) &= 18118.86835e^{-0.0145009} - 215555
\end{aligned}
$$

The evolution of M and ϕ along the stable manifold that converges to the equilibrium point is shown in figures 1 and 2.

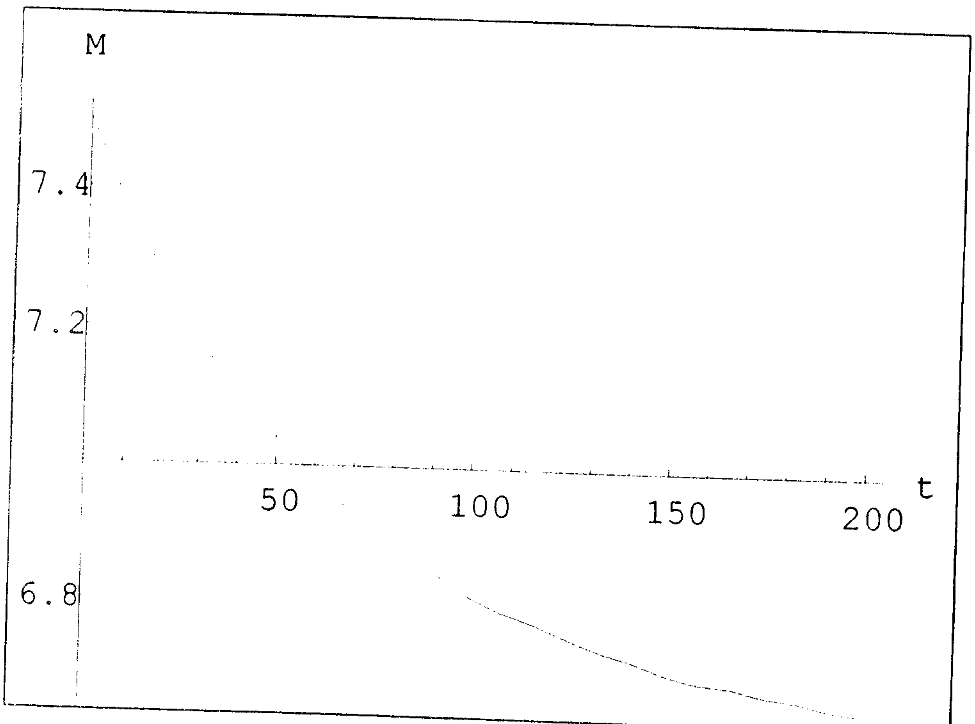

Figure 1: Evolution of CO_2 concentration

[4]All solutions and diagrams have been obtained using Mathematica 3.0 (1996).

[5]The equilibrium point is simple since the the eigenvalues of the linearized Jacobian are nonzero. Thus the linearization theorem of Hartman and Grobman can be used in order to study the behavior of the MHDS in the neigborhood of the equilibrium point using the linarized MHDS.

[6]These paths correspond to the negative (stable) characteristic root. The corresponding characteristic vector is $\{-1.0\ ,\ 0.0000496747\}$. The constant of the solution is dermined by the initial condition $M(0) = M_o = 7.5$ and the terminal condition $M^c_\infty = 6.60005$.

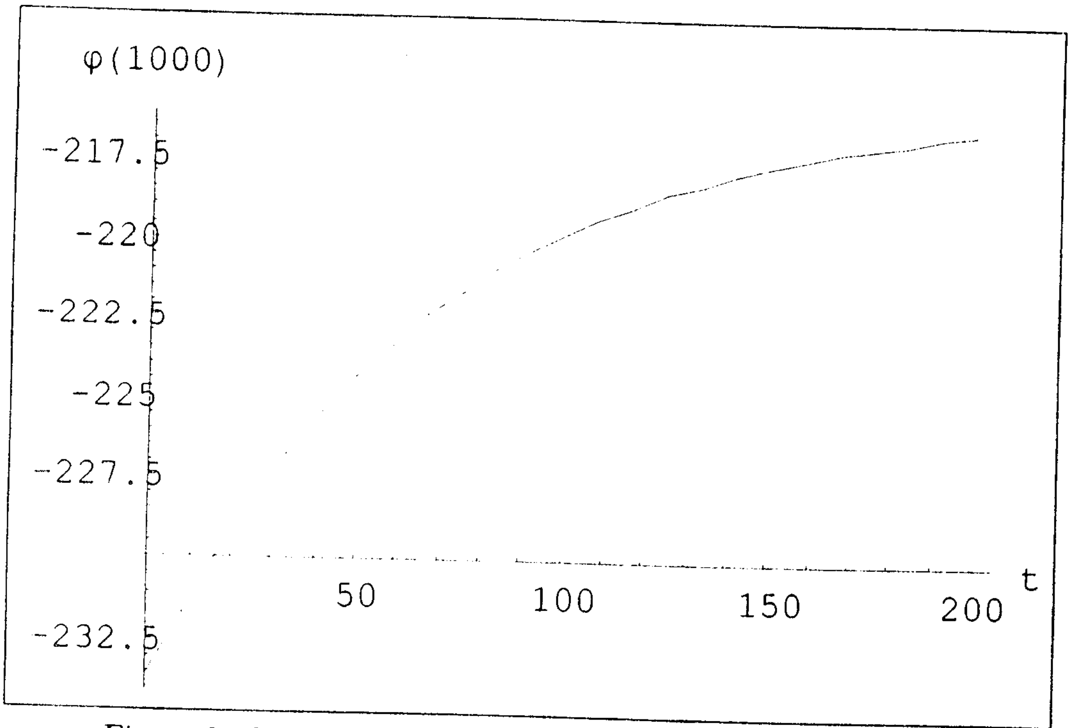

Figure 2: Evolution of the shadow cost of CO_2 concentration

It is well known that the shadow cost of CO_2 can be used as an optimal emission tax when the potential polluters do not take into account damages from global warming and they just maximize their benefits subject to any capacity constraints. In this case the optimal path for the carbon tax $\tau(t)$ is defined as $\tau(t) = -\lambda(t)$. As shown in figure 2 the optimal carbon tax is declining, a result which is in accordance with previous results in this area (e.g. Farzin and Tahvonen 1995). The evolution of the global temperature is obtained by substituting the solution for $M(t)$ into (8.2). This is shown in figure 3.

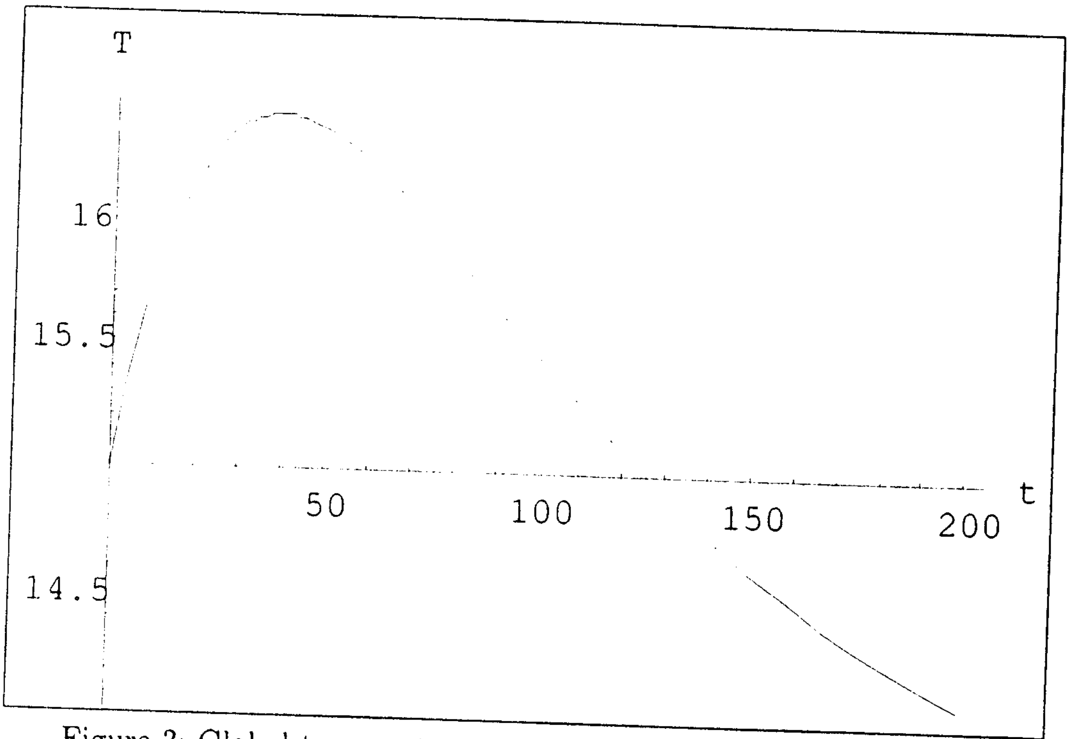

Figure 3: Global temperature evolution at the cooperative solution

It should be noted that at the beginning of the time horizon, global temperature increase slightly, that is $T(100) = 15.471$ and then it declines steadily.

4 Noncooperative Solution

The noncooperative solution is modelled in the context of a differential game with feedback information structure, where individual emissions depend on current accumulation of CO_2. Under the feedback information structure the equilibrium solution is that of the feedback Nash equilibrium (FBNE) The FBNE is a strongly time consistent solution in the sense of possessing the property of subgame perfectness (Basar and Olsder 1982; Fershtman 1987;Basar 1989). To analyze the FBNE it is assumed that each group uses linear Markov strategies (e.g. Xepapadeas 1992; Dockner and van Long 1993; Xepapadeas 1995) determined as:

$$E_i(t) = \overline{E}_i(t) - sM(t) \text{ , } s > 0 \tag{13}$$

This strategy implies that a group will reduce its emissions if the concentration of CO_2 increases.[7] For $s = 0$ we have an open loop information

[7]In analyzing both the cooperative and the noncooperative solution it is assumed that the groups can, through some type of political process, achieve a common policy within the group regarding CO_2 emissions.

structure which, as is known, is somewhat unrealistic since it implies an infinite period of commitment. Under the feedback information structure the problem for each group is to maximize its own net welfare subject to (8.1), (8.2) and (13). The current value Hamiltonian for group i, given the specification of the functions adopted above, is determined as:

$$\begin{aligned} H_i &= A_i E_i^{b_i} - \left[A_i T_o^{\alpha} - \alpha A_i T_o^{\alpha-1}(T - T_o)\right] + \\ & \phi_i \left[\beta \left(E_i + \sum_{j \neq i}^{n} (\overline{E}_j - sM\right) - \delta M\right] \\ i &= 1, \ldots, 5 \end{aligned}$$

Optimal noncooperative emissions in the short run are determined as

$$E_i^N(t) = \left(\frac{-\phi_i(t)\beta}{b_i a_i}\right)^{\frac{1}{b_i - 1}}, \; i = 1, \ldots, 5 \tag{14}$$

while the evolution of the shadow cost of the CO_2 for each group and the evolution of the accumulated CO_2 are determined as:

$$\begin{aligned} \dot{\phi}_i &= \left(\omega_i + \delta + (n-1)6.3\sigma\lambda\left[\frac{1}{M_o} + \frac{1}{M_o^2}(M - M_o)\right]\right)\phi_i \\ &+ \left(\alpha A T_o^{\alpha-1}\right)\left(6.3\sigma\lambda\left[\frac{1}{M_o} + \frac{1}{M_o^2}(M - M_o)\right]\right) \qquad (15.1) \\ \omega_i &= r - g_i \; , \; i = 1, \ldots, 5 \\ \dot{M} &= \beta \sum_{i=1}^{n} E_i^N - \delta M \qquad (15.2) \end{aligned}$$

The MHDS in the case of the noncooperative equilibrium consists of six differential equations. The steady state long-run equilibrium is determined as the point at which $\dot{\phi}_1 = \ldots = \dot{\phi}_5 = \dot{M} = 0$. The equilibrium point depends however on the feedback parameter s. In table 5 we have calculated long-run equilibrium points for a number of possible values for s.

Table 5. Long-run equilibrium for different values of s

s	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	M
0	-232235	-109797	-283387	-17846	-84501	87.5
-0.1	-231148	-105065	-282042	-17771	-74501	88.09
-0.5	-226848	-102280	-275959	-17475	-51490	90.31
-1	-221559	-98791	-268556	-17707	-37064	93.17

The above results are in accordance with the theoretical results obtained in previous studies (van der Ploeg and de Zeeuw 1992; Xepapadeas 1995). The concentration of CO_2 at the noncooperative equilibrium exceeds the concentration at the cooperative equilibrium, and the concentration at the FBNE exceeds the open loop case corresponding to $s = 0$. Thus the use by the countries of feedback strategies will deteriorate the situation regarding the concentration of CO_2. The eigenvalues of the linearized Jacobian of the MHDS are:

$$\left(\begin{array}{c} u_1 = 0.105381 \ , \ u_2 = 0.0927688 \ , \ u_3 = 0.0869005 \ , \ u_4 = 0.0775588 \\ u_5 = -0.0166809 \ , \ u_6 = 0.0120422 \end{array} \right)$$

There is one negative eigenvalue implying the existence of a one-dimensional manifold converging to equilibrium.. Since the equilibrium point is simple the linearization theorem can be used again to study the behavior the system along the stable manifold.[8]. The evolution of M and ϕ_i, $i = 1, ..., 5$ along this stable manifold is shown in figures 4-9.

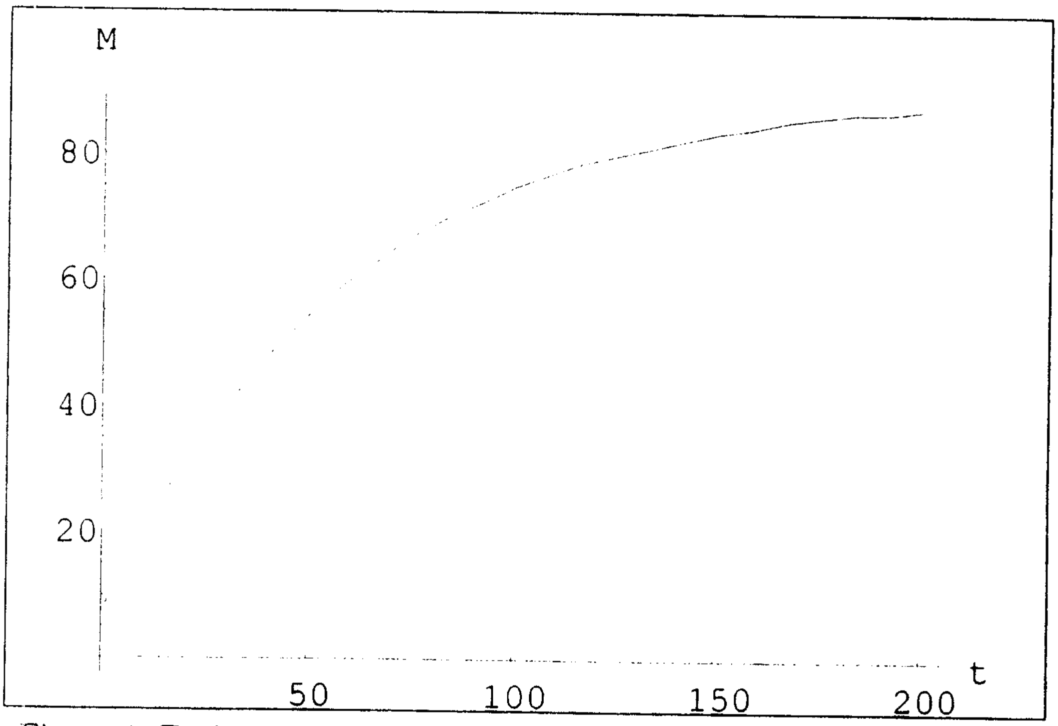

Figure 4: Evolution of CO_2 concentration at the noncooperative solution

[8]These paths correspond to the negative (stable) characteristic root. The corresponding characteristic vector is $\{0.56599, 0.24489, 0.67893, 0.044003, 0.39596, -0.00028071\}$. The constant of the solution is dermined by the initial condition $M(0) = M_o = 7.5$ and the terminal condition $M_\infty^N = 90.3$.

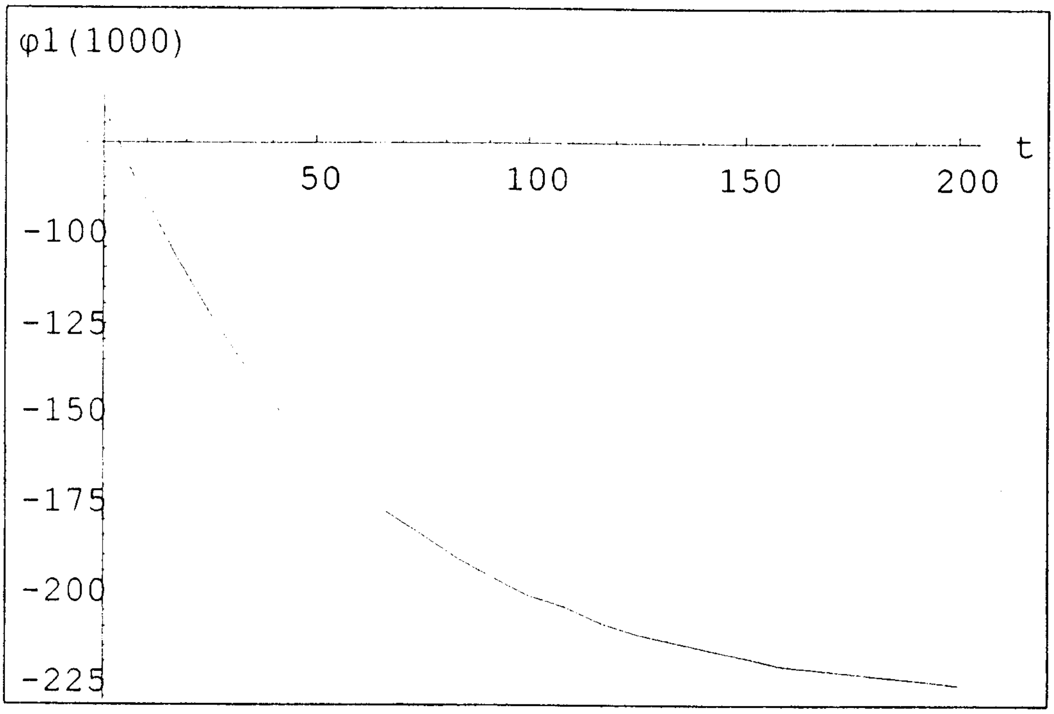

Figure 5: Evolution of ϕ_1

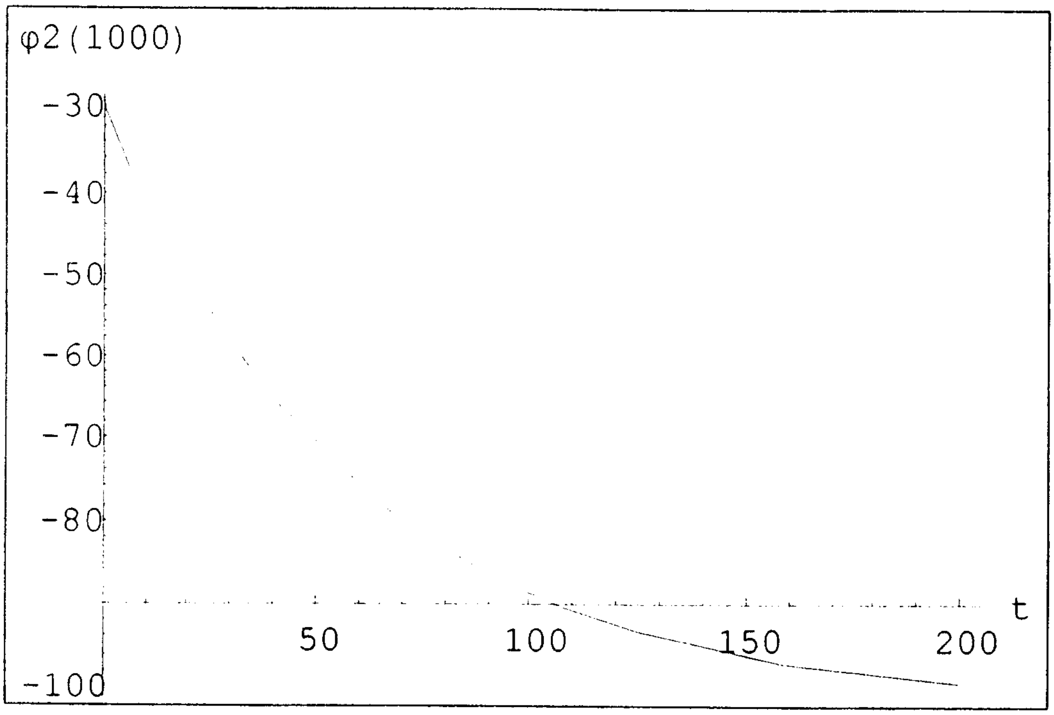

Figure 6: Evolution of ϕ_2

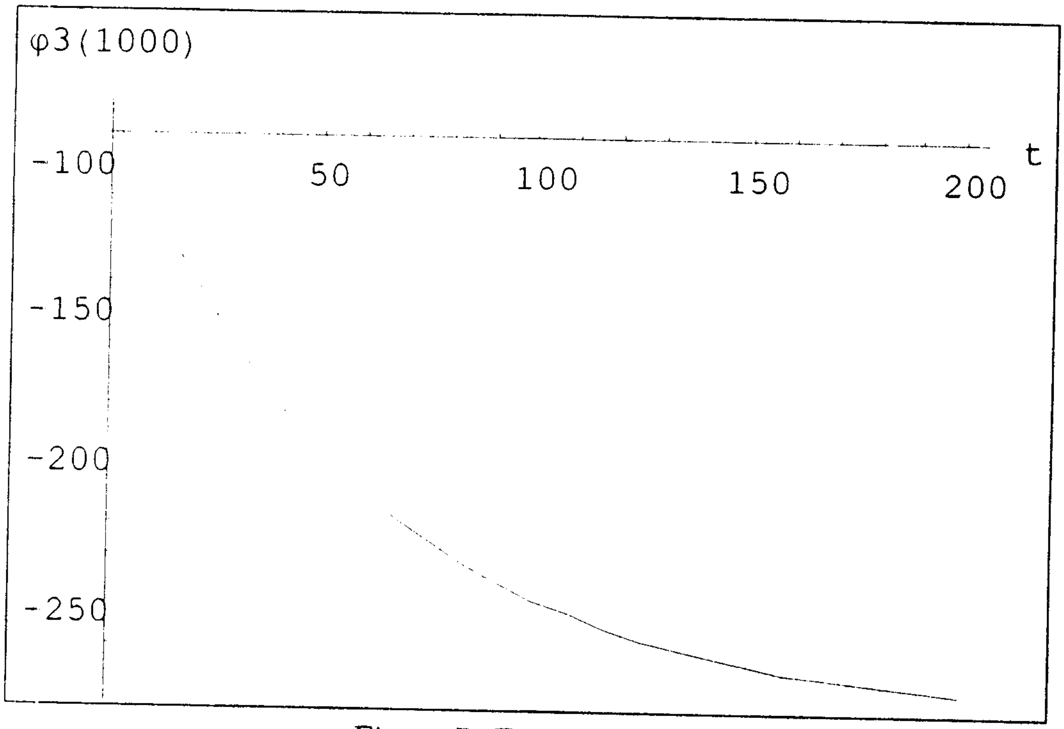

Figure 7: Evolution of ϕ_3

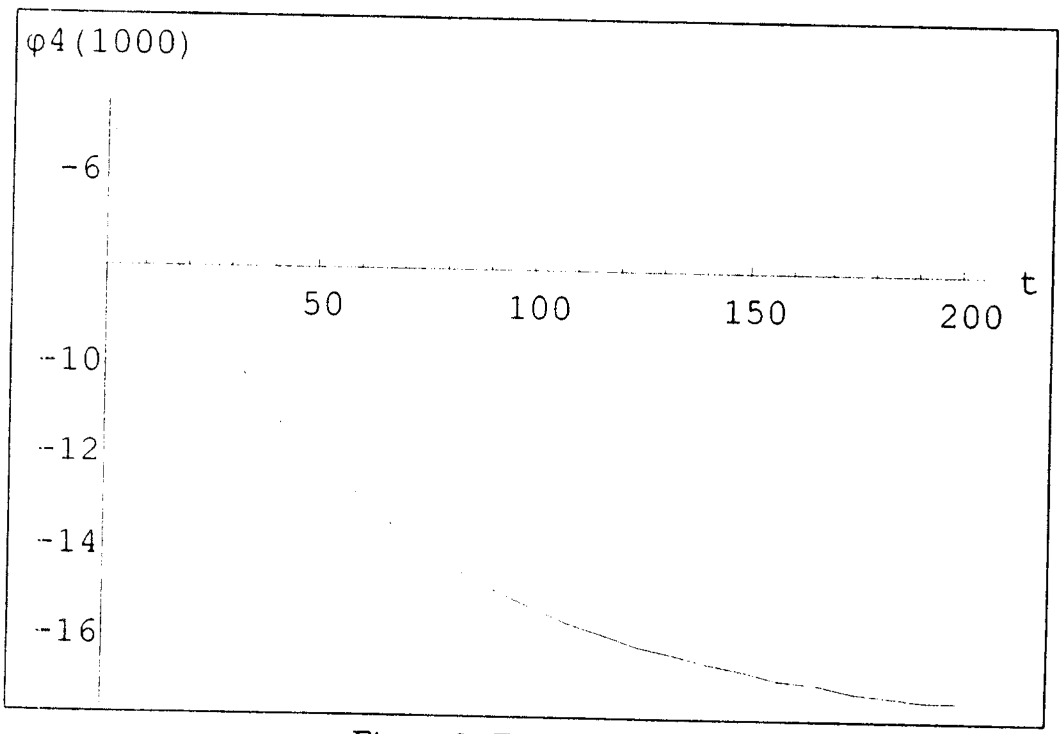

Figure 8: Evolution of ϕ_4

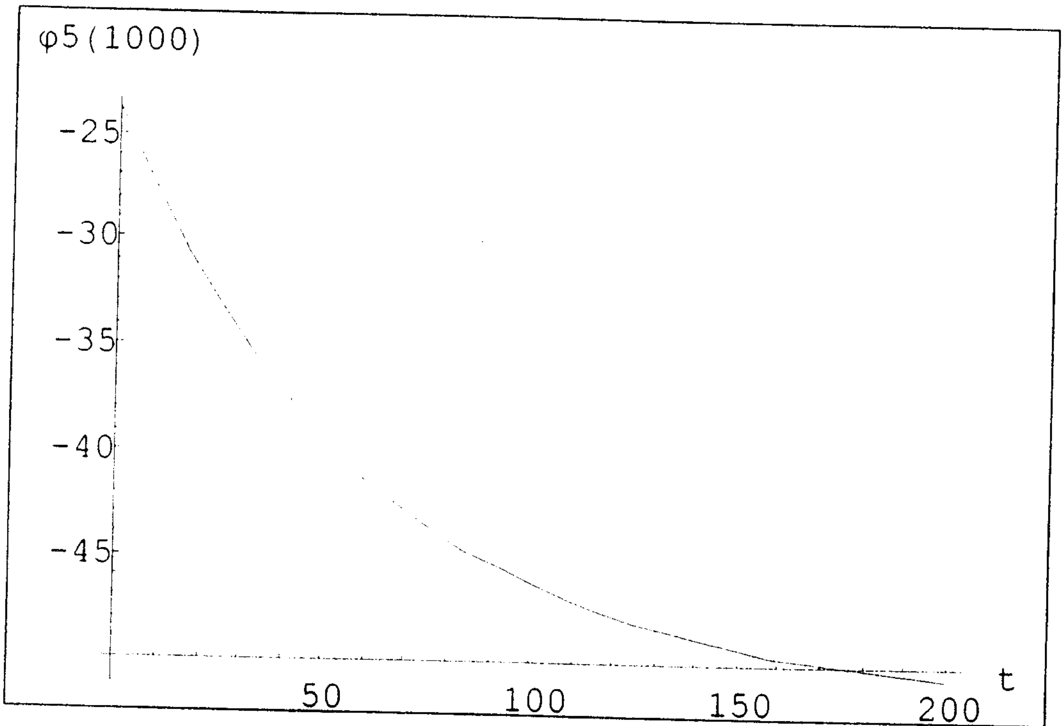

Figure 9: Evolution of ϕ_5

The evolution of the global temperature is obtained as before and is shown in figure 10.

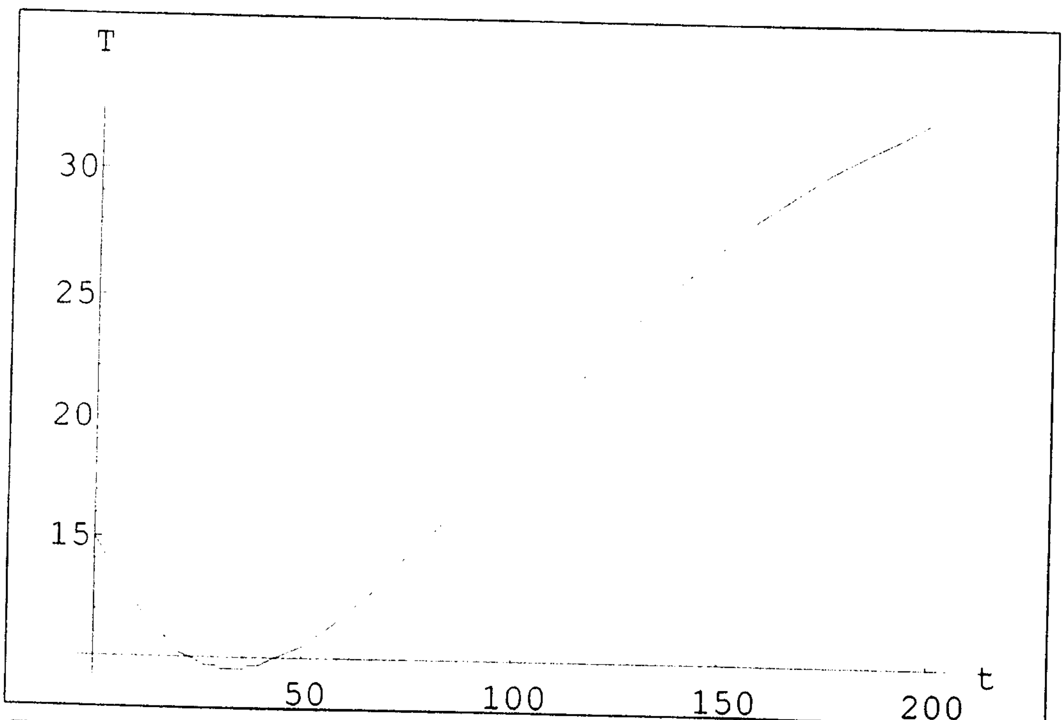

Figure 10: Evolution of global temperature at the noncooperative solution

The evolution of temperature indicates that there is a slight decrease at the beginning but then temperature increases monotonically. In 100 years the forecasted temperature increase is 3.9 degrees.

5 Policy Issues

The basic policy issue in this type of problem is whether the cooperative solution can be supported. When comparing total welfare for each group at the optimal emission paths corresponding to the cooperative and noncooperative solution we find that in all cases the cooperative welfare exceeds noncooperative welfare substantially, with the exception of groups 4 and 5 where cooperative welfare exceeds noncooperative welfare by 3.1% and 5.2% respectively. Thus there are substantial gains from cooperation. In choosing the policy instruments for achieving the cooperative solution we concentrate on emission taxes. As has been shown (Xepapadeas 1966) the optimal emission tax is determined by the difference between the shadow cost of CO_2 at the cooperative and the noncooperative solution. Thus the optimal carbon tax is determined as:

$$\tau_i(t) = \phi(t) - \phi_i(t) \ , \ i = 1, ..., 5$$

The time paths for the carbon taxes in each group are shown in figure 11.

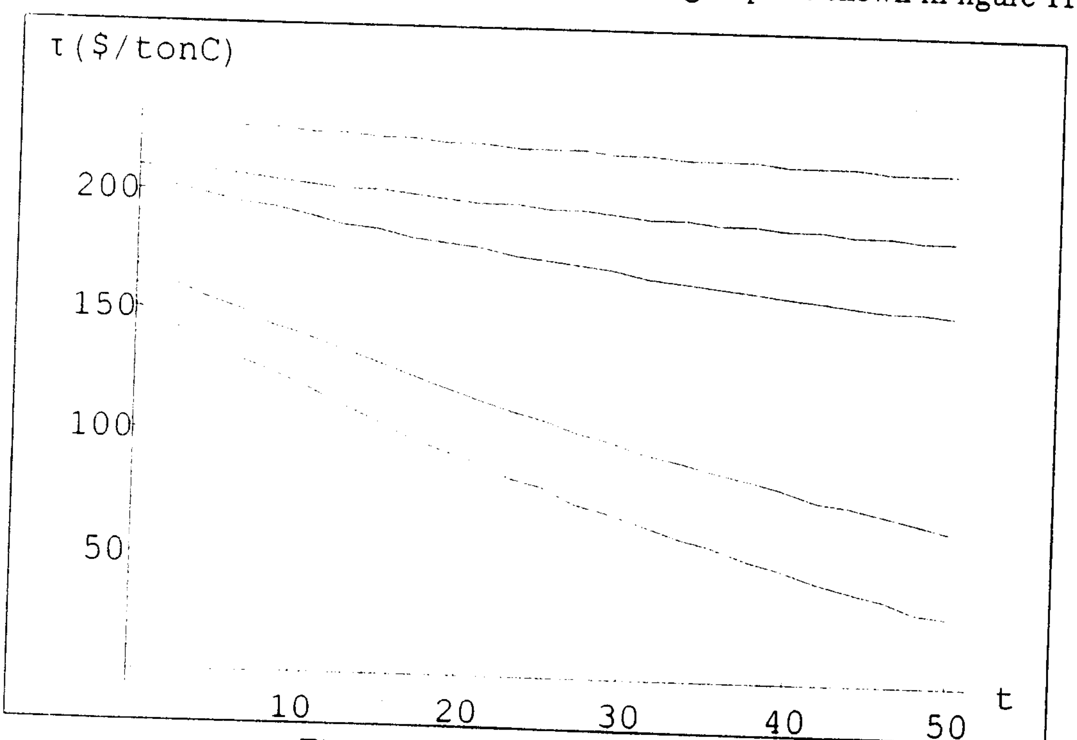

Figure 11: Optimal carbon taxes

The taxes are declining and their sizes are $\tau_4 > \tau_5 > \tau_2 > \tau_1 > \tau_3$ for all $t \in [0, 50]$. It should be noticed that groups 4,5 and 3 pay higher taxes since their shadow cost of CO_2 accumulation is always lower than the corresponding shadow cost of groups 1 and 3.

6 Concluding Remarks

The purpose of this paper was to analyze empirically cooperative and noncooperative solutions in global warming models. By using econometrically estimated benefit functions and disaggregated damage functions for five groups of countries and by making some appropriate simplifications of the functions of the climate sub-model, it was possible to solve for the cooperative and the noncooperative solutions as infinite horizon optimal control and differential games respectively.

The solutions are in agreement with the predictions of the theoretical models. In particular the long-run steady state equilibrium for the cooperative solution exhibits the saddle point property, while the noncooperative steady state is characterized by conditional stability where convergence is obtained along a one-dimensional manifold. The steady state accumulation of CO_2 increases as we move from the cooperative solution to the open loop Nash equilibrium and consequently increases even further as we move to the FBNE, as predicted by theoretical models.

Welfare at the cooperative solution substantially exceeds welfare at the noncooperative solution in groups 1 to 3. In groups 4 and 5 the cooperative solution again exceeds welfare at the noncooperative solution, but only by a small amount. This might imply that given the sensitivity of the solution to changes in the parameters, side payments might be required in order for groups 4 and 5 to enter some agreement to reduce emissions. This also implies that if emission taxes are used to achieve the cooperative solution these groups will have to face higher taxes.

The empirical model presented here can be improved in many directions. Longer time series of data will improve the estimates of the benefit functions especially for groups 4 and 5. Also better data will allow estimates of benefit functions for the rest of the world which is now treated as exogenous, especially for the countries of Eastern Europe and the Former Soviet Union. The results can also be improved by better approximations of the damage functions and especially the damages associated with the 3^o rise in temperature. In the absence of any other information the parameters for the Markov strategies have to be assumed, but different values can be used in order to examine the sensitivity of the solution to parameter changes. Another issue of future research is the impact of nonlinear Markov strategies. It has been shown by Dockner and van Long (1993) that the cooperative solution can be supported by nonlinear Markov strategies. If the structure of such a strategy can be determined, then the cooperative solution can be obtained as the outcome of a selfish welfare maximization by each group of countries.

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(xv) Paper presented at the Human Capital and Mobility Program "Designing Economic Policy for Management of Natural Resources and the Environment" Second Workshop FEEM, GRETA, University of Crete, Venice, May 12-13, 1995

(xvi) Paper presented at the International Workshop on "The Political Economy of Economic Policy - The Organization of Government" European Science Foundation and Fondazione Eni Enrico Mattei, Castelgandolfo (Rome), September 5-10, 1995

(xvii) This paper was presented at the Workshop on "Corporate Governance and Property Rights" organized by the Corporate Governance Network and by Fondazione Eni Enrico Mattei, Milan, 16-17 June 1995

(xviii) This paper was presented at the International Workshop on "Creation and Transfer of Knowledge: Institutions and Incentives" organized by the Fondazione Eni Enrico Mattei and the Beijer International Institute of Ecological Economics, Castelgandolfo (Rome), September 21-23, 1995

(xix) This paper was presented at the International Workshop on "Environment and Transport in Economic Modelling" organized by the Department of Economics - Ca' Foscari University, Venice for the "Progetto Finalizzato Trasporti 2" CNR and in cooperation with Fondazione Eni Enrico Mattei, Venice, November 9-10, 1995

(xx) This paper was presented at the Conference on "Technology, Employment and Labour Markets" organized by the Athens University of Economics and Business and Fondazione Eni Enrico Mattei, Athens, May 16-18, 1996

(xxi) This paper was presented at the Conference on "Applications of Environmental Accounting", sponsored by the Fondazione Eni Enrico Mattei and the State Science and Technology Commission of the People's Republic of China, Beijing China, March 11-13, 1996

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(xxiii) This paper was presented at the Conference on "The Economics and Law of Voluntary Approaches in Environmental Policy", Fondazione Eni Enrico Mattei and CERNA (Ecole des Mines de Paris), Venice, November 18-19, 1996

(xxiv) This paper was presented at the Conference on "Pressure Groups, Self-Regulation and Enforcement Mechanisms", Fondazione Eni Enrico Mattei, Milan, January 10-11, 1997

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