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A COUPLED CONSTRAINT GAME MODEL OF INTERNATIONAL CLIMATE POLICY

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A Coupled Constraint Game Model of International Climate Policy [1]

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Abstract

This paper proposes a dynamic-game theoretic model for the international negotiations that should take place to agree on a global mitigation scheme when the real extent of climate change due to anthropogenic emissions is known. The model assumes a non-cooperative behavior of the parties except for the fact that they will be collectively committed to reach a target on total cumulative emissions by the year 2050. The concept of normalized equilibrium, introduced by J.B. Rosen for concave games with coupled constraints, is used to characterize a family of dynamic equilibrium solutions in an m-player game where the agents are groups of countries and the payoffs are the welfare gains evaluated through a Computable General Equilibrium (CGE) model. The equilibrium is computed by implementing an oracle-based optimization method using the implicit definition of the payoffs to the different players obtained in simulations performed with the global CGE model GEMINI-E3. The simulation runs and the manifold of equilibria obtained when the weighting of players varies are discussed and interpreted in economic terms.

Key words: Climate change negotiations, dynamic game model, coupled constraints, general equilibrium modeling.

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Contents

1 Introduction

In this paper we use a computational economics approach to assess the strategic interactions of different groups of countries when they will have to decide on the way to stabilize the long term global greenhouse gases (GHG) concentration in the atmosphere. More precisely we develop a dynamic game model where the strategies of each player (a group of countries) refer to a schedule of emission quotas and the payoffs are obtained in terms of welfare gain (or loss) evaluated through a Computable General Equilibrium (CGE) model in which an international market for emission permits is represented. In addition, a coupled constraint is imposed on all players together to limit the total emissions over the whole planning horizon. We explore the manifold of normalized equilibria, a noncooperative solution concept to be elucidated shortly, that is obtained when one varies the weighting given to the different players in a global combined payoff. This game theoretic approach sheds a new light on the possible terms of the post Kyoto negotiations on climate change and the role that developing countries could have to play in long term climate change mitigation policies.

Provision of global public goods such as climate change mitigation are voluntary since countries can be invited but not forced to contribute to the global reduction of GHG emissions. In other words, international climate agreements must be *self-enforcing*. This condition has often been interpreted as a requirement for a policy that is a Nash equilibrium in a non-cooperative game for the nations involved in the climate negotiation process. For example several authors have used game theoretic paradigms to study incentives based on *issues linkages* consisting in exchanging concessions across different policy dimensions. Multilateral cooperation across different issues gives the possibility to form agreements and to enforce them. Several authors have proposed to link international climate agreements to international trade (e.g. Barrett (1997, 1999)), technology R&D and technology diffusion (e.g. Carraro and Siniscalco (1996); Katsoulacos (1996); Tol et al. (2000)) or sustainable development and greening development assistance (e.g. Beg et al. (2002); Toman (2002)).

In this paper we explore the possibility to build self-enforcing agreements on a schedule of emission caps for the different parties corresponding to different world regions. For that purpose we do not introduce the issue-linkage approach but we directly propose a dynamic game model for the international negotiations that will take place to share the burden of stabilizing in the long run the global GHG concentration in the atmosphere. The model assumes a non-cooperative behavior of the parties except for the fact that they will be collectively committed to reach a target on total cumulative emissions by the year 2050. The concept of normalized equilibrium is used to characterize a family of dynamic equilibrium solutions in an m-player game where the agents are (groups of) countries and the payoffs are the welfare gains obtained from economic activities, including trading of goods and emission permits. A coupled constraint is introduced to represent the needed global emissions abatement.

The dynamic game structure corresponds to the nature of the global climate challenge. As stated in the United Nations Framework Convention on Climate Change (UNFCCC), the ultimate goal is the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic human induced interference with the climate”. Based on the assessment of climate impacts of global mean temperature rise, scientists confirm previous reports that, globally aggregated, the danger level begins once global mean temperature rises 2°C above preindustrial levels. Our understanding of the sensitivity of the climate system to radiative forcing means that the GHG concentration should be stabilized at no more than 550 parts per million by volume (ppm). Achieving this target is a major challenge that will require a participation of large developing countries since they constitute an important potential source of GHG emissions in the future. As said in a recent EU paper, “An effective future multilateral climate change regime will require all major emitters to contribute by limiting or reducing their greenhouse gas emissions. Without the participation of other developed countries and key emitters among developing countries, substantial cuts in EU emissions alone will fail to achieve the 2°C target” (EC (2005)).

Different groups of countries have thus to agree on the long term GHG concentration target that should be reached collectively. Given this common target each (group of) nation’s respective contribution to the international effort will be guided by its own interest, if the agreement has to be self-enforcing. The battle against global warming is thus a mixture of cooperative (attainment of a common goal) and non-cooperative (economic selfishness) behavior. In that context, international emission trading might be used as a mean to reduce the economic costs of the emission constraint, and to create incentives for participation through financial transfers. Once the global goal is defined the degrees of freedom left to the players reside in the level and timing of their abatement commitments. The normalized equilibrium concept finds a solution associated with a weighting of the different players. For example if one increases the weight given to DCs, the share of burden for these nations in satisfying the global constraint is reduced and the sequence of abatement is obtained as a best reply to the decisions made by other (groups of) countries. Therefore, in addition to the global aim dictated by the climate dynamics, the negotiation will also have to decide the weighting given to the different groups of nations that will be parties in the agreement. In this paper we compute the manifold of normalized equilibria when we consider only 3 groups of nations, USA, rest of OECD, DCs, and when one varies the weighting given to these players in the equilibrium definition. The model used is a two-level dynamic game where governments try to get the best agreement for their respective economy knowing that, once quotas are fixed, the economic agents will be confronted to market competition for GHG emission quotas. This structure is very close to the one proposed by Helm (2003) and Carbone et al. (2003) who also use a two-level game approach to analyze emission quotas markets. However the major difference with these works comes from the type of equilibrium that we characterize. Whereas in Helm (2003) and Carbone et al. (2003) each player has a specific willingness to pay for abatement and a normal Nash equilibrium is looked for, in our model a common goal is imposed on all the players and then a normalized equilibrium is obtained. The use of normalized equilibria to deal with competition under a global environmental constraint has been first advocated in Haurie (1995) and Haurie and Zaccour (1995). It has been further used for local pollution models in Haurie and Krawczyk (1997), and Krawczyk (2005). In a companion paper by Haurie et al. (2005) we have used this concept in a multi-country optimal growth model where the only traded goods are the emission permits. In the present paper we apply the concept to a more encompassing economic model with a full representation of international trade and fiscal effects. For this modeling framework, the available numerical methods for computing equilibria used by Krawczyk and Uryasev (2000) could not be applied since the welfare gains are obtained from simulations done on a world CGE model. We have thus implemented an oracle-based optimization technique to compute the normalized equilibria from information provided by simulation runs.

The paper is organized as follows: the structure of the coupled game model is presented in section 2; in section 3, we briefly present the multi-sector and multi-country CGE model of the world economy that is used for numerical simulations; the Analytic Center Cutting Plane Method (ACCPM) implemented to solve the weak variational inequality problem is described in section 4; in section 5 we describe the results obtained for a case study where countries have to decide on their own abatement level under a global target on cumulative GHG emissions by 2050 which is consistent with a commitment to limit global temperature rise to 2 degrees Celsius above pre-industrial levels; sensitivity analysis is provided in section 6 and, in section 7, we conclude.

2 The model

2.1 Players, moves and payoffs

The game is played over T periods. M is a set of m groups of countries hereafter called *players* which must decide on the caps they impose on their respective global emissions of GHGs in each period. We denote $\bar{e}_j(t)$ the cap decided by player j for period $t = 1, ..., T$. A global limit $\bar{E}$ will be imposed on the cumulative emissions over the time horizon T. Therefore the following constraints are imposed on all players together

$$\sum_{j \in M} \sum_{t=1}^{T} \bar{e}_j(t) \leq \bar{E}. \tag{1}$$

Let $\bar{\mathbf{e}}(t) = \{\bar{e}_j(t)\}_{j \in M}$ denote the vector of caps decided for all players in period t. The result of a global economic m-country equilibrium defines a welfare gain for each player, hereafter called its payoff at t and denoted $W_j(\bar{\mathbf{e}}(t))$. Given a choice of moves $\bar{\mathbf{e}} = \{\bar{\mathbf{e}}(t)| : t = 1, ..., T\}$ also called an *emissions program* the total payoff to player j is given by

$$J_j(\bar{\mathbf{e}}) = \sum_{t=1}^{T} \beta^{t-1} W_j(\bar{\mathbf{e}}(t)) \quad j \in M. \tag{2}$$

where β is a common discount factor.

2.2 Normalized equilibrium solutions

We assume that the players behave in a noncooperative way but are bound to satisfy the global cumulative emissions constraints (1) that are consistent with a long term GHG concentration target. We therefore use the *normalized equilibrium* solution concept as proposed by Rosen (1965) to deal with concave m-player games when coupled constraints are linking the decisions of all players. We call $\mathcal{E}$ the set of emissions $\bar{\mathbf{e}}$ that satisfy the constraints (1). We denote $[\bar{\mathbf{e}}^{*-j}, \bar{e}_j]$ the emissions program obtained from $\bar{\mathbf{e}}^*$ by replacing only the emissions program $\bar{e}_j^*$ of player j by $\bar{e}_j$.

Definition 1 The emissions program $\bar{\mathbf{e}}^*$ is an equilibrium under the coupled constraints (1) if the following holds for each player $j \in M$

$$\bar{\mathbf{e}}^* \in \mathcal{E} \tag{3}$$

$$J_j(\bar{\mathbf{e}}^*) \geq J_j([\bar{\mathbf{e}}^{*-j}, \bar{e}_j]) \quad \forall \bar{e}_j \ s.t. \ [\bar{\mathbf{e}}^{*-j}, \bar{e}_j] \in \mathcal{E}. \tag{4}$$

Therefore, in this equilibrium, each player replies optimally to the emissions programs chosen by the other players, under the constraint that the global cumulative emission limits must be respected.

It is possible to characterize a class of such equilibria through a fixed point condition for a best reply mapping defined as follows. Let $\mathbf{r} = (r_j)_{j \in M}$ with

$r_j > 0$ and $\sum_{j \in M} r_j = 1$ be a given weighting of the different players. Then introduce the combined response function

$$\theta(\bar{\mathbf{e}}^*, \bar{\mathbf{e}}; \mathbf{r}) = \sum_{j \in M} r_j J_j([\bar{\mathbf{e}}^{*-j}, \bar{e}_j]). \tag{5}$$

It is easy to verify that, if $\bar{\mathbf{e}}^*$ satisfies the fixed point condition

$$\theta(\bar{\mathbf{e}}^*, \bar{\mathbf{e}}^*; \mathbf{r}) = \max_{\bar{\mathbf{e}} \in \mathcal{E}} \theta(\bar{\mathbf{e}}^*, \bar{\mathbf{e}}; \mathbf{r}), \tag{6}$$

then it is an equilibrium under the coupled constraint.

Definition 2 The emissions program $\bar{\mathbf{e}}^*$ is a normalized equilibrium if it satisfies (6) for a weighting $\mathbf{r}$ and a combined response function defined as in (5).

The RHS of (6) defines an optimization problem under constraint. Assuming the required regularity we can introduce a Kuhn-Tucker (K-T) multiplier λ^o for the constraint $\sum_{t=1}^{T} \bar{e}_j(t) \leq \bar{E}$ and form the Lagrangian

$$L = \theta(\bar{\mathbf{e}}^*, \bar{\mathbf{e}}; \mathbf{r}) + \lambda^o(\bar{E} - \sum_{j \in M} \sum_{t=1}^{T} \bar{e}_j(t)). \tag{7}$$

Therefore, by applying the standard K-T optimality conditions we can see that the normalized equilibrium is also the Nash equilibrium solution for an auxiliary game with a payoff function defined for each player j by

$$J_j(\bar{\mathbf{e}}) + \lambda^j(\bar{E} - \sum_{j \in M} \sum_{t=1}^{T} \bar{e}_j(t)), \tag{8}$$

where

$$\lambda^j = \frac{1}{r_j} \lambda^o. \tag{9}$$

This characterization has an interesting interpretation in terms of negotiation for a climate change policy. A common "tax" λ^o is defined and applied to each player with an intensity $\frac{1}{r_j}$ that depends on the weight given to this player in the global response function. Notice that this auxiliary game corresponds to the one proposed by Carbone et al. (2003) if we interprete the coefficients $\frac{1}{r_j}\lambda^o$ as willingness-to-pay indicators. In Carbone et al. (2003), these coefficients are exogenously defined whereas in this model they result from the coupled constraint to satisfy and the relative weight given to the different players.

Rosen has also given conditions, called diagonal strict concavity, on the function $\sum_{j \in M} r_j J_j(\bar{\mathbf{e}})$ which ensure existence and uniqueness of the normalized equilibrium associated with the weighting $\mathbf{r}$. Therefore, under these conditions, we can define a manifold of equilibria outcomes indexed over the set of possible weights $\mathbf{r}$. In general, when its relative weight r_j increases the burden of Player j in satisfying the coupled constraint diminishes and its payoff increases at equilibrium. We see here the relevance of this concept in the assessment of the terms of negotiations between developed and developing countries when the world is confronted with a global limit on cumulated GHG emissions. In the next section we describe how the payoffs of this game are obtained using a computable general equilibrium model.

3 Getting the payoffs via GEMINI-E3

3.1 General overview

The payoffs of the game are computed using GEMINI-E3 which is a dynamic-recursive CGE that represents the world economy in 21 regions and 14 sectors, and incorporates a highly detailed representation of indirect taxation (Bernard and Vielle (1998)). This version of GEMINI-E3 is formulated as a Mixed Complementarity Problem (MCP) using GAMS with the PATH solver (Ferris and Munson (2000); Ferris and Pang (1997)). GEMINI-E3 is built on a comprehensive energy-economy data set, the GTAP-5 database (Hertel (1997)), that expresses a consistent representation of energy markets in physical units as well as a detailed Social Accounting Matrix (SAM) for a large set of countries or regions and bilateral trade flows. It is the fourth GEMINI-E3 version in this succession that has been especially designed to calculate the social marginal abatement costs (MAC), i.e. the welfare loss of a unit increase in pollution abatement (Bernard and Vielle (2003)). The original version of GEMINI-E3 is fully described in Bernard and Vielle (1998) [2]. Updated versions of the model have been used to analyze the implementation of economic instruments for GHG emissions in a second-best setting (Bernard and Vielle (2000)), to assess the strategic allocation of GHG emission allowances in the EU-wide market (Bernard et al. (2005c)) and to analyze the behavior of Russia in the Kyoto Protocol (Bernard et al. (2005a); Bernard et al. (2003)).

For each sector the model computes the demand on the basis of household consumption, government consumption, exports, investment, and intermediate

[2] For a complete description of the model see our web site and the technical document downloadable at: http://ecolu-info.unige.ch/∼nccrwp4/GEMINI-E3/HomeGEMINI.htm.

uses. Total demand is then divided between domestic production and imports, using the Armington assumption (Armington (1969)). Under this convention a domestically produced good is treated as a different commodity from an imported good produced in the same industry. Production technologies are described using nested CES functions.

3.2 Welfare cost

Household's behavior consists in three interdependent decisions: 1) labor supply; 2) savings; and 3) consumption of the different goods and services. In GEMINI-E3, we suppose that labor supply and the rate of saving are exogenously fixed. The utility function corresponds to a Stone-Geary utility function (Stone (1983)) which is written as :

$$u_r = \sum_i \beta_{ir} \cdot ln(HC_{ir} - \phi_{ir}) \tag{10}$$

where HC_{ir} is the household consumption of product i in region r, ϕ_{ir} represents the minimum necessary purchases of good i, and β_{ir} corresponds to the marginal budget share of good i. Maximization under budgetary constraint :

$$HCT_r = \sum_i PC_{ir} \cdot HC_{ir} \tag{11}$$

yields

$$HC_{ir} = \phi_{ir} + \frac{\beta_{ir}}{PC_{ir}} \cdot \left[HCT_r - \sum_k \left(PC_{kr} \cdot \phi_{kr} \right) \right], \tag{12}$$

where PC_{ir} is the price of household consumption for product i in region r.

The welfare cost of climate policies is measured comprehensively by changes in households' welfare since final demand of other institutional sectors is supposed unchanged in scenarios. Measurement of this welfare change is represented by the sum of the change in income and the "Equivalent Variation of Income" (EVI) of the change in prices, according to the classical formula. In the case of a Stone-Geary utility function, the EVI for a change from an initial situation defined by the price system ($\overline{PC}_{ir}$) to a final situation (PC_{ir}) is such as

$$\frac{\overline{HCT}_r - \sum_i \overline{PC}_{ir} \cdot \phi_{ir}}{\Pi_i \left(\overline{PC}_{ir}\right)^{\beta_{ir}}} = \frac{\overline{HCT}_r + EVI_r - \sum_i PC_{ir} \cdot \phi_{ir}}{\Pi_i \left(PC_{ir}\right)^{\beta_{ir}}}. \tag{13}$$

The households' surplus is then given by

$$S_r = \left(HCT_r - \sum_i PC_{ir} \cdot \phi_{ir}\right) - \Pi_i \left(\frac{PC_{ir}}{\overline{PC}_{ir}}\right)^{\beta_{ir}} \left(\overline{HCT}_r - \sum_i \overline{PC}_{ir} \cdot \phi_{ir}\right). \quad (14)$$

In summary, the CGE model associates a welfare gain (cost) for each country and each period, with a given emissions program $\bar{\mathbf{e}}$ which defines caps for all countries at each period. It is important to remind that these welfare gains are obtained under the assumption that an international emissions trading system is put in place.

4 Oracle-based optimization framework

4.1 Normalized equilibrium and variational inequality

For concave games with differentiable payoff functions $J_j(\cdot)$, $\bar{\mathbf{e}}^*$ is a normalized equilibrium if and only if it is a solution of the following variational inequality problem

$$\langle F(\bar{\mathbf{e}}^*), \bar{\mathbf{e}}^* - \bar{\mathbf{e}} \rangle \geq 0 \quad \forall \bar{\mathbf{e}} \in \mathcal{E}, \quad (15)$$

where $\langle \cdot, \cdot \rangle$ denotes the scalar product and the pseudogradient $F(\cdot)$ is defined by

$$F(\bar{\mathbf{e}}) = \begin{pmatrix} r_1 \nabla_{\bar{e}_1} J_1(\bar{\mathbf{e}}) \\ \vdots \\ r_j \nabla_{\bar{e}_j} J_j(\bar{\mathbf{e}}) \\ \vdots \\ r_m \nabla_{\bar{e}_m} J_m(\bar{\mathbf{e}}) \end{pmatrix}. \quad (16)$$

It has been proved in Rosen (1965) that a normalized equilibrium exists if the payoff functions $J_j(\cdot)$ are continuous in $\bar{\mathbf{e}}$ and concave in $\bar{e}_j$ and if $\mathcal{E}$ is compact. In the same reference it is proved also that the normalized equilibrium is unique if the function $-F(\cdot)$ is strictly monotone, *i.e.* if the following holds

$$\langle F(\bar{\mathbf{e}}^2) - F(\bar{\mathbf{e}}^1), \bar{\mathbf{e}}^1 - \bar{\mathbf{e}}^2 \rangle > 0 \quad \forall \bar{\mathbf{e}}^1, \bar{\mathbf{e}}^2 \in \mathcal{E}. \quad (17)$$

We say that $\bar{\mathbf{e}}^*$ is a *weak* solution of the variational inequality problem if it satisfies

$$\langle F(\bar{\mathbf{e}}), \bar{\mathbf{e}}^* - \bar{\mathbf{e}} \rangle \geq 0 \quad \forall \bar{\mathbf{e}} \in \mathcal{E}. \tag{18}$$

If the payoff functions $J_j(\cdot)$ are continuous and if $-F(\cdot)$ is strictly monotone, then weak and (strong) solutions are equivalent. For a detailed discussion relating strong and weak solutions, see Chapter 7 in Nesterov and Nemirovskii (1994).

4.2 An oracle method to solve the variational inequality problem

In the game that has been defined in the previous section, the payoffs are not defined analytically but are revealed by simulation performed via a CGE model. Therefore we had to implement an oracle-based method where at each iteration the CGE model, hereafter called the "oracle" is queried and returns an information consisting of (i) the evaluation of the payoff values and, (ii) the evaluation of the pseudogradient at the query point. Oracle-based methods have been used with success in convex optimization problems. A critical issue in implementing such a method is the choice of the query point at each iteration. The Analytic Center Cutting Plane Method (ACCPM) selects the analytic center of the localization set (which contains the optimal point looked for) as the query point. Each reply of the oracle defines a cutting plane that will reduce the size of the localization set.

It has been shown by Nesterov and Vial (1999) that the weak variational inequality problems can be solved using the Analytic Center Cutting Plane Method (ACCPM). We summarize below our implementation of the ACCPM algorithm:

Step 0 (initialization)
Set $k = 0$ and the localization set $E^0 = \{\bar{\mathbf{e}} \,|\, 0 \leq \bar{e}_i \leq \bar{e}_j^{\max}\}$. Choose $\varepsilon > 0$.
Step 1 (computation of the analytical center)
Find $\bar{\mathbf{e}}^k$ the analytical center of the localization set E^k.
Step 2 (computation of the pseudogradient)
Compute $F(\bar{\mathbf{e}}^k)$.
Step 3 (stopping criterion)
Compute $\phi(\bar{\mathbf{e}}^k) = \max_{\bar{\mathbf{e}} \in \mathcal{E}} \langle F(\bar{\mathbf{e}}), \bar{\mathbf{e}}^k - \bar{\mathbf{e}} \rangle$
IF $\phi(\bar{\mathbf{e}}^k) \leq \varepsilon$ AND $\bar{\mathbf{e}}^k \in \mathcal{E}$ THEN STOP
ELSE GO TO STEP 4.
Step 4 (generation of a cutting plane)
IF $\bar{\mathbf{e}}^k \in \mathcal{E}$ THEN $E^{k+1} = E^k \cap \{\bar{\mathbf{e}} \,|\, \langle F(\bar{\mathbf{e}}^k), \bar{\mathbf{e}} - \bar{\mathbf{e}}^k \rangle \geq 0\}$
ELSE find $\mathrm{proj}(\bar{\mathbf{e}}^k) = \arg\min_{\bar{\mathbf{e}} \in \mathcal{E}} ||\bar{\mathbf{e}} - \bar{\mathbf{e}}^k||$,

$$E^{k+1} = E^k \cap \{\bar{\mathbf{e}} \,|\, \langle \text{proj}(\bar{\mathbf{e}}^k) - \bar{\mathbf{e}}^k, \bar{\mathbf{e}} - \text{proj}(\bar{\mathbf{e}}^k) \rangle \geq 0\}.$$

Increment k and GO TO STEP 1.

In the implementation, we evaluate the pseudogradient at each query point using finite differences.

5 Numerical experiments

5.1 Baseline and policy scenario

The baseline scenario of GEMINI-E3 is calibrated on international sources concerning projections of CO_2 emissions, energy consumption, GDP, and population as provided by the U.S. Department of Energy (2003), the International Energy Agency (2002b; 2002c), the World Bank database, and the United Nations population division, respectively. Non-CO_2 GHG emission projections and MAC curves per region and sector are from the Energy Modeling Forum 21 (Stanford) (Bernard et al. (2005b)).

The policy scenario is built on the assumption that we are collectively committed to stabilize global concentration at no more than 550 parts per million (ppm) CO_2 equivalent (corresponding approximately to a stabilization at 475ppm CO_2 only), in order to limit global temperature rise to 2°C above pre-industrial levels [3]. In our coupled constraint game approach, this GHG concentration target has to be translated into a global target on total cumulative emissions by 2050 (the coupled emission constraint). According to Eickhout et al. (2003), we assume that a global GHG quota of around 480GtC-eq. for the whole 2000-2050 period is consistent with a stabilization at no more than 550 ppm CO_2-eq. in 2100. It is thus supposed that the countries and regions decide unilaterally on their own abatement targets under this coupled emission constraint.

We only consider two periods of commitment of 25 years each (2000-2025 and 2025-2050). It means that countries and regions have to take decisions on their

[3] The risk of exceeding this threshold due to the uncertainties in climate sensitivity is not addressed here. However, as explained in Meinshausen (2000), the risk of “overshooting” 2°C is very high at 550ppm CO_2 equivalent, ranging between 68% and 99% for the different climate sensitivity probability distribution function’s with a mean of 85%. For stabilization at 550ppm CO_2-eq. the risk of overshooting a rise in global mean temperature by 3°C is still substantial, ranging from 21% to 69%. If GHG concentrations were to be stabilized at 450ppm CO_2-eq., then the risk of exceeding 2°C would be lower, in the range of 26% to 78% (mean 47%), but still significant.

own abatement reduction level in 2000 and 2025 [4] [5]. In this "balanced" policy case, the same weighting is *arbitrarily* put on the 3 players (1/3 each). The game has only three players: the United States (USA), the other industrialized countries (IND), and developing countries (SUD). Finally, households surplus (payoffs) computed by GEMINI-E3 are discounted at 3% per year, and the target is supposed to be reached through a global emissions trading system – without any constraint on permits trading (i.e. a "supplementary rule") or strategic market behavior. (see Haurie and Viguier (2003) for a model where strategic behavior is represented for the emissions trading market.)

5.2 Results

As shown in Figure 1, global GHG emissions are expected to be close to 15 GtC-eq. in 2050 in the business-as-usual (BAU) scenario. As said before, if GHG concentrations were to be stabilized at 550ppm CO_2-eq., the global GHG emission quota should be around 480GtC-eq. for the 2000-2050 period of time. Figure 1 presents the global GHG emission trajectory under the *unique* coupled equilibrium obtained when the same weight is put on the three players. The resulting GHG emission profile is characterized by early steep reductions in GHG emissions. Global emissions are reduced progressively compared to the BAU scenario in order to reach 11 GtC-eq in 2050 (30% less than the BAU emissions in 2050). This GHG emission pathway is slightly different from the one obtained in previous studies (Eickhout et al. (2003); Meinshausen (2000)) that include the Kyoto Protocol reductions for the 2000-2012 period. In Eickhout et al. (2003) and Meinshausen (2000), the delay of the global emissions peaking until 2020 impose steeper reductions hereafter. In these studies, stabilizing at 550 ppmv CO2-eq. without overshoot requires stringent action after 2012, and to return to approximately 1990 GHG emission levels by 2050.

Figure 2 depicts the burden sharing obtained when the same weight is put on the three players. Considering the global constraint on GHG emissions by 2050, the USA, the other industrialized economies, and the developing world would be committed to reduce their GHG emissions by -33%, -26%, and -47%, respectively. As shown on the graph, the players do not delay abatement at the equilibrium but decide to progressively reduce their emissions. Given these unilateral decisions on abatement, the GHG price increases smoothly from 108 \$/tC-eq in 2025 to 160 \$/tC-eq in 2050.

[4] Since GEMINI-E3 computes an equilibrium every year, we assume a linear emissions reduction rate for each period of 25 years.

[5] The kyoto Protocol (KP) is not considered in this scenario, and we assume that GHG emissions reductions can be higher (or lower) than the KP targets in the 2000-2012 period.

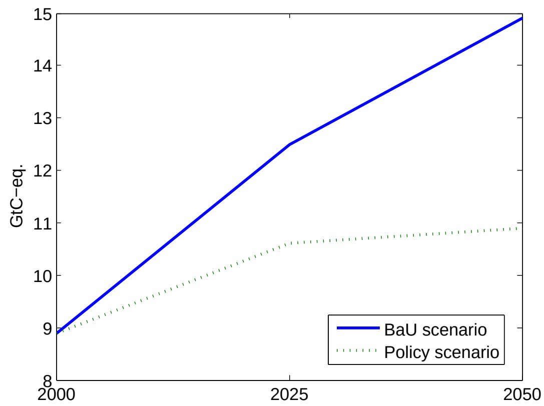

Fig. 1. Baseline and policy-constrained global GHG emissions, 2000-2050 (in GtC-eq)

The emissions schedule shown in Figure 2 might be surprising since welfare costs are discounted (at 3%/year). However, it is relatively easy to explain. GEMINI-E3 is a CGE model where emission reductions are largely obtained through substitutions in consumption and production decisions captured by substitution parameters in CES functions. In this approach, marginal abatement cost curves tend to increase drastically when high reduction rates are required. In this version of GEMINI-E3 (without backstop technologies), marginal abatement cost curves become very steep above a 30% reduction rate.

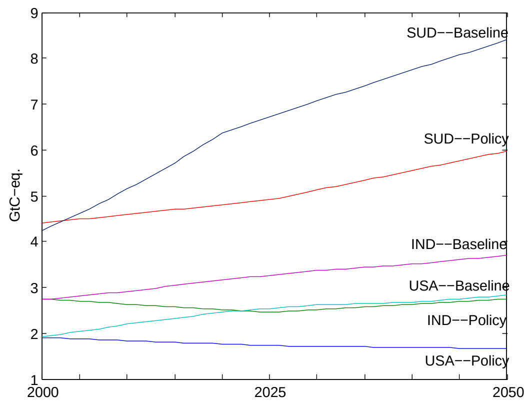

Fig. 2. GHG emission quotas at the coupled equilibrium, 2000-2050 (in MtC-eq)

Figure 3 gives the payoffs of the players at the equilibrium. The payoffs are the total discounted welfare costs associated with the GHG emissions constraint in each region for the whole 50 years. In absolute terms, total costs are almost the same for USA and IND; but the non-cooperative equilibrium is costly for SUD (DCs) which bears 60% of the global welfare cost. In the year 2050, the surplus loss (see definition in section 3) due to the climate policy is around -0.3%, -0.2%, and -0.9% of the total households consumption for USA, IND and SUD, respectively.

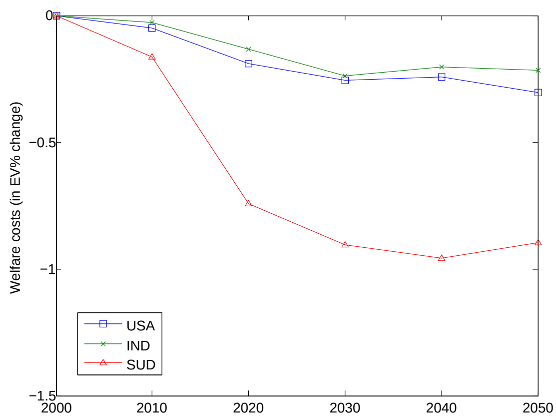

Fig. 3. Welfare costs by region, 2000-2050 (in % change)

5.3 Sensitivity analysis

As explained in Rosen (1965), the unique normalized equilibrium should change with the weighting **r** of the different players. In the previous section the same weight was put on the three players of the game. It is completely arbitrary, and probably a too strong assumption. This weighting might be defined in consistency with distributive justice precludes (Blanchard et al. (2003); Bernard et al. (2005b)). It could be based on population, macro-economic indicators (i.e. GDP, consumption) and/or environmental indicators (i.e. history of GHG emissions). The weighting could also reflect the negotiating power of the players. It is not in the aim of this section to try to define the "right" weighting but to explore how equilibria might change with different weights.

One simple test is to increase the weight of developing countries compared to the "balanced" policy case assessed in the previous section. As expected, this has the effect of reducing the cost of the climate policy for DCs (Figure 4). One can define a weighting that would lead to an equilibrium where DCs do not support any welfare cost. This equilibrium does not correspond to the burden sharing option, advocated in Philibert (2000), Philibert and Pershing (2001), and IEA (2002a) where the baseline emissions are given to the DCs (also called the "non-constraining target" option). It is a situation where the costs of meeting the domestic reduction targets are balanced by the gains associated with the selling of emission permits. Based on GEMINI-E3 estimates, we find that DCs might preserve their welfare growth while accepting a 20% reduction target (compared to their baseline). As shown in Figure 4, DCs are better off when their weight increases above 53%. They might voluntarily accept to

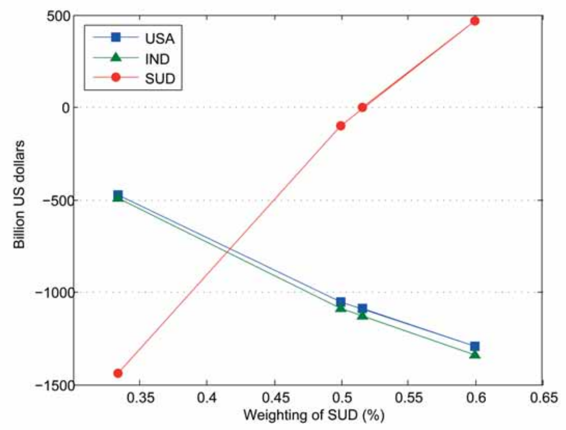

Fig. 4. The impact of changing the relative weight of SUD on discounted welfare costs for USA, IND and SUD, 2000-2050 (in billion USD)

reduce their GHG emissions in order to participate in international emission trading.

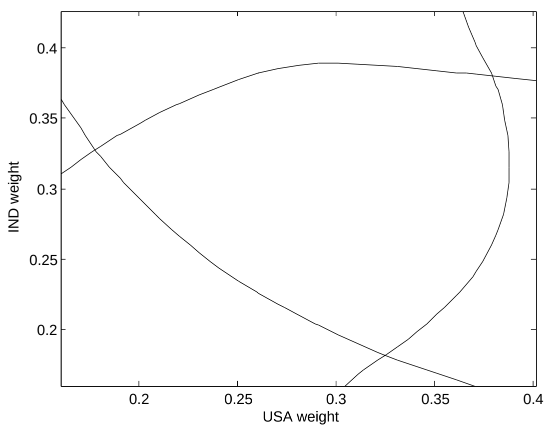

Fig. 5. Set of weights that yield "acceptable" coupled equilibria. The domain inside the curves corresponds to the weights for USA and IND yielding equilibrium payoffs that are not higher than in the BAU case.

In Figure 5 we explore the set of coupled equilibria that can be obtained from changing the weights of the different players. The x-axis represents the weight of the USA whereas the y-axis is for the weight of the other industrialized countries. The weight of DCs does not appear in this graph as the weights of the three players always sum to one. We assume that the players are not allowed to gain from the fight against global climate change. The weights can be changed to create incentive for participation and to define an acceptable allocation of the climate burden but the players are not supposed to be better off with the GHG emissions constraint than without. As depicted in Figure 5, the weights might range from 16% to 38% and 18% to 37% for the United States and the other industrialized countries, respectively. The weight of developing countries might go from 24% to 53%.

The resulting manifold of South (SUD) equilibrium outcomes is shown in Figure 6.

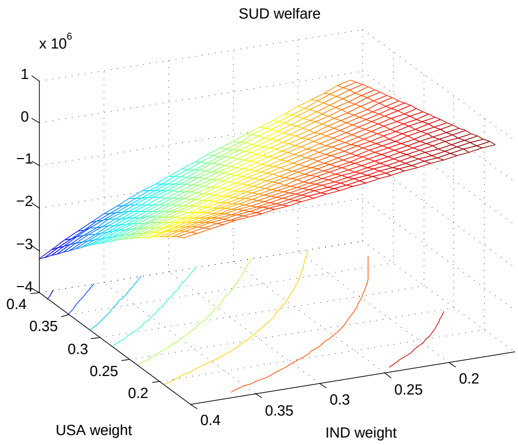

Fig. 6. South (SUD) manifold of equilibrium outcomes, 2000-2050 (in billion USD)

6 Conclusion

In this paper we have proposed a dynamic non-cooperative game model with a coupled constraint as a paradigm for the post-Kyoto negotiations that should take place when one knows the precise climate sensitivity and therefore the need to abate. In such circumstance, the nations will have to decide on abatement policies that achieve a common goal but remain in equilibrium in order to be self-enforcing. This justifies the use of the solution concept called normalized equilibrium by Rosen, which is based on a definition of a weighting of the players that influences their share of the burden in satisfying the common constraint. We have implemented a numerical method, using an oracle-based algorithm to obtain normalized equilibria for a 3-player game where the payoffs are implicitly defined by simulations done with a CGE model. The numerical experiments demonstrate the feasibility of the approach and the types of outcomes that result from this non-cooperative behavior.

In Carbone et al. (2003) the authors observe that the Nash equilibrium solution results in poor environmental performances. Indeed the players having a limited influence on the total emissions, and characterized by different willingness to pay coefficients, do not abate much in an equilibrium solution which is a typical "tragedy of the commons" situation. In the normalized equilibrium solution the players must reach collectively the desired abatement level. Given this objective they play an equilibrium. We claim that this type of solution is adapted to the representation of international negotiations on emissions quotas that will have to take place after Kyoto. We thus propose an alternative two-step negotiation framework on climate change. First, negotiators would have to agree on a long term global GHG concentration target based on current scientific knowledge on tolerable rate of global mean temperature change. Once the global emissions constraint is defined, the negotiators would then agree on a burden distribution of satisfying the coupled constraint. The burden distribution obtained at the equilibrium would result from the common Lagrange multiplier associated with the weighting vector r. The weight given to each country or region would ultimately reflect countries' willingness-to-pay, negotiation power, and/or developing countries' consideration. A global emissions trading system would be implemented for cost-effectiveness concern, and to create incentives for developing countries' participation.

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