# Side payments and international cooperation in a regionalised integrated assessment model for climate change[1]

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# Abstract

Human induced climate change is a global concern but climate impacts and possibilities for greenhouse gases (GHG) emissions reductions exhibit strong regional contrasts. This paper presents a modified version of the economic-climatic RICE model that computes regional temperature changes and discusses the impact of this regionalisation with respect to simulations using the global temperature trend only.

Financial transfers between countries are a possible mechanism to sustain a binding emission reduction international treaty. With respect to other contributions, this study reevaluates the possible gains from a voluntary worldwide coalitionally stable agreement on GHG emissions reductions in the context of a more refined division (in 13 regions) of the world.

The improved geographical representation highlights some contrasted interests to cooperate between countries otherwise aggregated in the "Rest of the World". The regional temperature change representation allows for more emission reductions in all scenarios as greater regional damages appear. In terms of transfers and welfare, the overall picture remains similar to previous results published with this model but greater contrasts appear between the regions considered.

# Introduction

Human induced climate change is a global concern but climate impacts and possibilities for greenhouse gases (GHG) emissions reductions exhibit strong regional contrasts. Indeed, GHG emissions are not evenly distributed and predicted regional climate change impacts vary considerably from one area to another. Some areas could "benefit" from slight changes on their climate, but others could be seriously negatively affected. Moreover, the potential for emissions reductions also differ, in terms of mitigation cost for instance.

Integrated assessment modeling studies attempting to consider regional aspects of the economical cost and climatic impact of GHG emissions reductions have appeared in the recent years (see a.o. Energy Modeling Forum, 1999). In Nordhaus and Boyer (1999, 2000) (RICE98 and RICE99 models), depollution and climate damage cost functions are defined per country or region considered but a single climate variable, the global mean atmosphere temperature, is considered to compute climate damage costs. As a first aim, this study presents a modified version of the RICE98 model that computes regional temperature changes and discusses the impact of this regionalisation with respect to simulations using the global temperature trend only.

On the economical and political side, reaching a global agreement on GHG emission reductions requires that countries (potentially) slightly affected by climate damages could benefit from incentives in order to consent to reduce significantly their GHG emissions. One of the possible mechanisms could be to organize international financial transfers in order to bring all countries to sign a binding emission reduction treaty. In this scope, Eyckmans and Tulkens (1999) have investigated the application of financial transfer mechanisms within the climate change framework using a model that considers six regions. Based on previous theoretical studies (Chander and Tulkens, 1995, 1997; Germain, Toint and Tulkens, 1997) the transfer schemes proposed renders international cooperation not only individually rational but also rational in terms of coalitions, in the sense that no country or group of countries can do better by itself than what it would obtain at the international optimum with transfers.

As an alternative to international cooperation, Eyckmans and Tulkens (1999) consider the non-cooperative Nash equilibrium, where each region defines its emissions taking into account the cost of potential climate damage on itself but not on the other regions. However, with the limited number of regions taken into account (Europe, USA, Japan, China, former Soviet Union and the Rest of the world), one may consider that the regionalisation of the world is too coarse, in particular in the case of the "Rest of the world" region. The second aim of this study is to reexamine the results from these authors using a model that considers 13 regions in order to reevaluate the possible gains from cooperation and the benefits from financial transfers that could bring the regions towards a worldwide voluntary agreement on GHG emissions reductions.

This paper is organized as follows: the first section describes the IAM used. A Ramsey type optimization model based on RICE98 (Nordhaus and Boyer, 1999) provides the economic component. The climatic component uses a single equation for the global temperature evolution and Global Circulation Model (GCM) outputs to compute regional temperature variations. Section 2 describes the four cases investigated. The first one is the international optimum (IO) where countries are supposed to internalize the impact of climatic change in an optimal way. The second case is the business as usual (BAU) scenario where no mitigation measure is taken. The third case simulates the Nash equilibrium (NE) where each country considers the climate damages on itself only and the last case is an intermediate possibility between IO and NE where a coalition of regions jointly define their decision variables in order to maximize the coalition's objective. All of these scenarios are computed with a system of non-linear equations (based on first order optimality conditions) that allows to compute the economies trajectory. Section 3 presents and discusses the results for each scenario. Section 4 applies the transfer function from Eyckmans and Tulkens (1999) in our model. The results confirm that such transfers make the international optimum scenario not only individually rational but also rational in the sense of coalitions. In section 5, we first proceed to a sensitivity analysis of the results to changes in the time horizon and to the discount rate. We then compare the results obtained in section 4 with those obtained when the atmospheric temperature is not regionalised. It appears that when temperature is regionalised, abatement of emissions is higher and the average temperature change simulated is smaller. Section 6 summarizes the main results.

# 1 The model

The model is what is called in the literature an *Integrated Assessment Model*, i.e. a model aimed at analyzing climate change from an economic point of view. This model holds in two main parts : an economic model component and a climate model component. The economic component is similar to the RICE-98 model developed by Nordhaus and Boyer (1999) : it is written as a simple optimal growth model à la Ramsey, with economic and climatic constraints. If the economic submodel is close to RICE-98 [1], the climatic submodel is somewhat developed as air-surface temperature are being regionalised.

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[1] With respect to RICE-98, the only difference is that we do not introduce a backstop energy technology supposed to appear during the 21th century and which does not emit $CO_2$.

## 1.1 The economic submodel

We first briefly describe the economic model component[2]. Let $n$ be the number of countries/regions indexed by $i \in \mathcal{N} = \{1, ..., n\}$ and $t$ denote time, with $t \in \mathcal{T} = \{1, ..., t_f\}$ where $t_f$ is the time horizon. The budget constraint of country $i$ at time $t$ can be written as :

$$Y_{it} = C_{it} + I_{it} + [p_t + m_{it}]E_{it} \tag{1.1}$$

where $Y_{it}$ is gross production, $C_{it}$ is consumption, $I_{it}$ is investment and $E_{it}$ is the carbon-energy consumption measured in $CO_2$ emissions. $p_t$ is the world price of carbon-energy defined below (including the Hoteling rent) and $m_{it}$ is the (region-specific) markup on carbon-energy for country $i$.

The production function is written as a Cobb-Douglas production function with three inputs :

$$Y_{it} = D_i(\Delta T_{a_{it}}) A_{it} K_{it}^{\gamma} E_{it}^{\beta_{it}} L_{it}^{1-\gamma-\beta_{it}} \tag{1.2}$$

where $D_i(\Delta T_{a_{it}})$ represents the damage function (see equation (1.6) below), $\Delta T_{a_{it}}$ being the regionalised atmospheric temperature change, $A_{it}$ measures total factor productivity, $K_{it}$ is the capital stock, $L_{it}$ is population (assumed proportional to employment), $\gamma$ and $\beta_{it}$ representing the elasticities of production to capital and carbon-energy, respectively. Capital accumulation is endogenous and is determined by the following familiar equation :

$$K_{it} = [1 - \delta]K_{i,t-1} + I_{i,t-1} \tag{1.3}$$

where $K_{i0}$ is given and $\delta$ is the prescribed depreciation rate of the capital stock $(0 < \delta < 1)$. The supply side of the energy sector is described by:

$$p_t = \xi_1 + \xi_2 \left[\frac{CC_t}{CC^*}\right]^{\xi_3} \tag{1.4}$$

with,

$$CC_t = CC_{t-1} + \sum_{i=1}^{n} E_{i,t-1} \tag{1.5}$$

($CC_0$ being given). World carbon-energy price ($p_t$) is supposed to increase with $CC_t$, the cumulative world extraction of carbon-energy. $\xi_1$, $\xi_2$ and $\xi_3$ are positive parameters. $CC^*$ is a parameter which represents the inflection point beyond which the marginal cost of carbon-energy begins to rise sharply.

The economic submodel includes the specification of a damage function for each country $i$ :

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[2] We refer the interested reader to Nordhaus et Boyer (2000) for more details, in particular concerning how the damage functions are constructed.

$$D_i(\Delta T_{a_{it}}) = \frac{1}{1 + d_{1,i}\Delta T_{a_{it}} + d_{2,i}\Delta T^2_{a_{it}}} \tag{1.6}$$

Damages in country $i$ are written as an inverse quadratic function of $\Delta T_{a_{it}}$, the atmospheric temperature change relative to preindustrial level in country $i$. $d_{1,i}$ and $d_{2,i}$ are exogenous parameters.

## 1.2 The climatic submodel

This component of the model is aimed at representing two fundamental climate processes: (1) the carbon cycle, which in this context is considered as the way anthropogenic carbon emissions modify the atmospheice carbon dioxide concentration. (2) regional temperature change which is chosen as the key variable to illustrate the effect of carbon dioxide concentration changes on the Earth climate.

The carbon cycle is represented with a *pulse* model following Hasselmann and Hasselmann (1996), the global temperature time evolution is computed with a single equation as in Nordhaus and Yang (1996) and regional temperatures are calculated using General Circulation Model outputs following the method introduced in Schlessinger et al. (1997).

## 1.3 The carbon cycle representation

The carbon cycle substitute used here follows Hasselmann and Hasselmann (1996) and consists of a convolution integral which mimics the oceanic uptake of anthropogenic $CO_2$ obtained by the Maier-Reimer and Hasselmann (1987) oceanic general circulation model. For small deviations about a stationary equilibrium state (roughly up to 530 ppm of $CO_2$), the response of the coupled ocean-atmosphere carbon cycle to $CO_2$ input can be summarized in term of a linear impulse function $P_a(t)$ expressed as a superposition of a number of exponentials of different amplitude $A_i$ and relaxation time $\nu_i$.

$$P_a(t) = A_o + \sum_{i=1}^{n} A_i \, e^{-t/\nu_i} \tag{1.7}$$

> where $A_o + \sum_{i=1}^{n} A_i = 1.0$ and $\nu_i$ is the time constant governing the decrease in the fraction $A_i$ of the initially injected $CO_2$. $i$ is defined for four exponential terms.

In equation (1.7), the amplitude $A_o$ represents the asymptotic airborne fraction for the equilibrium response of the ocean-atmosphere system to any finite-duration unit integral input function. The amplitudes $A_i$ may be interpreted as the relative capacity of other reservoirs, which are filled up independently by the atmospheric input at rates characterized by the relaxation time scales $\nu_i$ (Maier-Reimer and Hasselmann, 1987). $A_i$ and $\nu_i$ are given in the parameter list of the appendix.

Based on these Ocean General Circulation Model (OGCM) results, the variation of atmospheric $CO_2$ concentration $C_a$(t) -as a result of an emission perturbation and oceanic uptake of $CO_2$- is computed here as the convolution of the emission function with the pulse response $P_a$(t) of the ocean to an instantaneous injection of $CO_2$ into the atmosphere corresponding to a doubling of the initial $CO_2$ amount.

$$C_a(t) = \int_{t_o}^{t} e(t')\, P_a\, (t - t')\, dt' \; + \; C_a(t_o), \;\; (for \;\; t \; \geq \; t_o) \tag{1.8}$$

The integral is evaluated between time $t_o$ (the supposed preindustrial climate equilibrium) and time $t$ at which the atmospheric concentration is calculated. $e(t)$ represents the rate of $CO_2$ emissions. For stronger emission levels, e.g., producing a four-fold increase in the $CO_2$ concentration, the linear response underestimates the atmospheric concentration predicted by the full model by about 30%. This is due primarily to the nonlinear decrease of solubility of $CO_2$ in sea water with increasing $CO_2$ concentration. Note that the increased storage of $CO_2$ in the terrestrial biosphere through $CO_2$ fertilization and the significantly slower loss of $CO_2$ through sedimentation in the ocean is not included in such a formulation.

## 1.4 Global and regional temperature change representation

As consequences of a global temperature change, regional damages are geographically unevenly distributed on Earth. Therefore and as the economic submodel is regionalised, we present here a simple way to construct a time-dependent geographical distribution of change in climatic quantities due to human activities. Such basic method combines the geographical distribution of equilibrium climate change simulated by an Atmospheric General Circulation/Mixed-Layer Ocean model (AGCM/MLO) (Schlessinger et al, 1997), with the time-dependent change in annual global-mean surface-air temperature simulated by a single equation relating the radiative forcing to the global-mean surface-air temperature.

### 1.4.1 Global transient response

The time dependent change in annual global mean surface air temperature is computed using equations similar to those used by Nordhaus and Yang (1996):

$$\Delta\overline{T_a}(t) = \tau_1 \Delta\overline{T_a}(t-1) + \tau_2 \Delta\overline{T_o}(t-1) + \tau_3 \Delta\overline{F}_{CO_2}(t-1) \tag{1.9}$$

with,

$$\Delta\overline{T_o}(t) = \tau_4\Delta\overline{T_a}(t-1) + (1-\tau_4)\Delta\overline{T_o}(t-1) \tag{1.10}$$

and

$$\Delta F_{CO_2}(t) = \Delta F_{2x}\frac{\ln(C_a(t)/C_0)}{ln(2)} - \overline{F}_{CO_2}(1990) + \overline{F}_{total}(1990) \tag{1.11}$$

where,

> $\Delta\overline{T_a}(t)$ is the change in the atmospheric temperature at time t relative to preindustrial level (assumed year 1765), ($\Delta\overline{T_a}(1990) = 0.5°\mathrm{C}$),
> $\Delta\overline{T_o}(t)$ is the change in the deep ocean temperature at time t relative to preindustrial level, ($\Delta T_o(1990) = 0.1°\mathrm{C}$),
> $\tau_1$, $\tau_2$, $\tau_3$ and $\tau_4$, are fitting parameters given in the appendix,
> $\Delta\overline{F}_{CO_2}(t)$ represents the change in anthropogenic $CO_2$ radiative forcing relative to preindustrial time, ($\Delta\overline{F}_{CO_2}(1990)= 1.514\ \mathrm{Wm}^{-2}$),
> $\Delta\overline{F}_{total}(1990)= 1.117\ \mathrm{Wm}^{-2}$ and represents the total (all greenhouse gases and aerosols) change in radiative forcing in 1990 relative to preindustrial time,
> $\Delta F_{2x} = 4.37\ \mathrm{Wm}^{-2}$ is the radiative forcing predicted for a doubling of the pre-industrial $\mathrm{CO}_2$ concentration (Harvey, 1997),
> $\mathrm{C}_o$ = 279 ppm and represents the preindustrial atmospheric $CO_2$ concentration.

### 1.4.2 Temperature regionalisation

The simple method used here was adapted from Schlesinger et al. (1997). In this method, an Atmospheric General Circulation Model coupled to a Mixed Layer Ocean model is used to simulate at first a reference equilibrium climate with a $CO_2$ concentration of 345 ppmv and then an equilibrium climate simulation for a doubled $CO_2$ concentration. The geographical distributions of experiment-induced equilibrium climate change are calculated for a large number of climatic quantities (e.g., geographical patterns of surface-air temperature, regional radiative forcing, etc.) and normalized by the corresponding change in annual global-mean surface-air temperature. Here we consider surface temperature change as single climate change variable. For each of the thirteen regions considered, the normalized regional temperature change coefficients ($Q_i$, $i$ from 1 to 13) for a $CO_2$ doubling are computed.

$$Q_i = \frac{T_{a_i,2x} - T_{a_i,ref}}{\overline{T}_{a,2x} - \overline{T}_{a,ref}}$$

where,

$T_{a_i}$ corresponds to the GCM air-surface temperature output averaged over the area covered by country $i$. The subscripts $2x$ and $ref$ refer to the doubled $CO_2$ and reference simulation respectively,
$\overline{T}_a$, represents the global air-surface temperature.

As the transient global surface temperature $\Delta\overline{T}_a(t)$ change is computed following equation (1.9), the annual mean regional temperature change at time $t$ relative to an arbitrary reference year are then calculated using $Q_i$:

$$T_{a_i}(t) = Q_i\left(\Delta\overline{T_a}(t) - \Delta\overline{T_a}(1990)\right) \tag{1.12}$$

where $T_{a_i}(t)$ is the regional temperature change relative to preindustial time on region $i$.

# 2 Cooperative and non-cooperative solutions

To endogenise the regions' carbon-energy and investment time paths, we present hereafter four different modes of behaviour: (1) the cooperative solution or international optimum, (2) the Nash equilibrium where countries optimize individually, (3) the partial agreement Nash equilibrium where a single coalition of countries is allowed to form, and (4) the business-as-usual scenario where countries ignore impacts of climate change.

## 2.1 The international optimum

In the international optimum (also called cooperative) scenario, a social planner is assumed to choose investment and carbon-energy consumption so as to maximize the world's total welfare defined as the sum of all countries' discounted utilities over the planning period. The problem to be solved is :

$$\max_{\{I_{it},E_{it}\}_{i\in\mathcal{N},t\in\mathcal{T}}} W = \sum_{i=1}^{n}\sum_{t=1}^{t_f}\rho_{it}U_i(C_{it}), \tag{2.1}$$

subject to constraints (1.1) to (1.12) for all $t \in \mathcal{T}$ and $i \in \mathcal{N}$, all variables (emissions, investment, $CO_2$ concentration,...) being positive. $C_{it}$ is the aggregate consumption for country $i$ during period $t$. $U_i$ is the utility function for country $i$. It is assumed to be a strictly increasing and concave function of consumption. Damages do not directly enter the utility function but cause a 'loss' of production (recall equation (1.2)). $\rho$ is the (time and country varying) discounting factor ($0 < \rho_{it} \leq 1$) obtained by integration of the social rate of time preference onwards.

First-order conditions for an interior maximum are given by[3]:

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[3] Prime indicates the function derivative.

$$\frac{\partial W}{\partial E_{it}} = \rho_{it} U_i'(C_{it}) \frac{\partial C_{it}}{\partial E_{it}} + \sum_{\tau=t+1}^{t_f} \sum_{j=1}^{n} \rho_{j\tau} U_j'(C_{j\tau}) \left[ \frac{\partial C_{j\tau}}{\partial \Delta T_{a_{j\tau}}} \frac{\partial \Delta T_{a_{j\tau}}}{\partial E_{it}} + \frac{\partial C_{j\tau}}{\partial p_\tau} \frac{\partial p_\tau}{\partial E_{it}} \right] = 0 \tag{2.2}$$

$$\frac{\partial W}{\partial I_{it}} = -\rho_{it} U_i'(C_{it}) + \sum_{\tau=t+1}^{t_f} \rho_{j\tau} U_j'(C_{j\tau}) \frac{\partial C_{j\tau}}{\partial K_{j\tau}} \frac{\partial K_{j\tau}}{\partial I_{it}} = 0 \tag{2.3}$$

$\forall t \in \mathcal{T}$, $\forall i \in \mathcal{N}$. Equation (2.2) (known as Samuelson's optimal condition for public goods) states that the marginal gain of utility from current consumption in country $i$ obtained by the emission of one extra ton of carbon today must be equal to the sum of future marginal losses of utility from consumption in all countries. As shown by the terms between square brackets in (2.2), these losses have two components. The first term is the loss of consumption due to the negative impact on production of the increase of atmospheric temperature in the future. The second is the loss of consumption due to the increase of the price of carbon-energy in the future induced by the extraction of one more ton of carbon-energy today.

Equation (2.3) states that the current marginal loss of utility in country $i$ due to an additional unit of investment must be equal to the sum of the future gains in utility from consumption obtained through the future higher capital stock induced by that extra unit of investment. (2.3) shows that country $i$'s investment policy doesn't have any direct impact on the utility of other regions. In the field of energy on the contrary, country $i$'s policy influences the welfare of other regions both through the price of carbon-energy and through climate change (the environmental externality).

## 2.2 The non-cooperative Nash equilibrium

In the non-cooperative open-loop Nash equilibrium, each player (country) is supposed to choose investment and carbon-energy consumption so as to maximize his total welfare defined as the sum of its discounted utilities over the planning period, given the strategies of all other players. Country $i$ solves the following problem :

$$\max_{\{I_{it}, E_{it}\}_{t \in \mathcal{T}}} \quad N_i = \sum_{t=1}^{t_f} \rho_{it} U_i(C_{it}), \tag{2.4}$$

subject to constraints (1.1) to (1.12) for all $t \in \mathcal{T}$, and given the other countries's energy and investment time paths.

Concerning carbon-energy, the first-order conditions for an interior maximum are given by:

$$\frac{\partial N_i}{\partial E_{it}} = \rho_{it} U_i'(C_{it}) \frac{\partial C_{it}}{\partial E_{it}} + \sum_{\tau=t+1}^{t_f} \rho_{j\tau} U_j'(C_{j\tau}) \left[ \frac{\partial C_{j\tau}}{\partial \Delta T_{a_{j\tau}}} \frac{\partial \Delta T_{a_{j\tau}}}{\partial E_{it}} + \frac{\partial C_{j\tau}}{\partial p_\tau} \frac{\partial p_\tau}{\partial E_{it}} \right] = 0 \tag{2.5}$$

$\forall t \in \mathcal{T}$. On the other hand, the optimal condition obtained by derivating $N_i$ with respect to investment is the same as in (2.3). Equation (2.5) states that the marginal gain of utility from current consumption in country $i$ obtained by the emission of one extra ton of carbon today must be equal to the sum of future marginal losses of country $i$ utility from consumption. Contrary to what happens at the international optimum (see equation 2.2), country $i$ takes only account of the impact of its marginal carbon emission (through the future increase of atmospheric temperature and world price of energy) on itself and ignores the impact on the others.

Solving the system of equations (1.1) to (1.12), (2.3), (2.5) $\forall i$ leads to the Nash equilibrium. It is an equilibrium in the sense that no country has interest to deviate from its trajectory if all other countries stick to their trajectory. Due to the fact that the players do not take account of the impact of their strategy on others, the Nash equilibrium is clearly suboptimal with respect to the international optimum. Formally, if $W$ is the world's total welfare at the international optimum, and $N_i$ country's total welfare at the Nash equilibrium, one must verify that $\sum_{i=1}^{n} N_i \leq W$.

## 2.3 The partial agreement Nash equilibrium w.r.t. a coalition

We introduce now a situation of partial cooperation, i.e. an intermediate case between the full cooperation situation illustrated by the international optimum, and the no cooperation case characterizing the Nash equilibrium. For doing so, we call upon the concept of *partial agreement Nash equilibrium w.r.t. a coalition* (PANE) introduced by Chander and Tulkens (1995, 1997). Suppose that the coalition $S \subset \mathcal{N}$ forms. Then the PANE w.r.t. to $S$ is an equilibrium where the members of $S$ maximize jointly the sum of their utilities, while the regions outside $S$ act individually. Formally, the PANE w.r.t. to coalition $S$ is the combination of strategies that solves simultaneously the following problems:
a) for $S$ :

$$\max_{\{I_{it}, E_{it}\}_{i \in S, t \in \mathcal{T}}} \sum_{i \in S} \sum_{t=1}^{t_f} \rho_{it} U_i(C_{it}), \tag{2.6}$$

given the emissions and investment paths of non-members of $S$ and subject to constraints (1.1) to (1.12) for all $t \in \mathcal{T}$ and $i \in S$;
b) for each region $j$ outside of $S$ :

$$\max_{\{I_{jt},E_{jt}\}_{t\in\mathcal{T}}} \sum_{t=1}^{t_f} \rho_{jt} U_j(C_{jt}), \tag{2.7}$$

subject to constraints (1.1) to (1.12) for all $t \in \mathcal{T}$, and given the other countries's energy and investment time paths.

Two remarks must be made about equations (2.6) and (2.7). First, they may be reinterpreted as describing a Nash equilibrium between a coalition $S$ and the non-members of $S$. Secondly, the PANE appears clearly as a generalization both of the cooperative solution (where $S = \{1, ..., n\}$) and of the Nash equilibrium (where $S$ is reduced to a singleton).

With respect to carbon-energy, the first order conditions associated with interior solutions of problems (2.6) and (2.7) are :

$$\rho_{it} U_i'(C_{it}) \frac{\partial C_{it}}{\partial E_{it}} + \sum_{k\in S} \sum_{\tau=t+1}^{t_f} \rho_{k\tau} U_k'(C_{k\tau}) \left[ \frac{\partial C_{k\tau}}{\partial \Delta T_{a_{k\tau}}} \frac{\partial \Delta T_{a_{k\tau}}}{\partial E_{it}} + \frac{\partial C_{k\tau}}{\partial p_\tau} \frac{\partial p_\tau}{\partial E_{it}} \right] = 0, \ i \in S \tag{2.8}$$

$$\rho_{jt} U_j'(C_{jt}) \frac{\partial C_{jt}}{\partial E_{jt}} + \sum_{\tau=t+1}^{t_f} \rho_{j\tau} U_j'(C_{j\tau}) \left[ \frac{\partial C_{j\tau}}{\partial \Delta T_{a_{j\tau}}} \frac{\partial \Delta T_{a_{j\tau}}}{\partial E_{jt}} + \frac{\partial C_{j\tau}}{\partial p_\tau} \frac{\partial p_\tau}{\partial E_{jt}} \right] = 0, \ j \in \mathcal{N} \backslash S \tag{2.9}$$

As far as investment is concerned, the first order optimal conditions remain the same as in (2.3).

## 2.4 The business-as-usual scenario

The business-as-usual (BAU) scenario is like the Nash equilibrium, except that countries are assumed to ignore the impact of climate change on their future welfare. In the BAU scenario, each player (country) is supposed to choose investment and carbon-energy consumption in order to maximise its total welfare defined as the sum of its discounted utilities over the planning period, given the strategies of all other players and ignoring future damages due to climate change. Formally, country $i$ solves the following problem :

$$\max_{\{I_{it},E_{it}\}_{t\in\mathcal{T}}} B_i = \sum_{t=1}^{t_f} \rho_{it} U_i(C_{it}), \tag{2.10}$$

subject to constraints (1.1) to (1.12) for all $t \in \mathcal{T}$, given the other countries energy and investment time paths, and assuming that the time evolution for atmospheric temperature in country $i$, $(\Delta T_{a_{it}})$, is exogenous[4] . In other words, country $i$ is supposed to ignore the influence of $E_{it}$ on $\Delta T_{a_{i\tau}}$, $\tau \geq t$.

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[4] So that the damages appearing in the production function are also exogenous (recall (1.2).

Concerning carbon-energy, the first-order conditions for an interior maximum are given by:

$$\frac{\partial B_i}{\partial E_{it}} = \rho_{it} U_i'(C_{it}) \frac{\partial C_{it}}{\partial E_{it}} + \sum_{\tau=t+1}^{t_f} \rho_{j\tau} U_j'(C_{j\tau}) \frac{\partial C_{j\tau}}{\partial p_\tau} \frac{\partial p_\tau}{\partial E_{it}} = 0 \qquad (2.11)$$

$\forall t \in \mathcal{T}$. On the other hand, the optimal condition obtained by derivating $B_i$ with respect to investment is the same as in (2.3). Contrary to what happens under Nash equilibrium conditions (equation 2.5), country $i$ takes account for the impact of its marginal carbon emission on itself only through the future increase world price of energy.

Solving the system of equations (1.1) to (1.12), (2.11), (2.5) leads to the BAU scenario. Due to the fact that the players do not take account for the impact of climate change, even on themselves, BAU is clearly suboptimal with respect to NE. Formally, if $B_i$ and $N_i$ are respectively country $i$'s total welfare at BAU and NE, one must verify that $B_i \leq N_i, \ \forall i \in \mathcal{N}$.

# 3 Simulations

## 3.1 Foreword

We now discuss some numerical simulations made with the model described in the preceding sections. In this section, we wish to illustrate the gains from international cooperation with respect to the Nash equilibrium and with respect to a business-as-usual (BAU) scenario. Whatever the type of behaviour chosen (cooperation, PANE, NE or BAU), the algorithm (written in Matlab) calculates the trajectories of the economies by solving the associated system of first order conditions. Its main advantage is its speed[5], which will appear to be very helpful in the next section when testing for coalitional rationality. Its main drawback comes from what makes its specialization : it is only suited to compute interior solutions and thus would not easily be adapted to integrate inequality constraints on some variables (for example a ceiling on temperature increase).

The "game" framework is the same as in RICE-98 (Nordhaus and Boyer, 1999). The world is divided in 13 regions or countries, which are European Union (Europe), Japan, USA, China, Russia, India, high-income OPEC (HIO)[6], Eastern Europe (EE), other high income (OHI)[7], middle income (MI)[8], lower

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[5] A run, for example the calculation of the IO, takes around 25 seconds on a PC Pentium III 450mhz. This is to be compared to the 15-30 minutes necessary to solve the full RICE-99 model on a 500 mhz machine (Nordhaus and Boyer, 2000, chapter 6).

[6] Saudi Arabia, Lybia,...

[7] Canada, Australia,...

[8] Brazil, Corea,...

middle income (LMI)[9], low income (LI)[10], Sub-Saharian Africa (Africa). Except for the climate module, almost all data were borrowed from RICE-98. A complete table of the parameters used is given in the appendix. Contrary to Nordhaus and Boyer (1999) who take a value of 3%, we have set the initial annual rate of time preference in the base case to 1%. It is indeed well known that climate change isq a long period phenomenon (compared to usual economic horizons). We thus give more weight to the future, in particular to the damages that will follow from climate change. As it will appear from the sensitivity analysis on the time preference parameter, choosing a rather low value for this parameter enhances the interest of international cooperation w.r.t. non-cooperative scenarios.

### 3.2 Numerical results

Results are shown for a time horizon of 160 years (i.e. until 2150), but to avoid boundary effects associated to this finite horizon problem, computations were made for a planning horizon of 300 years[11]. Periods are taken to be decades. The model considers only $CO_2$ emissions, i.e. other GHG are ignored. Figure 1 gives the average annual world carbon emissions for three scenarios : international optimum (IO), Nash equilibrium (NE) and business-as-usual (BAU).

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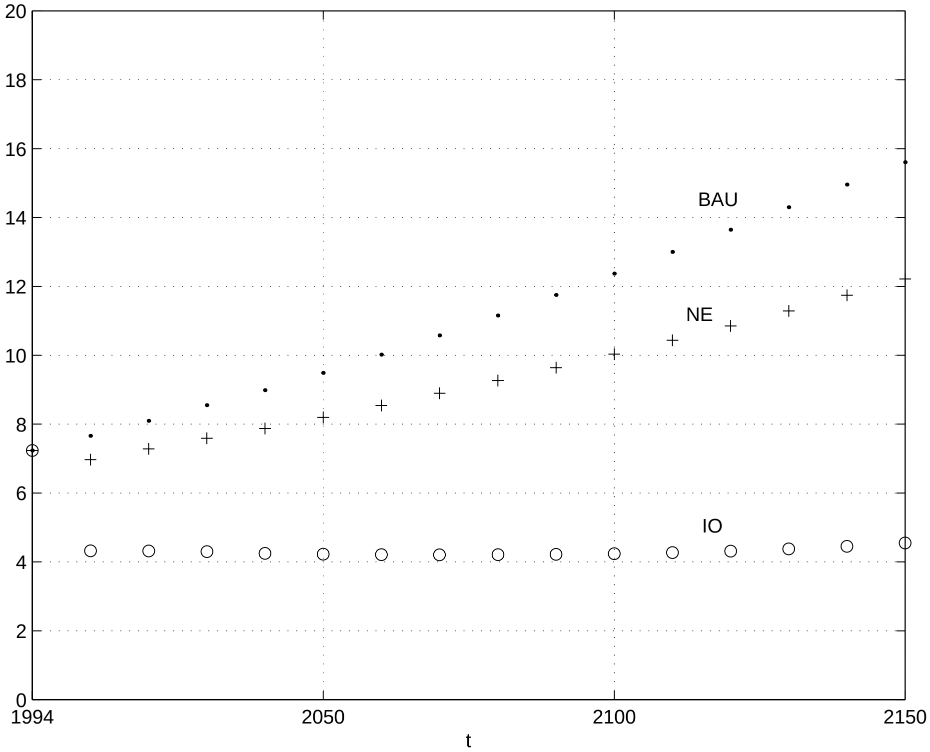
[9] Mexico, Turkey,...

[10] Indonesia, Pakistan,...

[11] In a finite horizon problem, the weight of damages due to climate change diminishes as one approaches the end of the planning period. Thus, at that time, emissions increase and lose their significance.

**Figure 1 : average annual world carbon emissions (in GtC/year)**



Emissions of $t = 0$ correspond to the emissions estimated in 1994 (Nordhaus and Boyer, 1999). In the BAU scenario, world emissions grow quasi linearly to reach about 13 GtC/year at the end of the 21th century. In the NE scenario, emissions grow at a slower rate but reach nevertheless an amount of 10 GtC/year in 2100. W.r.t. the two other scenarios, the consequences of an optimal policy (IO) is quite different: emissions drop abruptly during the first decade and increase then only slightly during the century. It would suppose immediate huge abatement rates of emissions, far beyond what has been announced in Kyoto for example. The objective of the Kyoto Protocol is to reach a reduction of the emissions in the Annex I Parties of about 5 % relative to the base year emissions (1990 for most Parties) in the period 2008-2010. In the optimal policy path here simulated, a reduction of about 54 % appears for the same period and for the World. This great impact of an optimal policy abatement depends mostly on the low rate of time preference that is commonly chosen in this type of study. A sensitivity tests on this crucial parameter is discussed below.

The BAU trajectory here simulated can roughly be compared to B2 storyline referred to in the IPCC Special Report on Emissions Scenario. However the B2 storyline and scenario family "describes a world in which the emphasis is on local solution to economic, social and environmental sustainability. (...) the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels" (IPCC, 2000). Therefore, it seems that the BAU scenario here simulated does not represent a scenario with growth rate of emissions that are compatible with the IPCC estimates. All scenarios in the IPCC report that could be associated to the BAU situation belong to the A1 or A2 category and show a much greater increase of the emissions in the first half of the 21st century. The quasi-linear trend here simulated in the BAU case is associated to the hypothesis chosen in the model construction and tend to underestimate the emission growth relative to other reviewed scenarios. Because the BAU scenario used here is "optimistic", the potential benefits of cooperation w.r.t. the "do nothing" hypothesis as measured hereafter will be underestimated.

On the other hand, the model did not show any trajectory that allows a growth of emissions followed by a decrease. Such path is simulated with other types of economic models but does not seem in the scope of the model of the "RICE type" as used here. Our goal here is not to provide with realistic emission scenarios as we rather concentrate on cooperation interests. The limitation shown here does not affect the nature of our results but it remains relevant to fix the limit of the scope of the results interpretation.

**Figure 2 : emissions per capita by country (tC/hab/year)**
(For each region, col. 1: BAU in 1990; col. 2, 3, 4: BAU, NE and IO in 2100)

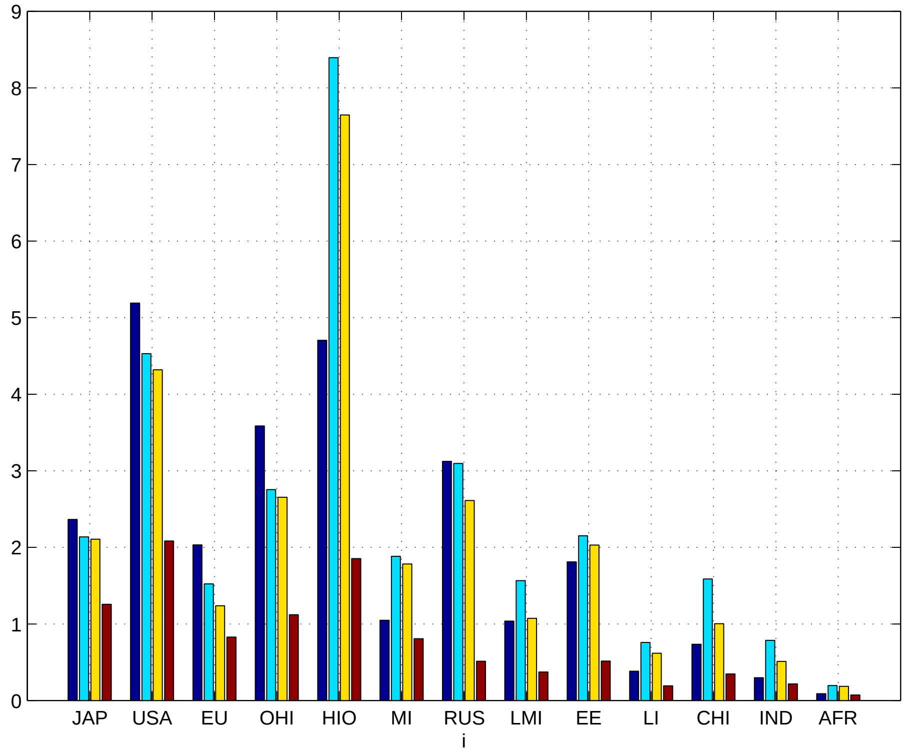


Figure 2 gives the emissions per capita in 2100 for three scenarios as well as the starting point, BAU in 1990. Regarding BAU (columns 1 and 2), one finds on the one side the industrialized countries where emissions per capita decrease, and on the other side, the others where emissions per capita increase. USA is the main polluter per capita today (a well known fact) but are overtaken by HIO (High Income OPEC) at the end of the century[12]. Now under the IO hypothesis, the picture is quite different (column 4). All countries reduce their emissions per capita w.r.t. the starting point and USA remains the first polluter per capita in 2100. Whatever the scenario chosen, the figure shows huge differences between emissions per capita per regions. The ratio of the maximum to the minimum of emissions per capita observed under BAU in 1990 is 58.5, to be compared to the correspondent values for BAU, NE and IO in 2100, i.e. 42.9, 41.2 and 29.1 respectively.

**Figure 3 : atmospheric carbon content (in GtC)**

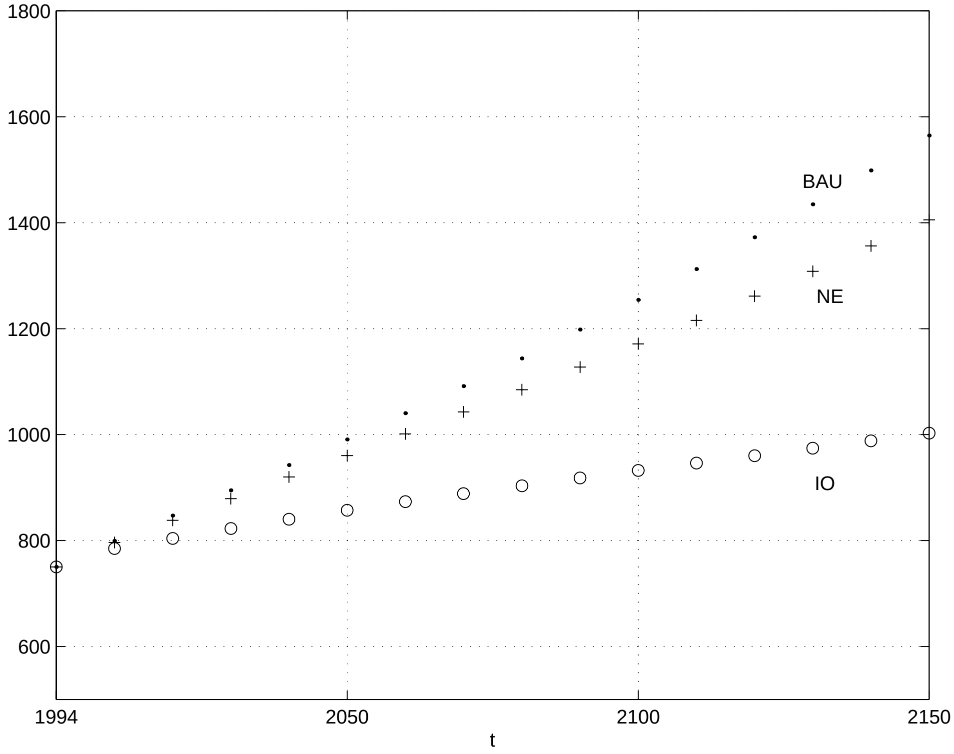


Figure 3 describes the evolution of the atmospheric carbon concentration under the three scenarios, starting with an initial concentration of 750.1 GtC (or

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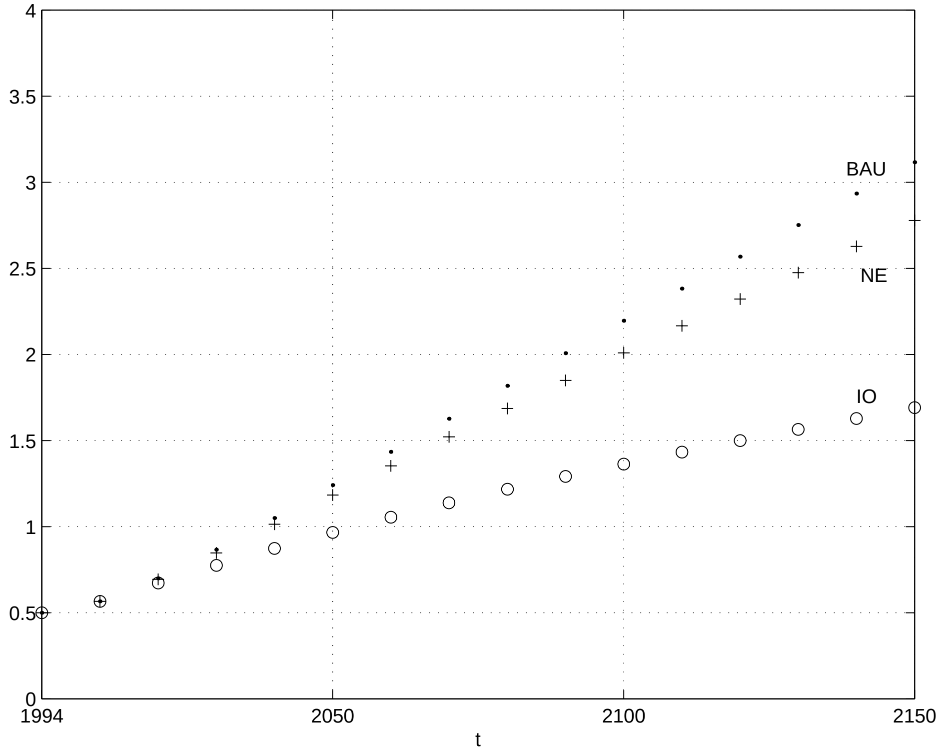
[12] This overtaking is explained by the fact that the output per capita of HIO grows at a higher rate than the one of USA.

equivalently 352 ppm (part per million [13]). It grows steadily in the three scenarios, reaching values around 1300 GtC (610 ppm) in 2100 for BAU. The increase is much weaker for IO, where the atmospheric concentration reaches a level of 960 GtC (451 ppm) around 2100. Note that even under the IO hypothesis, one may not speak of a stabilization of the atmospheric carbon concentration in the next two centuries.

**Figure 4 : world average surface atmospheric temperature increase relative to preindustrial estimates (1850) (°C)**



This is also the case for the world average atmospheric surface temperature which follows a quite similar trend, as shown in Figure 4. Again the IO scenario contrasts with the two others. W.r.t. its preindustrial level, atmospheric temperature will increase of around 1.3 °C in 2100, against approximatively 2.4 °C for BAU and 2.2 °C for NE.

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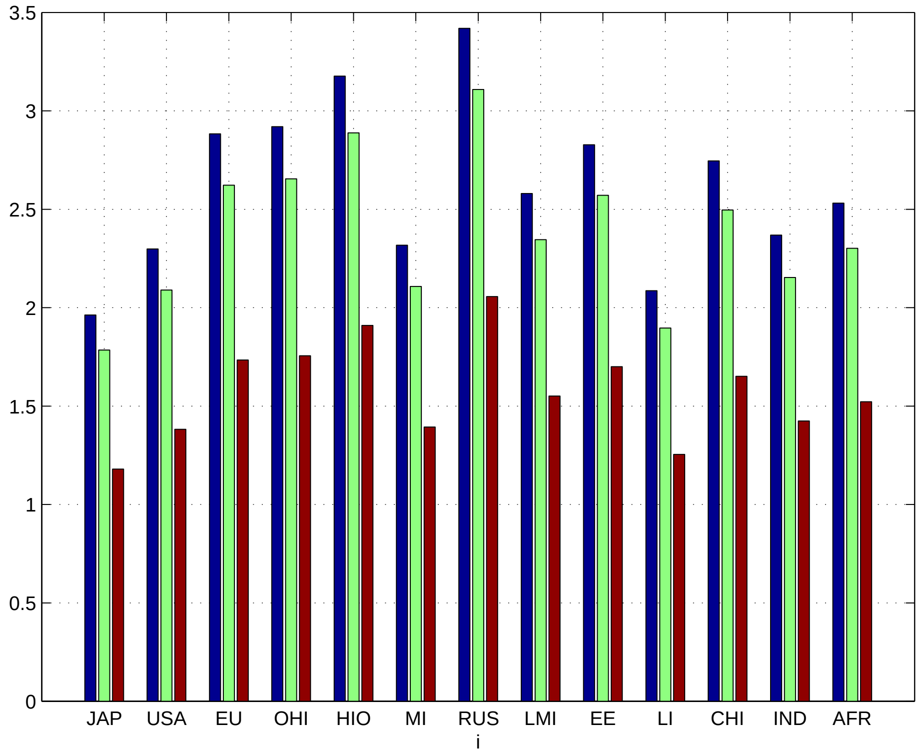
[13] The rate of conversion is 1 ppm = 2.13 GtC.

**Figure 5: regionalised atmospheric temperature increases in 2100(°C)**
(For each region, 1st, 2d and 3d columns refer respectively to BAU, NE and IO)



One of the interest of our climatic submodel is that atmospheric temperature is regionalised. Figure 5 shows that the simulated temperature increase for 2100 varies considerably between regions. All regions experience a warming, the weakest being of 1.9 °C (Japan) and the greatest reaching 3.4 °C (Russia) in the BAU scenario. In the IO scenario, the same regions undergo a warming of 1.2 °C and 2.1 °C, respectively. The magnitude of the temperature change depends on the climate GCM sensitivity and characteristics. The model on which our computations are based (Schlesinger et al., 1997) simulates a global temperature increase of 3.4 °C for a climate equilibrium under a doubling of the present day $CO_2$ concentration and does not represent the ocean dynamics. Such climate sensitivity is rather in the upper bound of the generally agreed magnitude and the lack of ocean circulation forces to ignore possible heat redistribution associated to ocean current changes. Nevertheless, for the purpose followed here, the GCM realism is relevant.

An important result concerns the rate of control of emissions, in particular in the optimal case. Figures 6.a and 6.b show the time path of optimal emission control per country. Formally, the optimal rate of control of emissions of country $i$ at time $t$ is defined by $\mu_{IO,it} = 100(1 - E_{IO,it}/E_{BAU,it}))$.

**Figure 6.a : optimal emission control rates (%)**

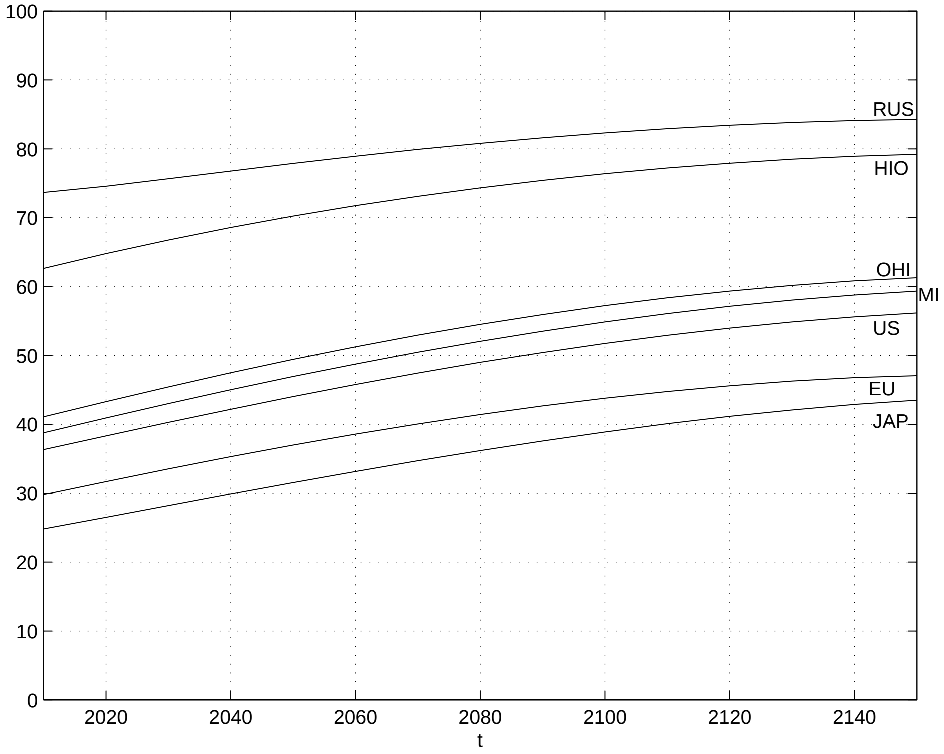
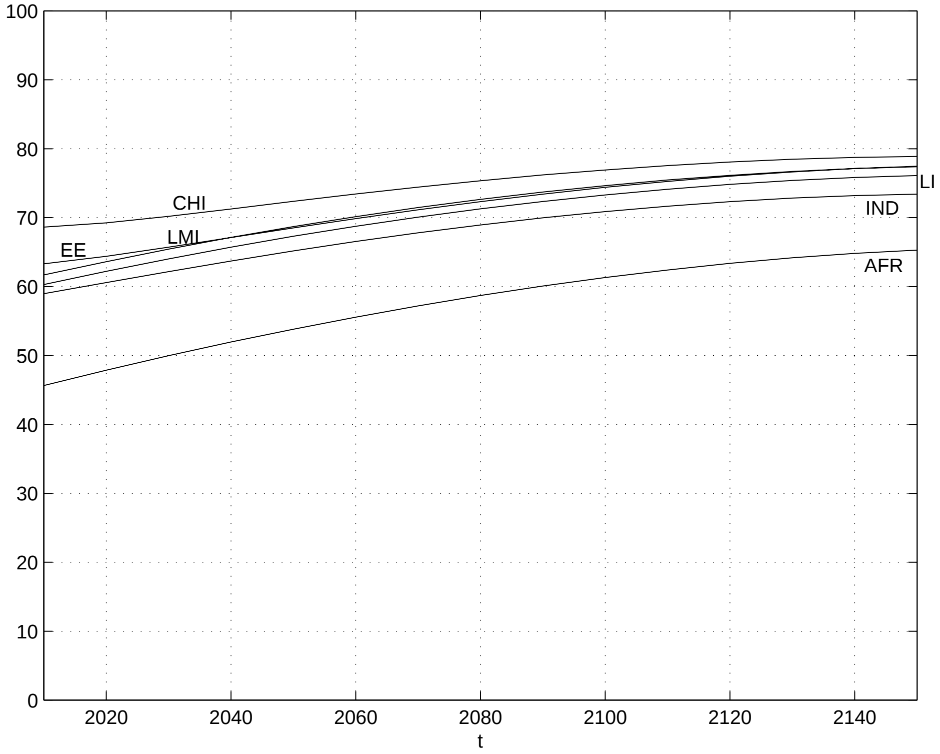


**Figure 6.b : optimal emission control rates (%)**



The IO scenario requires very high control rates, especially from countries or regions like Russia, China, HIO, LMI, EE and India, in which abatement rates vary between 60 and 85% during the century. On the contrary, industrialized countries like Japan and Europe (with abatement rates less than or around 50%), and to a minor extent USA and OHI, abate significantly less. This is not a surprising result. It is more efficient (less costly) to reduce emissions in countries where the productivity of energy (the ratio between output and energy used) is low.

**Figure 7 : relative welfare gains w.r.t. BAU (%)**
(For each region, 1st and 2d columns refer respectively to NE and IO)

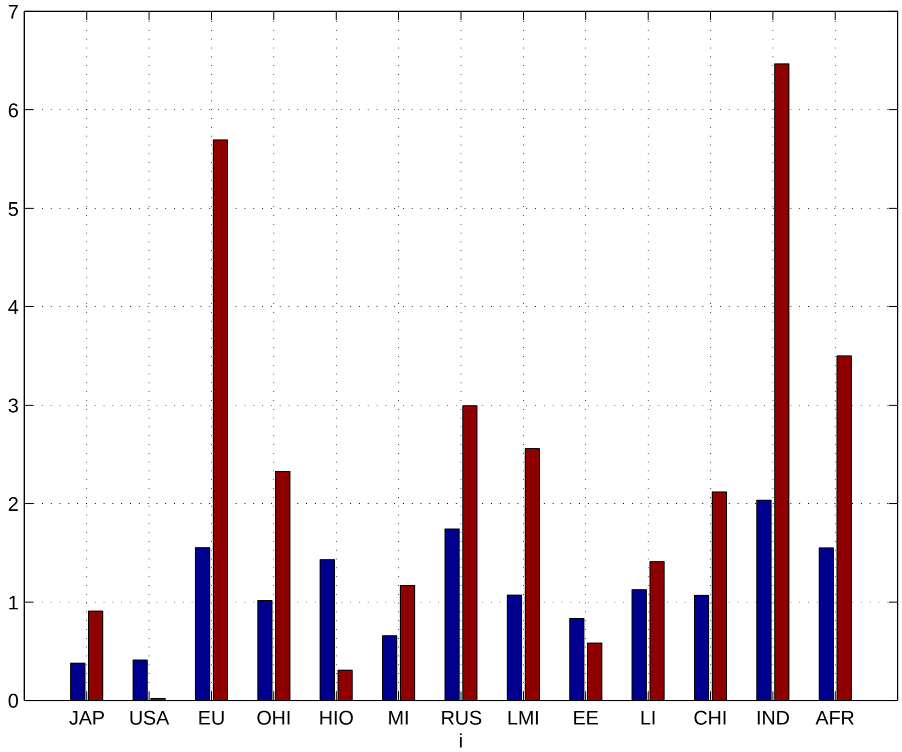


Figure 7 illustrates the relative welfare gains of NE and IO w.r.t. BAU. If everybody gets a positive gain at the NE w.r.t. BAU (recall subsection 3.4), this is not true for IO w.r.t. NE. Indeed, if the world as a whole gains from an optimal policy, Figure 7.b shows that the benefits are very unevenly distributed. W.r.t. BAU, the impact of applying an optimal policy appears to profit mainly to Europe and India (the two most vulnerable regions to climate change[14]). The problem is that a few regions (USA, HIO, EE) are better under NE than under IO. These countries have to abate a lot under IO (especially HIO and EE), while they suffer relatively little from climate change. So if there are no obstacle to move from BAU to NE (all countries have interest to do so), this does not hold when moving from NE to IO. The losing countries would ask for financial compensation if one hopes their voluntary collaboration to an international optimal policy. One way consists of financial sidepayments, and we turn now to them in the following section.

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[14] Recall that the damage functions are written as inverse quadratic functions of atmospheric temperature change (cfr. equation 1.6). Europe and India have the highest values for the parameter $d_{2,i}$ multiplying the quadratic term.

# 4 Financial transfers

## 4.1 The transfer formula

We make use of a theoretical transfer scheme proposed by Germain, Toint and Tulkens (1997) for stock pollution problems. This transfer scheme has been adapted and applied to the climate change problem by Eyckmans and Tulkens (1999) in the context of a partition of the world in 6 regions. The formula used by these authors is:

$$\theta_i = -[W_i - N_i] + \frac{\pi_i}{\sum_{k=1}^{n} \pi_k} \sum_{j=1}^{n} [W_j - N_j], \ i = 1, ..., n \tag{3.1}$$

where $\theta_i$ is the financial transfer received or given by country $i$, $W_i$ and $N_i$ are the total welfares obtained by country $i$ at the international optimum and at the Nash equilibrium respectively[15]. A positive (negative) transfer represents a sum received (payed). The transfers are defined as lump-sum quantities (i.e. for the whole planning period) and appear to be the sum of two terms. The first one corresponds to the opposite of what the country gains or loses between IO and NE. The second term assigns a share of the global surplus generated by international cooperation w.r.t. NE. With a transfer limited to the first term, region $i$ would be indifferent between IO *with* transfers (IOT) and NE. Note that from equation (3.1) the bigger $\pi_i$, the larger the fraction attributed to $i$. The weights $\pi_i$ are defined by

$$\pi_i = \sum_{t=1}^{t_f} \rho_{it} D_i'(\Delta T_{a_{it}}^{*}) Y_{it}^{*}, \ i = 1, ..., n \tag{3.2}$$

$D_i'(\Delta T_{a_{it}}^{*})$ is the marginal damage cost in relative terms affecting country $i$ at time $t$ along the optimal trajectory. $D_i'(\Delta T_{a_{it}}^{*}) Y_{it}^{*}$ is the same in absolute terms. Then $\pi_i$ is the discounted sum of country $i$'s marginal damage costs over the planning period and is thus a positive quantity.

From (3.1), it is clear that the sidepayments are balanced, i.e. $\sum_i \theta_i = 0$. Moreover, they make cooperation *individually rational* in the sense that

$$WT_i \triangleq W_i + \theta_i \geq N_i, \ \forall i = 1, ..., n \tag{3.3}$$

At the optimum with transfers, all regions are better off than at the Nash equilibrium.

## 4.2 Computation of the transfers

The principal results are summarized in the following figures.

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[15] In other words, $W_i$ is the share obtained by region $i$ of the world's total welfare given by the solution of problem (2.1), while $N_i$ is the solution of problem (2.4).

**Figure 8.a : Transfers and variation of welfare (in trillion 1990 US$)**
(For each region, col. 1, 2 and 3 give respectively $W_i - N_i$, $\theta_i$ and $WT_i - N_i$)

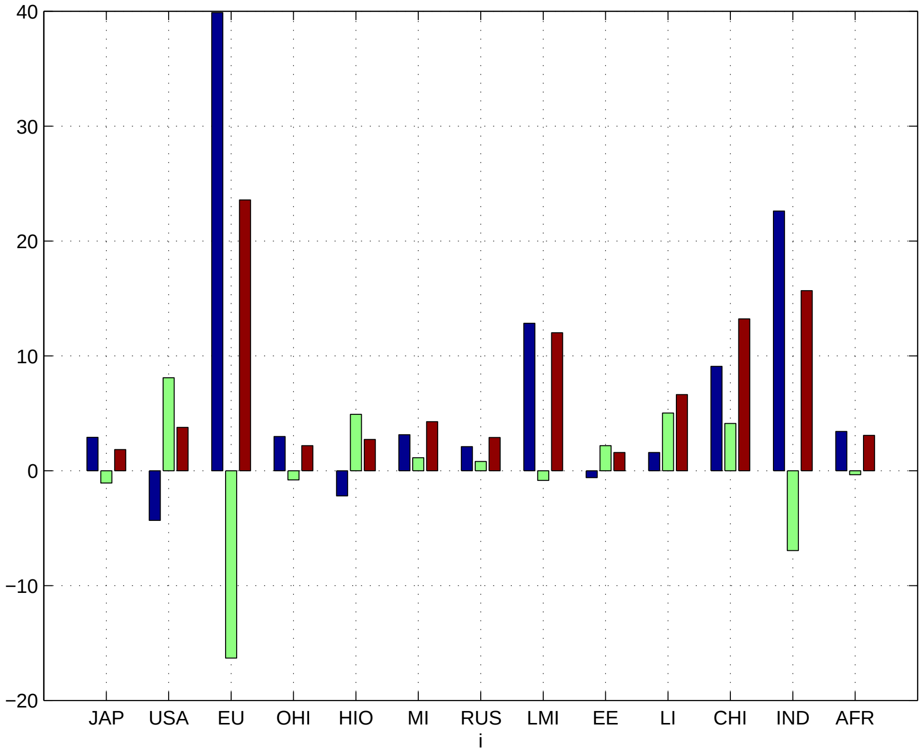
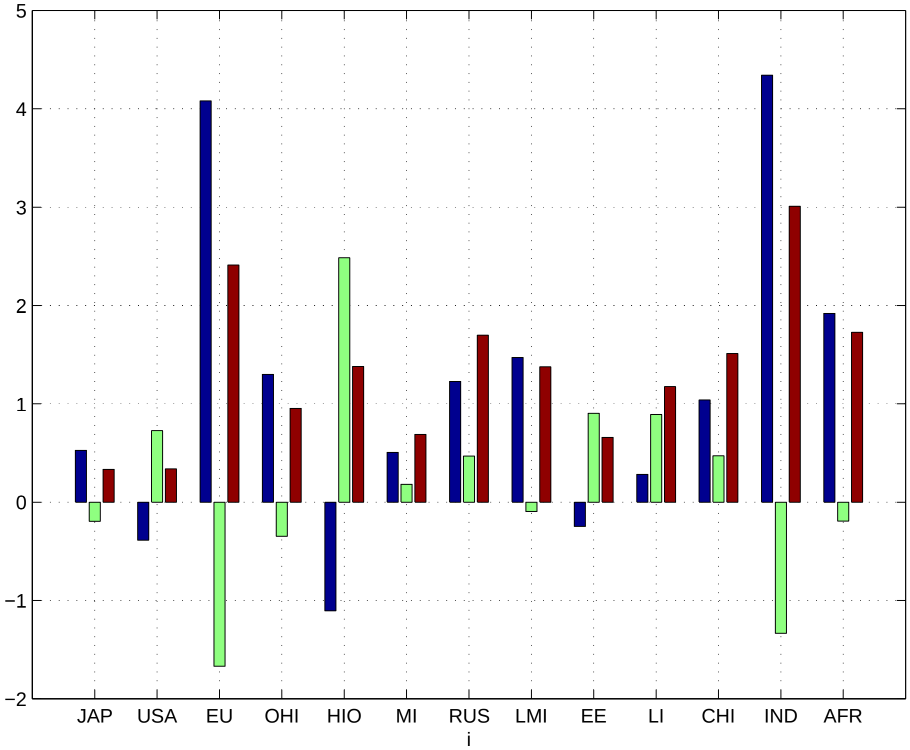


Figure 8.a gives for each country the difference between the welfare at IO and NE (column 1), the sidepayment received or payed (column 2), and the welfare obtained under IOT and NE (column 3). Figure 8.b gives the same values in relative terms, i.e. divided by $N_i$. The two main debtors of transfers are the two principal winners of cooperation : Europe and India. Other contributors are Japan, OHI, LMI and Africa but to a less extent. Among the main receivers of transfers in absolute terms, we find logically the three losers under IO w.r.t. NE, USA, HIO and EE but also China and LI. A priori, it could seem surprising that these two regions receive rather big transfers whereas they are winners of cooperation. The explanation comes from the fact that even if these two regions do not have interest to deviate individually from IO, they could have interest to as member of a coalition. Now the transfers defined by (3.1) are aimed to avoid not only individual deviations from IO, but also deviations of coalitions. We return to this issue in section 4.3.

**Figure 8.b : relative welfare gains with transfers (%)**
(For each region, columns 1, 2 and 3 give respectively $(W_i - N_i)/N_i$, $\theta_i/N_i$ and $(WT_i - N_i)/N_i$)



In relative terms, the picture is a little different (see figure 8.b). The first beneficiary is HIO, the main loser in relative terms. Far before the others, this region is followed by EE, LI), USA, Russia, China and MI. As shown by the second columns of Figure 8.b, an interesting feature is that the sidepayments represent a rather small fraction of the payoffs countries would obtain at NE (less than 2% in absolute value except for HIO). This means that it is possible to induce international cooperation without huge transfers of welfare between nations (at least in relative terms). A situation that is preferable for everybody as confirmed by the third columns of Figures 8.a-b. Thus, individual rationality is verified. Even if Europe and India are the main contributors of transfers, they remain the first two beneficiaries under IOT (more than 2% of welfare variation), followed by Russia, Africa, China, LMI (between 1% and 2%).

## 4.3 Checking coalitional rationality

In section 3.1, it was easily shown that international cooperation was individually rational (cfr. equation 3.3). No country has interest in deviating from IOT, because if it does, the other regions will react by returning to NE, where everybody (including the country that originally deviated) loses w.r.t to IOT. However there are no theoretical results that guarantee that this is also true for all subset (coalition) of regions.

We thus want to verify numerically if the subsequent conjecture is true : *Assume that if a coalition $S$ forms, then a partial agreement Nash equilibrium (PANE) w.r.t. $S$ such as described by (2.6-7) prevails. Then with the sidepayments defined by (3.1-2), no coalition has as a whole interest to deviate from the international optimum with transfers.*

Formally, what should be verified to guarantee that this conjecture is true is that

$$w(S) \leq \sum_{i \in S} WT_i, \ \forall S \subset \mathcal{N}, \ S \neq \mathcal{N}, \ |S| \geq 2 \tag{3.4}$$

where $w(S)$ is by definition the total welfare obtained by coalition $S$ at the PANE w.r.t. $S$, i.e. the solution of problem (2.6).

Considering one after the other each of the 8177 possible coalitions[16], we checked if inequality (3.4) was true. The conclusion is that (3.4) is always true. Thus with such transfers as defined by (3.1) and (3.2), *international cooperation is indeed rational in the sense of coalitions.*

# 5 Sensitivity analysis

In this section, we will test the impact of regionalising the atmospheric temperature w.r.t. the situation where temperature is not regionalised. We will also proceed to a sensitivity analysis on our simulations results to variations of the time horizon ($t_f$) and of the rate of time preference ($\rho$).

## 5.1 Regionalisation vs. no-regionalisation of temperature

The main originality of this model w.r.t. other Integrated Assessment Models is that atmospheric temperature is regionalised. It is interesting to analyze to which extent regionalisation of temperature modifies the results from the situation where temperature is assumed to be uniform around the world. In the reference case (RC), atmospheric temperature in region $i$ is related to world temperature by (1.12), where $Q_i$ is the i$^{th}$ component of the vector of exogenous parameters $Q = [0.82\ 0.96\ 1.21\ 1.23\ 1.33\ 0.97\ 1.44\ 1.08\ 1.19\ 0.88\ 1.15\ 0.99\ 1.06]$. In the alternative case (AC), all the components of $Q$ are equal to one.

Table 1 summarizes the main results. As shown by column 3 and 4 which give respectively for RC and AC the values observed in 2100 of the emissions

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[16] Indeed, there are $2^{13} - 15 = 8177$ possible subsets $S$ of $\{1, ..., n\}$, such that $S \neq \{1, ..., n\}$, $|S| \geq 2$. The 15 cases that are dropped correspond to $S = \{1, ..., n\}$ (IO), the 13 singletons (which each corresponds to NE) and the case where $S$ is empty.

per country (lines 1 to 13) and carbon concentration (line 14), all countries emit more carbon in AC, but the differences are not very important. The atmosphere carbon concentration is thus also greater in AC. Column 5 gives the atmospheric temperature simulated for each region in RC (lines 1 to 13) and in AC (line 15). Obviously, regions characterized by a parameter $a_i$ greater (lower) than 1 in RC record temperatures higher (lower) in RC than in AC. However, temperature regionalisation is not neutral : the average atmospheric temperature is higher in AC than in RC (1.48 °C instead of 1.43 °C). This can be explained by two reasons. First, countries characterized by $a_i > 1$ are more numerous than the others (8 vs. 5) and the difference $|a_i - 1|$ appears to be in average higher when $a_i > 1$. Secondly as damages are inverse quadratic functions of temperature (cfr. eq. 1.6), regionalisation of this variable induces more damages even if its mean value remains unchanged. The incentive to abate emissions is thus stronger in RC, explaining why emissions and average temperature are lower in this case.

**Table 1 : Regionalisation vs. no-regionalisation**
(RC (ref. case): regionalisation; AC (alt. case): no-regionalisation; $t = 2100$)

| | | $E$ | | $T_a$ | $\theta$ | | $WT$ | |
|---|---|---|---|---|---|---|---|---|
| | | RC | AC | RC | RC | AC | RC | AC |
| 1 | J | 0.14 | 0.14 | 1.18 | -1.07 | -2.91 | 553.78 | 550.80 |
| 2 | US | 0.73 | 0.78 | 1.38 | 8.10 | 5.46 | 1119.54 | 1118.24 |
| 3 | E | 0.30 | 0.31 | 1.73 | -16.31 | -11.76 | 1001.19 | 1012.62 |
| 4 | OHI | 0.10 | 0.10 | 1.76 | -0.79 | 0.05 | 231.61 | 233.43 |
| 5 | HIO | 0.21 | 0.24 | 1.91 | 4.91 | 5.39 | 200.50 | 203.36 |
| 6 | MI | 0.36 | 0.39 | 1.39 | 1.13 | -0.06 | 625.45 | 624.41 |
| 7 | RUS | 0.08 | 0.09 | 2.06 | 0.80 | 2.70 | 173.87 | 177.63 |
| 8 | LMI | 0.44 | 0.48 | 1.55 | -0.83 | -0.16 | 885.39 | 889.09 |
| 9 | EE | 0.11 | 0.12 | 1.70 | 2.18 | 2.50 | 242.74 | 244.00 |
| 10 | LI | 0.39 | 0.43 | 1.25 | 5.03 | 1.07 | 571.67 | 565.55 |
| 11 | CHI | 0.54 | 0.60 | 1.65 | 4.13 | 6.49 | 889.09 | 898.72 |
| 12 | IND | 0.37 | 0.40 | 1.42 | -6.94 | -8.26 | 536.55 | 534.79 |
| 13 | AFR | 0.15 | 0.16 | 1.52 | -0.34 | -0.51 | 181.38 | 181.84 |
| 14 | $C_a$ | 946.33 | 962.38 | | | | | |
| 15 | $T_a$ (AC) | | | 1.48 | | | | |

Columns 6 and 7 give for RC and AC the transfer $\theta_i$ received or payed by each country. Except for OHI (4) and MI (6), transfers do not change sign and for most of the regions values are not very different. An exception is Russia which becomes in relative terms the second receiver (after HIO). Having the highest regional temperature coefficient ($a_i$), Russia (7) records thus an important decrease of temperature when moving from RC to AC, damages are thus lower. Now, Russia is called to a big effort of abatement at the international optimum (which is the assumption made for both RC and AC). Russia being less vulnerable to climate change in AC, it is therefore logical that higher transfers are needed to convince that country to adhere to IO. The same story holds for China (11).

In terms of welfare (see columns 8 and 9) which give for RC and AC the welfare obtained at the optimum with transfers $WT_i$, the picture remains similar even if there are visible differences. These differences follow from the value of $a_i$ : if $a_i$ is smaller (greater) than 1, country $i$ obtains a smaller (higher) welfare in AC than in RC because it is in that case more (less) vulnerable to climate change.

## 5.2 Change of the time horizon

For evident computational reasons, the model is solved for a finite time horizon. In the above simulations, $t_f$ is set to 300 years[17]. Even if this time horizon value seems already long, it is finite and thus the model ignores what happens after the year 2300, in particular in terms of damages. It is thus interesting to see how results are affected if $t_f$ changes, in particular when the rate of time preference has been chosen to a low value.

**Table 2 : Change of the time horizon**

(RC (reference case) : $t_f = 300$; AC (alternative case) : $t_f = 400$; $t = 2100$)

| | | $E$ | | $\theta/W$ (%) | | $(WT-N)/N$ (%) | |
|---|---|---|---|---|---|---|---|
| | | RC | AC | RC | AC | RC | AC |
| 1 | J | 0.14 | 0.12 | -0.19 | -0.28 | 0.33 | 0.67 |
| 2 | US | 0.73 | 0.61 | 0.73 | 1.11 | 0.34 | 0.64 |
| 3 | E | 0.30 | 0.25 | -1.60 | -1.78 | 2.41 | 4.62 |
| 4 | OHI | 0.10 | 0.08 | -0.34 | -0.49 | 0.95 | 2.01 |
| 5 | HIO | 0.21 | 0.16 | 2.51 | 3.65 | 1.38 | 2.26 |
| 6 | MI | 0.36 | 0.30 | 0.18 | 0.55 | 0.69 | 1.12 |
| 7 | RUS | 0.08 | 0.06 | 0.46 | 0.03 | 1.70 | 3.39 |
| 8 | LMI | 0.44 | 0.35 | -0.09 | -0.21 | 1.38 | 2.36 |
| 9 | EE | 0.11 | 0.08 | 0.91 | 0.84 | 0.66 | 1.25 |
| 10 | LI | 0.39 | 0.31 | 0.89 | 0.91 | 1.17 | 1.97 |
| 11 | CHI | 0.54 | 0.43 | 0.47 | 0.15 | 1.51 | 2.56 |
| 12 | IND | 0.37 | 0.29 | -1.28 | -1.64 | 3.01 | 5.33 |
| 13 | AFR | 0.15 | 0.12 | -0.19 | 0.22 | 1.73 | 2.73 |
| 14 | $C_a$ | 946.33 | 912.66 | | | | |
| 15 | $T_a$ | 1.43 | 1.33 | | | | |

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[17] This value is similar to those chosen by other authors. For example, Nordhaus and Boyer (2000) take 350 years, while Eyckmans and Tulkens (1999) choose 320 years.

($E$ : emissions (GtC/year); $C_a$ : atmospheric carbon content (GtC); $T_a$ : atmospheric temperature change (°C); $\theta$ : transfers; $W$, $WT$, $N$ : welfare levels at the IO with and without transfers and at the Nash equilibrium)

Table 2 summarizes the comparison between the reference case (RC) where $t_f = 300$ and the alternative case (AC) where $t_f = 400$. The two cases assume international cooperation (IO). Columns 3 and 4 give respectively for RC and AC the values observed in 2100 of the emissions per country (lines 1 to 13), carbon concentration (line 14) and average atmospheric temperature (line 15). Because future damages are taken account on a longer horizon, emissions of all countries decline. A 3.7% decrease in the carbon concentration is associated with a 7.5% temperature change from RC to AC. Such an important variation from a model parameter that should not influence significantly the result reveals another limitation on the significance of the absolute results. Some trends and general insights can be drawn, but before extensive sensitivity analysis is performed great caution remains necessary in the model results interpretation.

In terms of welfare, one observes that the picture remains globally the same in the two cases. The principal winners of cooperation are still Europe and India and the two main losers remain USA and HIO. A difference is that now EE is a beneficiary. Because welfare levels and transfers are lump-sum quantities calculated on unequal planning periods in the two cases, it is meaningless to compare them in absolute terms. Columns 5 and 6 give respectively for RC and AC the ratio $\theta_i/W_i$ (in %) characterizing each country. Although the differences are visible, the picture remains similar for the principal donors (Europe and India) and the principal receivers (USA and HIO). Except for Africa, the sign of the transfers remains unchanged (Africa becomes a receiver of transfers under AC). Columns 7 and 8 give respectively for RC and AC the gain in relative terms between IOT and NE (i.e. $(WT_i - N_i)/N_i$; in %) characterizing each country. Here the differences appear to be more significant. The relative gains obtained by the countries are nearly multiplied by 2 when moving from RC to AC. So, even if it does not change fundamentally the results, one can conclude that choosing a longer planning period increases significantly the interest of cooperation w.r.t non-cooperation because future damages are taken account on a longer horizon.

## 5.3 Change of the rate of time preference

It is well known in the climate change literature that results can be very sensitive to the rate of time preference. In the reference case (RC), this parameter is fixed to a rather low value (1%) at the beginning of the planning period, and following Nordhaus et Boyer (1999, 2000), it is assumed to decrease slowly after[18]. In the alternative case (AC), we take for the initial value of the rate of time preference

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[18] The annual rate of decrease of the discount rate is equal to .226%. The values observed in RC for $t = 2100, 2200, 2300$ are then respectively .79, .61 and .47 %.

the value used by Nordhaus et Boyer (1999, 2000), i.e. 3%. Table 3 summarizes the results.

**Table 3 : Change of the rate of time preference**
(RC (reference case) : $\rho_1 = .01$; AC (alternative case) : $\rho_1 = .03$; $t = 2100$)

| | | $E$ | | $\theta/W$ (%) | | $(WT-N)/N$ (%) | |
|---|---|---|---|---|---|---|---|
| | | RC | AC | RC | AC | RC | AC |
| 1 | J | 0.14 | 0.19 | -0.19 | -0.08 | 0.33 | 0.02 |
| 2 | US | 0.73 | 1.15 | 0.73 | 0.05 | 0.34 | 0.64 |
| 3 | E | 0.30 | 0.43 | -1.60 | -0.21 | 2.41 | 0.40 |
| 4 | OHI | 0.10 | 0.16 | -0.34 | -0.20 | 0.95 | 0.04 |
| 5 | HIO | 0.21 | 0.44 | 2.51 | 0.68 | 1.38 | 0.39 |
| 6 | MI | 0.36 | 0.59 | 0.18 | 0.01 | 0.69 | 0.20 |
| 7 | RUS | 0.08 | 0.18 | 0.46 | 0.18 | 1.70 | 0.20 |
| 8 | LMI | 0.44 | 0.89 | -0.09 | 0.04 | 1.38 | 0.35 |
| 9 | EE | 0.11 | 0.22 | 0.91 | 0.22 | 0.66 | 0.09 |
| 10 | LI | 0.39 | 0.79 | 0.89 | 0.32 | 1.17 | 0.34 |
| 11 | CHI | 0.54 | 1.12 | 0.47 | 0.37 | 1.51 | 0.42 |
| 12 | IND | 0.37 | 0.71 | -1.28 | -0.45 | 3.01 | 0.80 |
| 13 | AFR | 0.15 | 0.26 | -0.19 | -0.09 | 1.73 | 0.58 |
| 14 | $C_a$ | 946.33 | 1126.29 | | | | |
| 15 | $T_a$ | 1.43 | 1.98 | | | | |

Columns 3 and 4 give respectively for RC and AC the values observed in 2100 of the emissions per country (lines 1 to 13), carbon concentration (line 14) and average atmospheric temperature (line 15). As expected, emissions increase significantly in all countries (in some of them by more than 100 %). Carbon concentration and atmospheric temperature follow accordingly. One observes that the variation of temperature w.r.t. RC is quite sharp (.55 °C), a 19% increase in the carbon concentration inducing a 38% temperature increase.

Because the discount rate in AC is higher, welfare levels and transfers (in absolute value) decline sharply compared to RC. This is also true in relative terms. Columns 5 and 6 give for RC and AC the ratio $\theta_i/W_i$ (in %) per country. The ratio (in absolute value) decreases everywhere. But if one looks to the direction of the flows, the picture is quite similar : transfers change sign only in the case of LMI. If one looks at the columns 7 and 8 which give for RC and AC the ratio $(WT_i - N_i)/N_i$ (in %), one observes that the gains of cooperation with transfers are much smaller. To summarize, the simulation confirms the well known fact that choosing a lower time preference rate enhances from a global point of view the interest of cooperation because the future is given more weight w.r.t. the present. But a lower discount rate also enhances the divergence of interests between countries w.r.t. cooperation. Transfers are thus higher, both in absolute and relative terms. However their directions do not change in general.

# 6 Conclusion

This paper describes an economic model of climate change that includes a representation of the regional temperature changes on the 13 geographical regions considered. Using financial transfers mechanisms as defined in Eyckmans and Tulkens (1999), we check the interest of countries or group of countries to deviate from the theoretical international optimal policy by financial transfer opportunities. These results obtained here with a more developed version of the model confirm the outcome of the previous analysis performed with the world represented with 6 regions and no regional temperature variation. However, we observe here some contrasted interests to cooperate between countries within the "Rest of the World" category of countries. India and the high-income OPEC countries have divergent interests and the improved but still insufficient geographical representation allows to taking such divergence into account.

The regional temperature change representation adds a little more realism to the crude physical representation of the climate system in this model. Under these hypotheses, more emission reductions are simulated in all scenarios as greater regional damages appear. In terms of transfers and welfare, the overall picture remains similar as previous results but more contrasts appear between the regions considered.

The sensitivity test on the choice of the time horizon showed an important limitation of this type of model. From a theoretical point of view, the time horizon has to be chosen in order to avoid any spurious effect on the results within the period studied. It is shown here that choosing a longer period for the time horizon significantly affects the results and increases the interest of international cooperation versus non-cooperation. Such bias reveals a model drawback.

The sensitivity to the choice of the discount rate is great and is a well-known limitation. Therefore, here as in any interpretation of the results with this model, the results will be closely linked to the value of this parameter.

The trajectories simulated in the different scenarios computed showed that the model in its present state does not simulate emissions trend that peak before the end of the period considered (except for the international optimal case. The BAU scenario under estimates emission growth relative to the IPCC. This characteristic is linked to the hypothesis underlying the model buildup and need to be investigated in depth but the underestimation of the BAU emissions growth rate has the consequence of underestimating the potential damage effect and therefore the potential benefits of international cooperation.

This leads us to conclude that beyond the analysis that confirms the interest of financial transfers to prevent free-riding and coalition formation, the model of the RICE type used here reveals some characteristics which all tend to reduce the impact of climate change and the interest to reduce the emissions in comparison with other economical models.

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# 7 Appendix

## 7.1 List of variables

$Y_{it}$: gross production of country $i$
$C_{it}$: consumption of country $i$
$I_{it}$: investment of country $i$
$K_{it}$: capital stock of country $i$
$L_{it}$: population of country $i$ (exogenous)
$E_{it}$: carbon-energy consumption of country $i$ (measured in $CO_2$ emissions)
$A_{it}$: total factor productivity of country $i$ (exogenous)
$p_t$: world price of carbon-energy
$m_{it}$: markup on carbon-energy of country $i$
$D_i(\Delta T_{a_{it}})$ : damage due to temperature change on country $i$
$CC_t$: cumulative world extraction of carbon-energy
$P_a(t)$: linear atmospheric $CO_2$ impulse function [GTC]
$t$: time [years]
$e(t)$: rate of $CO_2$ emissions into the atmosphere [GTC/year]
$\Delta \overline{T_a}(t)$: change in the atmospheric temperature at time t relative to preindustrial level (assumed year 1765) [$\circ$C)]
$\Delta \overline{T_o}(t)$: change in the deep ocean temperature at time t relative to preindustrial level [$\circ$C)]
$\Delta \overline{F}_{CO_2}(t)$: change in anthropogenic $CO_2$ radiative forcing relative to preindustrial time [Wm$^{-2}$]
$T_{a_i}$: GCM air-surface temperature output averaged over the area covered by

country $i$.

## 7.2 List and values of the parameters

$t_f$: number of periods : 30
$n$: number of regions : 13
$\delta$: annual depreciation rate of the capital stock : .1
$\gamma$: elasticity of production to capital : .3
Vectors of parameters of the damage functions :
$d_1 = .01\text{x}[-.42\ -.26\ -.1\ -1.08\ .41\ .39\ -1.08\ .22\ -.52\ .63\ .41\ .74\ 1.57]$
$d_2 = .01\text{x}[.25\ .17\ .49\ .37\ .15\ .13\ .33\ .26\ .19\ .25\ .2\ .49\ .1]$
Initial capital stocks (trillion 1990 US\$)[19] :
$K_0 = [12.93\ 25.11\ 29.32\ 5.09\ 1.07\ 5.86\ 1.71\ 4.99\ 1.84\ 2.51\ 3.08\ 1.62\ .63]$
Initial industrial emission levels (GtC) :
$E_0 = [.3075\ 1.4073\ .8208\ .2493\ .1294\ .277\ .4962\ .5606\ .3677\ .3274\ .8713\ .2480\ .0454]$
Initial agricultural emission levels (GtC)[20] :
$EL_0 = [0\ 0\ 0\ 0\ .00008\ .39637\ 0\ .21813\ 0\ .28007\ .04094\ .01774\ .17419]$
Vector of initial elasticities of GDP w.r.t. carbon energy :
$\beta_0 = [.078\ .1134\ .0707\ .077\ .082\ .082\ .132\ .077\ .146\ .099\ .165\ .13\ .098]$
Vector of rates of decrease of $\beta_{i0},\ i \in \mathcal{N}$ (per decade):
$\hat{\beta}_0 = -[.13\ .1\ .12\ .12\ .07\ .1\ .25\ .15\ .25\ .12\ .28\ .16\ .08]$
Vector of declining rates of $\beta_{it},\ i \in \mathcal{N}$ (per decade):
$d\beta = [.06\ .06\ .06\ .06\ .1\ .08\ .1\ .08\ .1\ .08\ .15\ .1\ .1]$
Elasticity of GDP w.r.t. carbon energy :
$\beta_{it} = \beta_{i0} \exp(\frac{\hat{\beta}_{i0}}{d\beta_i}[1 - \exp(d\beta_i[t-1])])$
Vector of initial populations :
$L_0 = [125.1\ 260.7\ 383.4\ 65.8\ 29.3\ 283.7\ 148.0\ 564.8\ 194.2\ 911.5\ 1198.5\ 918.6\ 549.1]$
(millions of inhabitants)
$L_0 = [.303\ 1.387\ .818\ .253\ .121\ .280\ .441\ .567\ .357\ .308\ .828\ .236\ .054]$
(production function units)
Vector of ratios of asymptotic to initial population :
$aL = 1.5\text{x}[.89\ 1.32\ .91\ 1.26\ 4.40\ 1.65\ 1.07\ 2.18\ 1.12\ 2.48\ 1.40\ 2.02\ 4.51]$
Vector of initial growth rates of population (per decade) :
$gL_0 = [-.07\ .09\ -.06\ .0977\ .3705\ .125\ .0117\ .20\ .014\ .22\ .0852\ .175\ .34]$
Population[21]:
$L_{it} = L_{i0} \exp\left(\log(aL_i)\left(1 - \left(1 - \frac{\log(1+gL_i)}{\log(aL_i)}\right)^{(t-1)}\right)\right)$

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[19] Calibrated so that the initial emission levels coincides with the one given for 1995 by Nordhaus and Boyer (1999).

[20] Supposed to remain constant.

[21] For Europe and Japan, the computation of population given by the following formula is slightly modified to take account of a decrease of population on the first four decades.

Initial total factor productivities[22]:

$A_0 = [3.492\ 1.916\ 3.101\ 2.058\ 1.163\ 2.133\ .638\ 1.162\ .792\ 1.096\ 0.632\ 0.971\ 1.453]$

Vector of productivity growth parameters :

$aA = [23.5\ 18.10\ 15.40\ 30\ 5.38\ 7\ 17\ 10\ 20.8\ 20\ 27.3\ 30\ 25]$

Vector of initial growth rates of total factor productivity (per decade):

$gA_0 = [.065\ .045\ .049\ .046\ .0914\ .1175\ .1346\ .1388\ .1506\ .1311\ .2126\ .1829\ .1]$

Total factor productivity :

$$A_{it} = A_{i0} \exp\left(\log(aA_i)\left(1 - \left(1 - \frac{\log(1+gA_i)}{\log(aA_i)}\right)^{(t-1)}\right)\right)$$

Markup over world price of energy ($/tC)[23]:

$m_{it} = [716\ 396\ 525\ 284\ 57\ 324\ 1\ 57\ 71\ 75\ 27\ 97\ 231],\ \forall t \in \mathcal{T}$

$CCs$: measure of coal supplies (GtC) : 6000

Parameters of the supply function (1.4) : $\xi_1 = 113$, $\xi_2 = 700$, $\xi_3 = 4$

$dr$: decline rate of social time preference per year : .0025719

$r_{i0}$: initial rate of social time preference : $.01\ (\forall i \in \mathcal{N})$

Rate of social time preference : $r_{it} = r_{i0} \exp(-10\, dr\, t)$

Discount rate : $\rho_{i,t+1} = \rho_{it}/((1 + r_{it})^{10}),\ \rho_{i0} = 1$

Coefficient derived from the Maier-Reimer and Hasselmann (1987) oceanic GCM for an impulse $CO_2$ input to the atmosphere of 2 times pre-industrial atmospheric $CO_2$ :

| $A_o$ | $A_1$ | $\nu_1$ (years) | $A_2$ | $\nu_2$ | $A_3$ | $\nu_3$ | $A_4$ | $\nu_4$ |
|---|---|---|---|---|---|---|---|---|
| 0.142 | 0.241 | 313.8 | 0.323 | 79.8 | 0.206 | 18.8 | 0.088 | 1.7 |

$\tau_1 = 0.6271$, $\tau_2 = 0.09944$, $\tau_3 = 0.62507061$, $\tau_4 = 0.02$

$\Delta\overline{F}_{CO_2}(1990) = 1.514\ \mathrm{Wm}^{-2}$: change in anthropogenic $CO_2$ radiative forcing in 1990 relative to preindustrial time (Harvey et al., 1997)

$\Delta\overline{F}_{total}(1990) = 1.117\ \mathrm{Wm}^{-2}$: total (all greenhouse gases and aerosols) change in radiative forcing in 1990 relative to preindustrial time (Harvey et al., 1997)

$\Delta F_{2x} = 4.37\ \mathrm{Wm}^{-2}$ : radiative forcing predicted for a doubling of the pre-industrial $CO_2$ concentration (Harvey et al., 1997),

$C_o = 279$ ppm: preindustrial atmospheric $CO_2$ concentration. (Harvey et al., 1997)

$Q_i$: normalised regional temperature change coefficients

$Q = [0.82\ 0.96\ 1.21\ 1.23\ 1.33\ 0.97\ 1.44\ 1.08\ 1.19\ 0.88\ 1.15\ 0.99\ 1.06]$

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[22] Calibrated so that the initial emission levels coincides with the one given for 1995 by Nordhaus and Boyer (1999).

[23] Supposed to remain constant.