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Integrated assessment of carbon and sulphur emissions, simulations with the CLIMNEG model*

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Abstract

Combustion of fossil fuels causes carbon emissions which contribute to global climate change. But combustion processes are also responsible for sulphur emissions and sulphate aerosols offset part of the global warming problem since they increase locally the albedo of the Earth's atmosphere. However, sulphate aerosols contribute to the regional acidification and acid rain problem. Integrated assessment analysis of climate change should incorporate these interactions between global and local environmental problems in a consistent way. This paper describes in a theoretical framework the trade off between carbon and sulphur emission control. Necessary conditions are derived for optimal investment, carbon and sulphur emission control rates in a Nash equilibrium and are compared to Pareto efficient policies. The theoretical results are illustrated by means of a numerical simulation model.

Keywords: environmental economics, climate change, integrated assessment model, sulphate aerosol
JEL codes: D9, D62, F42, Q2

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Contents

1 Introduction

After the seminal papers by Nordhaus (Nordhaus [9], Nordhaus and Yang [10], Nordhaus and Boyer [11]) integrated assessment (IA) models of climate change are plentiful and well established. Many of these IA models do not only consider carbon dioxide but also include other pollutants like methane, nitrous oxides, CFCs and sulphur dioxide, see, among others, MERGE (Manne et al. [8]), IMAGE (Alcamo et al. [2]), GEM-E3 (Capros et al. [3]). This raises interesting problems of interaction between several pollutants. For instance, consider the interaction between carbon and sulphur emissions. Both types of emissions result from combustion of fossil fuels. Carbon emissions lead to increasing atmospheric carbon concentrations causing global climate change on a relatively long time horizon. Given its accumulation in the atmosphere, carbon is typically a stock pollutant. Sulphur emissions have two effects. First there is a regional effect due to acid deposition and acid rain. The second effect comes from tropospheric sulphate aerosols that scatter some of the incoming sunlight and therefore offset partly the global warming effect.

Hence, a policy maker that decides to take measures to control sulphur emissions in order to combat local acidification and acid rain is in fact contributing to increase net global warming (greenhouse gas warming minus aerosol cooling) since the regional cooling effect of sulphate aerosols is reduced. To make things even more complicated, one should realize that emissions of carbon and sulphur are not independent. Since carbon emission abatement often involves increasing energy efficiency, sulphur emissions will be reduced as well. However, reducing sulphur emissions does not always result in a reduction of carbon emissions since desulphurization is often an end-pipe solution. Notice also that carbon is to be considered as a stock pollutant given its long atmospheric residence time of several centuries whereas sulphate aerosols can be considered as a flow pollutant since its atmospheric residence time is only a matter of days or weeks at most.

The problem for a rational policy maker is therefore to find an appropriate balance between emission control measures for different but correlated stock and flow pollutants that might have counteracting local and global environmental effects. To our knowledge, this issue of interrelated pollutants has not been studied explicitly yet.

For our analysis we construct a stylized multi-region and dynamic model of the world economy. This model is a multi-region Ramsey type of optimal growth model with endogenous capital accumulation driven by assumptions on regional technological progress, population growth and time preferences. This part of the model resembles closely the original RICE model by Nordhaus and Yang [10]. Emissions of carbon are a function of economic output, exogenous technological progress and endogenous emission abatement policies. Sulphur emissions are modeled as a function of carbon emissions and endogenous emission control policies. Hence, carbon and sulphur emissions are positively correlated. This model of the world economy and emission processes is coupled to a carbon cycle model and a climate model which accounts for the geographical distribution of climate change.

Using this integrated model framework, we derive theoretically optimal investment and carbon and sulphur emission control paths under different scenarios on international cooperation on environmental problems. These conditions reflect the stock and flow characteristics of the pollutants and there transboundary spill-over effects. It is shown that efficient emission reduction policies are inter-depend and cannot be treated separately. Compared to a situation without sulphur emissions, we derive that optimal carbon emission can be higher since they are partly offset by the local sulphate aerosol cooling effect. At the same time, also sulphur emissions are higher (emission control rates are lower) compared to a situation in which we only take into account the acidification effect of sulphur emissions.

We illustrate the theoretical analysis by means of a numerical simulation model called CLIMNEG (CLIMate NEGotiations). The parameterization of this model resembles closely the original RICE model by Nordhaus and Yang [10] although we use a somewhat different formulation of the climate feedback on consumption possibilities. We allow for regional differences in time preference and we re-calibrate the climate change damage parameters using the quantified emission limitation and reduction objectives (QELROs) of the 1997 Kyoto Protocol as a benchmark. In particular, the climate change damage parameters are chosen such that the non-cooperative solution of the model for the Annex B group of countries playing against the rest of the world yields an optimal GHG emission reduction of about 5% by Annex B by the year 2010. Finally, sulphur emission abatement costs and acidification damage functions were calibrated upon estimates with the GEM-E3 model. The simulation results confirm the theoretical insights and indicate that the carbon-sulphur interaction effect might start playing an important role in the medium term in regions severely affected by climate change.

This paper is organized as follows. Section 2 introduces notation and the different components (economy, emissions, carbon cycle and temperature change) of the integrated assessment model. First-order necessary conditions that characterize optimal investment, carbon and sulphur emission control paths for different scenarios (BAU, Nash, Kyoto and Pareto) of international cooperation on climate change are derived in section 3. Simulation results are reported in section 4. Section 5 concludes.

2 Model description

2.1 Economy module

The economic part of the model we will use in this paper resembles closely the seminal integrated assessment model RICE introduced by Nordhaus and Yang [10]. Similar to RICE our model is a multi-region optimal growth model in which growth is driven by exogenous population growth and technological change and by endogenous capital accumulation.

Compared to the original formulation of RICE we introduced some modifications and simplifications which will be discussed and justified in detail later. One of the most important differences is that we consider two pollutants, carbon and sulphur emissions, both of which influence global climate change. Moreover, sulphur emissions are responsible for acidification causing additional regional environmental damages. Let N denote the set of regions[1] indexed $i = 1, 2, \ldots, n$. The following equations describe the *economy* of a country i at time t:

$$Y_{i,t} \;\geq\; Z_{i,t} \;+\; I_{i,t} \;+\; C_{i,t} \;+\; D_{i,t} \tag{1}$$

$$Y_{i,t} \;=\; A_{i,t}\, F_i(K_{i,t}, L_{i,t}) \tag{2}$$

$$K_{i,t+1} \;=\; [1 \;-\; \delta_K]\, K_{i,t} \;+\; I_{i,t} \qquad \text{with} \quad K_{i,0} \text{ given} \tag{3}$$

$$C_{i,t} \;=\; CC_i(AC_{i,t}) \;+\; CS_i(AS_{i,t})) \tag{4}$$

$$D_{i,t} \;=\; DCC_i(\Delta T_{i,t}) \;+\; DA_i(ES_{i,t}) \tag{5}$$

A complete list of all variables and parameters is given in appendix. Equation (1) is a standard budget equation requiring that in every period production $Y_{i,t}$ is sufficient to cover the claims of consumption $Z_{i,t}$, investment $I_{i,t}$, emission abatement costs $C_{i,t}$ and environmental damages $D_{i,t}$ upon production[2]. Expression (2) defines production as a strictly increasing and strictly concave function of capital $K_{i,t}$ and labour input $L_{i,t}$. $A_{i,t}$ measures overall productivity. It is assumed that productivity increases exogenously as time goes by and technological progress is Hicks neutral. Also labour supply is assumed exogenous. In the sequel, both productivity and labour input will be subsumed in the functional form of the production function $F_{i,t}(K_{i,t})$. Expression (3) is a standard capital accumulation equation where δ_K stands for the rate of capital depreciation.

According to expression (4) pollution abatement costs consist of two components related to carbon emissions abatement $AC_{i,t}$ and sulphur emission abatement $AS_{i,t}$ respectively. The cost of abatement functions are assumed strictly increasing and strictly convex in

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[1] In the sequel we will always speak of "regions" even if a region contains only one country.

[2] This formulation is different from the one used by Nordhaus and Yang [10] because we use an additive instead of a multiplicative formulation of climate change damages. Translated into our notation, the budget equation (1) in RICE is given by:

$$\Omega_{i,t}\, Y_{i,t} \;\equiv\; \frac{1 - C_{i,t}/Y_{i,t}}{1 + D_{i,t}/Y_{i,t}}\, Y_{i,t} \;=\; Z_{i,t} \;+\; I_{i,t}$$

Conceptually, both formulations are identical in the sense that the costs of emission abatement and of damage from climate change reduce the amount of production that can be devoted to consumption or investment. The difference between both formulations stems from the fact that Nordhaus and Yang [10] allow for cross effects between emission abatement costs and climate change damages. This type of cross effects are precluded by our formulation.

abatement effort. Likewise, we distinguish in equation (5) between environmental damages related to climate change DCC_i and damages from acid depositions DA_i. Notice that climate change damages are driven by regional temperature change $\Delta T_{i,t}$ and acid deposition damages relate to regional sulphur emissions $ES_{i,t}$. We assume here that the regions are large enough such that acidification can be considered as a local pollution problem. There are no spill overs of sulphur emissions towards other regions. Acidification damages are a function of the flow of sulphur emissions whereas they are in reality a function of acid depositions. Hence, we are ignoring the complex processes of transport and deposition. Both these assumptions are not crucial for our arguments and can be relaxed relatively easily.

It is assumed that countries are choosing consumption, investment, carbon and sulphur emission paths that maximize their lifetime discounted consumption. Lifetime utility of player i is denoted by W_i:

$$W_i = \sum_{t=0}^{T} \frac{Z_{i,t}}{[1 + \rho_i]^t} \tag{6}$$

where ρ_i stands for the discount rate used by country i. Notice that in contrast to Nordhaus and Yang [10] utility is simply linear in consumption an we allow for difference in discount rates across regions.

2.2 Carbon cycle and temperature module

2.2.1 Carbon and sulphur emissions

This simple model of the world economy is coupled to a model of carbon and sulphur emissions, the global carbon cycle and of temperature changes. We start by describing the emission processes for carbon and sulphur.

$$EC_{i,t} = \sigma_{i,t} [1 - AC_{i,t}] Y_{i,t} \tag{7}$$

$$ES_{i,t} = ES_{i,0} [1 - AS_{i,t}] \left[\frac{EC_{i,t}}{EC_{i,0}}\right]^{\nu} \tag{8}$$

According to expression (7), carbon emissions are proportional to production. The emissions to output ratio $\sigma_{i,t}$ declines exogenously over time due to an assumed autonomous energy efficiency increase (AEEI). Carbon emissions can be reduced in two ways. First, one can choose for growing at a lower rate such that production and hence carbon emissions are lower in every period. Secondly, one can reduce carbon emissions at a rate $AC_{i,t} \in [0, 1]$ in every period though this is costly according to the cost function CC_i.

For sulphur emissions, we use a similar specification as in Yohe and Schlesinger [18]. The parameter ν denotes the elasticity of sulphur emissions w.r.t. carbon emissions, i.e. the degree to which sulphur emission change as a result of a change in carbon emissions. We add however, the possibility to reduce sulphur emission at a rate $AS_{i,t} \in [0,1]$. Notice the particular interaction between both pollutants. Sulphur emissions are assumed to be an increasing function of carbon emissions. Reducing carbon emissions most often involves increasing energy efficiency which results at the same time in a decrease of sulphur emissions. The other way round does not work. Lowering sulphur emissions often involves installing some end-pipe technology like a smoke stack scrubber which has only a negligible effect on carbon emissions. Hence, also sulphur emissions can be reduced in two ways. First, we consider the possibility of specific sulphur emission abatement at a rate $AS_{i,t} \in [0,1]$, the cost of which is given by the cost function CS_i. Secondly, sulphur can be abated indirectly by lowering carbon emissions $EC_{i,t}$. The ways to achieve carbon abatement were described higher. Technological progress (in particular the AEEI) also affects sulphur emissions because of the positive correlation between carbon and sulphur emissions.

2.2.2 Pulse-response model for atmospheric carbon concentration

The carbon system behaves in an approximately linear way as long as the atmospheric concentration does not vary much. Therefore, when considering the fate of anthropogenic CO_2, the emission into the atmosphere can be considered as a series of consecutive pulse inputs. Then, the development of the atmospheric CO_2 concentration for prescribed emissions can be given by the convolution integral of the emission history with the atmospheric pulse response (Siegenthaler and Oeschger [17], Oeschger and Heimann [12], Maier-Reimer and Hasselmann [7], Sarmiento et al. [15]). The atmospheric CO_2 concentration at time t, M_t, is represented in the model as being the initial atmospheric CO_2 concentration at time 0 (when the system was found to be in equilibrium), M_0, plus the sum of earlier emissions from this base year, $EC_{N,t'}$[3], at times t', multiplied by the fraction still remaining airborne after time $t - t'$.

$$M_t \;=\; M_0 \;+\; \sum_{t'=1}^{t} \tau_a(t-t')\, EC_{N,t'} \tag{9}$$

The linear response function (pulse response), τ_a, was computed from the Maier-Reimer and Hasselmann carbon-oceanic general circulation model (see Maier-Reimer and Hasselmann [7]) and expressed as a number of exponentials of different amplitude A_i and relaxation time ν_i in the form:

$$\tau_a(t) \;=\; A_0 \;+\; \sum A_i e^{-t/\nu_i} \tag{10}$$

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[3] At some instances we will denote the sum over a set of countries by means of a subscript: $EC_{N,t} \equiv \sum_{j\in N} EC_{j,t}$.

where, $A_0+\sum A_i = 1.0$ and ν_i is the time constant governing the decrease in the fraction A_i of the initially injected CO_2. The amplitude A_0 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 ν_i (Maier-Reimer and Hasselmann [7]).

2.2.3 Regional temperature change

In the theoretical model we consider a simplified version of the temperature change model in order to characterize the optimal emission strategies for a region under different scenarios of coordination of environmental policies. The simplification consists of writing temperature change in region i induced by carbon and sulphur emissions as a general function g_i that is increasing in atmospheric carbon concentration and decreasing in sulphur emissions. Notice that carbon emissions are treated as a stock pollutant accumulating in the atmosphere whereas sulphur emissions are treated as a flow pollutant. The difference between both is justified on the basis of the short atmospheric residence life of sulphur emissions.

$$\Delta T_{i,t} \;=\; g_i(M_t, ES_{N,t}) \qquad \text{with} \quad g_i^M \equiv \frac{\partial g_i}{\partial M_t} \geq 0 \quad \text{and} \quad g_i^S \equiv \frac{\partial g_i}{\partial E^S_{N,t}} \leq 0 \tag{11}$$

However, in the simulation section of the paper, the general function g_i is replaced by a more realistic representation of the climate system. The time-dependent regional distribution of temperature change, $\Delta T_{i,t}$ is computed according to a method (Santer et al. [14]) which combines the geographical distribution of equilibrium climate change ($T_{exp,i} - T_{con,i}$), simulated by a general circulation model (GCM), each normalized by its individual annual global mean surface air temperature change ($\bar{T}_{exp} - \bar{T}_{con}$), with the time-dependent change in annual global mean surface air temperature, $\Delta\bar{T}_{trans,t}$, simulated by simplified climate model relating anthropogenic forcing, ΔQ, to transient temperature change.

$$\Delta T_{i,t} \;=\; \Delta\bar{T}_{trans,t}\left(\frac{T_{exp,i} - T_{con,i}}{\bar{T}_{exp} - \bar{T}_{con}}\right) \tag{12}$$

where, the subscript $_{con}$ refers to the control GCM simulation (e.g., $1xCO_2$ simulation), and subscript $_{exp}$ to experiment-induced equilibrium climate change (e.g., $2xCO_2$ and $10xSO_4$ simulation). Reference GCM simulations of $2xCO_2$ induced and $10xSO_4$ aerosol-induced climate changes have been performed by means of the UIUC 11-layer atmospheric general circulation/mixed-layer-ocean model (AGCM/MLO) (Schlesinger et al. [16]).

Assuming that the normalized pattern of climate changes caused by indirect sulphate forcing is the same as that caused by the direct forcing (Schlesinger et al. [16]), the geographical patterns of surface-air temperature change in response to the anthropogenic CO_2

and SO_2 emissions is then provided by:

$$\Delta T_{i,t} \;=\; \Delta TC_t \left(\frac{T_{2\times CO_2,i} \;-\; T_{con,i}}{\bar{T}_{2\times CO_2} \;-\; \bar{T}_{con}} \right) \;+\; \Delta TS_t \left(\frac{T^{D}_{10\times SO_4,i} \;-\; T_{con,i}}{\bar{T}^{D}_{10\times SO_4} \;-\; \bar{T}_{con}} \right) \tag{13}$$

where, $\Delta TS_t = \Delta TS^D_t + \Delta TS^I_t$ is the change in the annual and global mean air surface temperature simulated in response to the direct plus indirect sulphate radiative forcing.

Finally, the time evolution of the annual and global mean surface air temperature response to a given radiative forcing (e.g., ΔTC_t and ΔTS_t) is computed according to the Nordhaus and Yang's [10] formulation. Nevertheless, in order to include the sulphate forcing (lacking in RICE), the radiative forcing at time t (relative to the pre-industrial era), ΔQ_t, has been re-written as follows:

$$\Delta Q_t \;=\; \Delta Q_{1990} \;+\; (\Delta QC_t - \Delta QC_{1990}) \;+\; (\Delta QS_t - \Delta QS_{1990}) \tag{14}$$

where, $\Delta Q_{1990} \;=\; 1.12\ \mathrm{Wm}^{-2}$ represents the total anthropogenic radiative forcing (all greenhouse gas plus sulphate) in the year 1990. $\Delta QC_t \;=\; \Delta QC_{2\times CO_2} \left(\frac{\ln(M_t/M_0)}{\ln(2)} \right)$ is the carbon dioxide radiative forcing at time t; $\Delta QC_{2\times CO_2} \;=\; 4.37\ \mathrm{Wm}^{-2}$ being the radiative forcing due to a doubling of the pre-industrial CO_2 concentration, M_t and M_0 the atmospheric CO_2 concentration at time t and at the pre-industrial level respectively. $\Delta QS_t = \Delta Q^D_{1990} \left(\frac{ES_{N,t}}{ES_{N,1990}} \right) + \Delta Q^I_{1990} \left(\frac{\log(1+ES_{N,t}/ES_{N,nat})}{\log(1+ES_{N,1990}/ES_{N,nat})} \right)$ is the total sulphate radiative forcing at time t with, $ES_{N,t}$ the global anthropogenic emission rate of sulphur in the form of sulphur dioxide ($ES_{N,1990}$ = 69.1 MtS), $ES_{N,nat}$ the natural emission rate (= 42 MtS), ΔQS^D_{1990} = -0.3 Wm^{-2} the sulphate direct radiative forcing in 1990, and ΔQS^I_{1990} = -0.8 Wm^{-2}, the sulphate indirect radiative forcing (Harvey et al. [6]).

The major assumption behind our regionalized climate representation is that while the real world climate system is by definition a highly non-linear system, such a system behaves in an approximately linear way as long as the anthropogenic radiative perturbations are not too large. This representation clearly enables us to account for possible future change in ocean circulation and the resulting geographical redistribution of climate change. Moreover, while the climate module allows us to consider the anthropogenic CO_2 radiative forcing and anthropogenic sulphate forcing perturbation as well, the geographical distribution of temperature change associated to this last forcing is governed by the present day anthropogenic sulphur sources emission distribution. Clearly, a number of limitations are associated to the climate module we propose. Nevertheless, while the method is imperfect, it is a practicable method to compute climate-change patterns that is far less computationally demanding than the arguably best-possible method.

3 Characterizing optimal emission policies under different policy regimes

3.1 Non-cooperative Nash equilibrium

Using the abstract formulation of the carbon cycle and regional climate changes we now turn to deriving necessary first-order conditions for optimal investment, carbon and sulphur emissions paths for an individual country. We assume *Nash behaviour* meaning that countries take as given the investment and emission decisions by all other countries. A Nash equilibrium can be characterized by maximizing every region's utility subject to the individual resource and capital constraint and the climate module for a given carbon and sulphur emission strategies $\overline{EC}_{-i,t}$[4] and $\overline{ES}_{-i,t}$ of all other players $j \neq i$ and $\forall t$:

$$\max_{Z_{i,t}, I_{i,t}, K_{i,t}, AC_{i,t}, AS_{i,t}, M_t} \quad \sum_{t=0}^{T} \frac{Z_{i,t}}{[1+\rho_i]^t} \tag{15}$$

subject to (for all $0 \leq t \leq T$):

$$\begin{aligned} F_{i,t}(K_{i,t}) &\geq Z_{i,t} + I_{i,t} + CC_i(AC_{i,t}) + CS_i(AS_{i,t}) + DCC_i(\Delta T_{i,t}) + DA_i(ES_{i,t}) \\ K_{i,t+1} &= [1 - \delta_K]\, K_{i,t} + I_{i,t} \qquad \text{with} K_{i,0} \quad \text{given} \\ M_t &= M_0 + \sum_{t'=1}^{t} EC_{N,t'}\, \tau_{t-t'} \end{aligned}$$

with $EC_{i,t} = \sigma_{i,t}[1 - AC_{i,t}]F_{i,t}(K_{i,t})$, $ES_{i,t} = ES_{i,0}[1 - AS_{i,t}][EC_{i,t}/EC_{i,0}]^{\nu}$ and $\Delta T_{i,t} = g_i(M_t, ES_{N,t})$. In addition, the variables $AC_{i,t}$ and $AS_{i,t}$ are required to be non-negative. We associate Lagrange multipliers $\zeta_{i,t}$ to the resource constraint, $\psi_{i,t}$ to the capital accumulation constraint and $\phi_{i,t}$ to the carbon accumulation process. First-order necessary conditions for an interior optimum can be written as follows (the superscript $^\circ$ refers to the equilibrium values of the variables for the Nash equilibrium, all functions are evaluated at

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[4] $EC_{-i,t}$ denotes the sum of carbon emissions over all countries except i: $\sum_{j \in N, j \neq i} EC_{j,t}$.

this Nash equilibrium):

$$\zeta^{\circ}_{i,t} = \frac{1}{[1+\rho_i]^t} = \psi^{\circ}_{i,t} \tag{16}$$

$$\begin{aligned} \psi^{\circ}_{i,t-1} &= \psi^{\circ}_{i,t} \left\{ F'_{i,t} + [1 - \delta_K] + F'_{i,t} \left[g^S_{i,t}\, DCC'_{i,t} + DA'_{i,t} \right] \frac{\partial ES_{i,t}}{\partial EC_{i,t}} \frac{\partial EC_{i,t}}{\partial Y_{i,t}} \right\} \\ &\quad + F'_{i,t} \frac{\partial EC_{i,t}}{\partial Y_{i,t}} \sum_{t'=t}^{T} \phi^{\circ}_{i,t'}\, \tau_{t'-t} \end{aligned} \tag{17}$$

$$\zeta^{\circ}_{i,t}\, CC'_{i,t} = -\, \zeta^{\circ}_{i,t} \left[g^S_{i,t}\, DCC'_{i,t} + DA'_{i,t} \right] \frac{\partial ES_{i,t}}{\partial EC_{i,t}} \frac{\partial EC_{i,t}}{\partial AC_{i,t}} - \frac{\partial EC_{i,t}}{\partial AC_{i,t}} \sum_{t'=t}^{T} \phi^{\circ}_{i,t'}\, \tau_{t'-t} \tag{18}$$

$$CS'_{i,t} = -\, \left[g^S_{i,t}\, DCC'_{i,t} + DA'_{i,t} \right] \frac{\partial ES_{i,t}}{\partial AS_{i,t}} \tag{19}$$

$$\phi^{\circ}_{i,t} = \zeta^{\circ}_{i,t}\, g^M_{i,t}\, DCC'_{i,t} \tag{20}$$

A Nash equilibrium is a simultaneous solution to this system of first-order conditions for all $i \in N$ and $0 \le t \le T$. If the non-negativity constraints on $AC_{i,t}$ or $AS_{i,t}$ would be binding, the equality signs in expressions (18) and (19) should be replace by a strictly greater than sign. The first set of conditions (16) says that the shadow cost of capital equals the shadow cost of the resource constraint and that both are equal to the region's discount factor. The evolution of the capital stock is described by conditions (17). Expressions (18) and (19) determine the optimal amount of carbon and sulphur emission control for country i. Expression (20) describes the evolution of the shadow price of atmospheric carbon concentration.

Sulphur control

Rewriting first-order condition (19) using the definition of sulphur emission (8), we derive the characterization of the optimal sulphur emission control path for country i in a Nash equilibrium:

$$\widetilde{CS}'_{i,t} \equiv \frac{CS'_{i,t}}{ES_{i,0}\, [EC^{\circ}_{i,t}/EC_{i,0}]^{\nu}} = g^S_{i,t}\, DCC'_{i,t} + DA'_{i,t} \tag{21}$$

($>$ if $AS^{\circ}_{i,t} = 0$). $\widetilde{CS}_{i,t}$ stands for the marginal sulphur emission abatement cost expressed in \$ per ton of sulphur. The denominator $ES^{\circ}_{i,0}\, [EC^{\circ}_{i,t}/EC_{i,0}]^{\nu} = \partial ES_{i,t}/\partial AS_{i,t}$ stands for the unabated sulphur emissions. The RHS stands for all marginal environmental damage effects of sulphur emissions. The first term $g^S_{i,t}\, DCC'_{i,t}$ stands for the instantaneous and local *cooling* effect of sulphur emissions through sulphur aerosols. The second term $DA'_{i,t}$ denotes the local *acidification* effect of sulphur emissions and subsequent depositions.

Observation 1 *In a Nash equilibrium sulphur emission control rates are lower compared to a situation in which the cooling effect of sulphate aerosols would not play.*

This observation is obvious from (21) since $g^S_{i,t} \geq 0$ and since sulphur emission abatement costs are assumed convex. The sulphate aerosol cooling effect reduces the need for sulphur emission control, hence, sulphur emission levels are higher than without cooling. If sulphate aerosols would have no cooling effect (or if we would not value climate change damages), the optimal sulphur emission control rates would only take into account the acidification effect of sulphur emissions and we recover the familiar condition that marginal abatement costs should be equal to marginal acidification damages. In an integrated assessment framework however, optimal abatement effort should balance the cooling benefits and acidification damages of sulphur emissions.

It might even happen that the cooling effect dominates the acidification damages if $g^S_{i,t}\, DCC'_{i,t} + DA'_{i,t} < 0$. In that case it is optimal not to reduce sulphur emissions at all: $AS^\circ_{i,t} = 0$. This is more likely to happen for regions with relatively high climate change damage valuations, strong aerosol cooling effect and relatively low acidification damages.

Carbon control

Using the end period condition $\phi^\circ_{i,T} = 0$ and integrating condition (20), we establish the necessary condition driving the optimal carbon emission control path for country i in a Nash equilibrium:

$$\widetilde{CC}'_{i,t} \;\equiv\; \frac{CC'_{i,t}}{\sigma_{i,t}\, F_{i,t}} \;=\; \left[g^S_{i,t}\, DCC'_{i,t} \;+\; DA'_{i,t}\right]\, \nu\, \frac{ES^\circ_{i,t}}{EC^\circ_{i,t}} \;+\; \sum_{t'=t}^{T} \frac{\tau_{t'-t}\; g^M_{i,t}\; DCC'_{i,t}}{[1+\rho_i]^{t'-t}} \qquad (22)$$

($>$ if $AC^\circ_{i,t} = 0$). The LHS of equation (22) denotes marginal carbon emission abatement costs expressed in \$ per ton of carbon. The denominator $\sigma_{i,t}\, F_{i,t}$ stands for the unabated carbon emissions and is used to redefine the units of measurement of carbon emissions. In a Nash equilibrium, every country i abates its carbon emissions in period t such that its individual marginal abatement costs of an additional ton of carbon abated are exactly equal to all the future marginal environmental damages, including climate cooling and warming and acidification, from emitting that extra ton of carbon.

Marginal damages consist of three terms. The first two terms refer to the flow pollution effect of sulphur emissions, the last term refers to the stock pollution effect of carbon accumulation. The first term $[g^S_{i,t}\, DCC'_{i,t}]\, \nu\, \frac{ES^\circ_{i,t}}{EC^\circ_{i,t}}$ describes the instantaneous climate change *cooling* effect of an additional ton of carbon emitted. Higher carbon emissions result in higher sulphur emissions and, hence, higher aerosol concentrations. These aerosol concentrations have a regional climate cooling effect (recall that $g^S_{i,t} \leq 0$). The second term $DA'_{i,t}\, \nu \, \frac{ES^\circ_{i,t}}{EC^\circ_{i,t}}$ stands for the instantaneous *acidification* effect of emitting an extra ton of carbon. Higher carbon emissions result in higher sulphur emissions and hence, locally, in higher acid depositions. The last term $\sum_{t'=t}^{T} \frac{\tau_{t'-t}\, g^M_{i,t}\, DCC'_{i,t}}{[1+\rho_i]^{t'-t}}$ denotes the marginal climate change damages from increased carbon emissions through its cumulative effect on future atmospheric carbon concentrations. It consists of the discounted sum from period t until the final period T, of marginal climate change damages weighted by the appropriate retention factor $\tau_{t'-t}$ and climate impact factor $g^M_{i,t}$.

Observation 2 *In a Nash equilibrium carbon emission control rates are higher (lower) if* $g^S_{i,t}\, DCC'_{i,t} + DA'_{i,t} \geq (\leq) 0$ *compared to a situation in which the cooling effect of sulphate aerosols would not play.*

Whenever the optimal sulphur emission control rate is strictly positive, condition (21) holds with equality and, hence, $g^S_{i,t}\, DCC'_{i,t} + DA'_{i,t} > 0$. Since carbon abatement costs are convex, carbon control rates must be higher compared to a situation without acidification and sulphate aerosol cooling effect. This is intuitively clear. If there is a benefit to sulphur emission control (i.e. if the acidification damages dominate the cooling benefits), carbon emission should be reduced a little more because there is a positive correlation between carbon and sulphur emissions. On the other hand, if the sulphate aerosol cooling benefits over-compensate the acidification damages, carbon emission control should be relaxed.

Finally, we notice three things. First, it may happen that the the non-negativity constraint on carbon emission control is binding if the sulphate aerosol cooling effect is very strong. The first (negative) term in (22) would dominate in that case the acidification and climate change components. This is a theoretical possibility but, as we will see later in the simulations, it will probably never occur in reality. Secondly, conditions (21) and (22) show very clearly the difference between stock and flow pollutants. For flow pollutants, the optimal control rate at time t only considers instantaneous damages. Stock pollutant control at time t on the other hand takes into account all future (discounted for time preference and natural stock decay) damages until the end of time. Thirdly, notice that in a Nash equilibrium every country only takes into account its own individual marginal damages from climate change and does not internalize the external effects of its carbon emissions on the other regions. This is a typical aspect of Nash equilibria in the context of global warming (Eyckmans and Tulkens [5]).

Capital accumulation

Finally, we can derive the characterization of the optimal investment and capital accumulation path.

$$\begin{aligned} F_i' \Bigg[1 \; - \; \sigma_{i,t}\,[1 - AC^\circ_{i,t}] \; \left[DCC'_{i,t}\, g^S_{i,t} \; + \; DA'_{i,t}\right] \nu \, ES^\circ_{i,t}/EC^\circ_{i,t} \; - \\ \sigma_{i,t}[1 - AC^\circ_{i,t}] \sum_{t'=t}^{T} \frac{\tau_{t'-t}\; g^M_{i,t}\; DCC'_{i,t}}{[1+\rho_i]^{t'-t}} \Bigg] \; = \; \rho_i \; + \; \delta_K \end{aligned} \tag{23}$$

It is useful to consider how this expression looks like if countries would not care about environmental damages, i.e. $DCC'_{i,t} = 0$ and $DA'_{i,t} = 0$. In that case, expression (23) boils down to simply: $F_i' \; - \; \delta_K \; = \; \rho_i$. Regions choose investment paths and hence capital stock such that the marginal value the last dollar consumed at time t equals the net marginal product of investing that dollar in next period's capital stock. This condition is equivalent to the standard *Ramsey-Keynes* optimal growth rule in a model without externalities. However, when regions do value environmental damages, i.e. $DCC_i' > 0$ and $DA_i' > 0$, the choice of optimal investment paths is affected by the environmental damages through the *stock* of airborne carbon emissions and the *flow* of sulphur emissions. Again we recognize the three damage components: sulphate aerosol *cooling*, sulphur *acidification* and carbon induced *climate change* in equation (23). The *acidification* and *climate change* components tend to decrease capital formation because it leads to more production, hence higher carbon and sulphur emission and therefore to increased acidification and global warming. The *cooling* effect tends to promote capital formation in order to increase production, carbon and hence sulphur emissions which causes some offsetting climate cooling through higher aerosol concentrations.

Observation 3 *In a Nash equilibrium capital accumulation will be lower (higher) if* $g^S_{i,t}\, DCC'_{i,t} + DA'_{i,t} \geq (\leq) 0$ *compared to a situation in which the cooling effect of sulphate aerosols would not play.*

This is another way of saying that if there is a need for carbon control (i.e. if the cooling effect in (22) does not over-compensate the acidification and climate change damages), optimal capital accumulation and GDP growth will be lower in a Nash equilibrium.

3.2 Pareto efficient allocation

In the previous section, we have considered only an individual region's optimization problem. This can be interpreted as a free market outcome in which regions act in function of their self interest without taking into account spill over effects of their emissions to their neighbours. It is a well established fact that this type of Nash equilibrium leads towards too much climate change damage compared to the socially desirable level of pollution. Basically, the problem of a hypothetical world planner consists in solving a joint welfare maximization problem with objective function:

$$\max_{Z_{i,t},\, I_{i,t},\, K_{i,t},\, AC_{i,t},\, AS_{i,t},\, M_t} \quad \sum_{i\in N}\sum_{t=0}^{T} \frac{Z_{i,t}}{[1+\rho_i]^t} \tag{24}$$

The necessary condition for a Pareto efficient sulphur emission abatement path is given by (the superscript * refers to the equilibrium values of the variables at the Pareto efficient allocation, all functions are evaluated at this Pareto efficient allocation):

$$\widetilde{CS}'_{i,t} \;\equiv\; \frac{CS'_{i,t}}{ES_{i,0}\,[EC^*_{i,t}/EC_{i,0}]^{\nu}} \;=\; DA'_{i,t} \;+\; [1+\rho_i]^t \sum_{j\in N} \frac{g^S_{j,t}\, DCC'_{j,t}}{[1+\rho_j]^t} \tag{25}$$

with $>$ if $AS^*_{i,t} = 0$. We can establish similar observations on the comparison between the Pareto optimal emission control rates and the situation in which we would not take into account the sulphur-carbon interactions. We will not repeat these observations but instead we will try to compare the Pareto optimal control rates with the Nash equilibrium abatement effort. Compared to the Nash scenario, the Pareto optimal sulphur control rate should also take into account the cooling effect in all other regions than i. There is no summing over all regions[5] of the climate cooling effects in condition (21). It is therefore likely that sulphur abatement will be lower (and hence, sulphur emissions will be higher) in the Pareto scenario compared to the Nash scenario[6]. Notice also that if discount rates are the same for all regions, expression (25) simplifies considerably to $\widetilde{CS}'_{i,t} = DA'_{i,t} + \sum_{j\in N} g^S_{j,t} DCC'_{j,t}$.

Pareto optimal carbon abatement is characterized by the following condition:

$$\begin{aligned}\widetilde{CC}'_{i,t} \;\equiv\; \frac{CC'_{i,t}}{\sigma_{i,t}\, F_{i,t}} \;=\; \left[DA'_{i,t} \;+\; [1+\rho_i]^t \sum_{j\in N} \frac{g^S_{j,t}\, DCC'_{j,t}}{[1+\rho_j]^t}\right] \nu\, \frac{ES^*_{i,t}}{EC^*_{i,t}} \;+ \\ [1+\rho_i]^t \sum_{t'=t}^{T} \tau_{t'-t} \sum_{j\in N} \frac{g^M_{j,t'}\, DCC'_{j,t'}}{[1+\rho_j]^{t'}}\end{aligned} \tag{26}$$

---

[5] At this point it is also easy to see what would be the effect of considering sulphur emissions as a stock pollutant and allowing for regional transfers of sulphur emissions. This would modify the conditions above only with respect to the acidification damages $DA'_{i,t}$ which would be replaced by a double sum: $\sum_{j\in N}\sum_{t'=t}^{T} \alpha_{i,j}\, DA'_{j,t}\, [\frac{\delta_S}{1+\rho}]^{t'-t}$ with α a $n \times n$ transfer coefficient matrix and δ_S the natural decay rate of sulphur concentrations in the soil (and assuming equal discount rates $\rho_i = \rho_j = \rho$)

[6] This claim is difficult to prove formally since we have not made assumptions on the concavity/convexity of the climate impact function $g_i(M_t, ES_{N,t})$. If both acidification and climate change marginal damages are constant (hence, damages are linear), and if the climate impact function is convex in sulphur emissions, then this claim holds for sure.

with $>$ if $AC^*_{i,t} = 0$. The difference with the corresponding condition (22) for a Nash equilibrium stems from the internalization of the spill over effects to other regions. Again, it is not obvious to determine a priori whether carbon emission control will be higher or lower compared to a Nash equilibrium. At the one hand, the global warming effect plays stronger because of the internalization of all regions' climate change damages. On the other hand, also the cooling effect is stronger because of the same reason. How these effects balance, is difficult to determine a priori.

In a Pareto optimal allocation, marginal carbon abatement costs need not always be equalized over all regions. Differences in marginal carbon abatement costs can arise as a result of, first, differences in marginal acidification damages, and, secondly, differences in discount rates. Even if discount rates would be equal in all regions[7], differences in marginal carbon abatement costs can be justified in a Pareto optimal allocation because marginal acidification damages need not be the same everywhere.

Finally, we report the necessary conditions for optimal investment paths under the assumption that discount rates are equal in all regions (extending the formula to different discount rates should be straightforward from the previous):

$$
\begin{aligned}
F'_i \Bigg[1 \;-\; \sigma_{i,t}\,[1 - AC^*_{i,t}] \Bigg[DA'_{i,t} \;+\; \sum_{j \in N} DCC'_{j,t}\, g^S_{j,t} \Bigg] \nu\, ES^*_{i,t}/EC^*_{i,t} \;- \\
\sigma_{i,t}[1 - AC^*_{i,t}] \sum_{t'=t}^{T} \tau_{t'-t} \sum_{j \in N} \frac{g^M_{j,t}\; DCC'_{j,t}}{[1+\rho]^{t'-t}} \Bigg] \;=\; \rho_i \;+\; \delta_K
\end{aligned}
\tag{27}
$$

For the same reason as before, the comparison between Nash and Pareto optimal capital accumulation trajectories is not straightforward. We will turn to simulations in order to answer these questions in the next section.

---

[7] In this case, condition (26) simplifies to:

$$
\widetilde{CC}'_{i,t} \;=\; \Bigg[DA'_{i,t} \;+\; \sum_{j \in N} g^S_{j,t}\, DCC'_{j,t} \Bigg] \nu\, \frac{ES^*_{i,t}}{EC^*_{i,t}} \;+\; \sum_{t'=t}^{T} \tau_{t'-t} \sum_{j \in N} \frac{g^M_{j,t'}\; DCC'_{j,t'}}{[1+\rho]^{t'-t}}
$$

4 Simulations

4.1 Parameterizing the simulation model

The world was divided into six regions: *USA*, *Japan*, *EU*, *China*, *FSU* (Former Soviet Union) and *ROW* (Rest of the World). For most parameters and functions, we use the values assumed by Nordhaus and Yang [10] in the original version of RICE. In Appendix, we report the functional forms and exact parameter values we used for the climate change damage functions DCC_i, the carbon abatement cost functions CC_i, the production functions F_i. Notice that in contrast to Nordhaus and Yang [10] we use different discount rates for the regions which, in our opinion, reflects better the different preferences the regions hold w.r.t. inter-temporal choices, see Table 3. Finally, economic growth predictions of *Former Soviet Union* are revised downward in order to match more closely recent data and predictions.

We also re-calibrated the climate change damage parameters (in particular the exponent of the climate change damage function) such that our model replicates the Kyoto agreement GHG emission abatement commitment by the Annex B countries. This means that we computed a non-cooperative Nash equilibrium in which we consider the Annex B countries as one region (notice that the Annex B is approximately equal to the coalition { *USA*, *Japan*, *EU*, *FSU* }). We had to increase the damage function exponent in order to make the Annex B countries choose about 5% carbon emission reduction w.r.t. 1990 to be achieved in 2010.

For the sulphur emission abatement cost function and regional acidification damage estimates, we used data from the European computable general equilibrium model GEM-E3. A description of this model can be found in Capros et al. [3]. The sulphur abatement cost function is based upon a cost function that was calculated for the German economy in the GEM-E3 model. We extrapolated this function to all other regions in our model[8]. The acidification damage valuations are based upon figures from the European ExternE project that were appropriately extrapolated to the other world regions in the GEM-E3 model.

4.2 Sulphur emission scenarios and policy regimes

We distinguish four different *sulphur emission scenarios*:

1. high sulphur emissions (HIGH)
   In the HIGH scenario, sulphur emissions are given by: $E^S_{i,t} = ES_{i,0}\ [EC_{i,t}/EC_{i,0}]^{\nu}$ with $\nu = 0.80$. The parameter ν denotes the elasticity of sulphur emissions w.r.t.

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[8] Details on this cost function are available from the authors upon request.

production. Hence, a 10 % increase in production will lead to an 8 % increase in sulphur emissions.

2. medium sulphur emissions (MEDIUM)
   In the MEDIUM scenario, the elasticity of sulphur emissions w.r.t. production is $\nu = 0.65$. This scenario will serve as reference point for the simulations including sulphur emissions. The elasticity was chosen because it generates a sulphur emission path that mimics the baseline scenario of the IMAGE 2.1 model as described in Alcamo et al. [1] and Posch et al. [13].

3. low sulphur emissions (LOW)
   In the LOW scenario, the elasticity of sulphur emissions w.r.t. production is $\nu = 0.40$.

4. constant sulphur emissions (CONSTANT)
   Finally, we consider a scenario with constant (1990) sulphur emissions: if $\nu = 0.00$, hence $E^S_{i,t} = ES_{i,0}$. This scenario is useful as a bench mark since it contains no fluctuations in sulphur emissions.

For each of these sulphur emission scenarios we computed three different *policy regimes*:

1. Business-As-Usual (BAU)
   The BAU scenario refers to a situation in which the regions do not take action to restrict emissions of carbon or sulphur, i.e. $AC_{i,t} = AS_{i,t} = 0$. Emissions and climate change are computed ex post after an economic optimization that ignores climate change and acidification damages.

2. Kyoto Partial Agreement Nash Equilibrium (KYOTO)
   The KYOTO scenario is a non-cooperative Nash equilibrium in which we consider the Annex B coalition of countries { *USA*, *Japan*, *EU*, *FSU* }) as only one player. The Annex B coalition chooses emission control and investment policies in order to maximize its joint discounted life time consumption. At the same time the remaining regions *China* and *ROW* individually maximize their life time consumption given the emission policy choices of the other players[9].

3. Pareto efficient allocation (COOP)
   In the COOP scenario, carbon emission trajectories are chosen to maximize overall welfare of all regions. Emission abatement policies internalize perfectly the climate change and acidification externalities.

Combining all sulphur emission scenarios and policy regimes, we have made $4 \times 3 = 12$ simulation runs. All these simulations were made for a sufficiently long time horizon of 320 years in order to minimize end-period effects. The graphs will be cut off at 250 years.

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[9] This solution concept is called a Partial Agreement Nash Equilibrium and is explained in detail in Chander and Tulkens [4] and Eyckmans and Tulkens [5].

4.3 Sulphur emissions, carbon accumulation and temperature change

Figure 1 shows world sulphur emissions under all the different sulphur emission scenarios and policy regimes. Business-as-usual sulphur emission trajectories are strongly diverting. World sulphur emissions in the year 2100 range from about 150 MtS for the BAU-L and 250 MtS for the BAU-M to 350 MtS for the BAU-H. The constant sulphur emission scenario fixes sulphur emissions at 69.1 MtS throughout the entire planning horizon. BAU emissions were computed ex post after an economic optimization that ignores climate change and acidification damages.

In contrast, KYOTO and COOP sulphur emissions are determined endogenously and are consistent with conditions (21) and (25) we derived in the theoretical section. For the time being we notice that overall sulphur emissions in the COOP policy regime are lower compared to the KYOTO and BAU regimes. For the KYOTO and COOP emission trajectories we notice a dip in the emission in the first periods 2000 and 2010. This is due to the assumption that sulphur abatement is zero in 1990. Though this assumption is hard to justify in reality, it has only a negligible impact on the rest of the simulated emission paths.

Figure 1: World sulphur emissions (MtS)

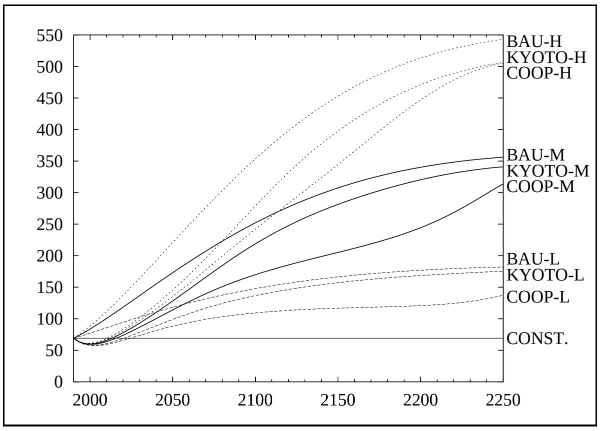


Figure 2: World carbon emissions (GtC)

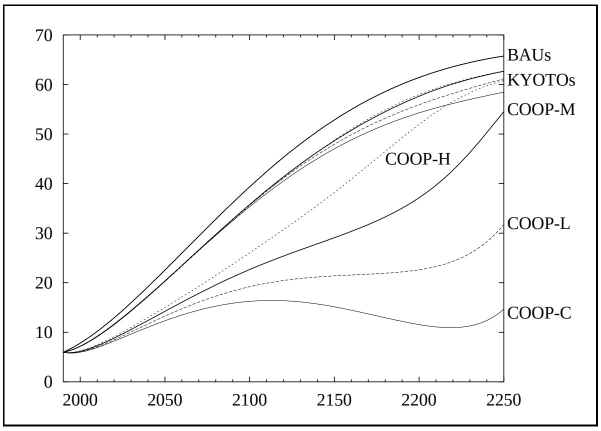


Figure 2 shows world carbon emissions under the different sulphur emission scenarios and policy regimes. The BAU carbon emissions trajectories coincide for all sulphur emission scenario since in BAU, we computed emissions ex post without taking into account environmental externalities. All KYOTO carbon emission paths are all close together and show only a moderate emission abatement effort compared to BAU. For the MEDIUM sulphur emission scenario, the Annex B group of countries reduces its emissions by little more than 5% in 2010 compared to 1990 emission levels. This was the bench mark we used for calibrating damage functions. Under the KYOTO regime, world carbon emissions amount to approximately 36 GtC in 2100 compared to 40 GtC under BAU.

There is a strong divergence between the COOP carbon emission trajectories depending upon the sulphur emission scenario. If the elasticity of sulphur w.r.t. carbon emissions (ν) is large as in the COOP-H scenario, Pareto optimal carbon emissions are close to the KYOTO emission trajectory. They divert however strongly for the COOP-L and COOP-C scenarios. For COOP-L and COOP-C, the optimal cooperative carbon emissions are levelling off or even decreasing after an initial period of emission growth.

Figure 3: World sulphur emission abatement (%)

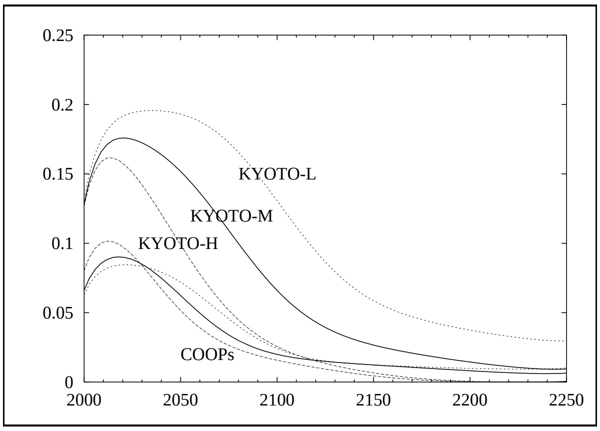
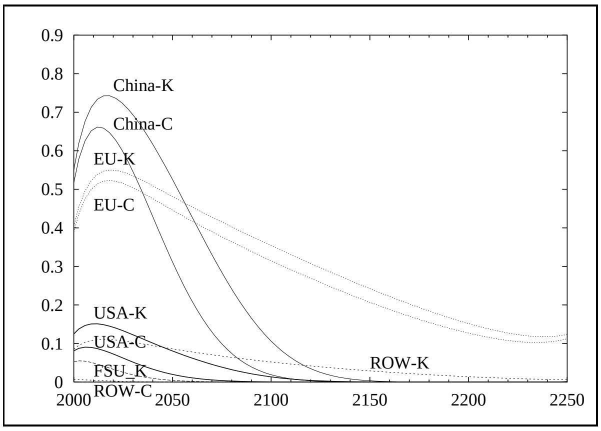


Figure 4: Regional sulphur emission abatement (MEDIUM) (%)



Figures 3 and 4 show world and regional sulphur emission control rates for the KYOTO and COOP policy regimes. The KYOTO-C (CONSTANT sulphur emissions) regime is not displayed since sulphur emissions are fixed in this case and sulphur abatement is set to zero. Sulphur emission control peaks in the first decades but decreases rapidly towards 2100. This is due to the fact that climate change damages are becoming more important and, hence, the cooling effect of sulphur emissions starts playing a more important role in determining the optimal sulphur control rate.

We see that the world sulphur abatement effort is considerably higher in the KYOTO than in the COOP policy regime for all the sulphur emission scenarios. The simulations confirm our a priori expectations based upon comparing conditions (21) and (25). In the COOP policy regime, the cooling effect plays stronger since it is summed over all regions. In the non-cooperative KYOTO scenario, only the regional cooling effect is taken into account. According to Figure 4, this effect plays for all regions individually as well.

Though *sulphur emission abatement* is clearly stronger in the KYOTO regime compared to the COOP regime, it is interesting to look back at Figure 1. We see that *sulphur* *emission levels* are higher in KYOTO than in COOP regime. This seems counter intuitive but can readily be explained by considering the sulphur emission process in (8). Indeed, sulphur emissions are also influenced by carbon emissions which are considerably lower in the COOP regime compared to KYOTO (see Figure 2).

Notice in Figure 4 that there are very pronounced differences in sulphur emission abatement across the regions. *China* and *EU* are characterized by the highest abatement efforts on both the KYOTO and COOP regime since they are characterized by relatively high valuations for acidification damages and relatively high sulphur emission levels. At the other end of the spectrum, *Japan* has only little incentive to curb its sulphur emissions because it values acidification damages very weakly. Initially, *ROW* and *FSU* have some interest in reducing their sulphur emissions because of acidification damages but this incentive is overruled by the strongly increasing climate change damages after a few decades. Recalling conditions (21) and (25) this implies that the climate cooling benefit over-compensates the acidification damages such that optimal sulphur abatement is driven to zero.

Figure 5: World carbon emission abatement (%)

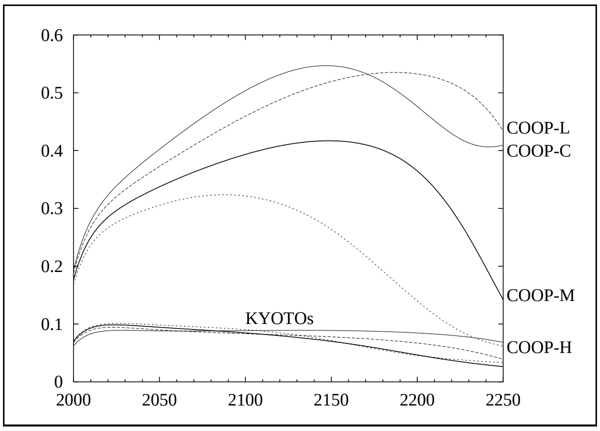


Figure 6: World shadow price carbon (1990US$/tC)

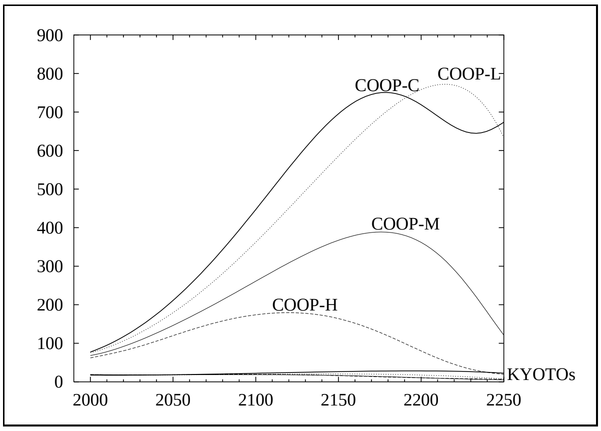


Figure 5 shows world carbon emission control rates for the KYOTO and COOP policy regimes. First, notice the strong difference between the KYOTO and COOP policy regimes in terms of carbon abatement. The KYOTO scenario fails to internalize an import part of climate change damages that will affect the nonsignatories *China* and *ROW*. Secondly, we clearly observe the role of the sulphur emissions and the aerosol cooling effect. For high sulphur emission scenarios, Pareto optimal carbon emissions will tend to be lower. The strong climate cooling effect allows for a more relax carbon abatement policy in this case. However, if sulphur emissions are low (COOP-L) or remain at their 1990 level (COOP-C), this cooling effect of sulphate aerosols plays less and the cooperative carbon emission policy is more stringent than in the medium sulphur scenario. The opposite effect is observed for the high sulphur emission scenario COOP-H. Finally, the dip in the COOP-C carbon emission abatement stems from the fact that *CHINA* is constrained to abate 100% of its carbon emissions towards the end of the time horizon.

According to Figure 6, the world shadow price of carbon[10] rises steeply in the COOP regimes in all sulphur emission scenarios. At the end of the horizon, the shadow cost is decreasing because of a final period effect. Recall that the shadow price consists of a discounted sum of all future climate change damages. The more we approach the end of the horizon, the less periods are left and, hence, the lower will be the shadow price of carbon. For the MEDIUM scenario, the world shadow price of carbon amounts to about 260US$/tC in the year 2100.

Figure 7: Regional carbon emission abatement KYOTO-M (%)

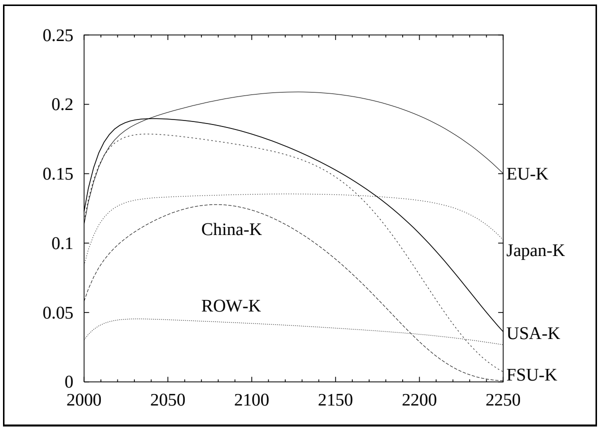
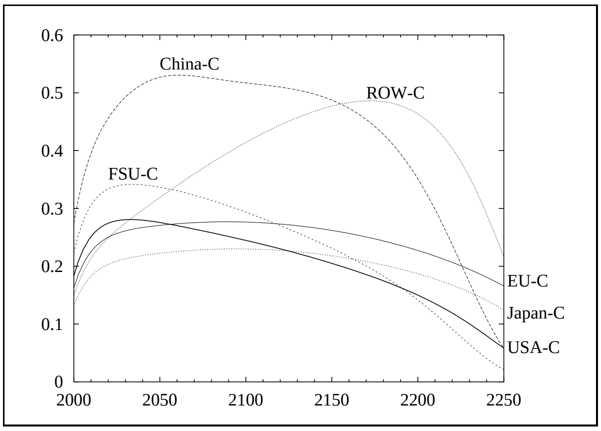


Figure 8: Regional carbon emission abatement COOP-M (%)



Figures 7 and 8 compare regional carbon emission abatement trajectories for the KYOTO and COOP policy regime and the MEDIUM sulphur emission scenario. In the KYOTO-M case, the Annex B regions perform the highest carbon abatement effort since they internalize the climate externality as far it concerns the Annex B territory. They do not take into account spill over effects towards *China* or *ROW*. *ROW* is strongly free riding upon the carbon abatement effort of the other regions in the KYOTO regime[11]. Concerning the COOP-M case, it is important to realize that *China* and *ROW* are characterized by relatively cheap carbon abatement options and high time preference. Therefore, they are

---

[10] The world shadow price of carbon is computed as the (carbon emission) weighted average of regional marginal carbon abatement costs. It should be noticed that these marginal abatement costs can differ across regions, even in the COOP policy regimes. The reason for these differences lays in the different regional discount rates and regional effects of sulphate aerosol cooling.

[11] We should note that for *ROW*, we allowed for a stronger free riding effect by deflating their climate change damages in the non-cooperative solution. If we did not do this, there would exist a strong internalization of climate change damages across the different countries that constitute the *ROW* region in our model. This is clearly not the case if we look at reality.

asked to perform much higher carbon control policies in the COOP regime compared to the industrialized regions in the model.

Figure 9: World carbon concentration (GtC)

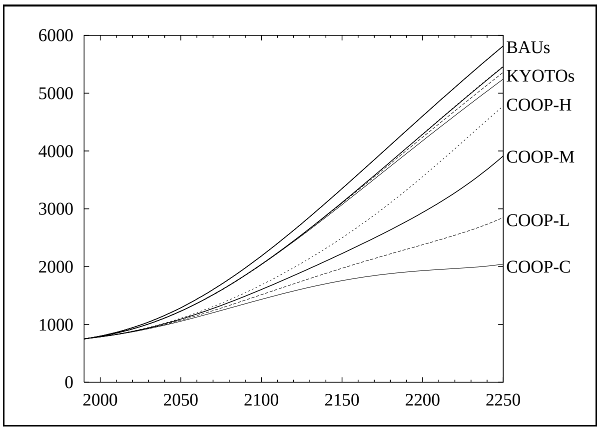


Figure 10: Global mean temperature change (°C)

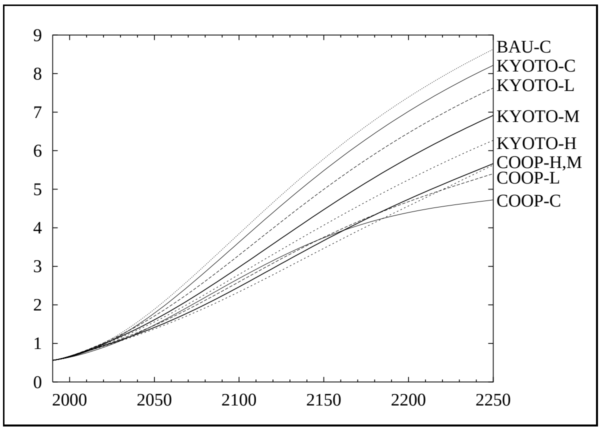


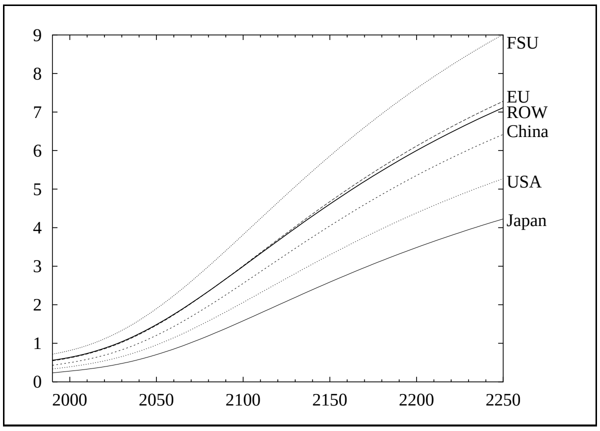
Figure 9 reports the evolution of world atmospheric carbon concentration. Only in the COOP-C regime, world atmospheric carbon concentrations tend to stabilize at about 2000 GtC by the end of the time horizon. For all other scenarios and regimes optimal carbon concentration paths are growing for ever.

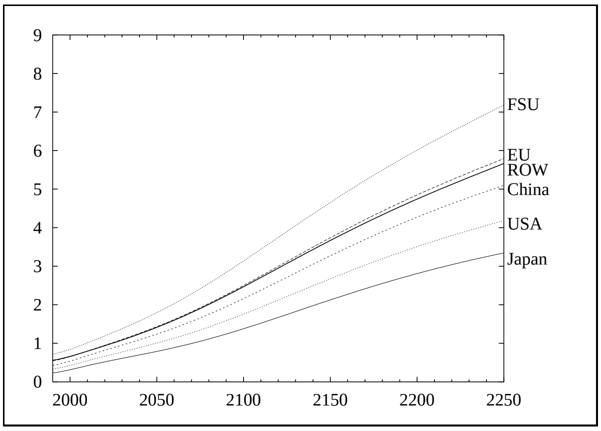
Figure 10 translates the carbon concentration trajectories into global mean temperature change. For the regionalized temperature module of our model, global mean temperature change basically coincides with temperature change for the dispersed group of countries in *ROW*. We observe substantial differences in global mean temperature change between the different sulphur emission scenarios and policy regimes. The lower sulphur emissions, the lower the sulphur aerosol cooling effect and hence, the higher temperature change. With constant sulphur emissions, the BAU and KYOTO global mean temperature increases by more than 8°C by the year 2250 against about 6°C for high sulphur emissions. Pareto efficient temperature change varies between 4.8°C for COOP-C and 5.7°C for COOP-H.

Finally, Figures 11 and 12 show regional temperature changes in the BAU and COOP policy regime for the MEDIUM sulphur emission scenario. Regional temperature change varies strongly between the six regions we distinguish in the model. As noted before, global mean temperature change corresponds to region *ROW*. In any scenario or policy regime *Japan* experiences the lowest temperature change (approximately 4.2°C by 2250 for BAU-M) and *FSU* the highest (about 9°C by 2250 for BAU-M). The ranking of the regions in terms of regional temperature differences remains the same over all regimes and scenarios. We therefore report only two extreme cases.

Figure 11: Regional temperature change BAU-M (°C)

Figure 12: Regional temperature change COOP-M (°C)





These regional difference are an important factor in our model since they influence the regional differences in sulphur emission abatement. Looking back at Figure 4, we saw that in particular *FSU* has little incentive to curb its sulphur emissions. This is not surprising given the fact that *FSU* is hit hardest by climate change according to Figure 12.

4.4 Composition of World GDP

In order to illustrate the impact of the climate change problem upon future consumption possibilities we plot the time path for macro economic expenditures for the world economy. Basically, the Figures 13 to 16 show the different terms of the budget equation (1). Total production or GDP can be decomposed into consumption (Z), investment (I), total emission abatement costs (C) and total environmental damages (D). All figures are reported in trillion (i.e. 10^{12}) 1990US$.

The dotted lines refer to the BAU scenario in which regions do not care about climate change damages. We computed the optimal capital accumulation trajectories ignoring environmental externalities and determined ex post the corresponding emissions of carbon and sulphur. Based on these emission trajectories we calculated environmental damages and deducted them from overall production. BAU production, investment and consumption are increasing over the entire time horizon. Climate change damages are negligible initially but start eating an ever increasing fraction of consumption after 2100. For the MEDIUM scenario (Figure 15), BAU environmental damages represent about 25% of GDP in the year 2250.

The solid lines refer to the cooperative Pareto efficient allocation. Notice that in the

Figure 13: Composition world GDP, CONSTANT

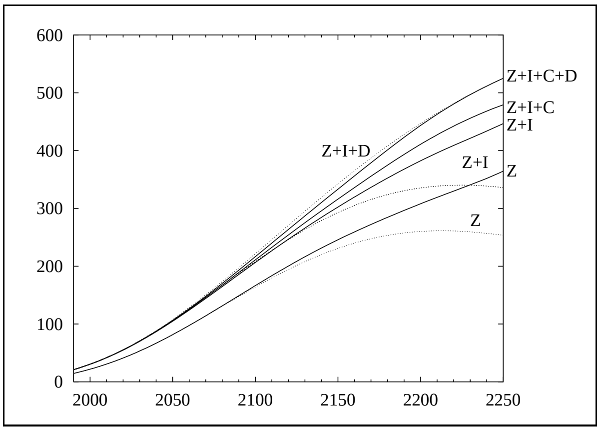


Figure 14: Composition world GDP, LOW

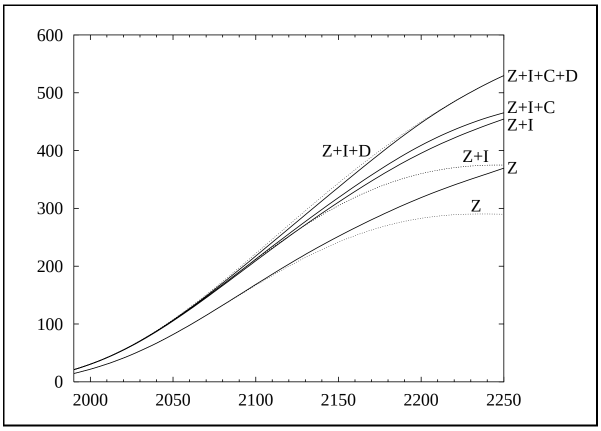


Figure 15: Composition world GDP, MEDIUM

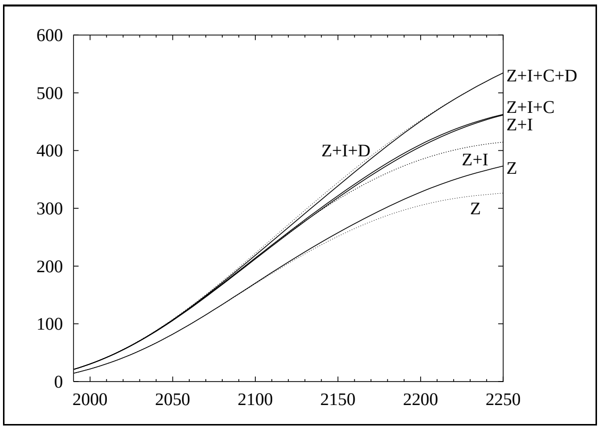
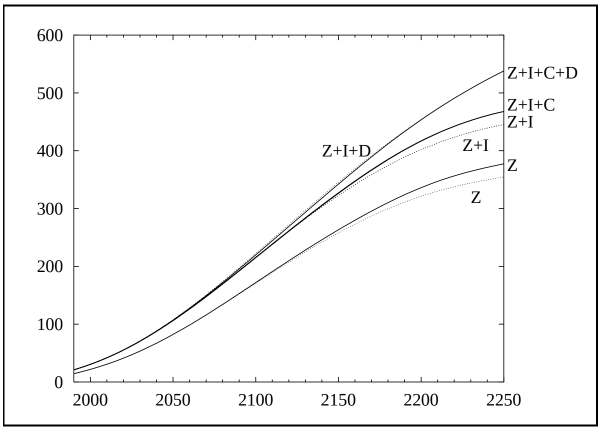


Figure 16: Composition world GDP, HIGH



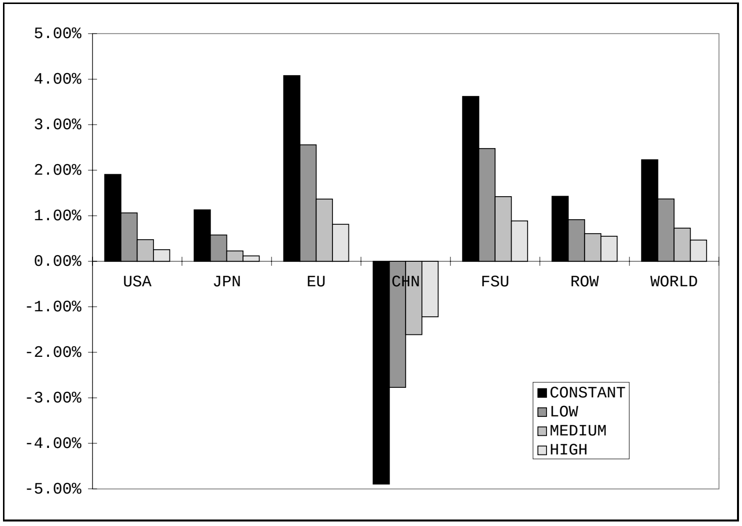
latter scenario, there is some expenditure on emission abatement costs (C) in contrast to the BAU scenario. Under the COOP regime, world production is a little less than BAU production and this difference is a little more pronounced for the low sulphur emission scenarios. We observe quite important differences in consumption trajectories between the BAU and COOP regimes for all sulphur emission scenarios. BAU consumption trajectories are always dominated by COOP consumption trajectories but again, the difference is more important for low sulphur emission scenarios. For the low sulphur scenarios consumption tends to stabilize in the BAU regimes whereas it is still growing in the COOP regime.

Overall the different Figures seem to suggest that high sulphur emission scenarios allow for higher consumption paths. The reason for this phenomenon is clearly that the sulphate aerosol cooling effect plays an important role in the long term. For the long time horizons considered in our simulations, climate change damages become more important than sulphur acidification damages. Therefore, sulphur emissions generate a substantial climate cooling effect without causing too much local acidification damages (according to the damage function we have used).

4.5 Winners and losers

Finally, we take a look at the picture of winners and losers of a full cooperative climate agreement compared to the Kyoto policy regime. The figures in Figure 17 stand for the percentage difference between lifetime discounted consumption in the COOP and KYOTO policy regimes. These differences are reported for the four sulphur emission scenarios.

Figure 17: Winners and losers (%)



China is the only region that is loosing from the COOP policy regime compared to the KYOTO regime. This is not surprisingly since they are characterized by relatively low carbon abatement costs and climate change damage valuation. In the COOP agreement they are required to undertake a large share of the global carbon emission abatement effort but they do no receive a compensation for that. It is clear that *China* will never accept such a cooperative agreement without transfers. This theme is explored in more detail in Eyckmans and Tulkens [5].

Notice that the overall surplus of cooperation is relatively small, only about one-and-a-half percent of world discounted consumption. However this figure hides important regional differences and, recalling the previous figures, huge differences in emission control rates and temperature change trajectories. The surplus of cooperation is higher for low sulphur emission scenarios since the climate externality is playing more severe in this case.

5 Conclusion

This paper presents an integrated assessment of both carbon and sulphur emission control in a dynamic, multi-region optimal growth model with environmental externalities. Carbon and sulphur emissions are positively correlated and are causing different local and global environmental damages. In the theoretical section it was shown that the cooling effect of sulphur emissions has a substantial impact on traditional efficiency conditions for carbon and sulphur emission abatement policies, both in a non-cooperative Nash equilibrium as in Pareto efficient allocations. Policy makers should balance the climate cooling benefit of sulphate aerosols and the acidification damages caused by sulphur depositions. This trade off is also reflected in conditions that characterize optimal carbon abatement policies. Because of the positive correlation between both pollutants, policy makers should strive for less carbon abatement if sulphate aerosol cooling benefits outweigh sulphur acidification damages and vice versa.

We illustrated these finding by means of a numerical simulation model in the same spirit as the RICE model. The simulations suggest that in the long term the sulphate aerosol cooling effect will play an important role and will reduce the need for sulphur emission control. For regions that are severely affected by climate change (e.g. *Former Soviet Union* in our model) or that value climate change only weakly (e.g. *Rest Of the World* in our model) this even leads to the complete absence of sulphur abatement in the medium term, i.e. starting from 2050 or earlier.

However, sulphate aersol cooling should not be used as an argument to delay or abandon carbon emission abatement policies. First, the regional scale of the sulphate forcing makes it difficult to compare this forcing with the one caused by the globally distributed greenhouse gases. Secondly, even if we assume that both forcings can be compared (on a hemispherical basis for example), a scenario in which we would rely heavily upon sulphate aerosol cooling could lead to a dangerous climate shock once all fossil fuel resources (and thus sulphur precursors) are depleted. At that time, the sulphate cooling would suddenly vanish and greenhouse warming would take off unchecked causing a sharp rise in global temperature. Thirdly, such a policy (e.g., masking GHG warming by sulphate cooling) would lead to an ever widening difference in the climate forcing between the two hemispheres (anthropogenic sulfur emissions occur mainly in the Northern hemisphere), which is potentially even more disruptive to the climate system than a uniformly distributed greenhouse effect (Wigley [19]).

Numerical simulation models are always subject to criticism because they require numerous heroic assumptions in order to make them running. Still we should mention the following important deficiencies in our modelling that need further research. First, the sulphur emission abatement cost and acidification damages were extrapolated in function of estimates from the GEM-E3 general equilibrium model for Europe. We definitely need more precise estimates of costs and damages, especially for the developing regions in the model. Secondly, we presented a wide range of sensitivity analysis on the correlation between carbon and sulphur emissions simply because we did not find a good empirical study on this. The reliability of the simulation results would benefit greatly from additional research into the interaction between carbon and sulphur emissions. Finally, we assumed that there are no regional spill overs in acid depositions and that these depositions can be considered as flow instead of stock pollution. Despite the size of our regions and the relative length of the time periods considered, this assumption should be relaxed, for instance by using a simplified version of the RAINS model (Alcamo et al.[1]).

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Appendix

Equation listing of the CLIMNEG model

$$Y_{i,t} = Z_{i,t} + I_{i,t} + C_{i,t} + D_{i,t} \tag{28}$$

$$Y_{i,t} = A_{i,t}\, K_{i,t}^{\gamma}\, L_{i,t}^{1-\gamma} \tag{29}$$

$$C_{i,t} = CC_i(AC_{i,t}) + CS_i(AS_{i,t}) = Y_{i,t}\, c_{i,1}\, AC_{i,t}^{c_{i,2}} + Y_{i,t}\, c_{i,3}\, AS_{i,t}^{c_{i,4}} \tag{30}$$

$$D_{i,t} = DCC_i(\Delta T_t) + DA_i(ES_{i,t}) = Y_{i,t}\, d_{i,1}\, \Delta T_t^{d_{i,2}} + d_{i,3}\, ES_{i,t}^{d_{i,4}} \tag{31}$$

$$K_{i,t+1} = [1 - \delta_K]\, K_{i,t} + I_{i,t} \qquad K_{i,0} \text{ given} \tag{32}$$

$$EC_{i,t} = \sigma_{i,t}\, [1 - AC_{i,t}]\, Y_{i,t} \tag{33}$$

$$ES_{i,t} = ES_{i,0}\, [1 - AS_{i,t}] \left[\frac{EC_{i,t}}{EC_{i,0}}\right]^{\nu} \tag{34}$$

$$M_t = M_0 + \sum_{t'=1}^{t} \tau_a(t-t')\, EC_{N,t'} \tag{35}$$

$$\tau_a(t) = A_o + \sum A_i e^{-t/\nu_i} \tag{36}$$

$$\Delta Q_t = \Delta Q_{1990} + (\Delta QC_t - \Delta QC_{1990}) + (\Delta QS_t - \Delta QS_{1990}) \tag{37}$$

$$\Delta QC_t = \Delta QC_{2\times CO_2} \left(\frac{\ln(M_t/M_0)}{\ln(2)}\right) \tag{38}$$

$$\Delta QS_t = \Delta QS^D_{1990} \left(\frac{ES_{N,t}}{ES_{N,1990}}\right) + \Delta QS^I_{1990} \left(\frac{\log(1 + ES_{N,t}/ES_{nat})}{\log(1 + ES_{N,1990}/ES_{nat})}\right) \tag{39}$$

$$\Delta TO_t = \Delta TO_{t-1} + \tau_3\, [\Delta T_{t-1} - \Delta TO_{t-1}] \tag{40}$$

$$\Delta TOC_t = \Delta TOC_{t-1} + \tau_3\, [\Delta TC_{t-1} - \Delta TOC_{t-1}] \tag{41}$$

$$\Delta T_t = \Delta T_{t-1} + \tau_1\, [\Delta Q_t - \lambda \Delta T_{t-1}] - \tau_2\, [\Delta T_{t-1} - \Delta TO_{t-1}] \tag{42}$$

$$\Delta TC_t = \Delta TC_{t-1} + \tau_1\, [\Delta QC_t - \lambda \Delta TC_{t-1}] - \tau_2\, [\Delta TC_{t-1} - \Delta TOC_{t-1}] \tag{43}$$

$$\Delta TS_t = \Delta T_0 - [\Delta TC_t - \Delta T_{t-1}] \tag{44}$$

$$\Delta T_{i,t} = \Delta TC_t \left(\frac{T_{2\times CO_2,i} - T_{con,i}}{\bar{T}_{2\times CO_2} - \bar{T}_{con}}\right) + \Delta TS_t \left(\frac{T^D_{10\times SO_4,i} - T_{con,i}}{\bar{T}^D_{10\times SO_4} - \bar{T}_{con}}\right) \tag{45}$$

Table 1: Variables

$Y_{i,t}$	production (billion US$ 1990)
$A_{i,t}$	productivity
$Z_{i,t}$	consumption (billion US$ 1990)
$I_{i,t}$	investment (billion US$ 1990)
$K_{i,t}$	capital stock (billion US$ 1990)
$L_{i,t}$	population (billion people)
$C_{i,t}$	total emission abatement cost (billion US$ 1990)
$CC_{i,t}$	carbon emission abatement cost (billion US$ 1990)
$CS_{i,t}$	sulphur emission abatement cost (billion US$ 1990)
$D_{i,t}$	total environmental damages (billion US$ 1990)
$DCC_{i,t}$	climate change damages (billion US$ 1990)
$DA_{i,t}$	acidification damages (billion US$ 1990)
$EC_{i,t}$	carbon emissions (gigaton of carbon, GtC)
$ES_{i,t}$	sulphur emissions (megaton of sulphur, MtS)
$\sigma_{i,t}$	carbon emission-output rate (kg carbon per US$
$AC_{i,t}$	carbon emission control rate (%)
$AS_{i,t}$	sulphur emission control rate (%)
M_t	atmospheric carbon concentration (gigaton of carbon, GtC)
ΔQ_t	change in total radiative forcing (Watt per square meter, W/m^2)
ΔQC_t	change in carbon radiative forcing (Watt per square meter, W/m^2)
ΔQS_t	change in sulphate radiative forcing (Watt per square meter, W/m^2)
ΔQS_t^D	change in direct sulphate radiative forcing (Watt per square meter, W/m^2)
ΔQS_t^I	change in indirect sulphate radiative forcing (Watt per square meter, W/m^2)
$\Delta T_{i,t}$	regional total temperature change (degrees Celsius, °C)
ΔTC_t	carbon induced temperature change (degrees Celsius, °C)
ΔTS_t	sulphur induced temperature change (degrees Celsius, °C)
ΔTO_t	deep ocean temperature change (degrees Celsius, °C)
ΔTOC_t	carbon induced deep ocean temperature change (degrees Celsius, °C)

Table 2: Global parameter values

δ_K	annual capital depreciation rate	0.10
γ	capital productivity parameter	0.25
ΔQ_{1990}	total radiative forcing in 1990	1.12 W/m^2
$\Delta QC_{2\times CO_2}$	forcing due to 2xCO$_2$	4.37 W/m^2
ΔQS^D_{1990}	sulphate direct radiative forcing	-0.3 W/m^2
ΔQS^I_{1990}	sulphate indirect radiative forcing	-0.8 W/m^2
τ_1	parameter temperature relationship	0.226
τ_2	parameter temperature relationship	0.44
τ_3	parameter temperature relationship	0.02
λ	parameter temperature relationship	1.41
M_0	carbon concentration pre-industrial era	590 GtC
$ES_{N,nat}$	natural sulphur emissions	42 MtS
ΔT_0	initial temperature change	0.50 °C
ΔTO_0	initial temperature change deep ocean	0.10 °C

Table 3: Regional parameter values

	$c_{i,1}$	$c_{i,2}$	$c_{i,3}$	$c_{i,4}$	$d_{i,1}$	$d_{i,2}$	$d_{i,3}$	$d_{i,4}$	ρ_i
USA	0.07	2.887	0.0038	1.80	0.01102	2.50	0.40	1.50	0.015
Japan	0.05	2.887	0.0038	1.80	0.01174	2.50	0.68	1.50	0.015
EU	0.05	2.887	0.0038	1.80	0.01174	2.50	2.07	1.50	0.015
China	0.15	2.887	0.0038	1.80	0.01523	2.50	0.14	1.50	0.030
FSU	0.15	2.887	0.0038	1.80	0.00857	2.50	0.05	1.50	0.020
ROW	0.10	2.887	0.0038	1.80	0.02093	2.50	0.05	1.50	0.030

Table 4: Initial conditions

	$Y_{i,0}$	$K_{i,0}$	$L_{i,0}$	$EC_{i,0}$	$ES_{i,0}$
USA	5464.796	14262.51	0.250	1.360	11.0172
Japan	2932.055	8442.25	0.124	0.292	0.4069
EU	6828.042	18435.71	0.366	0.872	9.1152
China	370.024	1025.79	1.134	0.669	14.0560
FSU	855.207	2281.90	0.289	1.066	11.0814
ROW	4628.621	9842.22	3.103	1.700	23.4233
World	21078.750	54290.38	5.266	5.959	69.1000

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