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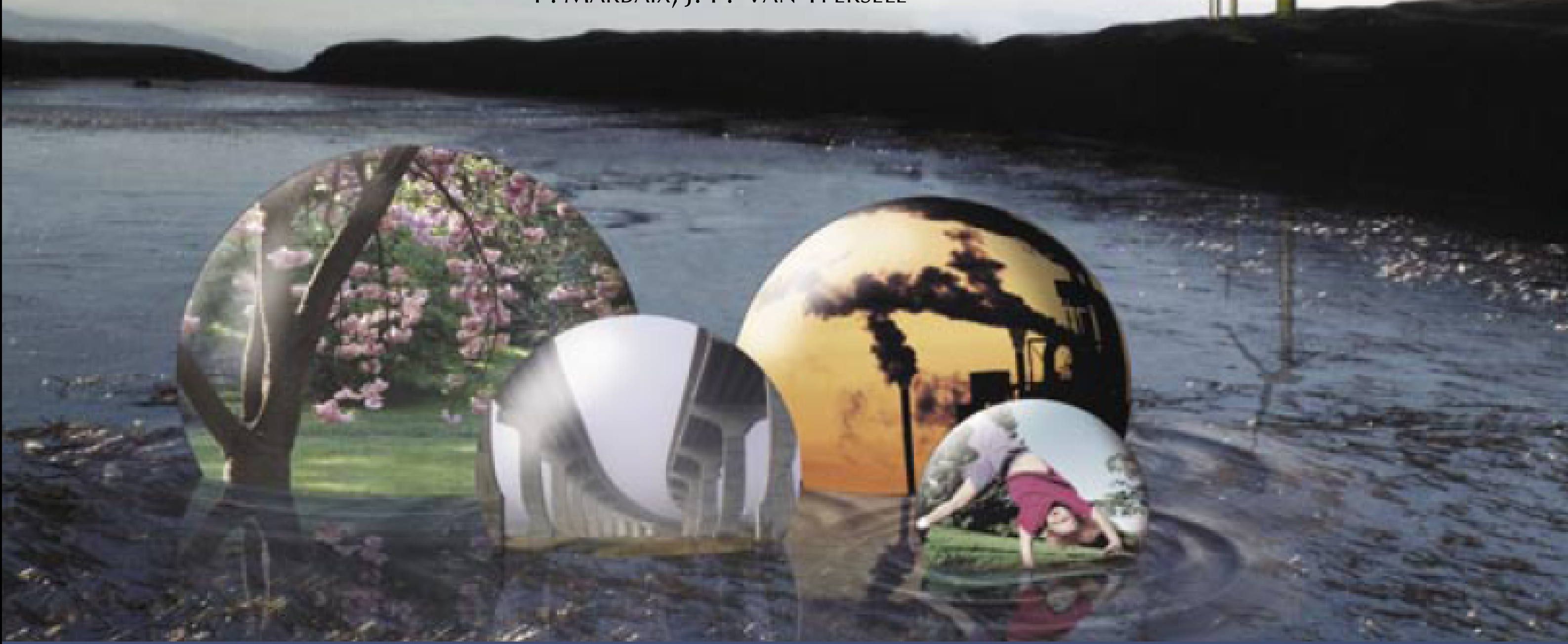
SCIENCE FOR A SUSTAINABLE DEVELOPMENT

Climate, Coalitions and Technology

"CLIMNEG III"

SD/CP/05A

T. Brechet, R. Boucekkine, J. Eyckmans, A.Gerard,
P. Marbaix, J.-P. van Ypersele



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SCIENCE FOR A SUSTAINABLE DEVELOPMENT
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Climate

FINAL REPORT

CLIMATE, COALITIONS AND TECHNOLOGY

"CLIMNEG III"

SD/CP/05

Promotors
Thierry Bréchet
Chair Lhoist Berghmans in Environmental Economics and Management
Louvain School of Management (LSM)
Université catholique de Louvain,
Center for Operations Research and Econometrics
(UCL-CORE)
Voie du Roman Pays 34, B-1348 Louvain-la-Neuve
Tél.: +32 (10) 47.43.21 and +32 (10) 47.81.86
thierry.brechet@uclouvain.be
Johan Eyckmans
Hogeschool-Universiteit Brussel (HUBrussel)
Onderzoeksgroup Economie en Beleid
Stormsrtaat 2, 1000 Brussels
Tél : +32 (0) 2 609 82 59
johan.eyckmans@HUBrussel.be
Jean-Pascal van Ypersele
Université catholique de Louvain,
Institut d'Astronomie et de Géophysique
(UCL-ASTR)
Chemin du Cyclotron 2, B-1348 Louvain-la-Neuve
Tél : +32 (10) 47.32.96
jean-pascal.vanypersele@uclouvain.be

Authors
Thierry Bréchet (UCL), Raouf Boucekkine (UCL),
Johan Eyckmans (HUBrussel), Alexis Gérard (UCL),
Philippe Marbaix (UCL),
Jean-Pascal van Ypersele (UCL)

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BELGIAN SCIENCE POLICY

BELGIAN SCIENCE POLICY

Rue de la Science 8
Wetenschapsstraat 8
B-1000 Brussels
Belgium
Tel: +32 (0)2 238 34 11 – Fax: +32 (0)2 230 59 12
http://www.belspo.be

Contact person:
Mr Georges Jamart : +32 (0)2 238 36 90

Projet Website : www.climneg.be

Thierry Bréchet, Raouf Boucekkine, Johan Eyckmans, Alexis Gérard, Philippe Marbaix, Jean-Pascal van Ypersele. ***Climate, Coalitions and Technology "CLIMNEG III"*** Final Report Brussels : Belgian Science Policy 2009 – 85 p. (Research Programme Science for a Sustainable Development :)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

This report presents the main outcomes of the CLIMNEG research project undergone on behalf on the Belgian Science Policy during the period 2006 to 2008. Within a limited amount of pages the purpose of this report is to show how the project contributed to both the academic literature and the policy process, in accordance with its initial objectives.

The project focuses on three key issues: climate change, the way coalitions of countries may face that problem, and the role of technology. From a methodological standpoint, the project aimed at combining theoretical approaches, computational ones, and policy support. Furthermore, the project fostered interdisciplinary between economists and climatologists, with some extensions to political scientists.

The leading partners of the projects were the following:

- Thierry Bréchet, Professor of Environmental Economics, UCL;
- Johan Eyckmans, Professor of Environmental Economics at HUBrussel;
- Jean-Pascal van Ypersele de Strihou, Professor of Climatology, UCL.

The main researchers involved in the project were Philippe Marbaix (ASTR, UCL), Alexis Gérard (CORE, UCL), Raouf Boucekkine (CORE, UCL), François Gerard (CORE, UCL), Paul Holzweber (Tech. University of Vienna) and Henry Tulkens (CORE, UCL).[1]

The purpose of the project was the exploration of the potential for post-Kyoto climate regimes with respect to two key issues: (*i*) how stable coalitions of countries could emerge to significantly mitigate climate change, (*ii*) what could be the contribution of technological progress for a sustainable climate?

The objectives were twofold:

1. to better understand the climate negotiation process and the role of technological progress for severe GHG emission abatements in order to propose policy designs. One crucial element is how potentially stable climate architectures could be influenced by long term R&D-oriented policies and instruments;
2. to help decision-makers and relevant stakeholders better understand climate issues, policy questions and scientific backgrounds, both in climate science and economic modelling, in particular by evaluating the effectiveness of potential international climate policies and agreements with numerical simulations.

One of the ambitions of this project was to narrowly link academic research and decision-making, both ways. Clearly, this requires specific efforts, and the whole project was designed to that purpose.

The project was organized in four topics:

[1] The list of all the researchers associated to the project is provided in annexe 6.5.

1. Coalition theory analysis. During recent years, considerable progress has been made in theoretical economic analysis of international environmental agreements. Incentives of governments to sign, ratify and implement agreements are relatively well understood in a static, *i.e.* one shot game, context in which governments decide to participate once and for all in an agreement or not. The role of transfers and alternative institutional has been studied extensively. One dimension that has not been adequately covered up to now is the dynamics of coalition formation, *i.e.* the question of how cooperation evolves over time in a dynamic context;
2. Narrowly linked to the previous issue, technological progress has been repeatedly invoked to be the decisive engine to achieve sustainable development, in particular energy-saving technologies. Nonetheless, the possibility to keep emissions under control and to guarantee positive long run growth might be challenged on several grounds. We shall examine all these issues in vintage capital modelling and dynamic general equilibrium theoretical settings to represent the scrapping process of carbon intensive technologies;
3. Applied policy results will be provided to policy-makers and stakeholders by developing and using the integrated assessment model CWS.

The report is organized as follows.

In the first part, the analysis of the literature and the outcome about coalition formation is presented. The second part presents the research results on technology, with a focus on vintage capital models and dynamic general equilibrium. The third part of the report is devoted to the update of the integrated assessment model developed during the previous CLIMNEG project, namely the CWS model. The fourth part presents two policy applications that combine coalition theory and CWS computations. The Annexes provide supplementary material, including publications of the network, codes and database of the CWS model, and the composition of the Follow-up Committee.

All the material presented in this report is publicly available on the following websites:

- CLIMNEG website: www.climneg.be
- CORE and Chair Lhoist Berghmans : www.uclouvain.be/en-chaire-lhoist.html
- ASTR: www.climate.be
- Hogeschool-Universiteit Brussel (HUB) : www.hubrussel.be

1. INTERNATIONAL CLIMATE AGREEMENTS

1.1 State of the art and progress

During the course of the CLIMNEG project, the follow-up of the game theoretical and economics literature on international environmental agreements has been done by Johan Eyckmans.[2]

Overall, two main conclusions emerge from the follow-up of the literature during the period covered by the project: (*i*) there has not been a major theoretical breakthrough in the literature on international environmental agreements (IEAs), and (*ii*) there seems to emerge more literature on sequential agreement formation.

1.2 One-shot concepts of coalitional stability

First, there has not been a major breakthrough development of new concepts that would have rendered the existing concepts obsolete. In 2003, many experts believed that a major breakthrough in the game theoretic literature on the formation of coalitions under externalities might happen after a working paper by Maskin (2003).[3] However, soon after, some inconsistencies were discovered in the approach and it became clear that it would not revolutionalize the game theoretic analysis of coalition formation (see Chander and Tulkens, 2005, and de Clippel and Serrano, 2008)[4]. In fact, many of the game theoretical concepts, to which members of the CLIMNEG group have contributed internationally in the past, are still considered state-of-the art approaches to model the basic incentives of sovereign nations to join international environmental agreements.

Datasets generated by the newest CWS model versions (see Part 3 of this report) were used also for analyzing the potential of transfers and institutional changes to improve stability of international climate agreements. This has resulted in several new publications of which we will discuss only two prime examples in this report. Firstly, Bréchet, Gerard and Tulkens (2007)[5] compared cooperative and non-cooperative approaches to coalition formation with different versions of the CWS simulation model. This paper will be discussed in more detail later in the report (see section 4). Secondly, Eyckmans and Finus (2008)[6] have analyzed the effect of different transfer schemes and membership rules on the stability of IEAs. Both aspects of an IEA are believed to be crucial parameters of the success of an IEA. In particular, monetary transfers are believed to be able to overcome conflicting incentives of countries with very different abatement cost and climate change damage characteristics. If high climate

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[2] Intermediate results of this work were presented at the meeting of the Follow-up Committee on June, 23 2006.

[3] Maskin E. (2003), "Bargaining, coalitions and externalities", working paper, Institute for Advanced Study, Princeton University.

[4] Chander and Tulkens, "Cooperation, stability and self-enforcement in international environmental agreements: a conceptual discussion", chapter 8 in Guesnerie, R. and H. Tulkens (eds), *The Design of Climate Policy*, CESifo Seminar Series (MIT Press, Cambridge Mass USA) 2009 , and de Clippel, G. and R. Serrano (2008), "Bargaining, Coalitions and Externalities: A Comment on Maskin", working paper Brown University.

[5] Bréchet, T., F. Gerard and H. Tulkens (2007), "Climate coalitions, theoretical and computational appraisal", CLIMNEG working paper 92.

[6] Eyckmans, J. and M. Finus (2008), "Transfer Schemes and Institutional Changes for Sustainable Global Climate Treaties", chapter 6, pp 103-135, in: Guesnerie, R. and H. Tulkens (eds), *The Design of Climate Policy*, CESifo Seminar Series (MIT Press, Cambridge Mass USA), 2009.

change damage countries would pay financial transfers to low cost abatement countries, substantially more abatement can be achieved than without transfers. In addition, some degree of exclusive membership, *i.e.* insiders have to agree on accession of newcomers, cannot but improve (external stability). In order to verify how strong these arguments play in the context of climate change, numerical simulation experiments were conducted with CWS 1.2. Various international transfer schemes, based on different ecological or economic criteria, have been considered and two different assumptions on the procedure for entering a coalition: exclusive (open) membership requires (no) approval of existing coalition members.

The main results are summarized in Table 1.

Table 1: Example of output of different transfer and access rules for CWS model

Nr.	Size	Membership	welfare	No Transfers 0	Egalitarian 1	Ability to Pollute 2	Ability to Pay (ia=1) 3	Ability to Pay (ia=10) 4	Ecological Subsidy 5	Status Quo 6	MC x MD 7	Inverse MC x MD 8	MC / MD 9	Inverse MC / MD 10	Chander-Tulkens 11
8	3	USA,CHN,ROW	86.3												o e
18	3	USA,JPN,ROW	65.1							e					
19	3	USA,FSU,ROW	64.4							e					
21	2	USA,ROW	61.6				e	e	e	e		e	e	o e	
25	2	EU,ROW	54.7				e	e	e			e	e	o e	
27	3	CHN,FSU,ROW	49.3	e			o e		o e				o e		
28	2	CHN,ROW	42.1		o e	o e		o e	e			e	e	o e	
29	3	JPN,FSU,ROW	41.4	e						o e					
30	2	JPN,ROW	36.7	e	o e		e	e	e		o e	e	e	o e	
31	2	FSU,ROW	32.8		o e		e	e				o e		o e	
36	4	USA,JPN,CHN,FSU	24.5							o e					
37	3	USA,JPN,CHN	22.4							e					
40	2	USA,CHN	19.8					o e				e			
43	2	EU,CHN	16.0					o e				e			
46	2	JPN,CHN	5.8					o e				e			
49	2	CHN,FSU	3.5					o e				o e			
50	2	USA,EU	3.0	o e				e							
56	2	JPN,EU	0.9					e							
Open membership, # I&E				**1**	**3**	**1**	**1**	**5**	**1**	**2**	**1**	**2**	**1**	**5**	**1**
Exclusive membership, # I&E				**4**	**3**	**1**	**5**	**11**	**5**	**6**	**1**	**9**	**5**	**5**	**1**

*List of coalition structures that are internally and externally stable in at least one scenario. Coalition structures are sorted in descending order of global welfare; welfare is measured in relative terms as described in the legend of Table 1. "Nr" refers to the rank in terms of the welfare closing the gap index in Table 1. "o" means internally and externally stable under open membership, "e" means internally and externally stable under exclusive membership, assuming unanimity voting.

As can be seen from this table, and somewhat contrary to common wisdom, transfer schemes are not always leading to more stable coalitions. Some transfer rules even perform equally poor as the no transfer case. Only those transfer rules that are able of moving vast amounts of financial resources to low abatement cost – low damage countries (like the ability to pay "Ability to pay ia=10" or the "inverse MC/MD" for instance) can substantially improve upon the no transfer case. The best performing coalitions (in terms of global welfare) are combination of rich countries with the ROW, see coalition numbers 8 (=USA+China+ROW), 21 (USA+ROW) and 25 (=EU+ROW). The best performing coalition (number 8) is able to achieve 86% of the gap between the extreme cooperative (Pareto efficient situation) and non-cooperative (Nash equilibrium) scenarios.

Note also that the number of coalitions that can be stabilized is not always a good measure of success of transfer rules. For instance, the Chander-Tulkens transfers rule can stabilize only one coalition (*i.e.* equally little as the no transfer case) but this one coalition happens to be a very successful one in terms of global welfare (see above). Hence, not the number of stable coalitions, but the identity of coalition members and hence, impact on global welfare matter.

Note finally that exclusive membership performs better than open membership arrangement but the degree of progress depends on the transfer rule.

1.3 Sequential concepts of coalitional stability

A second conclusion of the literature review is that there is a small but growing line of literature that considers coalition formation as a sequential, *i.e.* dynamic and gradual process.

During the last half year of the project, Michael Finus (University of Stirling in Scotland), Bianca Rundshagen (University of Hagen in Germany) and Johan Eyckmans (HUBrussel) have implemented for the first time a dynamic coalition formation concept using simulation data of the CWS version 1.2 model developed under CLIMNEG (see Finus, Rundshagen and Eyckmans, 2008).[7] In this paper, the negotiation process leading to an international environmental agreement is modeled in an abstract way as a so-called sequential move unanimity game SMUG, see Bloch (1995). Players can make proposals which are either accepted or countered by other proposals. The game assumes that players are ordered according to some fixed rule. The player with the lowest index (*i.e.* the initiator) starts by announcing a list of coalition members including itself. Every member on the list is asked whether he or she accepts the proposal. The player with the lowest index on this list is asked first, then the player with the second lowest index and so forth. If all players on the list agree, the proposed coalition is formed. If, somewhere in the sequence, a player rejects a proposal, he can make a new proposal that is subjected to approval to all players involved. Important in the set up is that multiple coalitions can form. After a particular coalition has formed, the remaining players may form additional coalitions according to the same bargaining protocol.

A major problem in the computation of the equilibria of this game is that the outcome of the bargaining game depends on the order of players. Therefore, the entire game is solved for all possible index sequences and coalition structures receive a score depending on the number of times they emerge as an equilibrium outcome over all possible index sequences. Finally, different versions of the model are compared: with or without transfer payments, with or without international moderator.

Coalition structures are ordered according to World welfare (CGX = closing the gap index, *i.e.* the share of the gap between full cooperation and complete absence of cooperation that a particular coalition can achieve). In the case of no transfers, 11 different (multiple!) coalition structures emerge as equilibria. Some of these only emerge for a very small number of orderings of the player set (in particular the 4th, 9th and 11th coalition structures that are equilibria for at most 2 orderings out of 720 possible index sequences). Other coalition structures are very robust (in particular the 3rd structure that emerges 515 out of 720 times). In general we see that countries with similar interests (similar abatement cost and damage profiles) are forming clusters. Allowing for transfers *à la* Eyckmans and Tulkens (2003) leads to a much smaller set of possible equilibria. The first one is however very robust (706 our of 720). With transfers, countries with complementary abatement costs and damage profiles are more likely to merge into coalitions. In particular, the combination of USA + EU + China + ROW can be sustained as an equilibrium with transfers and achieves a welfare score of 94%. Compared to the previous section, we observe that sequential coalition formation approaches can make an important difference to the actual coalitions that are predicted to form. We

[7] Finus, M., B. Rundshagen and J. Eyckmans (2008). "Simulating a Sequential Coalition Formation Process for the Climate Change Problem: First Come, but Second Served?" Mimeo.

therefore believe that further developments of this sequential approach will attract a lot of attention in the scientific literature in the years to come.

Table 2: Example of output of sequential bargaining protocol for CWS model

No Transfers										
Coalition Structure	Ranking							CGX	PO	FR
	USA	JPN	EU	CHN	FSU	ROW	World			
{USA,EU,FSU},{JPN},{CHN,ROW}	1	1	1	5	9	1	1	80.7	yes/yes	32
{USA,JPN,EU},{CHN,ROW},{FSU}	3	3	3	6	1	2	2	80.3	yes/yes	52
{USA,EU},{JPN},{CHN,ROW},{FSU}	5	2	4	8	2	3	3	78.2	yes/yes	515
{USA,JPN,FSU},{EU},{CHN,ROW}	2	5	2	9	5	4	4	76.2	yes/yes	1
{USA},{JPN},{EU,FSU},{CHN,ROW}	4	4	5	10	4	9	5	73.7	no/no	16
{USA},{JPN,EU},{CHN,ROW},{FSU}	6	6	6	11	3	10	6	73.4	no/no	4
{USA,ROW},{JPN},{EU,FSU},{CHN}	8	7	7	1	10	5	7	72.2	no/yes	8
{USA,ROW},{JPN,EU},{CHN},{FSU}	9	10	8	2	6	6	8	71.9	no/yes	10
{USA,ROW},{JPN,FSU},{EU},{CHN}	10	8	9	3	8	7	9	71.3	no/yes	2
{USA,ROW},{JPN},{EU},{CHN},{FSU}	11	9	10	4	7	8	10	70.8	no/yes	78
{USA},{JPN},{EU,ROW},{CHN},{FSU}	7	11	11	7	11	11	11	63.8	no/no	2
								∅ = 77.3		
Transfers										
Coalition Structure	Ranking							CGX	PO	FR
	USA	JPN	EU	CHN	FSU	ROW	World			
{USA,EU,CHN,ROW},{JPN},{FSU}	2	1	1	1	1	1	1	94.6	yes/yes	706
{USA},{JPN},{EU,FSU},{CHN,ROW}	1	2	2	2	2	2	2	73.7	no/yes	14
								∅ = 94.2		

* Ranking: ranking of equilibrium coalition structures in terms of valuations "World" in descending order; CGX: closing the gap index as explained in Table 1, ∅=average welfare over all possible index sequences; PO: first entry = Pareto-optimal coalition structure in the set of all coalition structures, second entry = Pareto-optimal coalition structure in the set of equilibria; FR: frequence of appearance of coalition structure as an equilibrium out of the total number of index sequences that is 720.

2 GENERAL EQUILIBRIUM, DYNAMICS, AND TECHNOLOGICAL PROGRESS

This part of the CLIMNEG project was devoted to the analysis of economic dynamics and the role of technological progress for achieving significant environmental quality improvements in the long run. Technological progress has been repeatedly invoked to be the decisive engine to achieve sustainable development, in particular energy-saving or carbon-saving technologies. Nonetheless, the possibility to keep emissions under control and to guarantee positive long run growth might be challenged on several grounds. To tackle these issues, we used vintage capital modelling and dynamic general equilibrium theoretical settings in different ways. The vintage capital models allowed us to scrutinize the diffusion of new (and cleaner) technologies at the firm level, as well as the role of scrapping of old (and dirty) machines. Dynamic general equilibrium models allowed us to understand all the feedback effects related to some environmental targets or policies.

2.1 Environmental constraints with vintage capital models: the role of technological change

By using a vintage capital model, Boucekkine, Hritonenko and Yatsenko (2008) provide several insights about the effect of innovation under environmental constraint at the firm level.[8] The arguments for environmental regulation are usually based on what has come to be known as the Porter hypothesis. Porter (1991) and Porter and van der Linde (1995) argued that at least in some sectors, a carefully designed environmental regulation as a key feature of industrial policy can increase firm competitiveness by encouraging innovation in environmental technologies.[9] A similar hypothesis popularized by Hicks (1932) and widely applied to environmental economics, especially in its energy part (see Newell, Jaffe and Stavins, 1999, for a seminal contribution), is the so-called induced-innovation hypothesis. According to Hicks, the change of relative prices of production inputs stimulates innovation, an innovation of a particular type, directed to save the production factor that becomes relatively expensive. In the context of the energy consumption debate, this hypothesis stipulates that in periods of rapidly rising energy prices (relative to other inputs), economic agents will find it more profitable to develop alternative technologies, that is, energy-saving technologies. Just like the Porter hypothesis, the induced-innovation hypothesis in its energy-saving version has been intensively studied in recent years, with again highly diverging outcomes, depending mainly on the aggregation levels considered in the studies. In their well-known work, Newell, Jaffe and Stavins (1999) concluded that a large portion of efficiency improvements in US manufacturing seems to be autonomous, and therefore not driven by the Hicksian mechanism outlined above.

Be it stimulated by tightening environmental regulation, caused by the gradual exhaustion of fossil resources, dictated by international agreements like the Kyoto Protocol or by rapidly

[8] Boucekkine R., N. Hritonenko and Y. Yatsenko (2008). "Optimal firm behavior under environmental constraints", CLIMNEG discussion paper 97 (also CORE discussion paper 2008/24). See also the companion paper Boucekkine R., N. Hritonenko and Y. Yatsenko (2009). « On explosive dynamics in R&D-based models of endogenous growth », *Nonlinear Analysis Series A: Theory, Methods & Applications*, forthcoming.

[9] About the Porter hypothesis, see also Bréchet Th. and P.A. Jouvet (2009). "Why environmental management may yield no-regret pollution abatement options", *Ecological Economics*, forthcoming.

increasing energy-prices, the role of innovation at the firm level is the key in the two hypotheses described above. It explains why these hypotheses are actually shaping a substantial part of the environmental literature in economics. If the firms do effectively respond to the latter constraints and circumstances by doing more R&D, then the "environmental problem", understood as the burden involved by environmental constraints on economic development, can be partially solved.

Our analysis is devoted to understanding how and under which conditions, if any, firms would engage in R&D investments under environmental constraints and/or rising energy prices. In contrast to numerous papers written in this area (notably in the macroeconomic literature), which typical consider the R&D conducted outside the firms by specialized entities (see, for example, Hart, 2004), we start with the key assumption that firms, confronted with environmental constraints, may decide to individually engage in R&D activities. We do consider such an extension as essential to get through the puzzle, and there are several reasons for this approach to be preferred:

1. First of all, the role of "production" firms in the development of clean technologies cannot be under-scored because most environmental problems are firm or industry specific and cannot be simply solved by importing technologies;
2. Second, it has been repeatedly established that at least in the case of large corporations (see Carraro and Siniscalco, 1994), firms tend to respond to environmental policy measures through innovations, not by switching inputs or reducing output;
3. Last but not least, as mentioned by several authors (among them, Carraro and Siniscalco, 1994), very high taxes are needed to bring down carbon dioxyde emissions in the absence of innovations.

This justifies the approach taken in this paper: understanding how the firms (for example, subject to pollution quotas) engage individually in R&D is indeed a key task. Throughout this analysis, we shall consider vintage capital technologies. Capital goods produced at different dates embody different technologies, the youngest vintages are the most energy-saving, and, therefore, the least polluting. Beside realism, working with vintage capital production functions allows to capture some key elements of the problem under consideration, which would be lost under the typical assumption of homogenous capital. For instance, facing an emission tax, firms are tempted to downsize. However, in a typical framework where the firm also chooses the optimal age structure of capital, which is the main additional control variable in vintage capital models, downsizing entails modernization: the older and, thus, the dirtier machines and technologies are then removed. For productivity analysts, this is good news: contrary to the typical framework with homogenous capital, we have a clear productivity-enhancing effect of emission taxes in such a framework, thus giving a chance to the Porter "win-win" outcome to arise, even in the absence of firms' innovative activities.

Indeed, whether such an indirect modernization effect can compensate the so-called profit-emission effect according to which profits decline under emission taxes sounds as a highly intriguing question. Very few papers have tried to deal with this issue so far, mainly due to the sophisticated mathematical structure of vintage capital models.

Two valuable exceptions should be mentioned here. Xepapadeas and de Zeeuw (1999) provided the first inspection into this problem. They concluded that the costs of environmental regulation were mitigated if firms responded to emission taxes by scrapping the older and dirtier technologies. Therefore, the indirect modernization effect offsets a substantial part of the negative profit-emission negative effect, but not totally. Feichtinger, Hartl, Kort and Veliov (2005) introduced a more accurate specification of embodied technological progress underlying the considered vintage capital structure. They concluded that if learning costs are incorporated into the analysis (that's running new machines at their full productivity potential takes time), then the magnitude of the modernization effect is strongly reduced, and environmental regulation has a markedly negative effect on industry profits.

Our analysis extends the two previous papers, where the pace of technological progress is kept exogenous, and endogenizes R&D decisions. We characterize optimal firm behavior both asymptotically and in the long run, and we extract several new results, thanks to the endogenous nature of technological progress. In particular, we outline two crucial results:

1. In the long run, tighter emission quotas coupled with liquidity constraints do not prevent firms from growing in the long run, thanks to endogenous innovation. However, these constraints have an inverse effect on the growth rate of profits. In other terms, while R&D is crucial for firms to keep on growing despite environmental and financial constraints, we get the natural outcome (at least, at the firm level) that no Porter-hypothesis is expected to arise in the long-run, namely, strengthening environmental regulation does not improve the situation of the firms in the long-run, under the conditions of the model (price-taking liquidity-constrained firms);
2. In the short-run, the results are even clearer. For example, we establish that firms which are historically "small" polluters find it optimal to massively pollute in the short run: during the transition, new and clean machines will co-exist with old and dirty machines in the productive sectors, implying an unambiguously dirty transition. Therefore, the model provides micro-foundations for an essential part of the so-called Environmental Kuznets Curve.

Last but not least, we show that under some specific but reasonable circumstances, higher energy prices induce shorter lifetime for capital goods, but they depress investment in both new capital and R&D, featuring a kind of reverse Hicksian mechanism.

2.2 Emission permits in a vintage capital model: how firm's decision affect equilibrium

Veliov, Bréchet and Tsachev (2008)[10] developed a model in which capital accumulation is related to the technologies of different vintages distinguished by their productivity and polluting emission rates. The model takes into account that newer technologies are more productive and less polluting. The optimal investment policy for a given exogenous emission tax is explicitly characterized and the resulting emission intensity is determined as a function of the emission tax. Some basic properties of this function are established, that allowed to internalise the emission tax by introducing a market mechanism. Namely, the total amount of emission permits (the emission cap for the industry or for the country, determined by the regulator on the ground of environmental targets) is auctioned and the price of emission is determined by auction price. The issue of the existence and the stability of the market for emission permits proved to be rather delicate. We established both theoretically and numerically the possibility of a market failure and the possible high volatility of the market

[10] Veliov V., Th. Bréchet and T. Tsachev (2008). "On emission permits in a vintage capital model", CLIMNEG working paper 96.

price due to firm's investment and scrapping decisions.

A main finding is that the length of the periods on which the emission restrictions are specified may have a regularizing role on the market. Longer periods may avoid market failure in cases where the market fails for shorter-period or instantaneous specification of the emission cap. The high fluctuations of the market price after quick decreases of the emission cap, that we observed numerically, are damped in the case of longer periods. This result may shed a new light on the collapse observed in the EU-ETS market in April 2006.

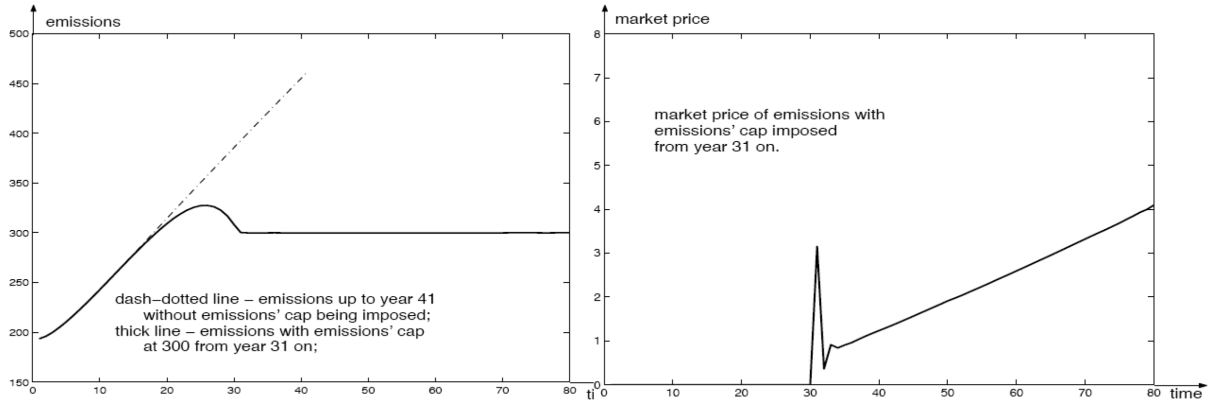
The analysis of existence of a market price is a rather complicated problem, mathematically formulated as a nonlinear and non-smooth functional equation, which required a profound investigation involving high-tech mathematics.

On the ground of that first paper, further investigations have been done to explore the implications of some non-optimal use of free permits endowment at the firm level. Bréchet, Tsachev and Veliov (2009)[11] define a scenario for a sub-optimal utilization of the free endowments given to a firm, in which permits endowments are distributed among technologies by the firm's manager and this distribution is not necessarily optimally designed. The managers of the different technologies optimize their investment and production decisions on technology level. We establish that on rather general assumption this non-optimal utilization of endowments leads to higher polluting emissions for the firm, because of a sub-optimal capital structure. An important consequence of this result is that a non-optimal utilization of free endowments by a single firm leads to a higher market price of permits in equilibrium, which affects negatively the firms that do not receive free endowments, or those who use their permits optimally. This creates a "double penalty" for the firms that do not receive free endowments. The proof of the above fates is also a complicated mathematical task due to the non-smoothness of the equations describing the model.

Finally, we establish a so-called "anticipation effect". This effect lies in the fact that the firms may react to an expected emission restriction by changing their investment policies even before the restriction has taken effect. The vintage structure of the model allows us to exhibit such effect. Before the date of the restriction, the firm has an incentive for downsizing because, when the restriction will be active, some machines will have to be scraped. So the emissions of the firm decrease with respect to their level in the business-as-usual scenario. In equilibrium, this has strong implications on the permits price. The price become positive when the market is active, but it drops sharply just after because of the scrapping of old and polluting machines and the anticipation effect that led to a cleaner capital structure. Figures 1 illustrates these results.

[11] Bréchet Th., T. Tsachev and V. Veliov (2009). "Tradable emission permits and firms: a vintage capital approach", CLIMNEG working paper 100.

Figure 1: Anticipation effect with emission permits



2.3 Burden sharing rules: a coupled constraint equilibrium approach

The burden sharing of abatement efforts among countries or jurisdictions is a topical issue in climate policies in many areas. A novel methodological approach is proposed by Boucekkine, Krawczyk and Vallée (2008).[12] The framework is game theoretic, based on the concept of coupled constraint equilibrium, allowing us to address an important policy problem of national governments of multi-regional countries. The need for regulation might result from the regulator's wish to comply with a national emissions' quota assigned to the country through an international agreement, like the Kyoto Protocol. The model helps answering two policy issues that are of major importance for climate policies: *(i)* how to efficiently share the burden of environment regulations (like emissions quotas) across regions?, *(ii)* how to enforce such a sharing?

The problem is particularly acute when there exist significant structural differencies across regions. In the case considered in the paper, regions differ in their energy efficiency. If the national government has to allocate emission permits across the regions, what could be the most efficient sharing rule for the country? An example of such a problem is a disagreement between Wallonia and Flanders regarding sharing the pollution cleaning burden, recently studied in Boucekkine and Germain (2007) and Germain, Monfort and Bréchet (2007). In those papers, an impact of "grandfathering" emission permits on regional revenues in a small open multi-sector (multi-regional) economic model of Heckscher-Ohlin type is considered. Other multi-ethnic countries like Canada, the UK or Switzerland might be facing similar problems.

In this paper, industries (or regions) are considered as competitive agents. We analyze the resulting equilibrium policies as well as the corresponding outputs and payoffs, as a consequence of adoption of a « sharing rule », for apportioning a pollution quota to each region. To some extend this may apply to the EU as a whole. What makes this paper essentially different from the above cited publications is that we allow for an emission constraint upon the agents' joint strategy space. Assuming the presence of an industry-independent regulator, we vary the levels of the agents' responsibility for the coupled

[12] Boucekkine R., J.B. Krawczyk and Th. Vallée (2008), "Towards an understanding of tradeoffs between regional wealth, tightness of a common environmental constraint and the sharing rules", CLIMNEG working paper 95 (also CORE discussion paper 2008/55).

constraint's satisfaction and suggest which « sharing rule » might be preferred by the regulator. The problem's setup in this paper is conceptually similar to that of Haurie (1994), Haurie and Krawczyk (1997), Krawczyk and Uryasev (2000), Krawczyk (2005). The common feature is that all those papers deal with coupled constraints games in which competitive agents maximize their utility functions subject to constraints upon their joint strategy space. However, in this paper, we make explicit the relationship between a solution to the problem and the weights, which the regulator may use to distribute the responsibility for satisfaction of a joint constraint, among the agents. In that, we follow the seminal work Rosen (1965) and use a coupled-constraints equilibrium as a solution concept for the problem.

Under this solution concept the regulator can compute (for sufficiently concave games) the agents' strategies that are both unilaterally non-improvable (Nash) and such that the constraints imposed on the joint strategy space are satisfied. If the regulator can modify the agents' utilities and impose penalties for violation of the joint constraints then the game will become « decoupled » and the agents will implement the coupled constraints equilibrium in its own interest, to avoid fines associated with excessive pollution. These penalties, which prevent excessive pollution, can be computed using the coupled constraints Lagrange multipliers. However, for this modification of the players' utilities to induce the required behavior, a coupled-constraints equilibrium needs to exist and be unique for a given distribution of the responsibilities for the joint constraints satisfaction, among the agents.[13] Reports on that the energy more intensive sector's revenue is proportionally more affected by the environmental policy than that of its less-intensive counter-part are provided by Germain, Monfort and Bréchet (2007). Our model suggests that the decision on apportioning a higher or lower energy share to a region should depend on an analysis of externalities the regions exert on each other. We also report on the various degrees of market "distortion" as a consequence of the imposition of pollution quotas and of the alteration of the rules for sharing the burden of the joint constraints' satisfaction. This model may help the regulator discover which rules imply an acceptable degree of market distortion.

In order to give substance to this discussion we have considered the case Wallonia *vs.* Flanders. Wallonia is more energy intensive than Flanders while the contribution of the latter to Belgian GDP is larger. It could be thought that having to enforce a national pollution norm, in accordance with international agreements, the regulator should penalize the more polluting, or deviating, region, especially if its contribution to national wealth is markedly lower than that of the less polluting regions. This is clearly the case of Wallonia in Belgium. Our paper makes a point in this respect: the reasoning that leads to limiting Wallonia's energy use does not take into account the fact that regions do interact in several ways, such that penalizing the more deviating region (from an energy efficiency norm) may turn out to be inefficient in terms of the joint production maximization. In our model, the existence of inter-regional externalities is a fundamental ingredient of the story. Hence, there is no simple theorem for efficient regulation of cost sharing across regions. One has not only to look at the differences in factor intensity but also to scrutinize the economic interactions between regions, which is far from easy. Our analysis points at a further and more political ingredient: the government may choose an uneven distribution (across regions) of the responsibility for the joint constraint satisfaction to force a particular outcome.

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[13] Obviously, the game has to possess the same properties should the sharing rules be implemented through a political process rather by threatening the regions with penalties.

2.4 Two-sector dynamic general equilibrium: can optimality and acceptability be reconciled with emission permits?

The debate between optimality and acceptability is key in implementing climate policies under the UNFCCC objectives. Despite the fact that recent research using general equilibrium models (see *e.g.* Parry *et al.*, 1999) suggests that auctions or emission taxes generally dominate a market for emission permits on the ground of optimality, free endowments to polluters remains the usual way of issuing emission permits. The Kyoto Protocol has popularized the idea of setting up pollution rights freely allocated as an instrument of environmental policy for the reduction of greenhouse gas. According to Stavins (1998), the main reason why many actors favor free allocation is *political acceptability*. Because existing firms convey free endowment into rents (what is called "windfall profits"), no one is worse-off because of the regulation, in contrast to an emission tax, for example.

By developing a two-sector dynamic general equilibrium model, Bréchet, Jouvet, Michel and Rotillon (2008) revisit this debate. The aim of the paper is to analyze the effects among sectors (a polluting one - power generation - and a non polluting one - final good -) and over time (with overlapping generations of households) of a market for emission permits. We compare the conditions for optimal growth to the competitive general equilibrium with such a market.[14]

We confirm that giving permits for free to the polluting sector violates the conditions for optimal growth. Giving a rent to that sector (the "windfall profits") artificially increases its capital return, thus leading to too much capital accumulation in that sector to the detriment of the final good sector. It can be shown that, in such a situation, the price increase of the output of the polluting sector (electricity) is stronger than in the optimal solution. Another direct implication is that the intertemporal trade-off between consumption and savings is also altered, leading to too much consumption in the old age.

As it is already known, a first way to restore optimality is to issue emissions permits by an auction, and not for free. The sectoral dimension of the model allows us to explore innovative ways to cope with that problem and to combine it with the debate on acceptability. If one seeks at restoring equal capital return among the productive sectors of the economy, then it immediately follows that giving permits for free to all sectors may solve the problem, provided some allocation rule. This rule is the following: the ratio between free endowment and capital stock must be equal among sectors. In this case, capital allocation among sectors is optimal. Nevertheless, optimal growth is not restored since too much capital is accumulated in the economy.

This result shows that, by giving adequately permits for free to all firms, dynamics conditions on capital allocation among sectors can be restored. Because the final good sector does not pollute, giving it some pollution permits is equivalent to give it some lump sum transfer. Importantly, this transfer is valued at the market price of tradable permits in equilibrium, which coincides with the optimal price since the emission cap is equal to the socially optimal emission level. It can be noted that equilibrium does not depend on the proportion of permits that are given for free.

[14] This paper generalizes Jouvet, Michel and Rotillon (2005) by considering two productive sectors and general specifications for the production functions.

One may be puzzled by the fact that emission permits are given to firms that do not pollute. Two arguments can be provided as a justification:

- cost pass-through: the final good sector bears a cost because the power sector increases its output price when the price of carbon increases in the market for tradable permits, so some compensation should be given to these firms;
- fairness: if a lump sum is to be given to some firms which increases their market value (the power sector), then it should also be given to all other firms in the economy.

A striking point in that result is that optimal capital allocation can be restored whatever the proportion of emission permits that are given for free, as long as the regulator applies the optimal sharing rule. This has to do with a key issue in the political implementation of markets for emission permits. It is well established that an emission fee is far more expensive for firms than a market for tradable emission permits with free endowment. In the former case, firms have to pay for every unit of pollution while, in the latter case, they only bear the opportunity cost of pollution, which is valued at the market price of emission permits.

Within a rather close setting (overlapping generations model and optimal growth), Bréchet, Lambrecht and Prieur (2009) explored the role of intertemporal flexibility of emission quotas in climate policies.[15] In this paper it is shown that, for a country committed to some non-optimal emission quota, allowing for a two-period flexibility with both banking and borrowing allows to replicate the optimal growth path of the economy. In other words, full intertemporal flexibility of emission quotas is not necessarily required to meet optimality, and some rule-of-thumb (presented in the paper) that may be politically and practically implementable can play that role.

2.5 Environmental innovation and the cost of pollution abatement

A last point that was explored in the CLIMNEG project was the effect of environmental innovation on the marginal (and total) abatement cost at the firm level. In a general setting, Bréchet and Jouvet (2008)[16] show that, contrary to the usual assumption made in the literature, environmental innovation does not necessarily reduce the firm's marginal abatement cost.

Even though this point may seem of minor interest, it is far from being the case, actually. First, the whole literature related to the ranking of policy instruments in terms of incentive to innovate relies on that fake assumption. Second, in equilibrium, it entails that innovation may lead to a higher marker price for emission permits, for example, or that a firm facing an emission fee may pollute more after innovation than before. Thus, a higher tax does not necessarily yield a positive incentive to innovate in clean technologies. Clearly, the implications of that paper are manifold. This is subject of ongoing researches at CORE.

[15] Bréchet Th. Lambrecht S. and Prieur F. (2009). "Intertemporal transfers of emission quotas in climate policies", *Economic Modeling* 26(1), 126-134.
[16] Bréchet Th. and P.A. Jouvet (2008). "Environmental innovation and the cost of pollution abatement revisited", *Ecological Economics*, 65(2), 262-265.

3 MODELING CLIMATE POLICIES WITH CWS

In this part of the report the update and upgrades of the integrated assessment model CWS are presented.

In a first phase, the economic part of the CWS model has been updated. This led to the CWS 1.2 version, and subsequent publications.

Then, a second and more profound update was made during 2007-2008. It consisted in a disaggregation into 18 regions/countries. This resulted in the CWS 2.0 model. Furthermore, in that new version many improvements were implemented: new cost functions for greenhouse gas emission reduction, a new calibration procedure and baseline scenario, an explicit representation of emissions trading, a new climate change impact module, new output representation tools, the implementation of adaptation and so on.

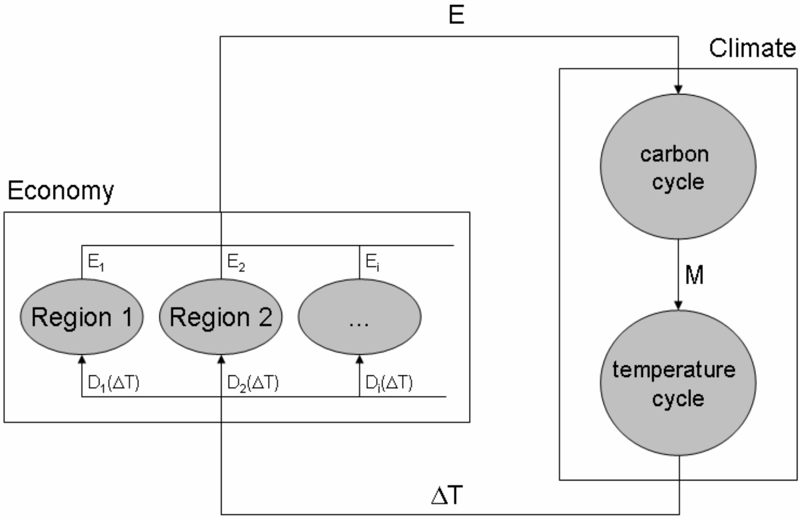
Some revisions were not foreseen originally in the project but were considered important to include during the course of the project, for instance the construction of a completely new baseline scenario and the inclusion of adaptation policies. Other objectives of the revision of the model were not fully achieved. Experiments were conducted to include a form of endogenous technological progress, alternative welfare functions and a more elaborate carbon cycle model. These experiments have not all been successful because of technical implementation problems (for instance carbon cycle modeling) or limited human resources. The basics of the CWS 2.0 model are described in Holzweber (2008). Further publications with the CWS 2.0 are planned for early 2009.

The whole network was involved in these updates. ASTR contributed to the evaluation of the consistency of the socio-economic input data and results of CWS by comparison to standard climate scenarios (in particular, improvement of the comparability with scenarios from the Special Report on Emissions Scenarios (SRES) of the IPCC, 2000).[17] HUB heavily contributed to the economic update and climate module update, and played a major role in the upgrade of the GAMS codes.

The principle of the CWS model is the following. The world is divided into n regions. Each region I runs its economy independently from the others (trade is excluded), causing at every time t emissions $E_{i,t}$. The aggregated emissions of all the regions affect the climate. First in the carbon cycle, the emissions influence the carbon concentration in the atmosphere M_t^{AT}, which determines further a global temperature change T_t^E. This temperature change has again an impact on the economies, which experience damage through higher temperatures. This basic cycle is illustrated in diagram 1. The main equations of the model are available in Annexe 6.1.

[17] Note that although the IPCC is currently discussing the development and use of scenarios inside the climate community for the next assessment report (AR5), the SRES are still a valid reference since no agreed socio-economic scenarios exist in the new framework (IPCC, 2008).

Diagram 1: Overview of the CWS model



3.1 Update of the economic part of the CWS model

The aim of this section is to present how this update was made, detailing every step to ease similar future exercise. In particular, demographical and technological (overall productivity and carbon intensity of the economy) projections have been updated for every region. As a result, world carbon emissions paths are lower than with the previous version (even if higher in the United States) so that global optimal abatement is reduced.

The main reason why the CWS model has been updated is that it has been created from the RICE model of Nordhaus and Yang (1996). Thus, the initial year period as well as all the initial values linked to this base year came from RICE 96. This base year was 1990, so the numerical results were 10 years old already. During the 90s, a lot of new tendencies appeared (for example, China has known a strong growth and FSU a recession during the first half of the century). These may have provoked divergences between initial conditions of the model and what is currently real at the end of the first ten years period (1990-2000). The new base year is 2000[18].

Four initial values are required for the model to run: the capital stock for each region, the atmospheric concentration of CO_2 (M_0), the increase of mean temperature in deep oceans since pre-industrial times (T_0^o), and the mean temperature increase on earth since the pre-industrial times (ΔT_0). Moreover, three exogenous trends (population ($L_{i,t}$), total factor productivity ($A_{i,t}$), carbon intensity of production ($\sigma_{i,t}$)) must be constructed for each period and region. Eyckmans and Tulkens (2003) use a functional form generating those values from three reference values: an initial value, an initial growth rate and an asymptotical value. This function is strictly increasing (decreasing in the case of $\sigma_{i,t}$) and concave (convex).

[18] Analysis of the effect of this update on climate coalitions stability is provided in Bréchet, Gerard, Tulkens (2007).

3.1.1 Initial values and exogenous trends

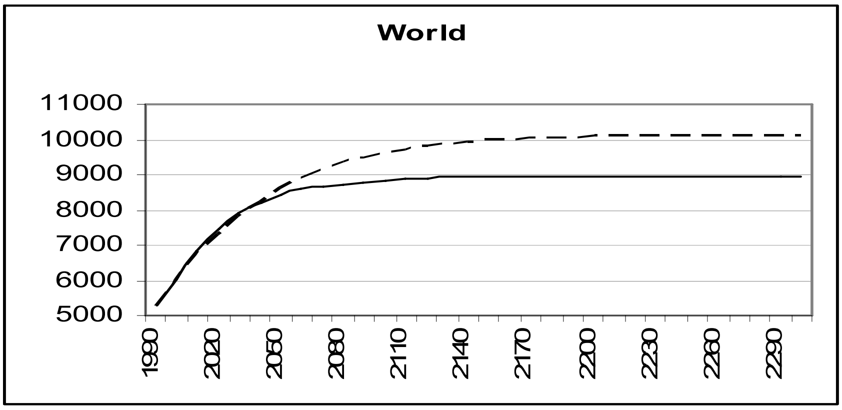
Let us first consider the problem of initial values, which are the capital stock, M_0, T_0^o, ΔT_0.

The capital stock is not observable directly nor computable in an easy way. We then assumed an identical rate "capital stock/GDP" in 1990 and in 2000, different for each region. Knowing this rate for 1990 (cf. previous CWS version) and the levels of production for 2000 (see *www.cait.wri.org*), we can compute the initial capital stock values for 2000.

The physical module consists in three initial values: M_0, T_0^o, ΔT_0. The atmospheric concentration of CO_2 in 2000 (calculated from Nordhaus and Boyer, 2000) is the only one that is necessary to this part of the update. Initial variations of temperature have been then adapted according to the equations of the model without using any database.

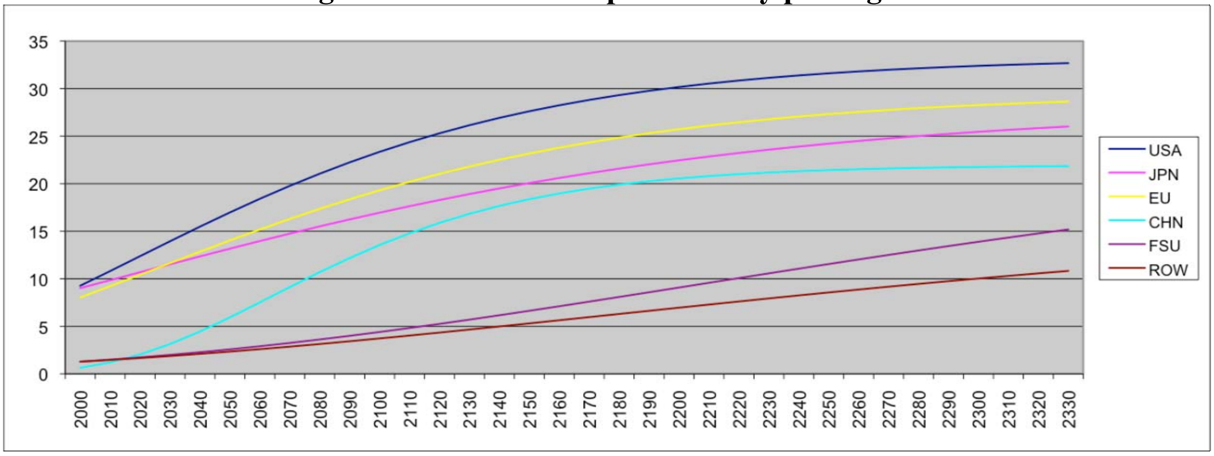
Some exogenous trends have to be assumed for simulations. These are the population, the technical progress and the carbon intensity. We now use projections from the United Nations, *World Population to 2300* (2004), according to which world population will be lower of about one billion of people compared to previous projections. Only three of our regions will face a higher population level in 2300 than in 2000 (USA, CHN, ROW). Figure 2 shows the world population projections for the previous CWS model (CWS 1.1) and the new one (CWS 1.2).

Figure 2: World population in CWS 1.1 and CWS 1.2 (billion people)



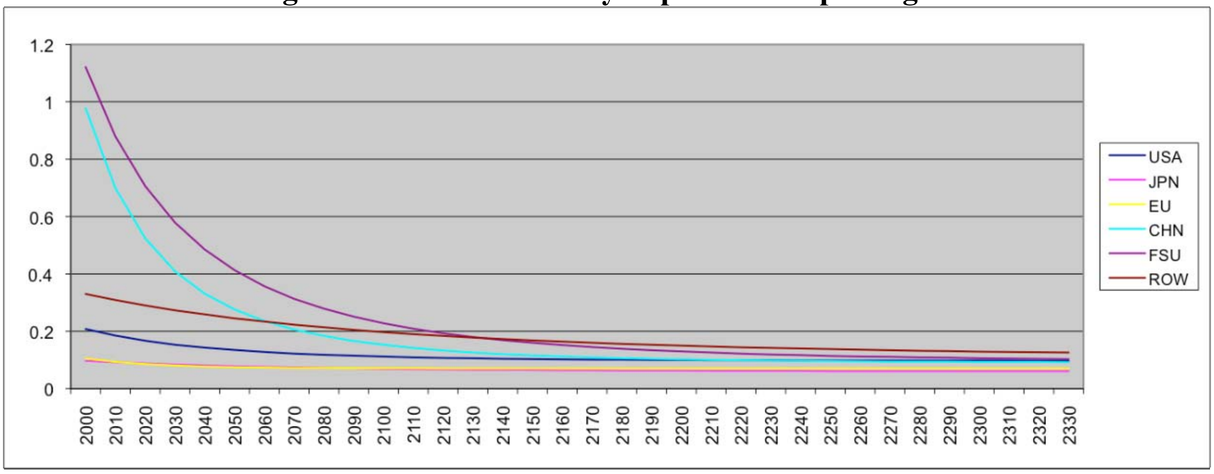
For the total factors productivity, we obtain original values directly from the production function, while the growth rate is the one between 1990 and 2000. Long-term assumptions remain the same (convergence for all the regions) but we had to change the asymptotical value to be coherent with these assumptions. Productivity is higher for China thanks to the economic growth this country faced during the nineties. The same is true for other regions. FSU is the only exception, having undergone a crisis during the first half of the nineties. We limit thus the initial growth rate period to the second half of this decade. Figure 3 shows the generated time series for total factor productivity in each region.

Figure 3: Total factors productivity per region



The carbon intensity of production is equal to the ratio emissions/GDP. Emissions in 2000 are provided by the CAIT, and include emissions from some industrial processes in addition to the emissions linked to the consumption of energy. The initial growth rate is also the actual rate of growth between 1990 and 2000, including the new sources of emissions for 1990 in order to avoid any influence over the rate. The carbon intensity asymptotical value has been adapted in the same way than the total factors productivity. See Figure 4 for regional carbon intensity of production.

Figure 4: Carbon intensity of production per region



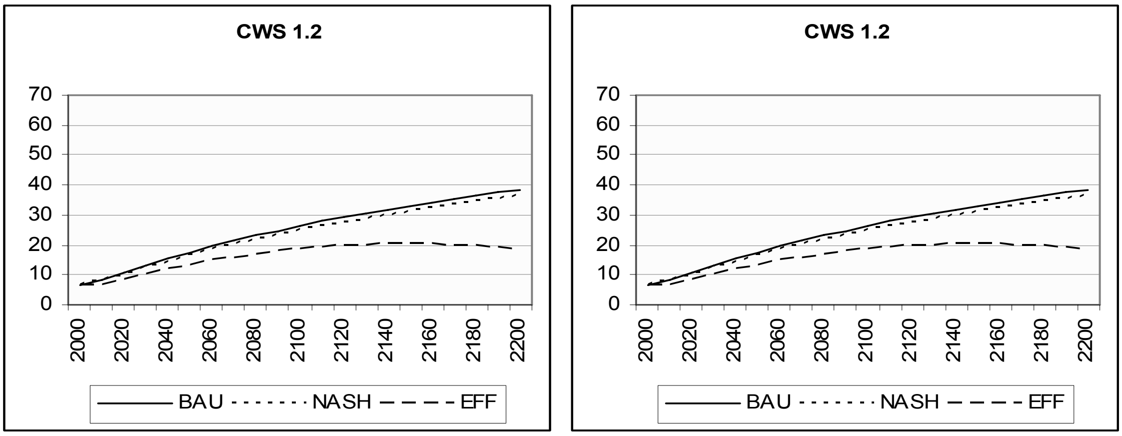
3.1.2 Main results of the update

It is interesting to compare the basic simulations provided by the updated CWS 1.2 with respect to CWS 1.1.

Future world CO_2 emission levels are lower in CWS 1.2 for all the scenarios. But the shape of the curves remains the same than before. A peak is reached in the PARETO scenario (around 2150) and then, emissions decrease in both versions. The two other scenarios see their CO_2 levels continuously increase till the end of the studied period. The variation between scenarios is lower in the new version. Finally, the US emissions are always higher for the BAU scenario.

The lower emission levels lead to lower concentration levels. Trajectories are also comparable to the previous version. Here, the inertia of the climatic system implies that there is no peak reached during the studied period.

Figure 5: World CO_2 emissions (E_t, left) and concentration (M_t, right)



The evolution of the temperature being closely linked to atmospheric concentration of CO_2, we can expect a lower temperature variation for each scenario (see figure 6). As before, the increase is stronger in the BAU and NASH than in the PARETO scenario. Table 3 compares the mean temperature increase in 2100 and 2200.

Figure 6: Temperature change in °C (*w.r.t.* pre-industrial temperature)

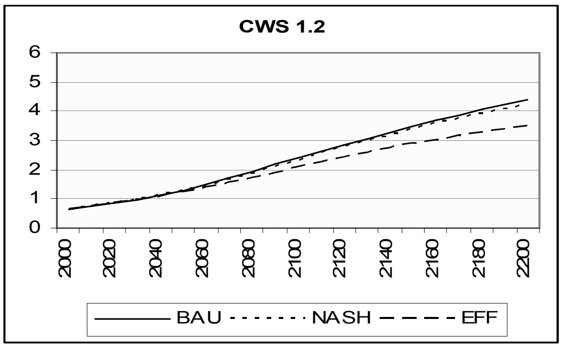


Table 3: Mean temperature increase in 2100 and 2200 (°C)

	CWS 1.1			CWS 1.2		
	BAU	NASH	EFF	BAU	NASH	EFF
Temperature increase in 2100	2.8	2.7	2.2	2.4	2.3	2.1
Temperature increase in 2200	5.4	5.3	3.9	4.4	4.2	3.5

Considering the abatement rate (comprised between 0 and 1), some differences are obvious in comparison with CWS 1.1. In the NASH scenario, the USA abate more while China does a initial higher effort then lowered and FSU abate less. The PARETO scenario sees China doing less abatement effort because of the increase in energy efficiency. At the global level, the compensation comes from ROW that makes as much reductions as before. Thus in a global strategy, ROW has to abate more because it is not possible anymore to abate as much as before for China.

Two main conclusions come out about the GDP and its distributions between the different possible expenses (see table 4) :

- The distribution of world expenses between consumption, investment, damages and abatement costs remain constant between the different scenarios;
- The update leads to a slower economic convergence between standards of living.

Table 4: World GDP structure in BAU and COOP (%)

	CWS 1.2 (BAU)				CWS 1.2 (COOP)			
	Z	I	C	D	Z	I	C	D
2020	73,5%	26,3%	0,0%	0,2%	73,8%	25,9%	0,1%	0,2%
2050	76,3%	23,3%	0,0%	0,4%	76,7%	22,9%	0,1%	0,3%
2070	77,3%	22,0%	0,0%	0,7%	77,8%	21,4%	0,2%	0,6%
2100	78,0%	20,6%	0,0%	1,4%	78,8%	19,8%	0,3%	1,0%
2130	78,0%	19,7%	0,0%	2,3%	79,0%	18,8%	0,6%	1,6%
2150	77,8%	19,2%	0,0%	3,0%	77,9%	19,3%	0,8%	2,0%
2170	77,4%	18,9%	0,0%	3,7%	77,9%	18,4%	1,2%	2,5%
2200	76,4%	18,8%	0,0%	4,8%	77,8%	17,0%	2,1%	3,0%

3.2 Upgrade of the climatic part of the CWS model

The climatic part of the CWS model begins with greenhouse gas emissions and computes concentrations and resulting temperatures. As many other integrated assessment climate models (IAMs), CWS uses a simplified representation of the climate system components that is based on the DICE/RICE models (Nordhaus, 1999). As it is a simple model, the key objective when designing and setting the model parameters is to make the main results consistent with current complex models (coupled atmosphere-ocean general circulation models, also called AOGCMs). We followed the summary work done for the 4th assessment report (AR4) of the IPCC (2007a) regarding the key parameters that reflect the behaviour of a complex model, such as climate sensitivity.

3.2.1 Carbon model update and calibration

The first IAMs used a crude representation of the "carbon cycle" - one or two equations that computed atmospheric carbon dioxide concentration from the anthropogenic emissions. It is long know that these early representations, in particular the one from Nordhaus (1992) resulted in unrealistic concentration estimates. A fundamental problem with the early approach was that it assumed that a fraction of the emitted CO_2 instantly "disappeared" from the atmosphere, introducing the notion of "airborne fraction" that remained in. More recent versions of the DICE/RICE models, starting from Nordhaus and Boyer (1999), did not include such hypotheses and provided better results. However, our experiments suggested that the results where still quite far from the expected values from more complex models including a detailed representation of processes (*i.e.* models focusing on the physical / chemical aspects of climate, with computation requirement that are much larger than possible in the framework of integrated assessment). The representation of the carbon cycle in a IAM is thus the result of a compromise between detail (accuracy) of the computation and calculation time / difficulties. We made two kinds of attempts at improving the carbon concentration calculations in the CWS model :

- use the RICE/DICE model equations, but with updated parameters. The latest version was DICE 1999 in the begging of the project (Nordhaus and Boyer, 1999, hereafter

DICE99), but was improved in 2007 /2008 (DICE08, Nordhaus 2008). This last version uses the same equations as DICE99 (with a minor implementation change) but parameter values where revised. We developed our own version of the model parameters (see below);

- construct a CWS version of the model from Joos (1999) and colleagues, which is still a simplified representation, but includes the highly non-linear effects related to the penetration of carbon in the ocean that are missing in DICE99 (and DICE08).

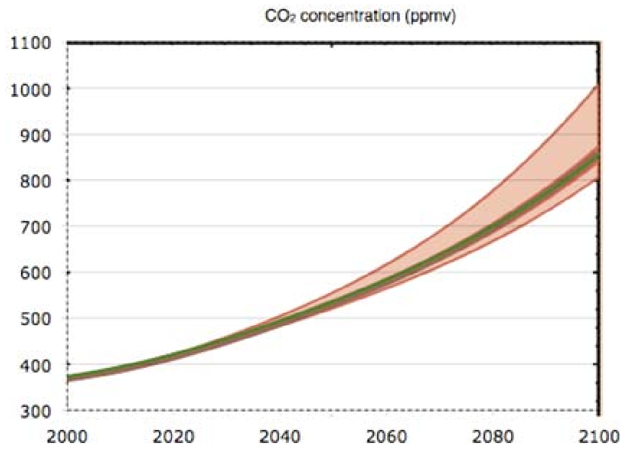
There are several models based on the DICE approach ((a) above), but tests showed that it is very unlikely that this approach could accurately follow, with the same set of parameter values, both high emissions scenarios and concentration stabilization scenarios (mitigation). This is why we were interested in using the Joos *et al*. model (approach (b) above): it is, by conception, more able to represent key non-linear processes that are part of the carbon cycle. Both approaches have been implemented in CWS, with different advantages, and will be discussed below.

Using the JCM model for CWS calibration

To facilitate the comparison of CWS to complex models, we used our interactive climate model, JCM (Romstad, 2005, and www.climate.be/jcm; partly developed during the previous CLIMNEG project). This model also uses a simplified representation of climate processes, but it is significantly more complete than that found in integrated assessment models such as CWS, and we can use a number of scenarios with it (IPCC Special Report on Emission Scenarios (SRES, 2000) and adjustable mitigation scenarios are included). An advantage of using JCM for the validation of CWS is that we can easily perform comparisons for various scenarios, including high emission cases that may occur in CWS during the 22nd century. This approach is based on considerations that have clear similarities with IPCC developments in preparation for the next assessment report (AR5, planed for 2013-2014): while coordinating the use of new scenarios in climate models, specifically by proposing the new "Representative Concentration Pathways", the IPCC (2008) wanted to include both low concentration, stabilisation paths and very high emission scenario scenarios. It is logical that IAMs also have some ability to deal with such scenarios diversity.

Thus, as we want to facilitate the calibration of CWS by using JCM, we first verified that JCM itself is consistent with IPCC AR4. This is the case to a very satisfying level, as shown for example in figure 7 for the SRES A2 scenario. While the AR4 figure used for comparison is also based on a "simple climate model" and has known limitations (AR4 WG1, appendix 10.A.1), these relates to the simulation of temperatures, while for carbon cycle it provides a range of scenarios, with uncertainties associated with an ensemble of AOGCMs, that form a good basis for the verification of our results.

Figure 7: Example of comparison between the JCM model and IPCC AR4



CO_2 concentration (ppmv) projected for the 21st century, with emissions from IPCC SRES A2 scenario. Red solid line (at the center, behind de green line) : simple climate models result from AR4 WG1, figure 10.26. The shaded area represent +/- 1 standard deviation from AR4, following tuning to 19 3D climate models (AOGCMs). The green line is the JCM result (with defaults parameters, as used here, but closely following SRES A2 except at the very beginning of the century, where updated emission data is used)

Updated DICE parameters (approach a.)

The representation of the carbon cycle in the DICE model is based on 3 main equations. These equations refer to the change in carbon amounts in 3 reservoirs that are reminiscent of a very simplified view on the physical system: the atmosphere, a biosphere + surface ocean layer, and the "deep" ocean (Figure 8). There are minor differences between DICE99, DICE08 and our model. Nordhaus is always using a 10 years time-step, while we prefer to use a 1-year time step[19]. DICE08 also introduced changes in the integration of carbon emissions to form concentration, in relation with the 10-year period (averaging of beginning + end concentrations[20]).

The calibration of the model consists in defining the initial carbon content of the biosphere (M_{up}) and deep ocean (M_{low}), as well as coefficients defining the exchange rates between these reservoirs (F_{ij} in Figure 8). The atmospheric carbon content (M_{atm}) is well defined from direct or indirect measurements (the pre-industrial concentration is around 280 ppm and 380 ppm was reached at the beginning of the 21st century). The derivation of the DICE99 parameters made use of some consideration about actual carbon contents in the climate system, but mainly relayed on calibration in order to match results from a simple climate model; in DICE08, the climate model used is MAGICC (v5, see Meinshausen *et al*., 2008, for the last version). As this model is very similar to JCM, our approach is very similar to that of Nordhaus. However, there are two important differences:

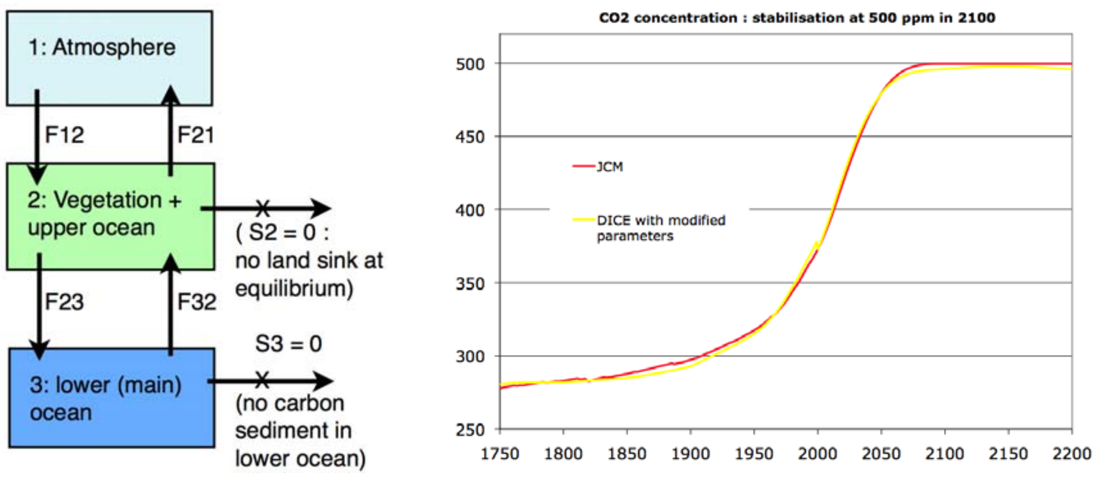
1. Nordhaus (2008) is using the SRES A1FI emission scenario (it is the only one shown in the accompanying notes[21]), while we are using both the SRES B2 scenario and a concentration stabilisation scenario at 500 ppm generated with JCM;
2. we base our analysis on 200 years in the future, while Nordhaus only considers the 21st century. We think that as economic models may be increasingly used to analyse low stabilisation scenarios, which are relevant to the policy debate, it is important that their climate component is providing correct results also in these cases.

[19] However, we also used 10 years step with average *emissions* (unlike in DICE99), with little change from 1-year step.
[20] This is how it appears in the on-line code from Nordhaus (2007), but apparently there are differences with the text.
[21] See http://nordhaus.econ.yale.edu/Accom_Notes_100507.pdf

Another hypothesis that was partly done in our calibration, and at least partly in the last version of DICE, is that the model is at equilibrium with pre-industrial concentrations. This sets constraints on the F_{ij} fluxes in relation to the pre-industrial box CO_2 contents. For the F_{12} and F_{21} fluxes, we have imposed equilibrium in 1750, but for F_{23} and F_{32}, we found that imposing this was making it more difficult to calibrate the model for future concentrations. To facilitate the calibration, we thus started from F_{23}/F_{32} at equilibrium, but introduced a "desequilibrium" factor that we adjusted in order to improve the results for the future in our 2 scenarios. The content of the "ocean" boxes and the magnitude of the F_{12},F_{21} (together) and F_{23},F_{32} fluxes form a minimal set of variables that need adjustment and has a quite clear meaning; it was progressively adjusted to obtain a satisfying agreement with both the B2 and stabilisation scenario. Although these multiple criteria might possibly be included in a precise mathematical optimisation framework rather than done "by hand" as we did, the key factor influencing the result is not the detail of this calibration procedure but the choice of the reference scenarios. The result for the 550 ppm scenario is shown on Figure 8.

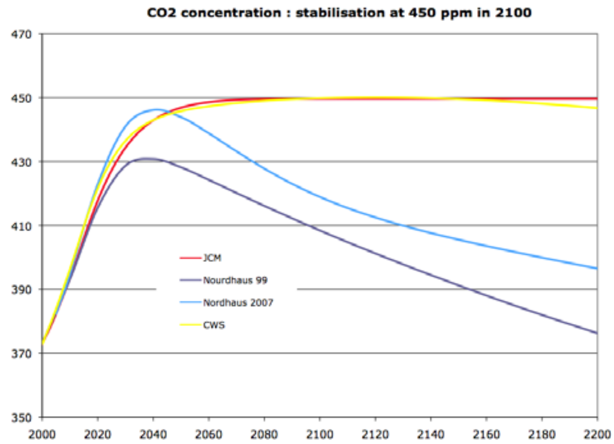
Figure 9 compares the results for different scenarios that where not used for calibration, and confirms that the proposed calibration provides very good results for the stabilisation case and good results in a significantly different scenario (stabilisation of temperature). For scenarios that involve much larger emissions, the results are significantly less good, but still not worse than those from DICE08 for A1FI (in spite of the fact that it forms the basis for the DICE calibration, but only over the 21st century). However, this confirms that the approach, while interesting due to its simplicity and rapidity of calculation, cannot be accurate for both low and high emission cases.

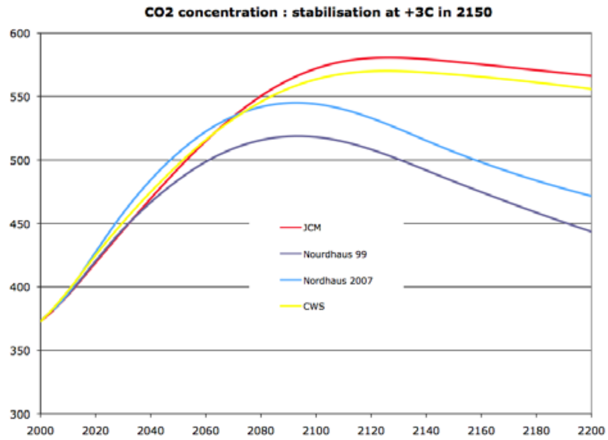
Figure 8: Principles behind the DICE model and its (re)calibration



Left panel: the model uses 3 "reservoirs" of carbon with exchange fluxes proportional to the content of each box.
Right panel: our calibration is considering both past and future (model starts at equilibrium, see text).

Figure 9: Results from (re)calibrated DICE model





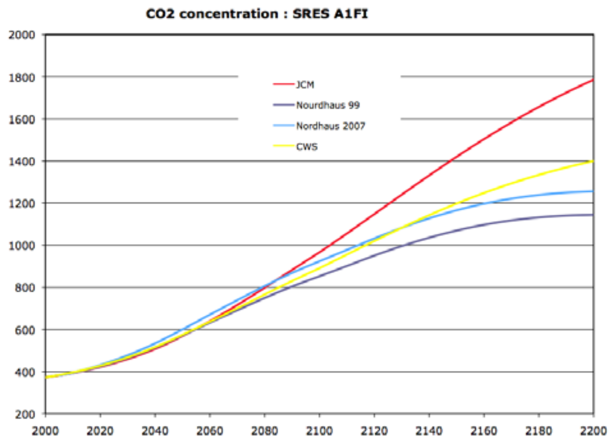


Figure 9:
Results form re-calibrated DICE prepared for CWS compared to JCM, DICE with parameters from Nordhaus and Boyer (1999) and DICE with parameters from Nordhaus (2008). JCM was used for the calibration but with 2 other scenarios (see text).

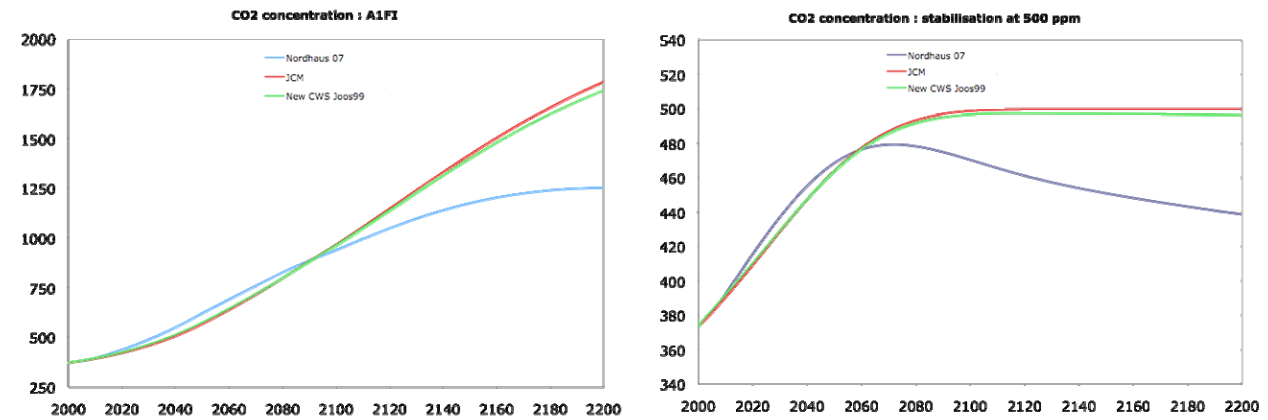
New carbon cycle component (approach b.)

We analysed the model of Joos *et al.* (1999) and implemented a first version in CWS. We also had contacts with the authors, which provided a suggestion regarding the implementation of the model, but their work was done in a somewhat different context so that they did not have to deal with the computational efficiency issues described below (it is likely that the number of experiments typically done with CWS is large compared to other uses of similar models).

The details of our implementation in CWS are described in Marbaix and Gerard (2008). It was necessary to adapt the coefficients of the pulse response functions to mach JCM results (as these are itself matching recent AOGCMs from the AR4, which are expected to be somewhat different from those available 10 years ago one the model was proposed by Joos and colleagues). However, the model proves able to closely follow JCM results both for low and high emission scenarios, unlike the more simplified approach (above). This is illustrated on Figure 10, comparing JCM, the new version developed here for CWS and the above approach with the Nordhaus (2008) parameters.

However, computational efficiency in a model requiring repeated calculations (for optimisation and analysis of a large number of coalitions) proved difficult to reach. For cases that involved high emissions sustained over more than a century, the carbon component needed to be run with a time step shorter than 1 year (while standard DICE uses 10 years, and the standard CWS uses 1 year). Second, difficulties also occurred in connection with the optimisation of the emission path that is performed in CWS: it might fail and needed new developments in order to provide a "first guess" that facilitates convergence. Part of this problem was related to the use of an highly non-linear formula for the calculation of carbon uptake by the ocean in the Joos (1999) model, as explained in our report (Marbaix *et al.*, 2008, equation 8). However, this formula contains series that can be truncated without loosing much accuracy in the final results. In the case of figure 10, only the first 4 powers of the surface ocean layer carbon concentration where included (dropping the 5th), enabling the use of a 1-year time step even for the relatively high concentration reached by the continuation of the A1FI scenario into the 22nd century (however, the model was not re-calibrated after this truncation, which explains part of the small mismatch between the new CWS module and JCM at the end of the period).

Figure 10: Tests of the carbon cycle component



On Figure 10, we can see the results of a test of the carbon cycle component based on Joos (1999). Values are CO_2 concentration in ppmv, outputs of the JCM model (see section 3.3.1) are shown comparison, as well as outputs from the Nordhaus 2007 model. All 3 models receive the same emission scenario for input. Left panel: example of high-emission scenario: A1FI (FI is for Fossil Intensive) from IPCC SRES (2000), with an extension for the 22nd century (that was not available from the SRES report). Right panel: stabilisation at 500 ppm CO_2 computed by JCM (*i.e.* JCM provided the emission scenario so that concentration stabilises).

Discussion and consideration for future work

The progresses of climate research and the publication of IPCC AR4 incited both the developers of the DICE model and ourselves to revise the calibration of our carbon cycle sub-model. In our re-calibration of the DICE model, we could take better account for scenarios involving stabilised concentrations or temperatures at a low level. This is was not important as long as IAMs did only consider relatively "high emission" cases without stabilisation in the considered time frame, in part because common economical analyses of the climate issue, knowing the difficulties of giving a monetary value to all impacts, rarely produced such scenarios (a counter example might be the Stern (2006) Review on Climate Change, but it did not perform cost-benefit analysis). However, for improved IAM and future use of economic models, it appears normal to require that low emissions scenarios can be considered and provide accurate results, also knowing that such scenarios are generally advocated by impact specialists. To be able to compare the costs of stabilisation and high emission scenarios, the IAMs must become able to compute CO_2 concentrations accurately in both cases.

Representing the carbon cycle in a way that is appropriate for both low and high emission cases is not easy due to the highly non-linear nature of the process of carbon penetration in the ocean (it is not just proportional to the amount of carbon in the atmosphere or another simple formula). While we could improve the results from the simple formulation used in DICE (approach a), our implementation still has limitations for high emission cases. As we knew that this problem could arise, we prepared a representation of the carbon cycle based on the model of Joos *et al.* (1999), which is still simple but more detailed than DICE (approach b). This approach provided very good results, but it could not yet be used in standard CWS simulations as it may cause numerical problems and certainly increased the computation time. Thus the "revised DICE" approach was selected as the default carbon representation in the updated CWS. However, the developments based on the more detailed approach are promising, and it is very likely that small simplifications in this new carbon sub-model or the addition of appropriate "first guess" values in CWS could make it work efficiently. Most of the work towards a much better representation of the carbon cycle that could work efficiently in an IAM has been done, and we think that it should be continued in the future, being useful not only to CWS users, but also to users of other models of similar types.

3.2.2 Climate (temperature) component calibration

Concerning temperature changes related to the increase of greenhouse gas concentrations, we concluded that the approach used in CWS, based on DICE99, remains satisfying to follow the main characteristics of complex climate models in a simple way. We thus focused on updating CWS parameters so that the results follows those of complex models (GCMs) prepared for the 4^{th} assessment report of the IPCC. An addition to the work method with CWS is that we included 6 consistent sets of parameters, each set being based on a different GCM. We selected these parameters sets in order to cover a realistic range of equilibrium climate sensitivities and transient climate response (Figure 11).

Figure 11: Climate sensitivity and transient response

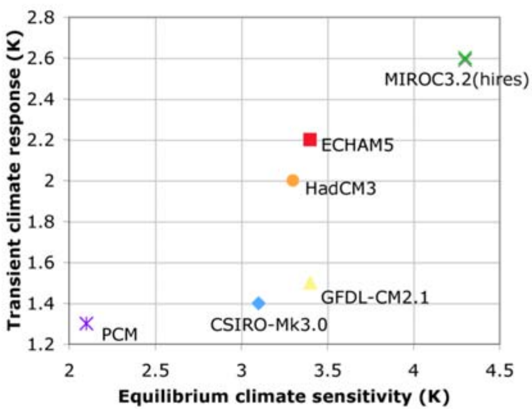


Figure 11 : Climate sensitivity and transient response for a selection of models, based on IPCC AR4 WG1 report, chapter 8, table 8.2. The selection is representative of the range of values found in AR4.

As many CWS experiments cannot be repeated with several climate sensitivities (due to the large number of potential coalitions, and thus runs, that are investigated), a reference case was selected so that it is close to the « medium » sensitivity and transient response: we use the "HadCM3" calibration. We then developed a methodology to define the parameters of the DICE99 climate component using the data available in the AR4 (these are mainly climate sensitivity, transient climate response and ocean heat uptake efficiency). Finally, we compared the behaviour of the updated CWS to that of a version of JCM also adapted to AR4 (knowing that JCM uses a somewhat more complex representation of the climate systems, dividing the Earth into a few boxes with several layers for the ocean, following an approach similar to that used in MAGICC). We also compared our results to the AR4 itself for the SRES scenarios. In spite of the inherent limitations of a simplified model such as CWS, our results show that it is able to follow the behaviour of GCMs quite closely for a wide range of scenarios (figure 12). The other important consequence of our work is that CWS is now able to follow the behaviour of an ensemble of GCMs (not only the one used as reference case), including low, middle, and high sensitivity to greenhouse gas concentration changes. Uncertainties in both the sensitivity and inertia (transient response) of the climate system may thus be taken into account when making experiments with the integrated assessment model.

Figure 12: Results of the CWS climate module

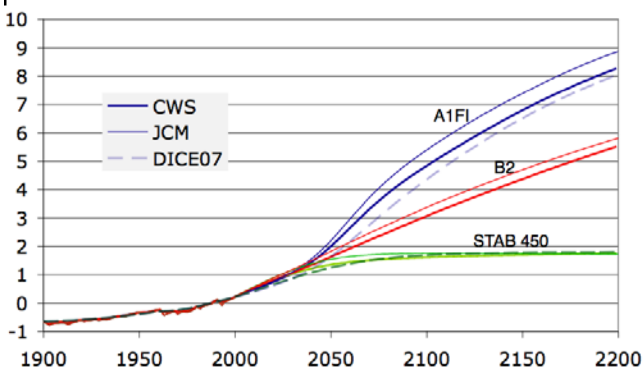


Figure 12: Results of the CWS climate module calibrated according to the HadCM3 AOGCM, for 3 forcing scenarios : B2 and A1FI from IPCC SRES, and a scenario for stabilisation of CO_2 concentration at 450 ppm in 2100 generated by the JCM model.

These updated carbon cycle and temperature components are described in a working paper (Marbaix and Gerard, 2008). The consequences of these changes on the integrated model results were investigated, showing that the changes are moderate with the "reference" climate model parameters (HadCM3, which has an equilibrium sensitivity of 3.3°C for doubling CO_2 concentration). In the high sensitivity / transient response cases, temperatures computed in CWS are evidently higher; as a consequence, damage costs are larger, and finally the economically optimal emission levels are lower.

3.2.3 Sea level rise

Sea level rise is generally considered in IAMs, such as DICE, as an impact that directly depends on instantaneous temperature, although possibly considering the possibility of dangerous thresholds. However, sea-level change has its own dynamics, and is much slower than temperature change: thermal expansion follows heat uptake by the oceans, not instantaneous temperature, and the melting of continental ice in Greenland and Antarctica can take several centuries or millennia, although recent analyses complicate the picture by suggesting that part of it might be much quicker (*e.g.* Ramstorf, 2007). We made preliminary experiments to investigate the possibility of computing an explicit sea level in CWS.

Accurate computation of thermal expansion and continental ice melt requires complex models. In spite of the sketchy nature of representation of the oceans in CWS (or DICE : there are only 2 ocean boxes with a volume that is not explicitly defined), we made attempts at computing sea-level rise from thermal expansion. A simple and efficient solution could be to simply compute an estimate of the heat warming up the oceans as the integral of the radiative imbalance[22], as the sea level increase due to thermal expansion is expected to be roughly proportional to the total absorbed heat. Although it is a function of physical quantities such as expansion factor and ocean volume, the most appropriate values for practical application could be set so that the result correspond to selected 3D AOGCM experiments, following the same logic as for other components of very simplified models.

Simple formulas for estimating Greenland and Antarctica ice-melt are provided in the AR4, although some adaptation is needed. However, the most complicated aspect is the finding, during the past few years, that dynamical effects may accelerate the dislocation / melting of continental ice sheets: as noted in the AR4, current 3D models are not able to represent these effects, and the available information is thus limited to "back of the envelope" calculations that suggest a maximum value for the sea-level rise in the 21st century or simple models that are mainly based on extrapolation of past trends. As we do not know the probability of such fast sea-level increase, only theoretical experiments in which it is assumed that it will indeed be quick could possibly be done in the near future. We have also explored the available literature linking sea-level to adaptation needs and damages (*e.g.* Nicholls (2004) and the DINAS-COAST[23] EU project), but further work at a more detailed level is necessary before being able to include resulting functions in an highly aggregated model such as CWS (see also Marbaix and Nicholls, 2007).[24]

3.3 Climate impacts and damage functions

A literature review about the costs of climate change damages was done, in particular by studying the Stern Review (Stern, 2006) and the underlying PAGE2002 model (Hope, 2006).[25] Beyond the discussion on the climate parameters, it is of primary importance to account for the uncertainties and value judgements that renders any estimates of damages costs arbitrary. A range of alternative cost estimates could be tested and used in CWS to analyse their impact on the different scenarios and coalition formation. Another important source we investigated was the estimate from Tol (2002) and the one from the RICE/DICE models, including the recently released version (Nordhaus, 2007).

We carried out sensitivity experiments regarding the damage functions. They were conducted for exploring the level of damage costs associated to a given "optimal temperature maximum" in the model, such as the EU policy objective of (maximum) +2°C from pre-industrial temperatures.

Furthermore, a Master's thesis was achieved on that topic by a student in economics at UCL (Sylvie Aznar). She replicated the whole work done by Nordhaus in order to update it. Thanks to that work we now have a comprehensive set of worksheets that allows us to test, to upgrade

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[22] Computed as $F - \lambda T$ where F is the radiate forcing due to greenhouse gases and λ is the climate sensitivity. This imbalance vanishes at equilibrium.

[23] www.dinas-coast.net

[24] The consequences of localised cooling due to sulphate aerosols were previously studied with CWS. The conclusions were mainly qualitative, but after evaluation, we concluded that working on this now would hardly provide reliable quantitative information on the regional effects. We thus did not consider it as a priority during this project, although the issue should be re-examined in the future, knowing that the most difficult part would likely by the economy/mitigation aspects.

[25] A set of reading seminars was organized in that purpose within the network.

and to re-calibrate the damage functions of the CWS model (at, if necessary, a higher level of regional desegregation).[26]

While disaggregating the CWS model into 18 regions, the damage functions were upgraded. Notably, they now allow for negative damage values for low warming. This will be presented in the next section.

3.4 A new 18-region model: CWS 2.0

During the project it turned out that disaggregating the CWS model would be very beneficial to coalition analysis. So we did it. Interestingly, in the meantime we upgraded the model in many ways.[27] In this section we will present this disaggregation as well as its implementation under GAMS. The main results will also be provided.

The update consisted in disaggregating the original 6 regions into 18 in order to increase the number of possible coalitions and to have more general results about the stability of these coalitions. This disaggregation also allowed us to decrease the number of countries included in the Rest of the World region (a quite large region in CWS 1.1). On the other hand, the disaggregation led to a larger number of possible, which raised computational problems. Some adaptations in the code were necessary to handle such a large number of regions (exogenous parameters, partition matrix…).

3.4.1 Main differences between CWS 1.2 and CWS 2.0

Level of disaggregation

The original 6 regions have been disaggregated into more homogeneous ones considering two conditions: first, a region should include only geographically close countries, and second socio-economical context must be similar between countries.

Now if we take a look at the table in Annex 6.6, what are the main characteristics of the new regions? Europe has been divided into three parts EU, CEA and OEU, the two first forming together the current European Union with 27 countries. Many other regions are made up with only one country (India, China, Japan, USA, Canada). South America is separated between LAM (richer countries) and LAO (poorer ones). All the black countries form a region (AFR). Muslim countries are distributed in two regions (MED and MEA). Other Asian countries lie in EAS, RAS. Russia and its European neighbourhood are FSU and Australia together with New-Zealand are AUZ. The region rest of the world (ROW) is composed with residual countries, mainly islands, for which data are sometime missing. Consequently, conclusion about this region can be considered as meaningless. However, we managed to reduce its size from a hundred countries to less than 20.

So far the code was explicitly written for 6 regions. For every scenario 6 coalitions got formed (which is the maximum number of coalitions in one allocation with 6 regions) which occurred explicitly in the code. To overcome this problem and to make the code also suitable

[26] See annexe 6.5 for the whole list of the associated researchers, including the list of Master's theses undergone under the project.

[27] Paul Holzweber realized its Master's Thesis on that disaggregation, including the computational issues. He came from the Technical University of Vienna and visited CORE from March 2008 to June 2008.

for any size of region, the "partition matrix" got introduced as a useful instrument to deal with an arbitrary number of regions in a flexible way.

New exogenous trends

The second important part of the update to 18 regions concerns the data of the regions, which enter the program through a new data file. Once the data mining has been done, the aggregation of country data to the regions is performed in a separate Excel sheet. These so gained pure input data will not be discussed here.

For the population $L_{i,t}$, the productivity $A_{i,t}$, and the carbon intensity $\sigma_{i,t}$, time series are generated. For the last two of them, these are based on the initial value of a variable X_0, the initial growth rate X_0^G (in contrast to the previous functional form taken from Nordhaus) and asymptotic value X_T.

Two ways have been introduced for generating time series for $A_{i,t}$ and $\sigma_{i,t}$. First through a polynomial of degree 3. The requirements on the polynomial are given by fixed values of X_0, X_0' and X_T (with T the last period) and X_T' = 0 (to model something like asymptotic behaviour). Whereby the initial slope of the variable X_0' is simply given as $X_0' = X_0 X_0^G$ with the initial growth rate X_0^G. With this conditions the coefficients of the polynomial follow to:

$$c_0 = X_0$$
$$c_1 = X_0'$$
$$c_2 = \frac{-X_0' - 3/T(X_T - X_0 - X_0'T)}{-T}$$
$$c_3 = \frac{-X_0' - 2/T(X_T - X_0 - X_0'T)}{T^2}$$

The path of the exogenous variable X_t can be finally calculated to:

$$X_t = c_0 + c_1 t + c_2 t^2 + c_3 t^3$$

The advantage of this method is that non-monotone shapes are also possible. The disadvantage is that when the initial slope is too steep the curve can crash into the end value even before the last period, which results in a kink. Therefore in the current version of the code this time series are calculated as exponential functions.

The second way of generating these time series is to use an exponential function. Whereas also in the previous version of the model exponential functions as in Nordhaus have been used, the current formulation is easy to interpret and can deal with a given start value for the slope. For this the exponential function is simply stretched and shifted (and if necessary turned) to meet the requirements.

$$X_t = (X_0 - X_T)e^{\frac{X_0'}{(X_0 - X_T)}} + X_T$$

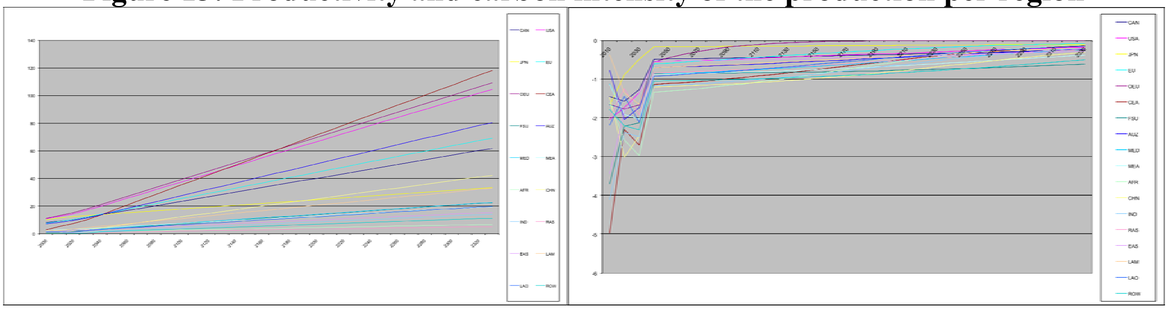
$A_{i,t}$ and $\sigma_{i,t}$ are chosen in that way, that the resulting emissions are conform to the results from other predictions (such as from *IPCC*). This is done for the variables $A_{i,t}$ and $\sigma_{i,t}$. These two variables represent high uncertainties in the model since both affect through

$$E_{i,t} = \sigma_{i,t}(1-\mu_{i,t})A_{i,t}K_{i,t}^{\gamma}L_{i,t}^{1-\gamma}$$

directly the emissions $E_{i,t}$, and the asymptotic values for both are more less rough guesses. Whereas the starting values can get calculated directly, it is assumed that these variables converge by the end of the considered period for all the regions to one value.

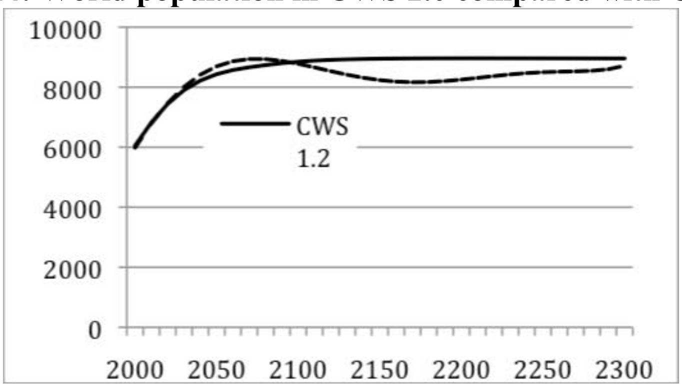
$A_{i,t}$ and $\sigma_{i,t}$ are chosen in such a way that the resulting emissions are conform to the results from other predictions (such as from IPCC). Moreover, growth rates' predictions from the International Energy Outlook made by the US Department Of Energy have been used for the three first decades.

Figure 13: Productivity and carbon intensity of the production per region



For the population $L_{i,t}$ more data are available. The *UN* give projections of population by country from 2000 till 2300 in steps of 50 years. In order to fit these values a polynomial interpolation is used to generate the time series $L_{i,t}$. Precisely, we implement the Neville's algorithm in GAMS to calculate the values of $L_{i,t}$ with a polynomial with degree 6.

Figure 14: World population in CWS 2.0 compared with CWS 1.2



World population will reach 9 billion around 2070 and after that, it will fluctuate between 8 and 9 billion till the end of the period. This is close to what we had in CWS 1.2.

The structure of the GAMS code

Once the main calculations are done (exogenous trends…), scenarios can be chosen, for which a solution will be calculated. With scenarios are meant different forms of allocations. The main scenarios are the NASH scenario (absence of cooperation - every region acts as a singleton) and the COOP scenario (full cooperation). Further the model can be fed with other scenarios like all allocations with one coalition against singletons or all the partitions.

For other scenarios a key-matrix has to be fed in. This key matrix (taken from another file which has to be modified or changed for different scenarios) consists simply of one allocation per line. For all these allocations in the key matrix the equilibrium will be calculated and the relevant variables displayed in an output file.

For the representation of a coalition in this key matrix two ways are possible. These will be described now. For simplicity the case of only 6 players {A, B, C, D, E, F} is discussed.

- binary key for only one coalition S: in the case of only one coalition for each allocation a binary key of n digits can be given. The i^{th} digit is 1 if the i^{th} player joins the coalition and 0 otherwise; *e.g.* players B, C and F form a coalition whereas players A, D and E stay as singletons, the key would be (011001);

- alphanumeric key for multiple coalitions: in the case with multiple coalitions a binary key is not sufficient anymore. A suitable key therefore is to put on the i^{th} digit the number of the coalition the i^{th} player joins. Also singletons are treated here as a coalition. To exclude multiple representations of an allocation in this key, there has to be introduced the rule, that the digits have to appear in a lexicographical order; *e.g.* players A and F form a coalition S1, players B and C form another coalition S2 whereas players D and E stay as singletons, the key would be (122341). When exceeding 9 players, the digits have either to contain letters or more digits have to be reserved for each player.

During this work the code has been modified so that the program can handle both representations.

The partition matrix

The partition matrix is a 2-dimensional binary key representing the given allocation in a unique way (a n × n-matrix where the columns indicate the players and the rows the coalitions). When the i^{th} player joins the j^{th} coalition the value at (i, j) equals to 1. Otherwise it equals to 0.

With this partition matrix as a tool, it is easy to formulate all the actions done in the code as loops, which reduces massively the size and readability of the code. The loop over all coalitions is done as a loop over all the rows that have elements different from 0.

Whereas the partition matrix is used for computing, the 1-dimensional keys discussed before are still more practical to illustrate an allocation in the input and output. Therefore, as soon as the different scenarios are entering the program through the key-matrix (in a 1-dimensional key), they get immediately translated into the partition matrix. Hereby the program can deal with both representations (binary key and alphanumerical key).

New abatement and damage cost functions

Both damages and abatement cost functions are essential to the model. Abatement costs function are now calculated from the marginal abatement costs function:

$$C_i'(\mu_{i,t}) = Y_{i,t} c_i \log(1 - \mu_{i,t})$$

with $c_i < 0$. It is constructed so that it is strictly increasing and strictly convex in abatement $\mu_{i,t}$, with $\lim_{\mu \to 1} C_i' = \infty$, which makes 100% abatement unaffordable. Also, the abatement cost $C_i(\mu_{i,t})$ itself is strictly increasing and strictly convex in abatement $\mu_{i,t}$.

The abatement cost $C_i(\mu_{i,t})$ represents the monetary effort that has to be done to achieve an abatement rate of $\mu_{i,t}$. This function is defined as:

$$C_i(\mu_{i,t}) = -Y_{i,t}\gamma_{i,t}((1-\mu_{i,t})\log(1-\mu_{i,t}) + \mu_{i,t})$$

The damage costs $D_i(T_t^E)$ are the amount of damage in monetary terms which the region *I* faces for an average global temperature change of T_t^E. In the previous CWS version, the damage function was:

$$D_i(\Delta T_t) = Y_{i,t}\theta_{i,1}\left(\frac{\Delta T_t}{2.5}\right)^{\theta_{i,2}}$$

We now use a functional form such that it allows for negative values. In other words, climate change could benefit some regions while making worse off the others:

$$D_i(T_t^E) = Y_{i,t}(\alpha_{1,i}TE_t + \alpha_{2,i}TE_t^2)$$

Computing time

Because of the number of potential coalitions with this 18-region CWS model, computing time becomes an issue. It is a reasonable (and tested assumption) that computing time is mainly determined by the number of solver calls during the run of the program. Besides to the number of players (which is given), the computing time is proportional to the number of iterations per allocation, which should be the focus for improvement in the computing time.

We managed to extract the time to a separate output file at the beginning of the program thanks to a new parameter "*timestart*" initialized with the current system time in second. After each allocation, the key of the allocation, the number of needed iterations and the time since starting the program gets written to the output file.

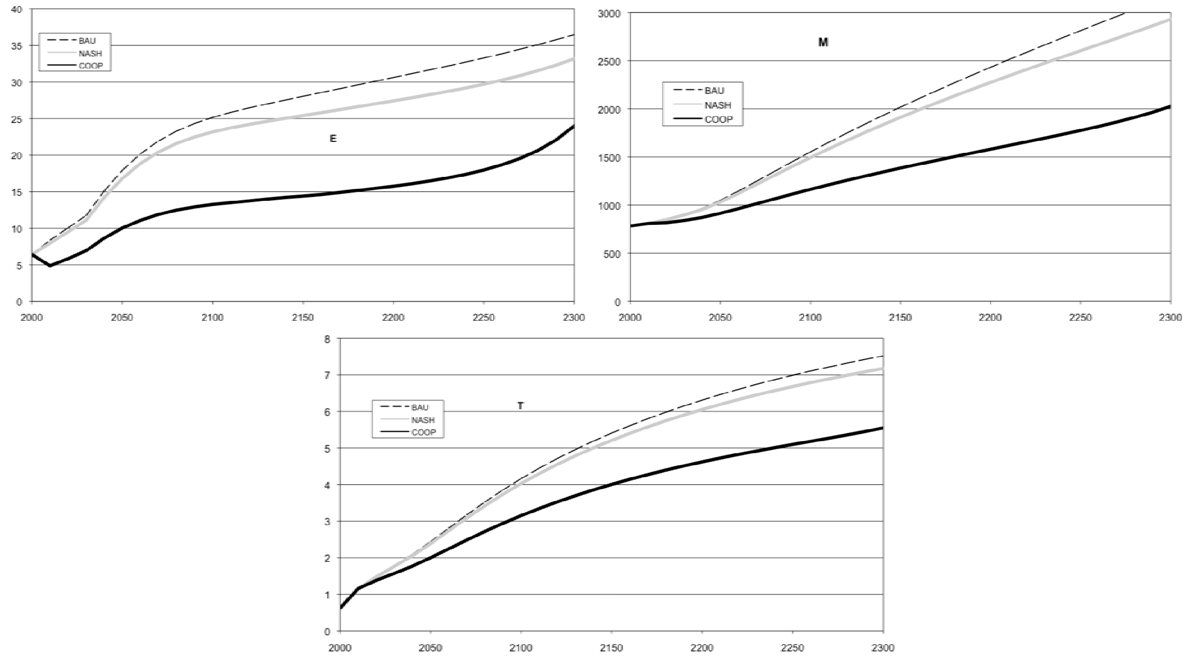
Following to a first test, it appears that the calculation time for one allocation is around 100 seconds. A day of 86.400 seconds, which allows the calculation of less than 1000 allocations, seems to be rather short. Considering "only" the 262.143 allocations with just one coalition, around on year is needed to calculate them all. Reducing the computing time is thus an important objective. Some approaches should be analyzed, such as creating a better stop criterion, putting the allocations in an optimal order, calling the solver for each player in an optimal order, reducing the needed memory with not writing output. For a detailed discussion on these points, see Gérard and Holzweber (2008).

3.4.2 Main results with CWS 2.0

In the following it will be looked at a comparison of global variables for the three main scenarios BAU (no abatement), NASH (absence of cooperation - every region acts as singleton) and COOP (Pareto solution). The importance of these scenarios is given by the fact that in case of superadditivity (which is assumed to hold here) they represent the boundaries of what can be achieved with coalitions. No coalition can do better than the grand coalition in COOP and scenarios with partial coalitions will not be worse off than NASH or even BAU.

A first comparison is done in Figure 15 for the aggregate CO_2 emissions. It can be seen that for all the scenarios a sharp increase till 2100 followed by a smaller one for the rest of the period to a level 7, 6 and 3 as high then nowadays respectively for BAU, NASH and COOP scenario is expected. This can be explained by the endogenous growth of output, which will be later compensated with higher carbon efficiency. Optimal behaviour of the regions just optimizing their own welfare in the NASH would lead to only a little improvement compared to the BAU. This could be also interpreted that the actual current emissions of the regions are close to their national optimum. A sharp emission reduction of about 40% is achieved in the COOP scenario *w.r.t.* the NASH situation in 2200.

Figure 15: CO_2 emissions E (billion tons carbon per year), carbon stock M^{AT} (billion tons carbon) and Temperature change T^E (degrees Celsius compared to 1800)

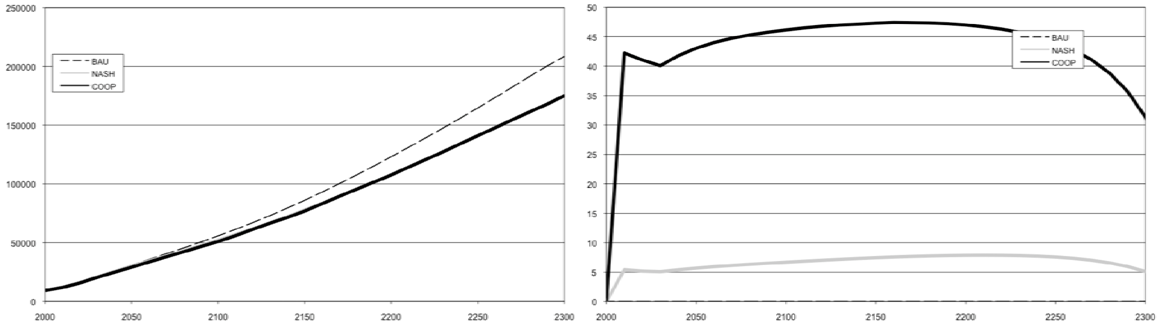


About the resulting carbon stock in the atmosphere (M), the time lag from the emissions to the carbon concentration can be seen with the flat shape of the curves at the beginning. Nevertheless, in all three scenarios the carbon concentration won't reach its maximum within the viewed period, as emissions are never decreasing. However, it is important to note that the increase of the emissions in the 22nd is due to a boundary effect, as there are no calculation beyond 2300, thus no damage beyond 2300. As with emissions, the difference between BAU and NASH scenarios is very little. With cooperation the carbon stock will grow to around one third less than in the other scenarios.

We now come to the predicted global temperature increase (*T*), also displayed in figure 15. From this it can be said that pure economical behaviour will cause a certain climate change in form of a temperature increase of about 7.5°C in the BAU scenario. When regions act like individually (NASH) the decrease in temperature change is rather low (not even 0.5°C). One might say that this is a marginal improvement, but one has also to consider that this improvement can be achieved without cutting back on consumption. Still, optimal behaviour under cooperation will internalize the externalities and reduces the impacts on the global climate. This reduce in global warming through cooperation would be around 1.8°C.

Now a closer look should be taken on the optimal values of the control variables that are leading to this result on climate. From Figure 16 it can be seen that total investment (*I*) is hardly depending on cooperation. It ensures mainly an optimal growth path for the economies.

Figure 16: Total investment *I* (billion 2000 US$) and Total abatement rate μ (%)

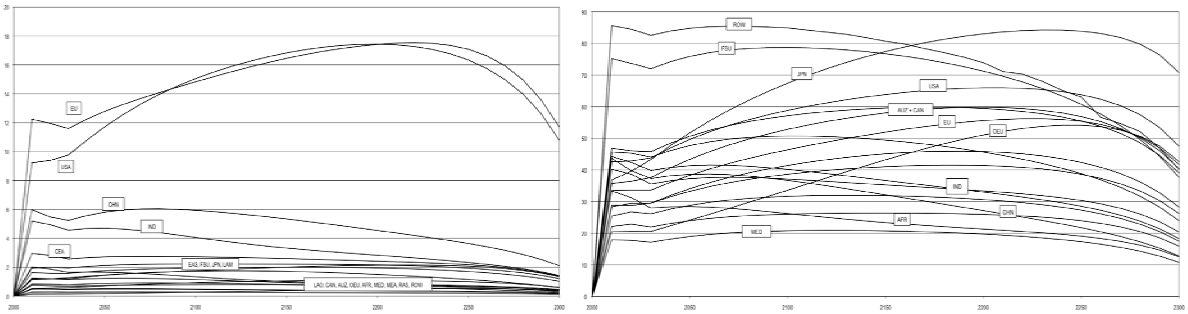


The global abatement rates (*A*) reflect the shares of through the output generated emissions which have to be abated in the optimum. For the BAU no abatement takes place, by definition. An abatement rate lying between 5 and 10% is optimal in the NASH scenario, which indicates again that the current situation is close to the national optimum. Contrary to that, in the COOP scenario significant abatement should take place. There, the optimal abatement path reaches around 47% and decreases afterwards again (this is mainly due to the exogenous carbon efficiency that makes additional abatement less necessary in the very far future).

It is interesting to see the abatement rates at the country level. The optimal paths by region are given in Figure 17 for NASH and in Figure 18 for COOP.

In the non-cooperative case, countries act just for self-interest. In that case it turns out that the EU and USA are expected to do a higher abatement effort than the other regions. China and India follow, with abatement rates reaching 6 and 5% respectively, and falling thereafter. Central Eastern Associates countries reduce their emissions to a level a bit higher than other regions, starting from around 3% to decrease slowly to about 1% at the end of the simulation period. For all the other regions, abatement rate lays between 0 and 2%.

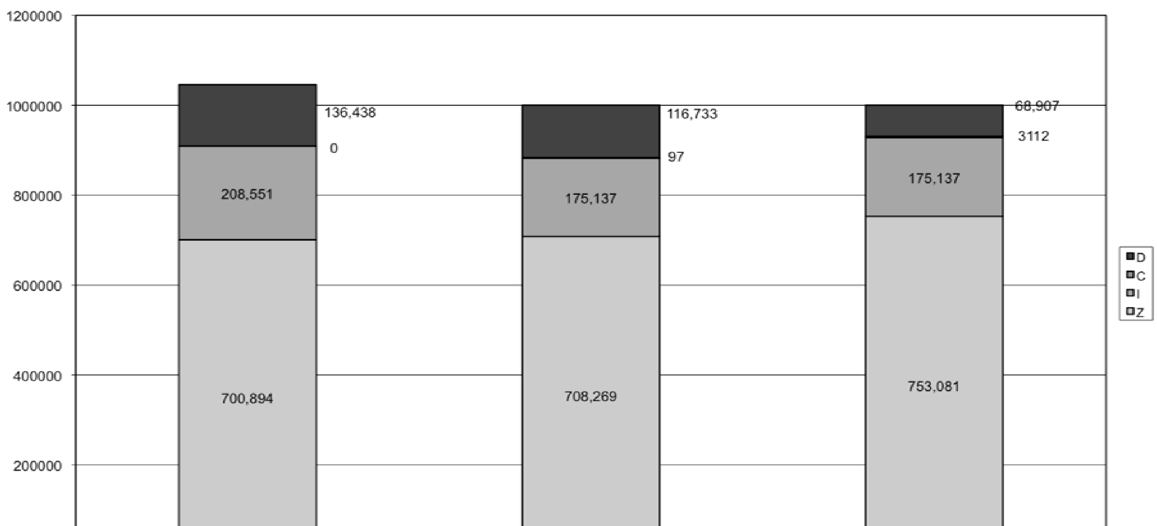
Figure 17: Regional abatement rates for NASH (left) and COOP (right)



In the cooperative case, regions behave a bit differently than in the non-cooperative one. Nevertheless, the shapes of the single curves in the COOP scenario look similar, but lower developed countries as FSU and JPN are expected to do higher efforts, up to around 80%. Developed regions that are AUZ, CAN, EU, and OEU abate up to 60% and even more for the USA (65%). Developing regions do the least but they still abate to a minimum level of almost 20%. [28]

A look at the composition of the output ($Y = Z + I + D + C$) for BAU, NASH and COOP is provided in Figure 18. This structure is compared for each of the three scenarios in 2300. It can be seen that optimal behaviour and cooperation sharply reduce climate damages and increase the green consumption Z.

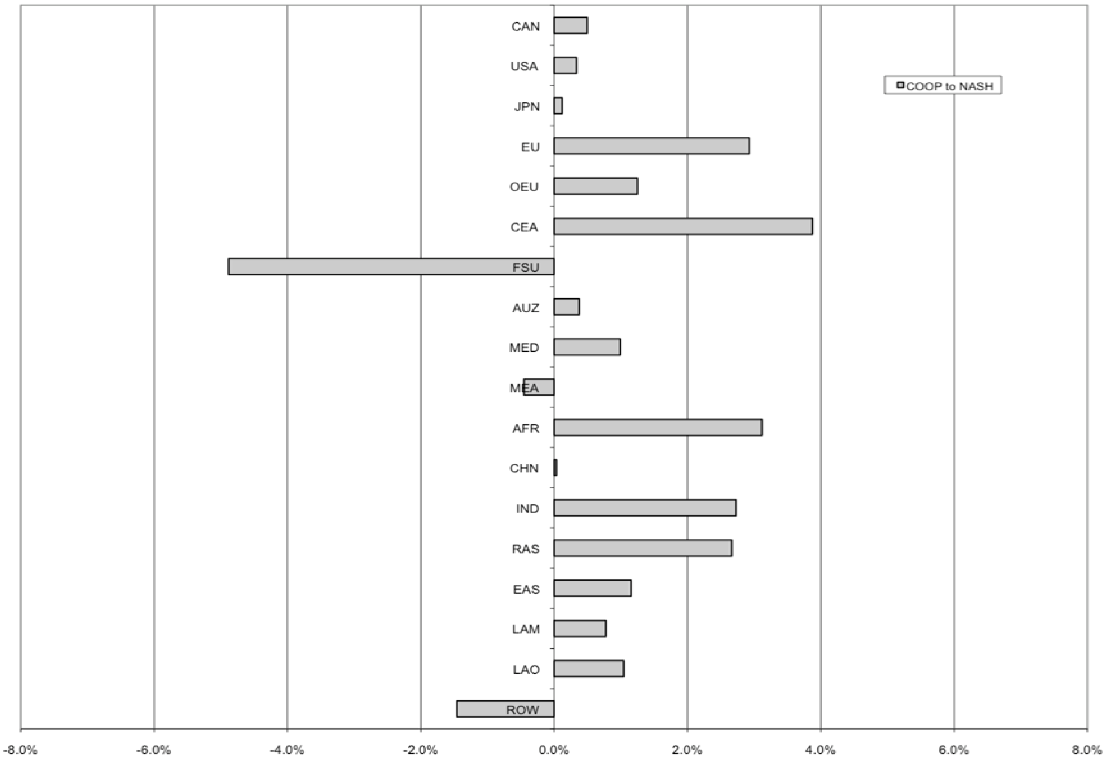
Figure 18: World output structure in 2300



Finally, the welfare improvement between NASH and COOP is provided in Figure 19. Although the aggregated welfare in COOP is higher than in NASH, three regions are worse off: FSU, MEA and ROW. In general, developing regions have a strong benefit to the grand coalition while most developed countries experience a small benefit, except the EU. Stability analyses of the grand coalition are provided in Part 4 of the report.

[28] One should not try to interpret the abatement rate of the region ROW, for this region lacks of data and has to be seen more as a dump.

Figure 19: Welfare improvements between NASH and PARETO (in % over the whole simulation period)



4 POLICY SUPPORT

One of the objectives of the CLIMNEG project was policy support. One specific ambition of the project was to bridge the gap between insights from theoretical analyses and policy issues. In that purpose, policy-oriented writings were produced in the network. Two papers were designed for publication in policy-oriented academic journals, and some others as contributions to collective books. Six Policy Briefs were also produced and are available on the website of the project.[29] Public seminars were organized on behalf of the project with renowned speakers, open to a large audience. Finally, the members of the network were all (more or less) involved in the policy process, in Belgium and abroad. In this part of the report we will present a short version of the two main papers devoted to policy issues (both are currently in the submission process). The last section will briefly presents the main activities engaged for policy support.

4.1 Stability *vs*. efficiency: climate coalitions

Numerical analysis of the coalitional stability problem has been initiated in Eyckmans and Tulkens (2003). This was followed and pursued in Carraro, Eyckmans and Finus (2006). By putting together these two explorations with the updated version of the CWS model (CWS 1.2), we can present an explicit comparison of cooperative and non–cooperative approaches, with the purpose of bringing to light the properties of potential coalitions in three respects: stability, climate performance and global welfare.

The contribution of this section is twofold. First, it is methodological. By testing on the same integrated assessment model the two alternative game theoretic stability concepts, we better show their relative merits. Second, it contributes to the policy debate. Assessing the properties of alternative climate coalitions in a concrete numerical context gives a powerful justification for recommendations as to the size and nature (homogeneity *vs* heterogeneity) of possible climate coalitions. Moreover, by showing explicitly which transfers among countries are appropriate to stabilize efficient coalitions, we also identify wider room for negotiation.

4.1.1 The stability concepts

In general, the core-stability theory focuses on strategies chosen jointly by the members of the grand coalition, that is, the set N of all players. The behavioral assumption just mentioned implies that, in the CWS model, N chooses the Pareto efficient scenario.

This scenario and the grand coalition that generates it are then said to be *stable in the core sense* if the scenario belongs to the core of a suitably defined cooperative game, that is, if it is such that *(i)* no individual player can reach a higher payoff by *not* adopting the strategy assigned to him in the efficient scenario and choosing instead the best individual strategy he could find; and *(ii)* no subset of players, smaller than N, can similarly do better for its members, that is, by rejecting the strategies assigned to them by the efficient scenario and adopting a strategy of their own. Consequently, the grand coalition N is called strategically stable and its scenario may rightly be dubbed *self enforceable* since no coalition can find a better one for its members.

[29] See annexe 6.3 for the full list of publications of the network.

Formally, let i refers to players (i = 1,…,n), $S \subset N$ denotes a coalition, the scalar $W(S)$ be the worth of coalition S and the vector $W = (W_1,\ldots,W_i,\ldots,W_n)$ denotes an imputation[30]. The imputation W will be said to belong to the core if the individual payoffs W_i satisfy the following two properties:

- Property *IR*: *Individual rationality* $\forall i \in N, W_i \geq W(\{i\})$
- Property *CR*: *Coalitional rationality* $\forall S \in N, \sum_{i \in S} W_i \geq W(S)$

For complete specifications of player's strategies, $W(\{i\})$ and $W(S)$, see Bréchet, Gerard and Tulkens (2008).

The internal-external stability theory considers the strategies S and the resulting individual payoffs that can be reached by every player along that scenario according to whether he is inside or outside of the coalition[31]. Being inside means for the player to follow the strategy he is assigned to within the coalition he is a member of, whereas being outside means behaving as a singleton, taking as given the behavior of the coalition he is not a member of as well as of the other players (assumed to behave as singletons too). A coalition S and the *PANE* scenario it generates are then said to be *stable in the internal-external sense* if the scenario is such that no insider prefers to stay out of the coalition and no outsider prefers to join the coalition rather than stay aside. Consequently, the coalition S is called stable and its *PANE* scenario *self enforceable*, not by reference to alternative coalitions as in the preceding concept, but instead because of the structure of the individual motivations of the players within and outside the coalition.

Formally, letting $W_i(S)$ denote the individual payoff of player i when coalition S is formed, this means that the payoffs satisfy the following two properties[32]:

- Property IS: Internal Stability $\forall i \in S, W_i(S) \geq W_i(S \setminus \{i\})$
- Property ES: External Stability $\forall i \notin S, W_i(S) \geq W_i(S \cup \{i\})$

4.1.2 Transfer schemes

In the context of the core-stability theory, transfers were proposed by Chander and Tulkens (1995, 1997) for the standard game with multilateral externalities used to deal with international environmental agreements. They proved analytically that transfers formulated as follows induce the stability property.

These transfers guarantee that each player receives a payoff at least equal to what it is in case of no cooperation and it divides the surplus of cooperation over non-cooperation according to weights π_i. In the multilateral environmental model, each weight is equal to the ratio of player i's marginal damage cost over the sum over all players of such marginal damage costs.

[30] An imputation is any vector of individual payoff W such that their sum is equal to the worth of the grand coalition, formally $\sum_{i \in N} W_i = W(N)$.

[31] It is assumed that a player can only either join the coalition or remain alone.

[32] The internal-external stability concept originates in the work of d'Aspremont *et al*. (1983) on the stability of cartels and has been imported in the literature on IEAs by Carraro and Siniscalco (1993) and Barrett (1994). The way it is presented here -- in particular its connection with the *PANE* concept -- owes much to Eyckmans and Finus (2004).

The internal-external stability theory proposes no specific transfer formula but introduces instead the notion of *potentially internally stable* coalitions. A coalition (of any size) is potentially internally stable if it can guarantee to all its members at least their free-rider payoff. For a given a coalition, the free-rider payoff of any of its members is the payoff the member would obtain in the *PANE* scenario *w.r.t.* that coalition if he would stay out and behave as a singleton in the face of that coalition.

Formally, for any coalition *S*, this reads as follows:

Property PIS: *Potential Internal Stability* $W(S) \geq \sum_{i \in S} W_i(S \setminus \{i\})$

The free rider payoff of a player *i vis-à-vis* some coalition *S* -- that is, each term of the sum in the right hand side of (2) -- may be seen as the minimum payoff player *i* requires to remain a member of the coalition. Coalitions whose worth under their *PANE* is large enough to meet this requirement for all their members can thus be stabilized at least internally[33].

The two approaches rest on different views when applied to international environmental agreements. The core-stability approach assumes that, if one or several countries attempt to free-ride on an efficient agreement with transfers, the other countries do not cooperate among themselves anymore, so as to make the free rider see that the country is better off by not free riding. This threat is what induces stability. In the internal-external stability approach, stability of an agreement within a coalition obtains if no individual country attempts to free-ride on it, assuming that free riding does not prevent the other countries from keeping cooperation among themselves.

4.1.3 Stability analysis of coalitions

We now apply the different concepts of coalition stability to the numerical CWS model, in both its original (CWS 1.1) and updated (CWS1.2) versions. Given the six regions, 63 coalitions can possibly form, for each of which we compute its worth W_S in the sense of the gamma-characteristic function, that is, at a partial agreement Nash equilibrium of the model. We focus on internal-external stability. See Annex 5.3 for core stability analysis.

Table 8 in annex 5.3 presents the results for the non-cooperative approach. The columns refer, for the various coalitions, to the three different stability properties (internal (*IS*), external (*ES*), and potential internal (*PIS*)) proposed by this approach. A cross in a column means that the property is satisfied for the corresponding coalition. We summarize the results as follows, distinguishing again between without and with transfers:

- Internal and external stability: In both CWS 1.1 and CWS 1.2, very few coalitions pass the *IS* test (8 or 7 of them, out of 57[34]). In particular, the grand coalition, that is, the one that would achieve the world efficient allocation without transfers, does not pass it. More coalitions (11, or 15, out of 56 -- the grand coalition is irrelevant here) pass the *ES* test. No coalition passes both tests however, except for one, namely the couple {USA, EU} which does so only in CWS 1.2.

[33] By using the *Almost Ideal Sharing Scheme* introduced in Eyckmans and Finus (2004). ``Sharing scheme" indicates that the authors do not propose a particular solution but are interested instead in identifying a class of sharing rules that stabilizes all *PIS* coalitions.
[34] Here we exclude singletons.

- Potential internal stability: Contrary to the *IS* and *ES* tests, the *PIS* test is one that implicitly refers to transfers within the coalitions, with the purpose of inducing internal stability. Here again, the grand coalition does not pass the test, but many smaller coalitions do in both CWS 1.1 and 1.2. More precisely, all of the five-country coalitions, 5 out of the 15 four-country coalitions and 2 out of the three-country coalitions did not pass the test in CWS 1.1. In the update, 4 five-country coalitions and 5 four-country coalitions do not pass the test whereas 1 five-country and all other coalitions of four countries or less do pass it.

4.1.4 Stability *vs.* performance

Can policy implications be derived from the above stability discussion and simulation results? In particular, how important are the coalitional stability properties we have identified? Should they serve as an argument to support or advocate specific structures for climatic international agreements such as small coalitions rather than large ones, or homogeneous rather than heterogeneous ones?

To answer these questions, let us consider two criteria measuring the global outcome resulting from an agreement, that is,

- the aggregate welfare level reached at the world level,
- the environmental performance achieved, expressed by atmospheric carbon concentration.

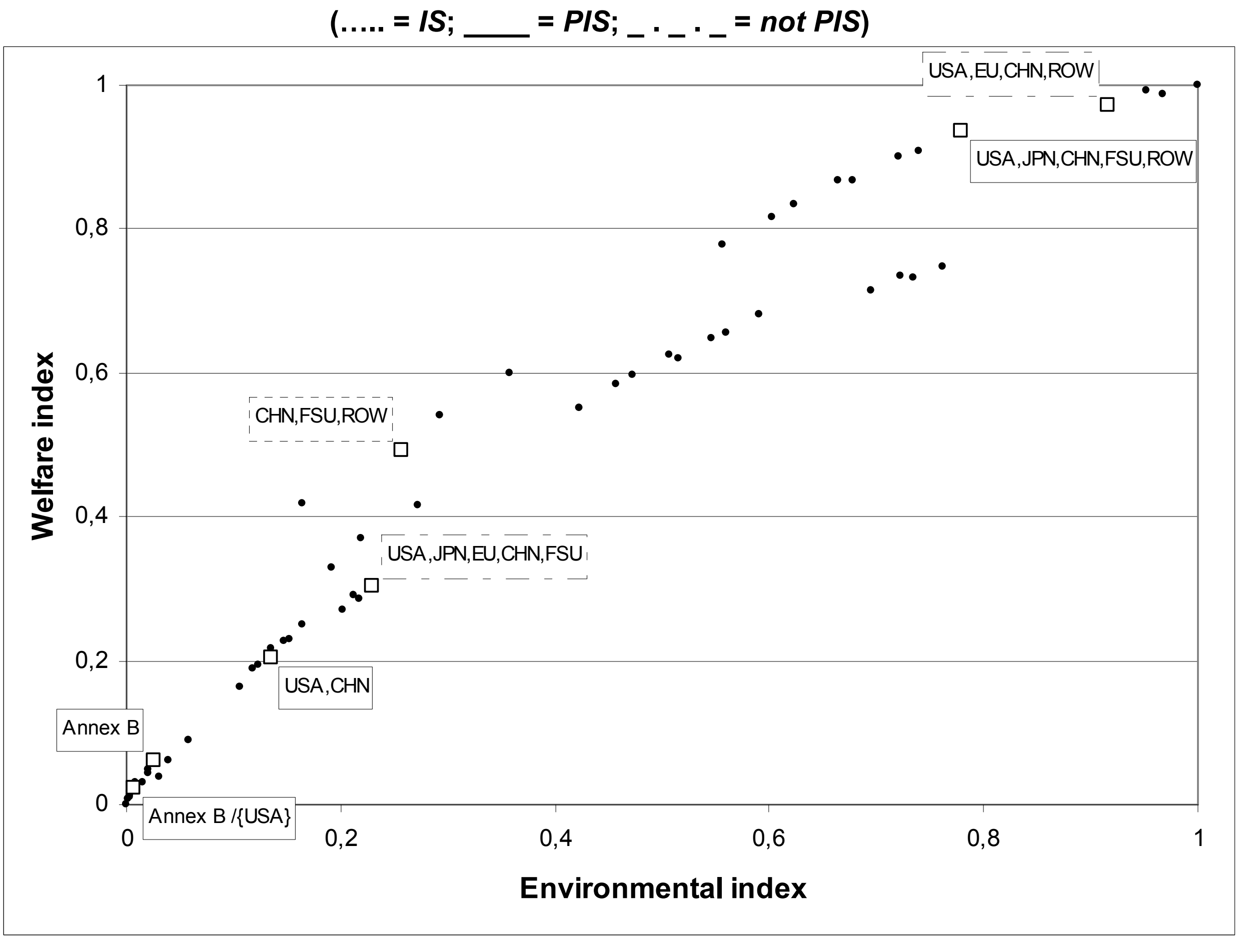
and consider how these are met by alternative coalition structures.

This is done in Figure 20 with the numerical results of CWS 1.2. On the two axes, we use a welfare and an environmental index respectively, that we borrow from CEF-06. Both indexes give the value "1" to the world efficient allocation (the grand coalition case) that produces the highest aggregate welfare and the lowest carbon concentrations, and the value "0" to the non-cooperative Nash case, that depicts the lowest aggregate welfare and the highest carbon concentrations. Formally, the indexes are computed as follows:

- Welfare index: $I^W(S) = \dfrac{\sum_{i \in \aleph}\left(W_i(S) - W_i^{NASH}\right)}{\sum_{i \in \aleph}\left(W_i^* - W_{2300}^{NASH}\right)}$,
- Environmental index: $I^E(S) = \dfrac{M_{2300}^{NASH} - M_{2300}(S)}{M_{2300}^{NASH} - M_{2300}^*}$,

where $\sum_{i \in \aleph} W_i(S)$ and $M_{2300}(S)$ are respectively the aggregate welfare and carbon concentration levels in 2300 under the corresponding coalition structure *S*, while ``*" refers to the world efficient allocation (full cooperation) and ``Nash" refers to the Nash case (no cooperation). An increasing relation is obtained with the non-cooperative Nash equilibrium (lowest global welfare, highest carbon concentration) at the bottom left and the grand coalition (highest global welfare, lowest carbon concentration) at the top right.

Figure 20: Global outcome (aggregate welfare and the environment) with alternative coalition structures



Remembering that internal stability in its potential form prevails with small coalitions while core-stability is achieved only with the largest one, the relation also depicts both the welfare and the environmental performances of alternative coalition sizes.

Clearly, accepting or recommending small coalition arrangements because of their potential internal stability virtues entails a loss on both counts that striving for an efficient and core stable alternative could avoid. Internal stability thus appears to be a weakly desirable objective.

4.1.5 Is coalition homogeneity desirable?

A common argument in the climate policy debate is that developed countries should engage themselves first, after what developing countries would be invited to join the agreement and participate to the mitigation of global warming. Although this argument seems reasonable on the basis of historical responsibilities[35], one may question its effectiveness. In this section we analyze the how the composition of a coalition, that is, its degree of *homogeneity*, which is to be defined), affects its stability.

The regions/countries considered in the CWS model can be split into two categories:

[35] This is the principle of common but differentiated responsibilities of countries enounced in the UN Framework Convention.

- developed-Annex B countries (USA, EU and JPN), with high per capita emissions and GDP,
- developing-non-Annex B countries (CHN and ROW), with low per capita emissions and GDP, and low-cost abatement opportunities.

In the following we will talk about an *heterogeneous coalition* when a coalition is formed by countries coming from more than a single category. Conversely, an *homogeneous coalition* will designate a coalition formed by countries from a single category. The FSU will move as a free electron in this categorization as it offers the characteristics of both a developed country (high emissions per capita) and a developing one (low cost abatement opportunities, low GDP per capita). Accordingly, our 57 coalitions (excluding singletons) are broken down into 42 heterogeneous coalitions and 15 homogeneous ones. We examine the relation mentioned above, successively without and with transfers

In the no transfer case, there appears to be more homogeneous stable coalitions after the update and less heterogeneous stable coalitions. Indeed on the one hand, in CWS 1.1 only 2 out of the 8 internally stable coalitions are homogeneous coalitions. With CWS 1.2, all the 4 homogeneous coalitions involving FSU and developing-non-Annex B countries pass now the *IS* test and the coalition {USA, EU} becomes both internally and externally stable.

On the other hand, in CWS 1.1, 6 of the 8 internally stable coalitions were heterogeneous coalitions (out of 42). With the update, two of these 6 heterogeneous coalitions still pass the *IS* test but those coalitions include only JPN as developed-Annex B country, which is the least important emitter of the six regions in both versions[36]. Moreover, in CWS 1.1, 4 coalitions involving at least one of the two main polluters in each category, that is, (USA or EU) and (CHN or ROW) passed the *IS* test. With the update, none of these coalitions passes this test anymore[37]. So, less heterogeneous coalitions are stable in the *IS*-*ES* sense after the update. In the same vein, finally, the grand coalition, clearly the largest heterogeneous one, is never core-stable without transfers in either version, with four more blocking coalitions after the update.

When the possibility of transfers is introduced, stability appears also to be enhanced by homogeneity after the update. In CWS 1.1, only 1 out of the 15 homogeneous coalitions did not pass the *PIS* test. That coalition, the Annex B coalition {USA, JPN, EU, FSU}[38], does satisfy the *PIS* property with the update. So it seems that there is more room for cooperation between these countries today than ten years earlier. Furthermore, with the update the Annex B coalition turns out to be more stable than the ``Annex B without the USA" coalition[39]. Indeed, this latter coalition does not satisfy the *ES* property (the property was satisfied with CWS 1.1). This means that the United States would be better off by coming back to the Annex B coalition.

In CWS 1.1, 13 heterogeneous coalitions were not stable in the *PIS* sense. In CWS 1.2, this figure is only 11 but the composition of these coalitions has changed to some extent. Indeed,

[36] JPN is less important in terms of emissions than USA or EU and even more with the update. In CWS 1.1, JPN emission share in the emissions of its category evolves as follow: 12% in 2000, 14% in 2050 and 12% in 2200. In CSW 1.2, those figures are: 12% in 2000, 8% in 2050 and 6% in 2200.

[37] Moreover, in both versions, none of the coalitions that involve the two main emitters of a category and at least one emitter of the other category is internally stable.

[38] The so-called *Old Kyoto* coalition in Carraro, Eyckmans and Finus (2006).

[39] The so-called *Present Kyoto* coalition in Carraro, Eyckmans and Finus (2006).

no four-country (or more) coalitions involving both the USA and the EU and at least one non-Annex B countries pass the *PIS* test after the update.

Homogeneity *vs* heterogeneity can also be analyzed by Figure 20. One can see that the *best* (in terms of global welfare) homogeneous coalition, namely {CHN, FSU, ROW}, leads to far lower global welfare and far higher carbon concentrations than both the *best* heterogeneous coalition (the grand coalition) and the *best* heterogeneous coalition satisfying the *PIS* property, that is, {USA, JPN, CHN, FSU, ROW}. As a consequence, promoting homogeneous coalitions would lead to very low mitigation policies at the world level, unable to tackle climate change issue as heterogeneous (larger) coalitions could do.

Finally, there seems to be a trade-off between stability and environmental effectiveness. Homogeneity in climate coalitions fosters stability but is detrimental to climate effectiveness.

4.2 The EU unilateral strategy and the stability of global agreements

4.2.1 The policy issue

In this section we analyze the EU decision regarding greenhouse gas emission reduction for the post-2012 era put forward by the European Council during the Spring 2007 (see Council of the European Union, 2007 and Commission of the European Communities, 2007a).[40] In particular, our purpose it to assess the potential effects of the EU proposal on the incentives for future international cooperation on climate policy after the first commitment period (2008-2012) of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The policy questions we address are the following:

- Will the unilateral 20% emission reduction commitment of the EU cause a "carbon leakage effect" in the countries who have not ratified the Kyoto Protocol (and/or possible subsequent developments). In other words, would they respond to the EU's unilateral commitment by substantially lowering their own emission reductions and therefore annihilating the EU efforts?
- What is the likely effect on non-EU countries who did ratify the Kyoto agreement? Will they be inclined to lower or to increase their contribution to a global solution in response to the increase in the EU effort?
- Will the contingent strategy of reducing emissions by 30% by 2020 if other industrialized countries follow, induce current outsiders to join and to step up their emission abatement efforts?
- What is the role of international emissions trading as a transfer mechanism in the EU proposals?

The objective of our analysis is not normative (*i.e.* what countries ought to do in order to combat future climate change), but rather descriptive (*i.e.* what self-motivated countries are likely to do). Methodologically, we use some game theoretic coalitional stability analysis to explore the strategic incentives of six major players to ratify an international climate

[40] Bréchet, T., Eyckmans, J., Gerard, F., Marbaix, P., Tulkens, H., Van Ypersele, J.-P. (2008). "The impacts of the EU's carbon emissions reduction proposals on the stability of global agreements", CLIMNEG working paper 98 (also CORE discussion paper 2008/61).

agreement: the USA, Japan, the EU, China, the former Soviet Union (FSU) and Rest of the World (ROW). For an introduction on the use of game theory to analyze the formation of international environmental agreements, we refer, among others, to Barrett (2003, 2005), Chander and Tulkens (2006) or Finus (2001, 2003). Given the strong heterogeneity among countries in terms of costs and benefits of greenhouse gas emission reductions, the research questions raised above can only be addressed by simulations with a numerical integrated assessment model. For that purpose we will use the CLIMNEG World Simulation CWS model (see Eyckmans and Tulkens (2003) or Bréchet, Gerard and Tulkens (2007) for a description) which is an integrated assessment model adapted for coalitional analysis from the RICE model by Nordhaus and Yang (1996).

We will compare two alternative scenarios reflecting the EU proposal to a reference scenario based on the Kyoto agreement. The reference *Kyoto scenario* assumes that the developed countries that ratified the 1997 Kyoto Protocol continue cooperating after 2012 and determine their emission targets by maximizing their joint discounted welfare and adopt an international emission trading system among agreement members. The first alternative scenario is labeled EU *unilateral commitment scenario* and assumes that the EU commits itself to an emission ceiling of maximally 80% (*i.e.* 20% reduction) of its 1990 emission level for all periods after 2020. The second alternative scenario is called *Annex-B multilateral commitment scenario* and assumes that all Annex-B countries observe an emission ceiling of 70% (*i.e.* 30% reduction) compared to 1990. For the last two scenarios, we consider two variants depending on the way the additional commitment makes use, or not, of emissions trading.

4.2.2 The modeling framework: integrated assessment and coalition theory

We now turn to the analysis of the EU proposals. We start by describing the three different scenarios: the reference Kyoto scenario, the EU unilateral commitment scenario, and the Annex-B multilateral commitment scenario. These scenarios differ from each other in terms of membership of the international climate agreement and emission reduction commitment. Table 5 (next page) summarizes the main elements of the three scenarios.

Table 5: Coalition membership and commitment in alternative scenarios

scenario number		1	2
scenario name	Reference Kyoto scenario	EU unilateral commitment	Annex-B multilateral commitment
USA	*out*	*out*	-30%
Japan	*in*	*in*	-30%
EU	*in*	-20%	-30%
China	*out*	*out*	*Out*
FSU	*in*	*in*	-30%
ROW	*out*	*out*	*Out*

Legend to Table 5:
"*in*": this country/region is member of an international climate agreement and its emission target is calculated in an endogenous way as to maximize discounted group welfare;
"-20%" and "-30%": this country is member of an international climate agreement and commits to a 20% or 30% emission reduction in 2020 and all future periods;
"*out*": this country is not a member of an international climate agreement and determines its emission strategy as to maximize individual welfare

4.2.3 Reference situation: the Kyoto coalition

As a reference situation throughout the paper we will consider the Kyoto coalition, that is, the current coalition formed by the developed countries which ratified the Kyoto Protocol and committed themselves to an emission target, *Japan*, *EU* and *Former Soviet Union* in the CWS model. It is assumed that these countries continue cooperating and agree on carbon emissions ceilings that maximize their joint welfare. This reference coalition is one particular Partial Agreement Nash Equilibrium (PANE) in carbon emissions among others.[41] The Kyoto coalition members coordinate their emission strategies as to maximize their joint welfare taking as given the equilibrium emissions of the non-members. Outsiders for their part maximize their individual payoff taking as given the equilibrium emissions strategies of other outsiders and of the Kyoto coalition. The resulting emissions allocation satisfies the following marginal first-order condition for all Kyoto member countries:

$$\forall i \in S: \qquad \frac{1}{\sigma_{i,t} \cdot Y_{i,t}} \cdot \frac{\partial C_i}{\partial \mu_{i,t}} = \sum_{\tau=t}^{\Omega} \frac{1}{[1+\rho]^{\tau-t+1}} \cdot \frac{\partial g_\tau}{\partial E_{N,t}} \cdot \sum_{j \in S} \frac{\partial D_j}{\partial \Delta T_\tau}$$

where S represents the coalition. According to this expression, agreement member i reduces its emission in period t in such a way that the marginal cost of reducing one more ton of carbon (*i.e.* the left hand side of the equation) equals the discounted sum of all future marginal damages due to additional temperature change caused by this additional unit of reduction (right hand side of the equation). At any point in time, Kyoto members internalize all the future negative climate damage externalities of their carbon emissions, to the extent that it affects their fellow coalition members. Climate damages affecting non-members are not taken into account by the members of the coalition.

Note that this condition implies that marginal emission abatement costs are equalized among all Kyoto Protocol members, which implies that their overall emission reduction target is achieved in a cost efficient way. Cost efficiency prevails when market based environmental policy instruments are used, as it is the case with the flexible mechanisms of the Kyoto Protocol.

The countries outside the Kyoto coalition take into account their own individual climate change damages, neglecting negative climate change externalities to other countries:

$$\forall i \in N \setminus S: \qquad \frac{1}{\sigma_{i,t} \cdot Y_{i,t}} \cdot \frac{\partial C_i}{\partial \mu_{i,t}} = \sum_{\tau=t}^{\Omega} \frac{1}{[1+\rho]^{\tau-t+1}} \cdot \frac{\partial g_\tau}{\partial E_{N,t}} \cdot \frac{\partial D_i}{\partial \Delta T_\tau}$$

Starting from this reference situation, which reflects the current state of international climate agreements, we can explore the implications of the unilateral EU strategy. We present now two scenarios designed for that purpose and reflecting the Council's proposal.

[41] For a precise definition of this game theoretic solution concept, see Chander and Tulkens (1995, 1997). See Eyckmans and Finus (2006a, 2006b) for an analysis with the CWS model of all possible PANEs.

4.2.4 The EU unilateral commitment scenario

Description

In this first scenario it is assumed that, starting from the Kyoto coalition, an additional constraint is imposed which requires that EU's carbon emissions cannot exceed 80% of their 1990 emissions level for all time periods beyond 2020.[42] Two cases will be considered in our scenario, depending on whether emissions trading is allowed or not.

Without *emissions trading* the following additional constraint is added to the Kyoto coalition optimization problem for the EU:

$$\forall t \geq 2020: \qquad E_{EU,t} \leq [1-0.20] \cdot E_{EU,1990}$$

It results that, in that coalitional equilibrium, the distribution of the reduction effort among the Kyoto coalition is no longer cost-efficient. Marginal abatement costs are equalized among all unconstrained coalition members but are now higher within the EU.[43] Since this difference in marginal abatement costs is hard to reconcile with the assumption that the Kyoto coalition fully makes use of market based environmental policy instrument, such as emissions trading, we therefore consider a second variant including full emissions trading.

In the variant *with emissions trading* a constraint is introduced in the whole Kyoto group emissions instead of individual emissions constraints for the EU only, as in the equation above. The new emissions constraint in replacing the last equation in the optimization problem for the Kyoto coalition now writes,

$$\forall t \geq 2020: \sum_{j \in S} E_{j,t} \leq \sum_{j \in S} \hat{E}_{j,t}$$

For the 'constrained coalition member', the EU, we set $\hat{E}_{EU,t} = [1-0.20] \cdot E_{EU,1990}$, *i.e.* 20% below 1990 emission levels. For all other coalition members, we set $\hat{E}_{j,t}$ equal to their emission level in the reference Kyoto coalition scenario.

The difference between the variants *with* and *without emissions trading* lies in the flexibility regarding where, and thus at what cost, emission reductions are actually taking place. In the scenario without emissions trading, the constrained countries have to perform all additional reduction effort domestically. In the scenario with emissions trading, any additional reduction commitment by one agreement member leads to higher demand and higher equilibrium prices for permits in the permit market. In that case, the additional reduction commitment can be shared over the different coalition members in a cost efficient way.

Regarding the initial allocation of permits in future commitment periods, we assume that all unconstrained agreement members get exactly their emissions of the reference Kyoto allocation. Constrained members' initial allocations (the European Union) are in line with their individual reduction commitment. Hence, initial permit holdings coincide with $\hat{E}_{i,t}$ as

[42] As the time step of the CWS model is 10 years, the transition path cannot be displayed.
[43] Marginal abatement costs will be higher only if the unilateral commitment entails stronger reductions than in the reference unconstrained Kyoto coalition equilibrium.

defined above and financial transfers related to permit trade transactions are captured by the transfer variable $X_{i,t}$ in every country's budget balance equation:

$$X_{i,t} = p_t \cdot \left[\hat{E}_{i,t} - E_{i,t}\right]$$

The equilibrium price p_t of emissions permits in period t corresponds to the shadow price of the joint emissions constraint.

The key issue of carbon leakages

From our computations it turns out that the EU unilateral commitment of limiting by the year 2020 its emissions to 80% of its 1990 emission level represents a more stringent emission policy than what the EU would be committed to under the *reference Kyoto* scenario. This will constitute a crucial point in our analysis. Actually, the additional emission reduction by the EU gives something like a 'climate bonus' to other countries since they will be confronted with lower climate change damages, which increases, everything else equal, their welfare. We will call this effect the *climate externality effect* of the EU's unilateral commitment. In the environmental economics literature, considerable concern has been raised about the fact that this positive externality gives other countries an incentive to lower their own contribution to solving the global climate change problem, see for instance Hoel (1992). This is called *carbon leakage*[44] and results from free riding reactions under the assumed selfish behavior of non-participating countries.

Though theoretically undisputable, the relevant policy question is whether this carbon leakage effect would be so strong that the EU's additional emission reduction effort is partially (or even completely) compensated by an increase in emissions by other countries. Because of the further decrease of EU emissions in comparison with the unconstrained scenario, world emissions and carbon concentrations are reduced, and the temperature rise is smaller, *ceteris paribus*. Therefore, climate damages borne by all regions are reduced, leading to a decrease in damages in all countries. Consequently, some more resources are available to be spent in consumption, investment in physical capital and on emission mitigation measures. The objective of each country being to maximize its net welfare over time, it chooses its optimal strategy under the following trade-offs:

- to increase its green consumption, (which does not yield further emissions);
- to invest in physical capital infrastructure so as to increase production in the forthcoming periods, (and consume more later on, leading to higher emissions during the periods when production is increased);
- to abate more emissions now to curb the temperature increase and avoid future damages.

In the following analysis, it is important to keep in mind that abatement efforts, and thus temperature increases, are endogenous in the CWS model in the sense where they result from the cost-benefit analyses undertaken in each country. Furthermore, the outcome of these cost-benefit analyses is coalition-dependent. Full numerical results of the simulations are reported in Table 11 in the appendix. We will focus here on the interpretation of these results.

[44] Carbon leakage is a more general term that is used for other spillover effects in international climate policy as well like for instance, delocalization of carbon intensive industries to non-participating countries. In this paper, the term carbon leakage only refers to strategic climate policy reactions by governments.

Slight carbon leakages, but welfare gains for outsiders

A first observation is that the 20% unilateral reduction commitment implies a real cut in EU's emissions. EU should reduce its emissions by an additional 24% in 2020 compared to what would have done in an unconstrained Kyoto scenario (see appendix, table 11). Outsiders (*i.e.* countries having no commitment) react only marginally to the EU's unilateral action. They increase their own emissions by about 0.13%, with some differences among countries: the USA +0.18%, China +0.34% and Rest of the World +0.03%. Carbon leakage elasticity is therefore extremely small. This constitutes a very positive signal from an environmental standpoint: an additional cut by one percent by the EU triggers an increase of only 0.005% by the outsiders, which can be seen as negligeable. Hence, carbon leakage to non-ratifying countries should therefore be little a concern. The reason for this moderate reaction is most likely the fact that future marginal climate change damages (hence marginal benefits of emission reductions) are rather insensitive to changes in current regional emissions due to the strong inertia in the carbon cycle and climate system. The fact that the CWS model considers a very long time span (which is adequate concerning global warming) may explain that result.
In spite of their small reaction in terms of carbon emission increases, outsiders of the Kyoto coalition do gain in terms of welfare: USA gains about 0.31%, China 0.62% and ROW 1.02% in the constrained compared to the unconstrained Kyoto scenario. This observation is important because it shows that EU strategy generates small, though not negligible, free riding incentives in other countries. Countries that do not participate in the Kyoto Protocol are better off if protocol members increase the efforts to limit their emissions and slow down global climate change. The same holds true for the other Kyoto ratifying countries. Japan and Former Soviet Union react similarly as the non-ratifying countries: they increase slightly their emissions in response to the EU's proposal in the absence of emissions trading (Japan +0.23% and FSU +0.53%). The reason is that they enjoy the same positive climate externality bonus as non-members. In spite of their reaction, the overall emissions of the Kyoto group go down because the additional commitment of the EU outweighs the other members' emission increases, which is the objective pursued by the EU.

The key role of emissions trading

The picture for agreement members looks different if a system of emissions trading among the Kyoto countries is assumed. In that case, other ratifying countries also decrease their actual emissions strongly after an additional commitment by the EU: Japan minus 9.32% and Former Soviet Union even minus 21.8%. The reason for the marked difference is that under emissions trading, it is profitable for the EU to buy some emissions permits in the market instead of meeting their minus 20% reduction commitment by means of internal emissions reduction projects only. As a result, the additional EU demand for permits pushes the equilibrium market price up and induces other market participants to produce more emission reduction. Through the permit price, the different signatories' reduction efforts are positively linked. This type of linkage is not present in the absence of emissions trading.

Both with and without emissions trading, the Kyoto coalition experiences a loss in welfare. This is obvious because the constrained Kyoto outcome is also a feasible solution to the unconstrained Kyoto welfare maximization problem. Adding an additional constraint on the effort allocation cannot but lead to a decrease in the optimal welfare of the group. The loss is more pronounced without emissions trading (-0.72%) than with emissions trading (-0.37%). Without trading, the allocation of efforts is not cost efficient for the Kyoto coalition. Trading allows for more flexibility in the abatement burden allocation and results in a cost efficient allocation of reduction efforts over all Kyoto members. Compared to the incomplete trading solution, the full trade equilibrium allows cutting total compliance costs by half.

On the stability of the Kyoto coalition

The overall welfare loss of the unilateral commitment for the Kyoto group implies that there is a smaller surplus compared to free riding payoffs, *i.e.* the welfare levels that current members can achieve if they would leave the coalition. The Kyoto coalition with 20% emission reduction for the EU would not be stable in a game theoretical sense. Making such commitment is a political choice that is not "rational" in the game theory framework: the sum of the payoffs within the coalition is not large enough to compensate for the welfare loss in the EU. The unconstrained Kyoto coalition (our reference Kyoto situation) was able to produce more welfare than the sum of the payoffs of their members under complete absence of cooperation[45] (*i.e.* the so-called Nash equilibrium). Given this surplus, there are numerous ways to redistribute the gains of cooperation (for instance through an appropriate initial assignment of emission permits under an emission trading scheme) such that every individual member is better off joining than not joining. This can be seen in Table 6. Without cooperation (Nash equilibrium), the Kyoto group {*Japan, EU, FSU*} achieves a payoff of 1421.59 trillion US$$_{2000}$, which is slightly less than in the reference scenario (1422.28 trillion). However, due to the unilateral commitment by the EU (scenario 1), the overall surplus for the Kyoto coalition drops to 1416.99, which is well below 1421.59 under the Nash scenario. In spite of that, the members of the coalition apart from EU (*i.e.* Japan and FSU) are still better off than in the reference situation. The stability of the coalition is thus maintained as long as he EU is willing to incur the loss to achieve its mitigation policy.

[45] Implicitly we assume here that if a member would defect from the Kyoto coalition, the agreement would completely collapse and we would revert to the complete absence of cooperation. Practically speaking, this is consistent with the ratification thresholds in the Kyoto Protocol. Theoretically speaking, this assumption corresponds to the notion of the core in cooperative game theory, see Chander and Tulkens (1995, 1997). However, it should be noted that there are other free riding notions in which it is assumed that after defection by one member, the remaining coalition members continue cooperating (see Barrett 2005). The later interpretation of free riding leads to even higher free riding incentives and would reinforce our arguments on (in)stability of the Kyoto coalitions.

The resulting discounted welfare levels for these scenarios are given in the following table.

Table 6: Coalitional welfare comparison

	Scenarios			
	Nash equilibrium	Reference Kyoto	1 EU unilateral commitment	2 Annex-B multilateral commitment
Kyoto *{Japan, EU, FSU}*	1421.59	1422.28	1416.99	1453.77
USA	1405.53	1406.37	1410.72	1391.59
Kyoto + USA *{USA, Japan, EU, FSU}*	2826.12	2828.65	2827.71	2845.36

Legend to Table 6:
Nash equilibrium refers to complete absence of cooperation under which every country maximizes its individual welfare taking as given similar behavior by all other countries. Emissions strategies would neglect environmental externality effects are governed by expression (5) for all countries/regions and time periods.
Figures refer to welfare measured as the discounted sum of payoffs between 2000 and 2300 in trillion US\$ (10^{12} US\$) of the year 2000.

Global temperature increase by 2100 amounts to +3.5°C without EU's unilateral commitment, versus +3.4°C with 20% additional commitment. Overall, the impact of the sustained minus 20% objective on temperature levels is limited because of the relatively small share of Kyoto countries in global emissions, and because of the relatively weak emissions target of 80% of 1990 emissions levels. We are well aware that it is very likely that for future periods beyond 2020 more ambitious targets and unilateral commitments might be implemented.

Global welfare increases by 0.33% (without emissions trading) or 0.42% (with emissions trading) compared to the reference Kyoto scenario. The welfare increase is due to the fact that the unconstrained Kyoto scenario is globally strongly inefficient given our damage parameters and discount rate. Global carbon emissions are too high compared to the global optimal level that maximizes world welfare. Thus, the EU's unilateral commitment is a move into the direction of the global optimum.

4.3 Policy support activities of the network

A major challenge of this project was to link academic research to policy support. In that purpose, two tools were used:

(i) public seminars with renowned speakers,
(ii) publication of Policy briefs tackling policy issues.[46]

The Follow-up Committee (see the annexe 6.6 for the list of the Follow-up Committee) was entirely part of the project, but it proved quite difficult to gather people and to give them an incentive to join the working meetings during the whole project.

In the same time, all the promotors of the CLIMNEG project were deeply involved, in different ways, into the policy processes.

[46] Six Policy Briefs were produced. They comprise reprints of papers published in newspapers or original writings. See annexes 6.4 and 6.3 for the list of seminars and Policy Briefs.

As far ASTR-UCL is concerned, researchers involved in the project participated in the review of the 4th assessment report of IPCC and in the plenary sessions that finalised the summaries for policy makers (as members of the Belgian delegation). These activities gained from the summary work done within the project. Jean-Pascal van Ypersele took part to the 12th conference of Parties to the Framework Convention on Climate Change in Nairobi, as well as to the meeting of the subsidiary bodies in Bonn, as scientific representative of the Belgian Science Policy in the Belgian delegation. Jean-Pascal van Ypersele and Philippe Marbaix took part in the COP14 UNFCCC Conference (2008) as members of the Belgian delegation.

Jean-Pascal van Ypersele was selected as the co-chair of a negotiation group regarding the "Brazilian proposal" (burden sharing based on historical contributions to warming) that came to conclusions that will guide the work on this issue during the next years. He also contributed to support policy makers as a vice-chair of the IPCC working group 2 and chair of the Energy and Climate group of the Federal Council for Sustainable Development (Belgium). He was invited as an expert speaker in meetings of parliament commissions at the European, Belgian, and regional levels, and participated in numerous outreach activities and media events. His involvement into these national and international areas gained from the work within the CLIMNEG project. Conversely, it was food for thought inside the CLIMNEG network, providing experience of the international negotiation process and the position of the parties.

Finally, Jean-Pascal van Ypersele was elected as vice-president of the IPCC in 2008.

Thierry Bréchet and Henry Tulkens are members of the Scientific Committee of the research programme of the French Minister of Ecology on Climate Impacts and Management (GICC).

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6 ANNEXES

6.1 Listing and parameters value for CWS 1.2

Tableau 1: Equations

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

$$Y_{i,t} = A_{i,t} K_{i,t}^{\gamma} L_{i,t}^{1-\gamma} \quad (2)$$

$$Y_{i,t} = Z_{i,t} + I_{i,t} + C_i(\mu_{i,t}) + D_i(\Delta T_t) \quad (3)$$

$$K_{i,t+1} = [1-\delta_K]^{10} K_{i,t} + 10 I_{i,t} \quad (K_{i,0} \text{ donné}) \quad (4)$$

$$E_{i,t} = \sigma_{i,t} [1-\mu_{i,t}] \; Y_{i,t} \quad (5)$$

$$C_i(\mu_{i,t}) = Y_{i,t} b_{i,1} \mu_{i,t}^{b_{i,2}} \quad (6)$$

$$M_{t+1} = \overline{M} + \beta \sum_{i=1}^{n} E_{i,t} + (1-\delta_M)[M_t - \overline{M}] \quad (M_0 \text{ donné}) \quad (7)$$

$$F_t = \frac{4.1 \ln(M_t / \overline{M})}{\ln(2)} \quad (8)$$

$$T_t^o = T_{t-1}^o + \tau_3 [\Delta T_{t-1} - T_{t-1}^o] \quad (T_0^o \text{ donné}) \quad (9)$$

$$\Delta T_t = \Delta T_{t-1} + \tau_1 [F_t - \lambda \Delta T_{t-1}] - \tau_2 [\Delta T_{t-1} - T_{t-1}^o] \quad (\Delta T_0 \text{ donné}) \quad (10)$$

$$D_i(\Delta T_t) = Y_{i,t} \theta_{i,1} \left(\frac{\Delta T}{2.5}\right)_t^{\theta_{i,2}} \quad (11)$$

Variables

$Y_{i,t}$	Production (milliards US$1990)
$A_{i,t}$	Productivité totale des facteurs
$Z_{i,t}$	Consommation (milliards US$1990)
$I_{i,t}$	Investissement (milliards US$1990)
$K_{i,t}$	Stock de capital (milliards US$1990)
$L_{i,t}$	Population (millions d'habitants)
$C_{i,t}$	Coûts de réduction d'émissions (milliards US$1990)
$D_{i,t}$	Dommages liés au changement climatique (milliards US$1990)
$E_{i,t}$	Emissions de CO_2 (milliards de tonnes de carbone)
$\sigma_{i,t}$	Taux émissions-production (kgC/US$1990)
$\mu_{i,t}$	Réductions d'émission (entre 0 et 1)
M_t	Concentration atmosphérique de CO_2 (milliards de tonnes de carbone)
F_t	Forçage radiatif (Watts par m²)
ΔT_t	Augmentation de la température moyenne à la surface du globe (°C)
T_t^o	Augmentation de la température moyenne du fond des océans (°C)
W_i	Bien-être sur l'ensemble des périodes (milliards US$1990)

Global parameters

δ_K	Taux de dépréciation du capital	0.10
γ	Elasticité de la production au capital	0.25
β	Part *aérienne* des émissions de CO_2 qu	0.64
δ_M	Taux d'absorption naturel du carbone	0.08333
τ_1	Coefficient de transfert de l'équation de température	0.226
τ_2	Coefficient de transfert de l'équation de température	0.44
τ_3	Coefficient de transfert de l'équation de température	0.02
λ	Paramètre de *feedback*	1.41
$\overline{M}$	Concentration atmosphérique préindustrielle de CO_2 (GtC)	590
M_0	Concentration atmosphérique initiale de CO_2 (GtC)	783
ΔT_0	Variation initiale de la température à la surface du globe (°C)	0.622
T_0^o	Variation initiale de la température du fond des océans (°C)	0.108

Regional parameters

	$\theta_{i,1}$	$\theta_{i,2}$	$b_{i,1}$	$b_{i,2}$	ρ_i
	Paramètres des dommages		Paramètres des coûts de réduction		Taux d'actualisation
USA	0.01102	2.0	0.07	2.887	0.015
JPN	0.01174	2.0	0.05	2.887	0.015
EU	0.01174	2.0	0.05	2.887	0.015
CHN	0.01523	2.0	0.15	2.887	0.030
FSU	0.00857	2.0	0.15	2.887	0.015
ROW	0.02093	2.0	0.10	2.887	0.030

Variable values in 2000 (reference year)

	$Y_{i,0}$	(%)	$K_{i,0}$	(%)	$L_{i,0}$	(%)	$E_{i,0}$	(%)
USA	7563.8099	27.45	19740.6885	27.97	282.224	4.66	1.5738	24.01
JPN	3387.9305	12.29	9753.9695	13.82	126.870	2.10	0.3295	5.03
EU	8446.9010	30.65	22804.4771	32.31	377.136	6.23	0.8875	13.54
CHN	968.9064	3.52	2686.0563	3.81	1262.645	20.86	0.9468	14.44
FSU	558.4360	2.03	1490.0376	2.11	287.893	4.76	0.6258	9.55
ROW	6633.4274	24.07	14105.2089	19.98	3715.663	61.39	2.1918	33.44
World	27559.4112		70580.4379		6052.4310		6.5552	
	(millards US$1990)		(millards US$1990)		(millions d'habitants)		(GtC)	

6.2 Listing and parameters value for CWS 2.0

New damage and abatament cost functions:

$$C_i(\mu_{i,t}) = -Y_{i,t}\gamma_{i,t}((1-\mu_{i,t})\log(1-\mu_{i,t})+\mu_{i,t})$$

$$D_i(T_t^E) = Y_{i,t}(\alpha_{1,i}TE_t + \alpha_{2,i}TE_t^2)$$

Variable initial values and parameters different from CWS 1.2.

Economic data for 2000

	Y0	L0	Y0/L0	K0	K0/L0	K0/Y0
CAN	714.458	30.769	23.220.059	2.052.638	66.711.230	2.873
USA	9.764.800	285.003	34.262.095	28.054.270	98.435.000	2.873
JPN	4.649.615	150.035	30.990.202	13.358.344	89.034.851	2.873
EU	8.027.668	377.335	21.274.645	23.063.490	61.122.054	2.873
OEU	421.584	11.928	35.344.064	1.211.211	101.543.497	2.873
CEA	402.052	68.676	5.854.330	1.155.095	16.819.491	2.873
FSU	352.493	282.353	1.248.412	1.012.712	3.586.689	2.873
AUZ	452.338	22.937	19.720.888	1.299.567	56.658.110	2.873
MED	557.409	231.016	2.412.859	1.601.436	6.932.143	2.873
MEA	443.778	119.994	3.698.335	1.274.974	10.625.316	2.873
AFR	338.556	640.874	528.272	972.671	1.517.726	2.873
CHN	1.198.480	1.282.022	934.836	3.443.233	2.685.783	2.873
IND	460.189	1.016.938	452.524	1.322.123	1.300.102	2.873
RAS	152.075	348.978	435.772	436.911	1.251.974	2.873
EAS	1.089.013	477.183	2.282.171	3.128.734	6.556.676	2.873
LAM	1.740.755	382.068	4.556.139	5.001.189	13.089.788	2.873
LAO	225.167	120.851	1.863.179	646.905	5.352.912	2.873
ROW	43.765	131.688	332.339	125.737	954.809	2.873
WORLD	31.034.195	5.980.648	5.189.102	89.161.242	14.908.291	2.873

Legend:

Y0	*gross domestic product PPP (billion US$2000)*
L0	*population (million people)*
Y0/L0	*per capita GDP PPP (US$2000 per head)*
K0	*capital stock (billion US$2000)*
K0/L0	*capital/labour ratio (US$2000 per head)*
K0/Y0	*capital stock to GDP ratio*

Cost/benefit parameters

	A1	A2	B1
CAN	-0.007	0.003	-0.054
USA	-0.003	0.002	-0.033
JPN	-0.003	0.002	-0.019
EU	-0.001	0.005	-0.032
OEU	-0.007	0.003	-0.028
CEA	-0.001	0.005	-0.079
FSU	-0.008	0.003	-0.120
AUZ	0.004	0.001	-0.045
MED	0.004	0.001	-0.188
MEA	0.004	0.001	-0.104
AFR	0.010	0.003	-0.130
CHN	-0.004	0.002	-0.162
IND	0.010	0.003	-0.096
RAS	0.010	0.003	-0.112
EAS	0.002	0.003	-0.089
LAM	0.004	0.001	-0.069
LAO	0.004	0.001	-0.107
ROW	-0.005	0.003	-0.063

Legend:
A1 *intercept climate damage function*
A2 *exponent climate damage function*
B1 *parameter emission abatement cost function*

6.3 Publications of the network

Publications in peer-reviewed journals and CLIMNEG Working Papers

Bertinelli, L., Strobl, E. and Zou, B., (2006). "Polluting technologies and sustainable economic development", *CLIMNEG working paper 85* (also *CORE discussion paper 2006/52*).

Boucekkine R., N. Hritonenko and Y. Yatsenko (2008). "Optimal firm behavior under environmental constraints", *CLIMNEG discussion paper 97* (also *CORE discussion paper 2008/24*).

Boucekkine R., N. Hritonenko and Y. Yatsenko (2009). "On explosive dynamics in R&D-based models of endogenous growth", *Nonlinear Analysis Series A: Theory, Methods & Applications*, forthcoming.

Boucekkine R., F. del Rio and B. Martinez (2009). "Technological progress, obsolescence and depreciation", *Oxford Economic Papers*, forthcoming.

Boucekkine R., J.B. Krawczyk and Th. Vallée (2008), "Towards an understanding of tradeoffs between regional wealth, tightness of a common environmental constraint and the sharing rules", *CLIMNEG working paper 95* (also *CORE discussion paper 2008/55*).

Boucekkine R. and M. Germain (2007). "The burden sharing of pollution abatement costs in multi-regional open economies", *CLIMNEG working paper 93* (also *CORE Discussion Paper 2007/11*).

Bréchet, T., Chevallier, J., Ellerman, D., Figuières, C., Gambardella, M., Gastineau, P., Heugues, M., Hikisch, S., Ishihara, H., Jouvet, P.A., Kinzig, A., Libecap, G., Rotillon, G., Swanson, T. (2009). "How to overcome the obstacles in International Cooperation?", forthcoming in *Ecological Economics*.

Bréchet Th. and P.A. Jouvet, (2008). "Environmental innovation and the cost of pollution abatement revisited", *Ecological Economics*, 65(2), 262-265 (*CLIMNEG working paper 81* and *CORE discussion paper 2006/40*).

Bréchet Th. and P.A. Jouvet (2009). "Why environmental management may yield no-regret pollution abatement options", *Ecological Economics*, forthcoming.

Bréchet Th. Lambrecht S. and Prieur F. (2009). "Intertemporal transfers of emission quotas in climate policies", *Economic Modeling* 26(1), 126-134.

Bréchet Th., T. Tsachev and V. Veliov (2009). "Tradable emission permits and firms: a vintage capital approach", *CLIMNEG working paper 100*.

Bréchet, T., Eyckmans, J., Gerard, F., Marbaix, P., Tulkens, H., Van Ypersele, J.-P. (2008). "The impacts of the EU's carbon emissions reduction proposals on the stability of global agreements", *CLIMNEG working paper 98* (*CORE discussion paper 2008/61*).
Bréchet Th., P.A. Jouvet, Ph. Michel and G. Rotillon (2008). "Tradable permits in dynamic

general equilibrium: can optimality and acceptability be reconciled?", *CLIMNEG working paper 94*.

Bréchet Th., F. Gerard and H. Tulkens, H. (2007). "Climate coalitions: a theoretical and computational appraisal", *CLIMNEG working paper 92* (also available as *CORE discussion paper 2007/3*).

Bréchet, Th. and B. Lussis (2006). "The Contribution Of The Clean Development Mechanism To National Climate Policies", *Journal of Policy Modelling* 28(9), 981-994 (also *CLIMNEG working paper 80*).

Finus M., Rundshagen and J. Eyckmans (2008). "Simulating a sequential coalition formation process for the climate change problem: first come, but second served?" mimeo.

Germain M., Ph. Monfort, and Th. Bréchet (2007). "Allocation des efforts de dépollution dans des économies avec spécialisation internationale", *Revue Economique* 57(2), 219–239.

Growiec J. and I. Schumacher (2006). "On technical change in the elasticities of research inputs", *CLIMNEG working paper 90*.

Guesnerie R. and H. Tulkens (2009). "The design of climate policy", CESifo Seminar Series, *The MIT Press*, Cambridge, MA, January 2009.

Marbaix, P. and F. Gerard (2008). "A new climate and carbon cycle representation for the CWS model", *CLIMNEG working paper 99*.

Marbaix P. and R. Nicholls (2007). "Accurately determining the risks of rising sea level", *EOS Trans*. AGU, 88(43), 441-442.

Perez-Barahona A., (2006). "Capital accumulation and exhaustible energy resources: a special functions case", *CLIMNEG working paper 87*.

Prieur F. (2009) "The environmental Kuznets curve in a world of irreversibility", *Economic Theory*, in press (*CLIMNEG working paper 86*).

Sanin M. E. (2006). "Market Design in Wholesale Electricity Markets", *CLIMNEG working paper 88* (also *CORE discussion paper 2006/100*).

Schumacher I. and B. Zou (2008). "Pollution perception: a challenge for intergenerational equity", *Journal of Environmental Economics and Management* 55(3), 296-309 (*CLIMNEG working paper 83*).

Schumacher I. (2006). "On optimality, endogenous discounting and wealth accumulation", *CLIMNEG working paper 89*.

Schumacher I. (2006). "Endogenous discounting via wealth, twin-peaks and the role of technology", *CLIMNEG working paper 91*.

Tulkens P. and H. Tulkens (2006). "The White House and the Kyoto Protocol: Double standards on uncertainties and their consequences", *CLIMNEG working paper 84* (also available as *TERI School of Advanced Studies Working Paper Series #1*).

Veliov V., Th. Bréchet and T. Tsachev (2008). "On emission permits in a vintage capital model", CLIMNEG working paper 96.

CLIMNEG Policy Briefs

Bréchet Th. (2006). "*Climneg Policy Brief #1: Kyoto, et ses labiles objectifs*"

Bréchet Th. (2006). "*Climneg Policy Brief #2: Le prix du CO2 s'effondre: bonne nouvelle, ou mauvaise nouvelle?*"

Gerard F. (2006). "*Climneg Policy Brief #3: Politique climatique post-2012, Une étude du Bureau fédéral du Plan*"

Bréchet Th. (2006). "*Climneg Policy Brief #4: Le prix du CO2 est bas? Tant mieux!*"

Marbaix Ph., W. Lefebvre and J.P. van Ypersele (2006). "*Climneg Policy Brief #5: Changements climatiques : ce que le doute scientifique ne justifie plus*"

Bréchet Th. and H. Tulkens (2007). "*Climneg Policy Brief #6: Vive le protocole de Kyoto!*"

Publications in books

Bréchet Th. and Eyckmans J. (2009), "Coalition Theory and Integrated Assessment Modeling: Insights for Climate Governance", in : E. Brousseau, P.A. Jouvet and T. Dedeurwareder (eds) *Governing Global Environmental Commons: Institutions, Markets, Social Preferences and Political Games*, Oxford University Press, forthcoming.

Bréchet Th. and U. Luterbacher (2009). "Computational models for policy support in climate issues", in U. Luterbacher and D.F. Sprinz (eds) *The Evolving Climate Change Regime*, MIT Press, forthcoming.

Chander P., J. Drèze, C.K. Lovell and J. Mintz (2006). "Public goods, environmental externalities and fiscal competition: selected essays in public economics" *by Henry Tulkens*, Springer Verlag, New-York.

Chander P. and H. Tulkens (2006). "Cooperation, stability and self-enforcement in international environmental agreements: a conceptual discussion", in: R. Guesnerie and H. Tulkens (eds.), *The Design of Climate Policy*, Proceedings of David Bradford Memorial Conference held in Venice by CESifo, Munich, July 22-23, 2005.

Eyckmans J. and M. Finus (2009). "Transfer schemes and institutional changes for sustainable global climate treaties" in : Guesnerie R. and Tulkens H. (eds), *The design of climate Policy, papers from a summer institute held in Venice*, CESifo Seminar Series, MIT Press, Cambridge Mass. USA.

6.4 Workshops and Seminars organized by the network

2008 dec. 18: "Common natural resources, property rights and biological spillovers", presented by Thierry Bréchet (with Carlotta Balestra and Stephane Lambrecht), UCL CORE

2008 nov. 20: "The effect of investment on bargaining positions. Over-investment in the case of international agreements on climate change", Mirabelle Muuls, Grantham Institute for climate change, Imperial College and CEP, London School of Economics

2008 nov. 13: "Tradable permits in a two-sector OLG model", presented by Pierre-André Jouvet, Université Paris-Nanterre

2008 nov. 6 : "Adaptation in climate policies", presented by Samuel Fankhauser, LSE and Grantham Institute for climate change, Imperial College.

2008 oct. 9: "Catastrophe avoidance, social discounting and environmental policy", presented by Stephane Zuber, UCL CORE

2008 sept. 18: "Do environmental regulation affect the location decisions of multinational gold mining firms?", presented by Lise Tole, University of Strathclyde Business School

2008 sept. 8: "Implementing adaptation in the CWS model", presented by Thierry Bréchet, Alexis Gérard and Violette van Dyck, UCL CORE

2008 Mar. 20: "The Economics of Endogenous, Climate-Driven Extreme Events and Insurance", (with Georg Müller-Fürstenberger), presented by Ingmar Schumacher, University of Trier

2008 Mar. 14: "Rencontre de l'Environnement", at University Paris I.

2008 Mar. 13: "Disentagling the Effects of Industrial Production and CO2 Emission on European Carbon Prices" , presented by Julien Chevallier, EconomiX and CNRS

2008 Mar. 10: "Optimal adaptation and the specification of damage cost functions", presented by Henry Tulkens, UCL CORE

2008 Mar. 10: "Climate change and sea level", presented by Philippe Marbaix, UCL CORE

2008 Feb. 29: "Belgian Environmental Economics Day BEED 2008", Workshop at EHSAL http://homepages.vub.ac.be/~kfvlaemi/Downloads/BEED.pdf

2008 Feb. 28, "Emission permits and market power with strategic intertemporal trade-offs", presented by Fabien Prieur, University of Savoie

2008 Feb. 15: "Kyoto et après : quels apports de l'analyse économique à la diplomatie climatique", presented by Henry Tulkens, UCL CORE

2008 Feb. 14: "Trading emissions permits under strategic interaction", presented by Maria-Eugenia Sanin with Joana Resende

2008 Feb. 14: "Strategic emission trading and the role of the fringe ", presented by Maria-Eugenia Sanin, UCL CORE

2008 Jan. 24-25 : "Climate coalitions : A theoretical and computational appraisal", presented by Henry Tulkens, CORE

2007 Dec. 06: "The environmental Kuznets Curve in a World of Irreversibility": presented by Fabien Prieur, University of Savoie ,CORE

2007 Nov. 8, Séminaire "Investments in Power Sector under the European Emission Trading Scheme", presented by Giorgia Oggioni, CORE

2007 Oct. 25: "Politique de lutte contre le changement climatique : quelles opportunités pour les approches sectorielles ? ", presented by Richard BARON, Internationale de l'Energie (OCDE), Division efficacité énergétique et environnement, CORE

2007 Oct. 4 : "Contributions of the social sciences and the humanities to research on global environment change", conférence de l'Association France-Allemagne Scientifique et Technique (AFAST-DFGWT) with Henry Tulkens.

2007 Jun. 13, "Coupled-constraint Markovian Equilibria in Dynamic Games of Compliance", presented by Jacek KRAWCZYK, CORE

2007 Apr. 19, "Incentives in the Hedonic MDP Procedures for the Global Atmosphere as a Complex of Gaseous Attributes", presented by Professor Kimitoshi SATO, Rykkyo University, Tokyo, CORE (Workshop of the Environment)

2007 Mar. 29: "Rencontre de l'environnement", CORE - PARIS1 - Panthéon Sorbonne (CORE, Louvain-La-Neuve)

2007 Jan. 18-20: "Network and Coalition Formation among Heterogeneous Agents: Theory, Applications and Experiments", (XII Coalition Theory Network Workshop, CORE, Louvain-La-Neuve)

6.5 Researchers associated to the project

Surname	First name	Function	Institution	Period
Bréchet	Thierry	Coordinator	CORE	2006-2008
Tulkens	Henry	Academic researcher	CORE	2006-2008
Eyckmans	Johan	Academic researcher	HUBrussel	2006-2008
van Ypersele	Jean-Pascal	Academic researcher	ASTR	2006-2008
Boucekkine	Raouf	Academic researcher	CORE	2006 - 2008
Marbaix	Philippe	Senior researcher	ASTR	2006-2008
Gérard	Alexis	Junior researcher	CORE	2008
Holzweber	Paul	Junior researcher	CORE	April – June 2008
Jouvet	Pierre-André	Academic researcher	U. Paris X	2008
Tsachev	Tsvetomir	Academic researcher	Bulgarian Academy of Science	2008
Veliov	Vladimir	Academic researcher	Tech. U. of Vienna	2008
Van Dyck	Violette	Junior researcher	CORE	July – August 2008
Sanin	Maria	Doctoral student	CORE	2006-2008
Gerard	François	Master's thesis	CORE	2006-2007
Aznar	Sylvie	Master's thesis on damage functions	UCL	2006-2007
Holzweber	Paul	Master's thesis on CWS disaggregation	U. of Vienna	2007-2008
Lepaige	Thomas	Master's thesis on discounting	UCL	2007-2008
Standaert	Simon	Master's thesis on alternative social welfare functions	UCL	2007-2008

6.6 Members of the CLIMNEG Follow-up Committee

NAME	INSTITUTION
Peter Wittoeck	Federal Ministry of the Environment and UNFCCC Belgian Focal Point
Dominique Simonis	European Commission, DG Enterprise, Unit Competitiveness aspects of Sustainable Development
Stéphane Cools	Administration of the Région wallonne, DG Environment
Hugues Nolleveaux	Administration of the Région wallonne, DG Technology
Jean-Claude Steffens	Suez, Chief of the Environment Department, and Prototype Carbon Fund, World Bank.
Annemie Neyens	Beleidsmedewerker Klimaat, Cel Lucht, AMINABEL-AMINAL, Ministerie van de Vlaamse Gemeenschap, Flemish Region

6.7 Geographical disaggregation of CWS 2.0

COUNTRIES	CODE
Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Congo Dem. Republic, Ivory Coast, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambian Zimbabwe	AFR
Australia, New Zealand	AUZ
Canada	CAN
Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia,	CEA
China, Hong-Kong	CHN
Indonesia, Malaysia, Philippines, Singapore, Thailand, Vietnam	EAS
Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom	EU
Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan	FSU
India	IND
Japan, Korea (South)	JPN
Argentina, Brazil, Chile, Mexico, Paraguay, Peru, Venezuela	LAM
Bahamas, Belize, Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Suriname, Trinidad & Tobago	LAO
Bahrain, Iran, Jordan, Kuwait, Oman, Saudi Arabia, United Arab Emirates, Yemen	MEA
Algeria, Egypt, Israel, Lebanon, Morocco, Syria, Tunisia, Turkey	MED
Iceland, Norway, Switzerland	OEU
Bangladesh, Cambodia, Laos, Mongolia, Nepal, Pakistan, Papua New Guinea, Sri Lanka	RAS
Albania, Barbados, Bhutan Brunei, Croatia, Fiji, Korea (North), Macedonia (FYR), Maldives, Myanmar, Saint Lucia, Saint Vincent & Grenadines, Samoa, Sao Tome & Principe, Serbia & Montenegro, Solomon Islands, Tonga, Vanuatu	ROW
United States of America	USA

6.8 Supplementary material to "Stability *vs*. efficiency of climate coalitions"

In this annexe some supplementary material to section 4.1 is provided. Full details about this analysis is available in Bréchet, Gerard and Tulkens (2007).

Core stability

Let us focus first on the results for the cooperative approach as they appear in Tables 9 and 10. In either table, the first column contains a six digit key specifying the structure of the coalition: if a region is a member of the coalition, it obtains a ``1" at the appropriate position in the key. For instance, the key ``111111" refers to S = N = (USA,JPN,EU,CHN,FSU,ROW). Column 2 contains the worth of a coalition (that is the aggregate welfare of its members, *W(S)*) at its corresponding partial agreement Nash equilibrium and column 3 contains the total of what members of each coalition get at the efficient allocation, as achieved by the grand coalition without transfers ($W_S^* = \sum_{i \in S} W_i^*$). Column 4 gives the difference between the values of the two previous columns. If this difference is negative, it means that *S* is worse off in the grand coalition. Column 6 gives the total amount of generalized *GTT* transfers for the coalition *S* ($\Psi_S = \sum_{i \in S} \Psi_i$).

Comparing the two tables reveals that:

- Without transfers, the world efficient allocation, which needs the grand coalition to be achieved, is not core-stable: 14 smaller coalitions (out of 63) can improve upon it in CWS 1.1 and 18 coalitions can do so in the updated version. Thus, in either case, the grand coalition without transfers cannot form. Note that among the 18 blocking coalitions in the update, 14 are all those that were blocking in CWS 1.1;
- With transfers, the world efficient allocation is core-stable in either case. In CWS 1.2, the amount of the transfers is in general smaller except for the USA. This last result is in line with the two main consequences of the update as presented before: less emission in every region (the extent of the externality is reduced) except in the USA.

The first result is especially important, as it confirms with two versions of the CWS model the possibility of achieving core stability of the world efficient allocation, thanks to *GTT* transfers. The concept thus appears as robust to updating. The presence of four newly blocking coalitions may be seen as revealing an increased instability of the efficient allocation without transfers. But this makes the transfers all the more necessary if efficiency is being sought in the international agreement.

Table 7: Non cooperative stability properties satisfied by different coalitions

	Carraro, Eyckmans and Finus (2006)			This version		
Coalition	*IS*	*ES*	*PIS*	*IS*	*ES*	*PIS*
Coalitions of 2 countries						
USA,JPN	X		X			X
USA,EU		X	X	X	X	X
USA,CHN			X			X
USA,FSU			X			X
USA,ROW	X		X			X
JPN,EU		X	X			X
JPN,CHN			X			X
JPN,FSU			X			X
JPN,ROW	X		X	X		X
EU,CHN			X			X
EU,FSU			X			X
EU,ROW	X		X			X
CHN,FSU			X	X		X
CHN,ROW			X	X		X
FSU,ROW	X		X	X		X
Coalitions of 3 countries						
USA,JPN,EU		X	X		X	X
USA,JPN,CHN			X			X
USA,JPN,FSU			X			X
USA,JPN,ROW	X		X			X
USA,EU,CHN					X	X
USA,EU,FSU		X	X		X	X
USA,EU,ROW			X		X	X
USA,CHN,FSU			X			X
USA,CHN,ROW			X			X
USA,FSU,ROW	X		X			X
JPN,EU,CHN			X			X
JPN,EU,FSU		X	X			X
JPN,EU,ROW			X			X
JPN,CHN,FSU						X
JPN,CHN,ROW			X			X
JPN,FSU,ROW	X		X	X		X
EU,CHN,FSU			X			X
EU,CHN,ROW			X			X
EU,FSU,ROW			X			X
CHN,FSU,ROW			X	X		X
Coalitions of 4 countries						
USA,JPN,EU,CHN		X			X	
USA,JPN,EU,FSU		X			X	X
USA,JPN,EU,ROW		X	X		X	
USA,JPN,CHN,FSU						X
USA,JPN,CHN,ROW			X			X
USA,JPN,FSU,ROW			X			X
USA,EU,CHN,FSU					X	
USA,EU,CHN,ROW			X		X	
USA,EU,FSU,ROW			X		X	
USA,CHN,FSU,ROW			X			X
JPN,EU,CHN,FSU						X
JPN,EU,CHN,ROW			X			X
JPN,EU,FSU,ROW			X			X
JPN,CHN,FSU,ROW			X			X
EU,CHN,FSU,ROW			X			X
Coalitions of 5 countries						
USA,JPN,EU,CHN,FSU		X			X	
USA,JPN,EU,CHN,ROW		X			X	
USA,JPN,EU,FSU,ROW		X			X	
USA,JPN,CHN,FSU,ROW						X
USA,EU,CHN,FSU,ROW					X	
JPN,EU,CHN,FSU,ROW						
Coalitions of 6 countries						
Grand coalition		irrelevant			irrelevant	

Table 8: Coalitions payoffs at all PANE *w.r.t.* a coalition (W_S^S) and at EFF (W_S^*); generalized GTT transfers (Ψ_S) (billion 1990 US$)

key	$W(S)$	W_S^*	$W_S^*-W(S)$	(%)	Ψ_S	$W_S^*+\Psi_S$	$W_S^*+\Psi_S-W(S)$	(%)
Coalitions of 1 country								
100000	78353	78986	633	0.808	-282	78704	351	0,448
010000	42909	43222	313	0.729	-121	43102	192	0,448
001000	102731	103650	919	0,895	-423	103226	496	0,482
000100	9141	8862	-279	-3.057	333	9195	54	0,591
000010	23794	24025	231	0,969	-123	23902	108	0,452
000001	81137	81093	-44	-0,054	616	81709	572	0,705
Coalitions of 2 countries								
110000	121264	122208	945	0,779	-403	121806	542	0.447
101000	181090	182636	1546	0,854	-706	181930	841	0,464
100100	87535	87848	312	0,357	51	87899	364	0,416
100010	102151	103011	860	0,842	-405	102605	455	0,445
100001	159829	160079	250	0,156	334	160413	584	0,365
011000	145642	146872	1230	0,845	-544	146328	686	0,471
010100	52062	52084	22	0,043	213	52297	235	0,451
010010	66705	67247	542	0,813	-244	67003	299	0,448
010001	124262	124315	53	0,043	495	124511	548	0,441
001100	111946	112511	566	0,505	-90	112421	476	0,425
001010	126531	127674	1143	0,903	-546	127128	597	0,471
001001	184315	184743	427	0,232	192	184935	620	0,336
000110	32944	32886	-58	-0,175	210	33097	153	0,463
000101	90467	89955	-512	-0,566	949	90904	437	0,483
000011	105134	105118	-17	-0,016	493	105610	476	0,453
Coalitions of 3 countries								
111000	224007	225858	1851	0,826	-826	225032	1024	0,457
110100	130486	131070	584	0,448	-69	131001	515	0,394
110010	145067	146233	1166	0,804	-526	145707	641	0,442
110001	202879	203301	422	0,208	213	203514	635	0,313
101100	190415	191497	1083	0,569	-372	191125	711	0,373
101010	204903	206660	1757	0,857	-829	205832	928	0,453
101001	263009	263729	719	0,274	-90	263639	630	0,239
100110	111367	111872	505	0,453	-72	111800	433	0,389
100101	169139	168941	-199	-0,117	667	169608	468	0,277
100011	183752	184103	352	0,191	211	184314	562	0,306
011100	154905	155734	829	0,535	--211	155523	618	0,399
011010	169448	170897	1448	0,855	-667	170230	781	0,461
011001	227376	227965	589	0,259	72	228037	661	0,291
010110	75880	76109	229	0,301	90	76198	318	0,420
010101	133513	133177	-336	-0,252	829	134006	492	0,369
010011	148160	148340	180	0,121	372	148712	552	0,372
001110	135788	136536	748	0,551	-213	136323	535	0,394
001101	193681	193604	-76	-0,039	526	194130	450	0,232
001011	208255	208767	512	0,246	69	208837	582	0,279
000111	114376	113979	-397	-0,347	826	114805	429	0,375
Coalitions of 4 countries								
111100	233398	234720	1322	0,566	-493	234227	829	0,355
111010	247830	249883	2053	0,828	-949	248933	1104	0,445
111001	306113	306951	838	0,274	-210	306741	628	0,205
110110	154332	155095	763	0,494	-192	154902	571	0,370
110101	212255	212163	-92	-0,043	546	212710	454	0,214
110011	226825	227326	501	0,221	90	227416	591	0,261
101110	214285	215522	1237	0,577	-495	215027	741	0,346
101101	272543	272590	48	0,018	244	272834	292	0,107
101011	286996	287753	757	0,264	-213	287540	544	0,190
100111	193119	192965	-154	-0,080	544	193509	390	0,202
011110	178761	179758	998	0,558	-334	179425	664	0,372
011101	236817	236827	10	0,004	405	237232	415	0,175
011011	251338	251990	652	0,259	-51	251938	600	0,239
010111	157457	157202	-255	-0,162	706	157907	451	0,286
001111	217685	217629	-57	-0,026	403	218032	346	0,159
Coalitions of 5 countries								
111110	257284	258744	1461	0,568	-616	258129	845	0,328
111101	315738	315813	75	0,024	123	315936	198	0,063
111011	330123	330976	853	0,258	-333	330642	519	0,157
110111	236267	236188	-79	-0,033	423	236611	344	0,146
101111	296612	296615	3	0,001	121	296736	124	0,042
011111	260851	260851	1	0,000	282	261134	283	0,108
Coalitions of 6 countries								
111111	339837	339837	0	0.000	0	339837	0	0.000

Table 9: Coalitions payoffs at all PANE *w.r.t.* a coalition (W_S^S) and at EFF (W_S^*); generalized GTT transfers (Ψ_S) (billion 1990 US$)

key	$W(S)$	W_S^*	$W_S^*-W(S)$	(%)	Ψ_S	$W_S^*+\Psi_S$	$W_S^*+\Psi_S-W(S)$	(%)
Coalitions of 1 country								
100000	148266	148946	680	0,459	-312	148633	368	0,248
010000	30645	30755	110	0,359	-42	30714	68	0,222
001000	108413	108886	473	0,437	-209	108677	265	0,244
000100	36156	36064	-92	-0,256	196	36260	104	0,288
000010	9745	9790	44	0,454	-23	9766	21	0,217
000001	52326	52107	-219	-0,419	389	52496	170	0,325
Coalitions of 2 countries								
110000	178914	179701	787	0,440	-354	179347	433	0,242
101000	256690	257832	1141	0,445	-521	257311	621	0,242
100100	184488	185009	521	0,283	-116	184893	406	0,220
100010	158016	158735	720	0,455	-335	158400	384	0,243
100001	200852	201052	200	0,100	77	201130	277	0,138
011000	139059	139641	582	0,418	-84	139558	498	0,358
010100	66804	66819	15	0,023	155	66973	170	0,254
010010	40391	40544	154	0,381	-65	40480	89	0,220
010001	83016	82862	-154	-0,185	348	83210	194	0,233
001100	144602	144949	348	0,240	-12	144937	335	0,232
001010	118160	118675	515	0,436	-232	118444	283	0,240
001001	160901	160993	92	0,057	181	161173	273	0,170
000110	45902	45853	-49	-0,107	173	46026	124	0,271
000101	88532	88170	-362	-0,409	586	88756	224	0,253
000011	62103	61896	-207	-0,333	366	62263	160	0,257
Coalitions of 3 countries								
111000	287346	288587	1241	0,432	-563	288024	679	0,236
110100	215156	215764	608	0,283	-158	215607	451	0,209
110010	188665	189490	825	0,438	-377	189113	448	0,238
110001	231556	231808	251	0,109	35	231843	287	0,124
101100	293010	293895	885	0,302	-324	293571	560	0,191
101010	266446	267621	1175	0,441	-544	267077	631	0,237
101001	309540	309938	398	0,129	-132	309807	267	0,086
100110	194248	194799	551	0,284	-139	194660	412	0,212
100101	237156	237116	-40	-0,017	274	237389	234	0,098
100011	210630	210842	212	0,101	54	210896	266	0,126
011100	175264	175705	440	0,251	-54	175651	386	0,220
011010	148808	149431	623	0,418	-274	149157	349	0,235
011001	191595	191748	153	0,080	139	191887	292	0,152
010110	76553	76609	56	0,073	132	76740	187	0,245
010101	119214	118926	-289	-0,242	544	119469	255	0,214
010011	92776	92652	-125	-0,134	324	92976	200	0,216
001110	154358	154739	381	0,247	-35	154704	346	0,224
001101	197157	197057	-101	-0,051	377	197433	276	0,140
001011	170672	170782	110	0,065	158	170940	268	0,157
000111	98294	97960	-334	-0,340	563	98522	228	0,232
Coalitions of 4 countries								
111100	323695	324650	956	0,295	-366	324284	590	0,182
111010	297104	298376	1272	0,428	-586	297791	687	0,231
111001	340268	340694	426	0,125	-173	340520	253	0,074
110110	224919	225554	635	0,282	-181	225373	454	0,202
110101	267888	267871	-17	-0,006	232	268103	215	0,080
110011	241338	241597	259	0,107	12	241609	271	0,112
101110	302782	303685	903	0,298	-348	303337	555	0,183
101101	345972	346002	30	0,009	65	346067	95	0,028
101011	319333	319728	395	0,124	-155	319573	240	0,075
100111	246948	246905	-43	-0,017	250	247156	208	0,084
011110	185022	185494	472	0,255	-77	185417	395	0,213
011101	227875	227812	-64	-0,028	335	228147	272	0,119
011011	201370	201538	168	0,083	116	201653	283	0,141
010111	128982	128715	-267	-0,207	521	129236	254	0,197
001111	206940	206846	-94	-0,046	354	207200	260	0,125
Coalitions of 5 countries								
111110	333468	334440	971	0,291	-389	334051	582	0,175
111101	376733	376757	24	0,006	23	376780	47	0,012
111011	350063	350483	420	0,120	-196	350287	223	0,064
110111	277685	277661	-25	-0,009	209	277869	184	0,066
101111	355782	355791	9	0,003	42	355833	51	0,014
011111	237663	237601	-62	-0,026	312	237913	251	0,105
Coalitions of 6 countries								
111111	386547	386547	0	0.000	0	386547	0	0.000

6.9 Supplementary material to "The EU unilateral strategy and the stability of global agreements"

In this annexe some tables related to section 4.2 are provided. Full details about the analysis are available in Bréchet, Eyckmans, Gerard, Marbaix, Tulkens and van Ypersele (2008).

Table 10: EU unilateral commitment (scenario 1)

		Reference Kyoto scenario	Kyoto plus EU minus 20			
			no trading		trading	
temperature change 2100		3.455	3.404	-1.47	3.404	-1.48
carbon concentration 2100		1523.607	1501.344	-1.46	1501.211	-1.47
carbon price 2020		54.98	n.a.	n.a.	112.78	105.12
accumulated emissions 2000-2100	Kyoto	226.615	179.347	-20.86	179.035	-21.00
	Non-Kyoto	1576.286	1578.229	0.12	1578.256	0.12
	World	1802.902	1757.575	-2.51	1757.291	-2.53
regional emissions 2020	USA	1.882	1.886	0.18	1.886	0.18
	Japan*	0.324	0.325	0.23	0.294	-9.32
	EU*	0.932	0.705	-24.39	0.848	-9.06
	China	1.721	1.727	0.34	1.727	0.34
	FSU*	0.517	0.520	0.53	0.404	-21.82
	ROW	5.047	5.048	0.03	5.049	0.03
	Kyoto	1.773	1.549	-12.63	1.546	-12.82
	Non-Kyoto	8.65	8.661	0.13	8.662	0.13
	World	10.424	10.211	-2.04	10.207	-2.08
regional discounted welfare	USA	1406.37	1410.70	0.31	1410.72	0.31
	Japan*	294.43	295.11	0.23	295.98	0.53
	EU*	1033.18	1021.93	-1.09	1024.34	-0.86
	China	1426.79	1435.65	0.62	1435.69	0.62
	FSU*	94.67	95.03	0.38	96.67	2.11
	ROW	1613.48	1630.01	1.02	1630.09	1.03
	Kyoto	1422.28	1412.08	-0.72	1416.99	-0.37
	Non-Kyoto	4446.64	4476.36	0.67	4476.51	0.67
	World	5868.93	5888.43	0.33	5893.49	0.42
				(%)		(%)