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Abstract

Using an updated version of the CWS model (introduced by Eyckmans and Tulkens in *Resource and Energy Economics* 2003), this paper intends to evaluate with numbers the respective merits of two competing notions of coalition stability in the standard global public goods model as customarily applied to the climate change problem. After a reminder of the model structure and of the definition of the two game theoretical stability notions involved – namely, core stability and internal-external stability, the former property is shown to hold for the grand coalition in the CWS model only if resource transfers of a specific form between countries are introduced. It is further shown that while the latter property holds neither for the grand coalition nor for most large coalitions, it is nevertheless verified in a weak sense that involves transfers (dubbed "potential internal stability") for most small coalitions. The reason for this difference is brought to light, namely the differing rationale that inspires the transfers in either case. Finally, it is shown that the stable coalitions that perform best (in terms of carbon concentration and global welfare) always are composed of both industrialized and developing countries. Two sensitivity analyses confirm the robustness of all these results.

Keywords: climate change, coalitions, simulation, integrated assessment

JEL classification: C71; C73; D9; D62; F42; Q2

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1 Introduction

The global public good character of combating the effects of climate change requires voluntary cooperation amongst countries if any improvement upon the *laissez faire* business-as-usual is sought for. Such cooperation, institutionalized in international environmental agreements consists in joint actions decided and implemented by the signatory countries on a voluntary basis. Negotiated under the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol represents the first legally binding agreement on climate. As such, it is now considered as a decisive step. However it is widely acknowledged that, in order to be effective, post-Kyoto agreements should include more countries and yield stronger carbon emission abatement. This twin issue (which countries and which abatement?) constitutes one of the cornerstone of the negotiation process under the UNFCCC, today and also for the coming years.

Calling a "coalition" the set of countries thus joining their efforts against climate change, an abundant literature has developed over the last 15 years dealing with the issue of the likeliness of "stable" climate coalitions. Two main theoretical stability concepts[1] are competing, respectively developed in either a cooperative or a non-cooperative game theoretical framework. An early summary is reported in Tulkens (1998) and taken up again in Chander and Tulkens (2005). Numerically, the cooperative approach was initiated in Eyckmans and Tulkens (2003) and the non-cooperative approach in Carraro, Eyckmans and Finus (2006). In both papers, use was made of a well-established integrated assessment model, the ClimNeg World Simulation (henceforth CWS) model, introduced for the purpose of coalitional analysis in Eyckmans and Tulkens (2003). The present paper pursues and extends these computational enquiries. The model allows for useful policy analyses by highlighting the properties of potential coalitions in three respects: stability, climate performance and global welfare.

The contribution of our paper is twofold. First, it is methodological. The use of alternative game theoretic stability concepts allows for crossed insights and shows how complementary they are for climate coalition analysis. Moreover, the usefulness of these theoretical concepts is reinforced by the use of an integrated assessment model, the combination of the two being original in the literature. Second, the paper contributes to the policy debate. Assessing the properties of alternative climate coalitions in a concrete context with an integrated assessment model proves to be a powerful methodology for better understanding the costs and benefits each country may have when joining an agreement. This is of major importance for policy support. By showing that some adequate transfers among countries may stabilize some coalitions, the paper also identifies wider room for negotiation.

The paper is structured as follows. After this introduction, Section 2 presents the CWS integrated assessment model, as well as an update of the exogenous data it makes use of. Section 3 reminds briefly the reader of the coalition stability theory. Section 4 contains the main numerical results concerning the two alternative stability concepts as applied to the CWS model, while Sections 5 and 6 comment on issues of homogeneity *vs* heterogeneity,

[1] One of the two concepts is often assimilated with "self enforcement" (of treaties signed by members of stable coalitions), as suggested initially by Barret (1994) and elaborated upon in Barret (2003). Actually, this attractive expression applies equally well to both stability concepts. There is thus no gain in using it here.

aggregate welfare and environmental performance of alternative coalitions in that model. Some sensitivity analyses are presented in Section 7 and the last section summarizes our main conclusions.

2 The ClimNeg World Simulation model (CWS)

2.1 Overview of the model

The ClimNeg World Simulation model (CWS) is an integrated assessment model of climate change and optimal growth, adapted for coalitional analysis from Nordhaus and Yang (1996). It encompasses economic, climatic and impact dimensions in a worldwide intertemporal setting. As a Ramsey-type model, growth is driven by population growth, technological change and capital accumulation. The time dimension is discrete, indexed by t, finite, but very long. The world is split into six countries/regions: USA, Japan, Europe[2], China, the Former Soviet Union and the Rest of the World. Let us note $\mathcal{N}$ the set of countries/regions indexed by $i = 1, ..., n$. In each region gross output is given by a Cobb-Douglas production function combining capital and population. Population is exogenous. Capital accumulation comes from (endogenous) gross investment less (exogenous) scrapping. Technical progress is Hicks-neutral. Carbon emissions stem from global output with an emission coefficient which can be reduced by national policies, $\widetilde{\sigma}_{i,t} = (1 - \mu_{i,t})\sigma_{i,t}$, where $\mu_{i,t} \in (0, 1)$ stands for the carbon abatement rate and $\sigma_{i,t}$ is the exogenous carbon intensity of the economy. Abatement costs are given by an increasing and convex cost function $C_i(\mu_{i,t})$. Carbon emissions accumulate in the atmosphere. Concentration, through a simplified carbon cycle, yields a global mean temperature, expressed as temperature change with respect to pre-industrial level, ΔT_t. The impacts of global warming in each region are considered through damage functions $D_i(\Delta T_t)$, increasing and convex. Thus, net consumption is given by the gross output minus investment, abatement costs and damages, $Z_{i,t} = Y_{i,t} - I_{i,t} - C_i(\mu_{i,t}) - D_i(\Delta T_t)$. The welfare of each country is measured as the aggregate discounted net consumption. Discount rates are exogenous and equal to 1.5% in developed countries and 3.0% in developing ones.

The model is used to determine, over the period 2000-2300, paths of investment (I_{it}) and emissions (through μ_{it}) over time and, consequently, capital accumulation, consumption, carbon concentration and temperature change, at the world and country/regions levels. This is done according to three alternative scenarios. First, the *Nash equilibrium*, which is the joint outcome of each country maximizing its utility taking the actions of the others as given. Second, the *partial agreement Nash equilibria with respect to a coalition*, each of which is the outcome of a subset of countries maximizing jointly their utility, while the others act individually (there are as many such scenarios considered as there are coalitions). And third, the *Pareto efficient* scenario where all countries act jointly so as to maximize the world welfare.

The complete set of equations, variable definitions, parameter values and initial values are gathered in the appendix in Tables I to VI.[3]

[2]Europe is defined as EU-15.

[3]The model runs under GAMS. All codes are available from the authors upon request.

Table 1: Population and technological change data update in CWS

	Population (millions)				Technological change							
					Carbon intensity of GDP (kgC/1990 US$)				Total factor productivity (indice)			
	ET-03		This version		ET-03		This version		ET-03		This version	
	2020	2100	2020	2100	2020	2100	2020	2100	2020	2100	2020	2100
USA	280.6	294.3	338.4	454.1	0.178	0.117	0.167	0.112	11.15	19.53	12.38	23.35
JPN	124.5	124.5	126.6	111.6	0.075	0.062	0.088	0.069	13.91	23.97	10.69	16.95
EU	403.3	427.0	391.1	377.0	0.094	0.073	0.086	0.071	10.23	18.50	10.43	19.31
CHN	1431.7	1655.8	1395.7	1272.5	1.181	0.499	0.524	0.153	0.90	4.66	2.04	13.55
FSU	332.5	366.3	276.2	244.8	0.773	0.318	0.706	0.228	2.35	7.49	1.74	4.40
ROW	4713.7	6737.9	4914.7	6389.4	0.285	0.176	0.290	0.197	2.37	7.36	1.66	3.73

2.2 Data set and calibration

In this paper we use an updated version of the CWS model. For two main sets of assumptions, time has revealed strong departing evolutions from what was expected a few years ago. These are population growth and technological progress. Table 1 displays our assumptions, previous ones (those used in Eyckmans and Tulkens (2003) – ET-03 hereafter) and current ones. Some comments are given hereafter. As far as population growth is concerned, the CWS model in ET-03 was using population forecasts of Nordhaus and Yang (1996), which came from the United Nations. A positive growth was expected in every region. Our update is based on the latest publications of the United Nations, *World Population to 2300* (2004) and *World Population Prospects: The 2004 Revision* (2005). At this horizon, world population is expected to reach 9 billion people, 1 billion less than the previous forecast. More important, the time profiles of various regions become more contrasted. Europe, Japan and China face a peak in their population between 2020 and 2030, or even before, and then experience a decline. The population in the Former Soviet Union is expected to decrease. In the USA, the population increase should be stronger than expected, mainly because of immigration and fertility rates. In the Rest of the World, short-term population growth should be stronger, but followed by a stronger slowdown. We assume that, in each country population size converges to a steady state value in the long run.

In the CWS model technological progress encompasses two elements, the global factor productivity and the carbon intensity of economic activity. As far as the former is concerned, high positive trends are expected for China and the USA, while lower progress would occur in Japan, FSU and ROW. The most striking update concerns carbon intensities which have exhibited contrasting patterns in the recent years. Our data come from the International Energy Agency for carbon emissions and from the World Bank for GDP[4]. Apparently, stringent industrial adjustments are in place that could yield sharp decreases in carbon in-

[4]In fact, we use the *Climate Analysis Indicators Tool* of the *World Resources Institute* that gathers data from the International Energy Agency and the World Bank.

tensities. This is particularly true for China and FSU. On the contrary, recent trends in Japan and ROW suggest lower carbon improvements than expected. No major changes have been noticed for the EU and the USA in comparison with the former version of CWS.

This update has two main consequences for climate issues. Firstly, world emissions are lower in the business-as-usual scenario than they were in ET-03. But, secondly, heterogeneity among countries is reinforced: national emission profiles are lower in all countries, in particular in China, while the USA experiences higher emissions. The implication of this is that the relative weight of the different countries in the global issue has significantly changed, and so did the costs and benefits of each country to participate to a given climate agreement. As a consequence, these new economic patterns may have major implications on a country's attitude towards climate negotiations, towards the coalitions they might form and on the room for agreement[5].

The analysis of climate coalition formation is based on theoretical concepts from coalition theory. These are briefly recalled in the following section.

3 A bird's eye view of coalition theory

The CWS model has been used to study coalition formation in two different ways. On the one hand, ET-03 adopt a cooperative game theoretic approach with the (*gamma*) core as stability concept. On the other hand, Carraro, Eyckmans and Finus (2006) (CEF-06 in the sequel) use a non-cooperative coalition formation approach with the concepts of internal and external stability. When coalitions are found not to be stable in one or the other sense, both approaches suggest introducing transfers to induce stability in the desired sense.

Let us describe more precisely the games under consideration. As suggested, two categories of games are associated with the CWS economic model, namely cooperative and non-cooperative. In either one the players are the countries/regions, each player's strategies are the values chosen for its economic decision variables over the whole period – namely abatement and investment – and the payoffs are the countries'/regions' welfare level at the end of the computation period. A family of n such strategies, one for each player, defines what we have called in Section 2.1 above a *scenario*: among the many conceivable ones we mentioned the Nash equilibrium scenario, the various scenarios of partial agreement Nash equilibrium with respect to a given coalition, and the Pareto efficient scenario.

While non-cooperative games deal essentially with strategies enacted by individual players (leading to, for instance, the Nash equilibrium concept), cooperative games typically consider in addition the strategies chosen jointly by groups of players, usually called coalitions, that is, subsets of players (including singletons and the all players set). In either case the behavioral assumption is made that the chosen strategy (by each individual player) or joint strategies (in the case of coalitions) result from payoff maximization over some feasible set: the individual payoffs in the non-cooperative setting, the joint payoffs of the coalition members in the cooperative setting, this joint payoff being called the *worth* of the coalition.

[5]A complete description of the update is provided in Gerard (2006, 2007).

3.1 Stability concepts

3.1.1 The "gamma" core stability concept

When the game is considered as a cooperative one, the approach focuses first on strategies chosen jointly by the members of the grand coalition, that is, the set $\mathcal{N}$ of all countries. Applying this to the CWS model, the behavioral assumption just mentioned implies that $\mathcal{N}$ chooses the Pareto efficient scenario[6], that is, the values of the variables that solve the dynamic optimization problem, stated in Table I in the appendix, for the case where the objective function is taken as the sum over all players of expression (A.1).

This scenario and the grand coalition that generates it, are then said to be *stable in the core sense* if they belong to the core of the cooperative game, that is, if the scenario 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 $\mathcal{N}$, 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.

Formally, let i refers to players ($i = 1, \ldots, n$), $S \subset \mathcal{N}$ 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[7]. 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* $\quad \forall i \in \mathcal{N}, \quad W_i \geq W(\{i\})$
- Property *CR*: *Coalitional rationality* $\quad \forall S \subset \mathcal{N}, \quad \sum_{i \in S} W_i \geq W(S)$

To be complete, the formal statement of these two properties should further specify what are the players' strategies implicit in the right hand sides of these expressions, namely $W(\{i\})$ and $W(S)$. In the former, the strategy and the ensuing payoff of player i are the ones of the Nash equilibrium scenario; in the latter, the worth of coalition S is the sum of the payoffs obtained by the members of S as they result from enacting the joint strategy that maximizes this sum; this is the scenario dubbed above partial agreement Nash equilibrium (*PANE*) with respect to a coalition[8]. In terms of the CWS model, a *PANE* scenario with respect to some S is obtained by computing a Nash equilibrium of the model (1)-(11) for the special case where the members of S are treated as if they were a single player (whose payoff function is equal to the sum of the individual payoffs, actually, the worth of S) and the remaining players are treated as singletons.

[6] $\mathcal{N}$ is the only coalition able to do that, as will be clear in the sequel.

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

[8] In a partial agreement Nash equilibrium with respect to a coalition, the coalition members are assumed, as usual, to maximize their joint payoffs, but it is assumed in addition – and this is not usual – that the players outside of the coalition choose, as singletons, the strategy that maximizes their individual payoff, given the coalition and the other singletons. The equilibrium concept derived from this assumption (called the "gamma" assumption) was introduced in Chander and Tulkens 1995 & 1997 as the essential building block of the "gamma core" concept they proposed, to be used hereafter. A powerful further justification of the assumption is provided in Chander 2003.

3.1.2 The internal-external stability concept

Rather than focusing on strategies of the grand coalition, the non cooperative approach starts from *any* coalition S and the payoffs of its members at the corresponding *PANE* scenario[9]. It then considers the strategies 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[10]. 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 and the *PANE* scenario it generates are then said to be *stable in the internal-external sense* if no insider prefers to stay out of the coalition and no outsider prefers to join the coalition rather than stay aside.

Formally, if $W_i(S)$ is the individual payoff of player i when coalition S is formed, this means that the payoffs satisfy the following two properties:[11]

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

3.2 Transfer schemes

It has often been suggested that when a coalition and its strategies are not stable, transfers of resources between countries may induce stability. How does this property of transfers apply to the two forms of stability just defined?

Following the cooperative approach ET-03 have used *generalized GTT transfers* to stabilize the grand coalition[12]. Let W_i^{Nash} be the payoff of player i at the Nash equilibrium of the non-cooperative game or equivalently, in the economic terms of the CWS model, the discounted total consumption of the region in the last period of the Nash equilibrium scenario, that is, in absence of cooperation; and let

$$W^*(\mathcal{N}) = (W_1^*, ..., W_n^*),$$

be the vector of the similarly discounted total consumptions of the regions at the end of the Pareto efficient scenario. Generalized GTT transfers consist of the following amounts of the consumption good (positive if received, negative if paid by i):

$$\Psi_i = -(W_i^* - W_i^{Nash}) + \pi_i(\sum_{j \in \mathcal{N}} W_j^* - \sum_{j \in \mathcal{N}} W_j^{Nash}) \quad i = 1, ..., n, \tag{1}$$

[9]Thus, the gamma assumption is used here too.

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

[11]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 the connection with the *PANE* concept – owes much Eyckmans and Finus (2004).

[12]GTT transfers are those formulated in Germain, Toint and Tulkens (1997) where the authors prove analytically that these transfers make global cooperation to be in the core of a dynamic environmental game with linear damage functions. These transfers extend to dynamics those formulated for the static case in Chander and Tulkens (1995-1997).

with $\pi_i \geq 0$ $\forall i$ such that $\sum_i \pi_i = 1$.

The transfer formula guarantees that each region receives at least its consumption level in case of no cooperation and divides the surplus of cooperation over non cooperation according to weights π_i. Each weight is equal to the ratio of region i's discounted marginal damage cost over the sum over all countries of such discounted marginal damage costs. The payoff vector

$$W^*(\mathcal{N}) + \Psi_{\mathcal{N}} =_{def} (W_1^* + \Psi_1, ..., W_n^* + \Psi_n),$$

is shown[13] by ET-03 to belong to the core of the cooperative game associated with the CWS economic model.

The non-cooperative approach 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.

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

$$\text{Property } \mathit{PIS}\text{: } \mathit{Potential\ Internal\ Stability} \qquad W(S) \geq \sum_{i \in S} W_i(S \backslash \{i\}) \qquad (2)$$

The free rider payoff of a player i – that is, each term of the sum in the right hand side of (2) – may be regarded as the threat that the player can exert if he is a member of the coalition. Coalitions whose worth under their *PANE* is large enough to overcome this threat for all their members can thus be stabilized at least internally[14].

The two approaches rest on different views when applied to international environmental agreements. The cooperative approach implicitly 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 she is better off by not free riding. The non-cooperative approach assumes instead that if a country attempts to free-ride on an agreement within a coalition she is a member of, this does not prevent the other countries from cooperating among themselves and even offering the free rider compensation for not doing so.

4 Stability of coalitions in the CWS model

We now apply the above concepts to the numerical CWS model, in both its original (CWS 1.1) and updated (CWS 1.2) 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. This is done according to formula (25)-(26) in ET-03.

[13]That $W^*(\mathcal{N}) + \Psi_{\mathcal{N}}$ is an imputation follows from the fact that (1) implies $\sum_{i \in \mathcal{N}} \Psi_i = 0$.

[14]By using the *Almost Ideal Sharing Scheme* introduced in Eyckmans and Finus (2004). "Sharing scheme" indicates that Eyckmans and Finus (2004) do not propose a particular solution but a class of sharing rules that stabilizes all *PIS* coalitions.

4.1 Core stability

Let us focus first on the results for the cooperative approach as they appear in Tables 2 and 3. 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 $S = \mathcal{N} = \{USA, JPN, EU, CHN, FSU, ROW\}$. 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:

- (i) 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.

- (ii) 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 emissions in every region (the extent of the externality is reduced) except in the USA.

Result (ii) 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.

4.2 Internal-external stability

Table 4 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 cases:

- 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[15]). In particular, the grand coalition, that is, the one that would achieve the world efficient allocation without transfers, does not

[15] Here we exclude singletons.

Table 2: Coalitions payoffs at all *PANE* *w.r.t.* a coalition ($W(S)$) and at EFF (W_S^*); generalized *GTT* transfers (Ψ_S) (billion 1990 US$): Eyckmans and Tulkens (2003)

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

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

pass it. More coalitions (11, or 15, out of 56 – the grand collation 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.

- 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, as revealed by Table 6.

4.3 Core and internal-external stability compared

Thus, without transfers, the world efficient allocation, that only the grand coalition, $\mathcal{N}$, can achieve, is lacking stability in both the core sense and the internal-external sense when computed with the CWS model.

By contrast, if transfers are introduced, the world efficient allocation achieved by $\mathcal{N}$ can be stabilized in the core sense, by means of GTT transfers within the grand coalition. This is not possible in the internal-external sense, however, by means of *PIS* transfers.

The reason for this difference is in the logic that lies behind the two stability concepts: in the core case, stability of $\mathcal{N}$ is obtained from threatening the objecting parties to be deprived of any part in the surplus generated by the collective move to efficiency. In the internal-external stability case, stability should result from offering each country its free rider payoff; but it occurs that the surplus generated by the move to efficiency is insufficient for ensuring that to *all* countries. This is due to the structure of the economic model, not to the internal-external stability concept itself.

As to the stability of coalitions other than $\mathcal{N}$, none of them can evidently be stable in the core sense because it is precisely the meaning of the core result that $\mathcal{N}$ with transfers can improve upon any of them. Concerning their stability in the internal-external stability sense, one finds in Tables 2 (or 3) and 4 hardly any correlation between those coalitions that meet either internal or external stability (coalitions with an 'x' in the *IS* or *ES* columns of Table 4) and those which could block in the core sense the efficient allocation without transfers (coalitions with a negative sign in column 4 of Tables 2 and 3). In short, this is because the reasons for blocking (which are, for the members of S, the hope to do better by themselves) are fundamentally different from those for free riding (which are the search for benefit from the others' actions). This last argument also explains that the *PIS* property prevails better with small coalitions: *vis-à-vis* a small coalition, there is little to free ride about (because the coalition does not achieve much), so that the surplus generated can be sufficient to deter from such behavior.

In summary, the core *vs* internal-external stability concepts have quite opposing properties, not only as to the grand coalition, $\mathcal{N}$, but also for smaller ones. One concept excludes small coalitions, whereas the other concept can be found to be satisfied with small coalitions.

Table 4: 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				
Grande coalition		undefined			undefined	

IS = Internal Stability, *ES* = External Stability, *PIS* = Potential Internal Stability.
"x" means that the property is satisfied for the coalition.

5 Homogeneity of coalitions and stability

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

- 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[16]. 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[17]. 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}[18], 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

[16] 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.

[17] 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.

[18] The so-called *Old Kyoto* coalition in CEF-06.

the USA" coalition[19]. 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, no four-country (or more) coalitions involving both the USA and the EU and at least one non-Annex B countries do pass the *PIS* test after the update.

6 Global outcome *vs* stability

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 carbon concentrations.

and consider how these are met by alternative coalition structures. This is done in Figure 1 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:

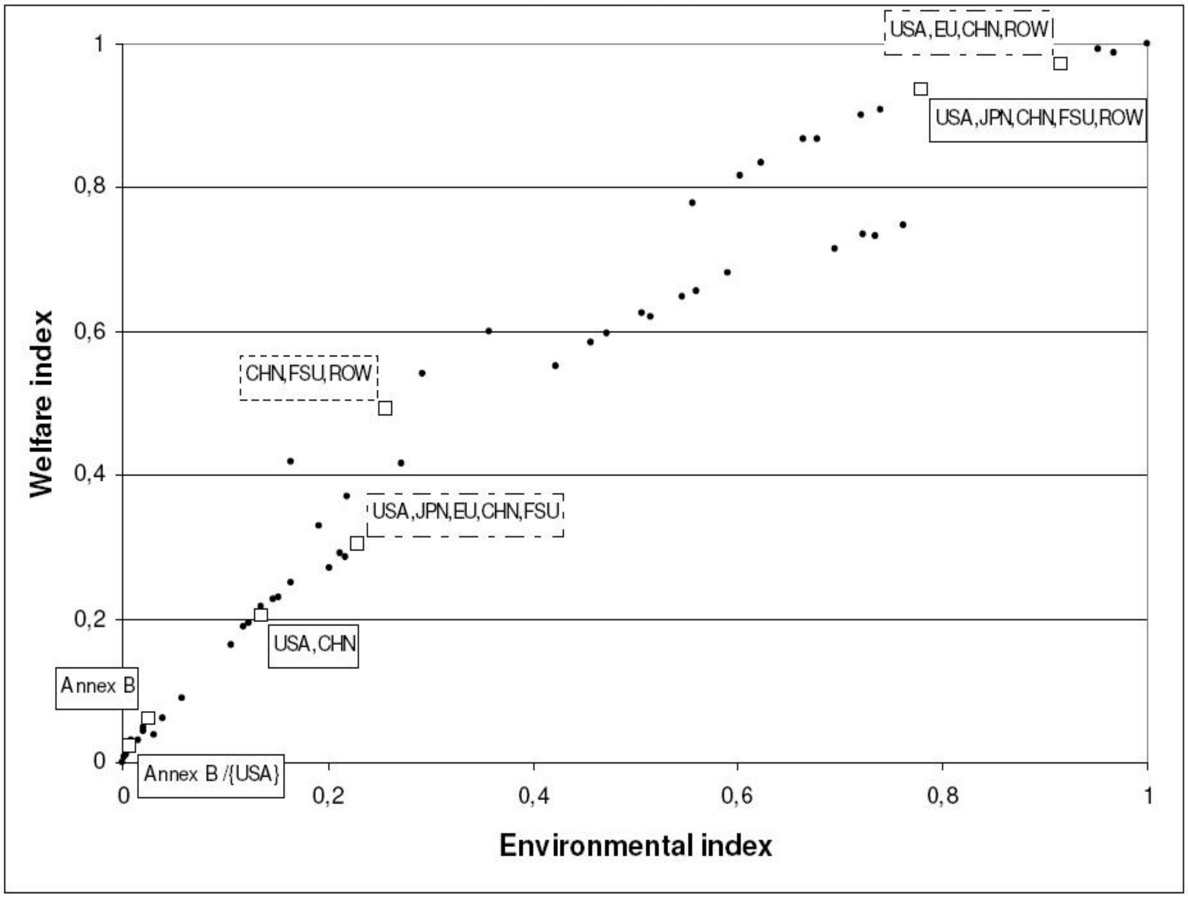
- Welfare index: $$I^W(S) = \frac{\sum_{i\in\mathcal{N}}(W_i(S) - W_i^{Nash})}{\sum_{i\in\mathcal{N}}(W_i^* - W_i^{Nash})} ,$$
- Environmental index: $$I^E(S) = \frac{M_{2300}^{Nash} - M_{2300}(S)}{M_{2300}^{Nash} - M_{2300}^*} ,$$

where $\sum_{i\in\mathcal{N}} W_i(S)$ 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.

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 an the environmental performances of alternative coalition sizes.

[19]The so-called *Present Kyoto* coalition in CEF-06.

Figure 1: Global outcome (aggregate welfare and the environment) with alternative coalition structures (..... = *IS*; ____ = *PIS*; _ . _ . _ = *not PIS*)



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.

As to homogeneity vs heterogeneity, Figure 1 reveals that the *best* (in terms of global welfare) homogeneous coalition, namely {CHN, FSU, ROW} leads to far lower global welfare and far higher 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.

7 Sensitivity analyses

The objective of this section is to test to what extent our results are robust to the choice of some key parameters. Extensive sensitivity analyses have revealed that two assumptions may be key (Gerard, 2006). The first one is the evolution of carbon intensity ($\sigma_{i,t}$ in equations of Table I) in China in the forthcoming years, and the second one is the slope of the damage functions in all countries.

China is expected to become the world largest carbon emitter soon, but *when* heavily depends on the assumption made on technological progress. In our model, carbon intensity and total factor productivity are calibrated and projected on the basis of past profiles, which yields a quite rapid – and optimistic – decarbonization of the Chinese economy in the forthcoming decades. As a first sensitivity analysis, we reduced the rate of decarbonization by half, while keeping the asymptotical value unchanged. This raises Chinese emissions by 60% in the *business-as-usual* scenario in 2100 while the level of emissions in the very long-term is kept unchanged. The fact that Chinese emissions are higher increases the climate externality generated (the effect of its own strategy on the other countries) and therefore the possible gain from cooperation. However, the free-riding incentive may also be stronger for the other countries in the coalitions including China because these coalitions will internalize a larger part of the global externality. Both effects potentially raise concern for stability.

The model shows that the gain in world welfare between the Nash equilibrium and the efficient scenarios is slightly increased by around 1%. Our main results on the core-stability of the grand coalition and the best *PIS* coalition (which includes China) still prevail. The effect on the stability of coalitions without China is negative: the difference between the aggregate welfare of the coalition and the sum of the free-riding claims of its members (definition of the *PIS* property) decreases for 23 out of the 26 coalitions considered; indeed, such coalitions internalize a smaller part of the externality. However, the effect on the coalitions including China is less clear: it increases for 16 out of 31 coalitions, but decreases for 18. In short, the model confirms the mechanisms at stake in this test and our main conclusions remain valid. The surprise may be that the effect on global welfare gain from cooperation is quite low.

The second sensitivity analysis concerns the damage functions. These, still borrowed from Nordhaus and Yang (1996), bear major uncertainties. The relationship between global temperature increase and climatic impacts is highly difficult to quantify, and the most recent studies (including the Stern Review and the Fourth IPCC Assessment Report) seem to suggest higher damage sensitivity. We did this by increasing the exponent of the damage functions ($\theta_{i,2}$ in equations of Table I) by 50% in all countries. Intuitively, this will reinforce the climate externality, and thus the desirability of cooperation. But, it is difficult to infer, *a priori*, the implication for stability because the free-riding incentive may also be stronger when the coalitions try to better internalize the climate externality.

After computation the CWS model confirms that the gain in global welfare associated with cooperation is stronger, and this time the increase is significant (the gain is three times higher). However, even with such a strong incentive for cooperation, our main results on core-stability of the grand coalition and the best *PIS* coalition remain valid. This means that the stronger gain from cooperation dominates the reinforcement of the free-riding incentives. No clear conclusion can be drawn about the impact on the stability of the other coalitions.

Indeed, the difference between the aggregate welfare of the coalition and the sum of the free-riding claims of its members increases for 38 out of 57 coalitions, but decreases for 19 others, making 6 coalitions no more *PIS*. The increase concerns mainly small coalitions, for which we have already mentioned that there is less to free-ride about.

8 Conclusion

In the context of international climate agreements, two game theoretic approaches discuss the stability of climate coalitions, using different stability concepts. With the CWS model (recently updated), this paper numerically compares and contrasts the results obtained from either approaches. It turns out that transfers are required to ensure the stability of most coalitions whatever the concept used. But transfers are not equally successful to stabilize coalitions in both approaches because of the logic that lies behind the two concepts. More precisely, if transfers can make the grand coalition stable in the gamma-core sense, it is never the case in the internal-external sense; only smaller coalitions, where there is less to free-ride about, are found stable in this sense, with transfers. Moreover we note that homogeneity among the members of a coalition appears to help the potential internal stability of a coalition. But the global outcome in terms of aggregate welfare or environmental performance as reached by small or homogeneous coalitions is far less attractive compared with the heterogeneous world efficient allocation. Thus, according to our simulations, promoting small or homogeneous coalitions for internal stability purposes is not a desirable recommendation.

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9 Appendix

Table I: Equation listing of the CWS model (for a country *i*)

$$\underset{\{\mu_{i,t}, I_{i,t}\}_{t=0,\dots,T}}{\text{Max}} \quad W_i = \sum_{t=0}^{T} \frac{Z_{i,t}}{[1+\rho_i]^t} \tag{A.1}$$

$s.t.$

$$Y_{i,t} = A_{i,t} K_{i,t}^{\gamma} L_{i,t}^{1-\gamma} \tag{A.2}$$

$$Y_{i,t} = Z_{i,t} + I_{i,t} + C_i\left(\mu_{i,t}\right) + D_i\left(\Delta T_t\right) \tag{A.3}$$

$$K_{i,t+1} = [1 - \delta_K]^{10} K_{i,t} + 10 I_{i,t} \qquad \mathrm{K}_{i,0} \text{ donné} \tag{A.4}$$

$$E_{i,t} = \sigma_{i,t}\left[1 - \mu_{i,t}\right] Y_{i,t} \tag{A.5}$$

$$C_i\left(\mu_{i,t}\right) = Y_{i,t} b_{i,1} \mu_{i,t}^{b_{i,2}} \tag{A.6}$$

$$M_{t+1} = \overline{M} + \beta \sum_{i=1}^{n} E_{i,t} + \left(1 - \delta_M\right)\left[M_t - \overline{M}\right] \qquad M_0 \; donné \tag{A.7}$$

$$F_t = \frac{4.1 \, \ln\left(M_t / M_0\right)}{\ln(2)} \tag{A.8}$$

$$T_t^o = T_{t-1}^o + \tau_3\left[\Delta T_{t-1} - T_{t-1}^o\right] \qquad T_0^o \, donné \tag{A.9}$$

$$\Delta T_t = \Delta T_{t-1} + \tau_1\left[F_t - \lambda \Delta T_{t-1}\right] - \tau_2\left[\Delta T_{t-1} - T_{t-1}^o\right] \quad \Delta T_0 \; donné \tag{A.10}$$

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

Table II: List of variables

$Y_{i,t}$	Production (billions 1990 US$)
$A_{i,t}$	Productivity
$Z_{i,t}$	Consumption (billions 1990 US$)
$I_{i,t}$	Investment (billions 1990 US$)
$K_{i,t}$	Capital stock (billions 1990 US$)
$L_{i,t}$	Population (million people)
$C_{i,t}$	Cost of abatement (billions 1990 US$)
$D_{i,t}$	Damage from climate change (billions 1990 US$)
$E_{i,t}$	Carbon emissions (billions tons of C)
$\sigma_{i,t}$	Carbon intensity of GDP (kgC/1990 US$)
$\mu_{i,t}$	Carbon emission abatement rate
M_t	Atmospheric carbon concentration (billions tons of C)
F_t	Radiative forcing (Watt per m²)
ΔT_t	Temperature increase atmosphere (°C)
T_t^o	Temperature increase deep ocean (°C)
W_i	Welfare (billions 1990 US$)

Table III: Global parameter values

δ_K	Capital depreciation rate	0.10
γ	Capital productivity parameter	0.25
β	Airborne fraction of carbon emissions	0.64
δ_M	Atmospheric carbon removal rate	0.08333
τ_1	Parameter temperature relationship	0.226
τ_2	Parameter temperature relationship	0.44
τ_3	Parameter temperature relationship	0.02
λ	Feedback parameter	1.41
$\overline{M}$	Pre-industrial carbon concentration	590
M_0	Initial carbon concentration in 2000	783[a]
ΔT_0	Initial temperature change atmosphere in 2000	0.622[b]
T_0^o	Initial temperature change deep ocean in 2000	0.108[c]

[a] Initial carbon concentration in 1990 (ET-03) was 750 billions tons of C.
[b] Initial temperature change atmosphere in 1990 (ET-03) was 0.5°C.
[c] Initial temperature change deep ocean in 1990 (ET-03) was 0.10°C.

Table IV: Regional parameter values

	$\theta_{i,1}$	$\theta_{i,2}$	$b_{i,1}$	$b_{i,2}$	ρ_i
	Damage function		Abatement cost function		Discount rate
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

Table V: 2000 reference year variables

	$Y_{i,0}$	(%)	$K_{i,0}$	(%)	$L_{i,0}$	(%)	$E_{i,0}$	(%)
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	100.0	70580.4379	100.0	6052.4310	100.0	6.5552	100.0
	billion 1990 US$	(%)	billion 1990 US$	(%)	million people	(%)	billion tons of carbon (GtC)	(%)

Table VI: 1990 reference year variables (ET-03)

	$Y_{i,0}$	(%)	$K_{i,0}$	(%)	$L_{i,0}$	(%)	$E_{i,0}$	(%)
USA	5464.796	25.9	14262.510	26.3	250.372	4.8	1.360	22.8
JPN	2932.055	13.9	8442.250	15.6	123.537	2.4	0.292	4.9
EU	6828.042	32.4	18435.710	34.0	366.497	7.0	0.872	14.6
CHN	370.024	1.8	1025.790	1.9	1133.683	21.5	0.669	11.2
FSU	855.207	4.1	2281.900	4.2	289.324	5.5	1.066	17.9
ROW	4628.621	22.0	9842.220	18.1	3102.689	58.9	1.700	28.5
World	21078.750	100.0	54290.380	100.0	5266.100	1000	5.959	100.0
	billion 1990 US$	(%)	billion 1990 US$	(%)	million people	(%)	billion tons of carbon (GtC)	(%)

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