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Efficiency *vs.* Stability in Climate Coalitions: A Conceptual and Computational Appraisal

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This paper evaluates with numerical computations the respective merits of two competing notions of coalition stability in the standard global public goods model of climate change. To this effect it uses the CWS integrated assessment model. After a reminder of the two game theoretical stability notions involved—core-stability and internal-external stability—and of the CWS model, the former property is shown to hold for the grand coalition if resource transfers of a specific form between countries are introduced. The latter property appears to hold neither for the grand coalition nor for most large coalitions whereas it is verified for most small coalitions in a weak sense that involves transfers. Finally, coalitions, stable in either sense, that perform best in terms of carbon concentration and global welfare are always heterogeneous ones. Therefore, if coalitional stability is taken as an objective, promoting small or homogeneous coalitions is not to be recommended.

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 treaties, consists in joint actions decided

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and implemented by the signatory countries. 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 environmentally effective, post-Kyoto agreements should include more countries and yield stronger carbon emission abatement. This twin issue (which countries and how much more abatement?) is at the heart of the on-going negotiation process that currently prepares, under the UNFCCC, for the post 2012 world climate regime.

Calling a "coalition" any set of countries 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. In that literature, two stability concepts are competing: the core-stability and the internal-external stability.[1] An early summary of that competition was reported in Tulkens (1998) with an update in Chander and Tulkens (2009). In brief, the core-stability concept focuses on strategies chosen by the members of the grand coalition, which gather all countries. By contrast, the internal-external stability focuses on strategies chosen by any coalitions of any size, and evaluates the benefits for each country of being inside or outside these coalitions.[2] Formal definitions are provided in Section 2.2 below. Up to now, the confrontation of the two concepts has been exclusively in terms of their logical properties.

In this paper we wish to make the confrontation at the level of an application, and discuss some policy implications. For that purpose we make use of a dynamic numerical integrated assessment model, namely the ClimNeg World Simulation (henceforth CWS) model, which lends itself to proceed fairly easily to the comparison we are interested in. Such a numerical approach of the coalitional stability problem has been initiated in Eyckmans and Tulkens (2003), who actually introduced the CWS model and used it to explore one of the two conceptual approaches just mentioned. This was followed and pursued in Carraro, Eyckmans and Finus (2006), who explored with CWS the other approach.[3] By putting together these two explorations with an updated version of the CWS model, the present paper presents an explicit comparison, with the purpose of bringing to light 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. By testing on the same integrated assessment model the two alternative game theo-

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.

2. In the literature it is sometimes referred to the latter as the *cooperative approach* and to the former as the *non-cooperative approach*, see *e.g.* Bréchet and Eyckmans (2010).

3. There exist some other works that also use game theory, *e.g.* Bernard *et. al.* (2008) or Yang (2008).

retic stability concepts, we better show their respective merits, most typically in terms of existence of stable coalitions in either sense. Second, the paper 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 composition of possible climate coalitions. Moreover, by showing explicitly which transfers among countries are appropriate to stabilize efficient coalitions, the paper also identifies a way of widening the scope of negotiations that the success of the Montreal Protocol has confirmed.

The paper is organized as follows. After this introduction, Section 2 presents the reader with the basic game theoretic concepts of coalition stability that we wish to put to a test. Section 3 presents the CWS integrated assessment model, including its calibration. Section 4 contains the main numerical results on the two alternative stability concepts when applied to the CWS model, and Sections 5 and 6 comment on the issues of homogeneity *vs* heterogeneity, aggregate welfare and environmental performance of alternative coalitions. Some sensitivity analyzes presented in Section 7 show the robustness of our results and the concluding Section 8 summarizes our main findings and derives their policy implications.

2. THE CONCEPTUAL FRAMEWORK

2.1 The climate-economic model and its associated games

The methodology we are using requires to make precise the relationship between the climate-economic model (CWS) and the games to which the alternative stability concepts are applied. In this section we deal with the game theoretic concepts while the economic model will be described in Section 3.

Two categories of games are involved, namely cooperative and non-cooperative ones. In either case the players are the countries, each player's strategies are the values chosen for the economic decision variables and the players payoffs are the countries' welfare level at the end of that period. A family of n such strategies, one for each player, defines what we call in the following section a *scenario*. Among the many conceivable ones we shall deal with *(i)* the Nash equilibrium scenario, *(ii)* various scenarios of partial agreement Nash equilibrium with respect to given coalitions, and *(iii)* the Pareto efficient scenario.

Non-cooperative games are those that consider strategies enacted by individual players; they lead essentially to the Nash equilibrium concept. Cooperative games, by contrast, 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 strategy chosen by individual players as well as the strategies chosen jointly by 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.[4]

2.2 The stability concepts

The two approaches of the stability of a coalition 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(s) see that their 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.

2.2.1 "Gamma core" stability

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 mentioned above 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 called *self enforceable* since no coalition can find a better one for its members.

Formally, let i refer to players $(i=1,\dots,n)$. W_i denote the payoff of player i. $S \subseteq N$ denote a coalition, the scalar $W(S)$ be the worth of coalition S and the vector $W=(W_1,\dots,W_i,\dots,W_n)$ denote an imputation.[5] The imputation W will be said to belong to the core of the cooperative game if the individual payoffs W_i satisfy the following property:

4. We deal only with transferable utility (TU) games, for two reasons. On the one hand, at the theoretical level, the stability concepts we use have been developed for such games only; on the other hand, only TU games are used in applied numerical works such as this one.

5. An imputation is any vector of individual payoffs W_i such that their sum is equal to the worth of the grand coalition, formally: $\sum_{i \in N} W_i = W(N)$. By construction it is induced by an efficient strategy.

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

Notice that this property implies:

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

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 those 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.[6]

2.2.2 *Internal-external stability*

Rather than focusing on strategies of the grand coalition, the internal-external stability theory considers *any* coalition *S* and the payoffs of its members at the corresponding *PANE* scenario.[7] It 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[8]. 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.

6. 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 what the coalition and the other singletons do. 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, which is to be used hereafter. A powerful further justification of the assumption is provided in Chander (2008).

7. Thus, the gamma assumption is used here too.

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

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:[9]

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

2.3 Transfer schemes

It has often been suggested that when a coalition and its strategies are not stable, transfers of payoffs (of economic goods, in economic games) between players may induce stability. To what extent is this the case for each of the two forms of stability just defined?

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.

Let W_i^{Nash} be the payoff of player i at the Nash equilibrium of the non-cooperative game, that is, in absence of cooperation; and let

$$W^*(N) = (W_1^*, \ldots, W_n^*),$$

be the payoff vector of the players at the Pareto efficient solution of the cooperative game. The transfers consist of the following payoff amounts (positive if received, negative if paid by i:

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

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

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. With these weights, the payoff vector,[10] given by

$$W^*(N) + \Psi_N =_{def} (W_1^* + \Psi_1, \ldots, W_n^* + \Psi_n),$$

9. The internal-external stability concept originates in the work of d'Aspremont *et al*. (1983) and (1986) 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).

10. That $W^*(N) + \Psi_N$ is an imputation follows from the fact that (1) implies $\sum_{i \in N} \Psi_i = 0$, *i.e*. the transfers budget balances.

is shown by Chander and Tulkens (1995, 1997) to belong to the core of the game.

The internal-external stability theory proposes no specific transfer formula but introduces instead, in Eyckmans and Finus (2004), 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 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:

- *PIS* Property (*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 the equation—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.[11]

3. THE CLIMNEG WORLD SIMULATION MODEL (CWS)

3.1 Overview of the model

The ClimNeg World Simulation model (CWS) is a dynamic 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,[12] China, the Former Soviet Union and the Rest of the World.[13] In each country/region[14] $i = 1, \ldots, n$ 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

11. By using the expression of "Sharing scheme" in the title of their paper, Eyckmans and Finus indicate that they do not propose a particular solution but are interested instead in identifying a class of sharing rules that stabilize all *PIS* coalitions.

12. Europe is defined as EU-15.

13. One may find that having 6 regions is too aggregated. This is true for the ROW where identifying some key countries, like India or Brazil would be desirable. But on the other hand it must be noticed that we have the key players, and that more players would make this kind of computational analysis non-manageble. As an example, a 18-region version of the CWS is currently under development: it generates about 270,000 PANEs.

14. For short, we henceforth use only *country*.

emission coefficient which can be reduced by national policies, $\bar{\sigma}_{i,t} = (1 - \mu_{i,t})\sigma_{i,t}$, 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 country are considered through damage cost functions $D_i(\Delta T_t)$, increasing and convex. Thus, consumption is given by the gross output minus investment, abatement costs and damage costs, $Z_{i,t} = Y_{i,t} - I_{i,t} - C_i(\mu_{i,t}) - D_i(\Delta T_t)$. The welfare of each country is measured as the aggregate discounted consumption until the end of the simulation period.

The model is used to determine, over the period 2000–2300, paths of investment (I_{it}) and emissions (through the abatement rate μ_{it}) over time and, consequently, capital accumulation, carbon concentration, temperature change and finally consumption, all at the world and country levels.

This economic model is converted into a six-player dynamic game by letting the six countries be the six players, whose strategies are the decision variables $I_i t$ and $\mu_i t$, $\forall i = 1,\ldots,6$, $\forall t = 2010,\ldots,2300$ (with a 10 year step size), and whose individual payoffs are their respective aggregate discounted consumptions until the end of the period as they result from capital accumulation, carbon concentration and temperature change.

The players-countries' strategies are specified according to a number of alternative scenarios. First, the *Nash equilibrium* scenario,[15] which is the joint outcome of each country maximizing its welfare taking the actions of the others as given. Next, the scenarios called *Partial Agreement Nash Equilibria with respect to a coalition*,[16] each of which is the outcome of a subset of countries maximizing jointly their welfare, while the others act individually (there are as many such scenarios considered as there are coalitions, that is, proper subsets of *N*). And, finally, the *Pareto efficient* scenario where all countries act jointly so as to maximize the world welfare.

The dynamic optimization problems whose solutions are the numerical values of each one of these scenarios are stated in Appendix.[17] Parameter values as well as initial values are gathered there also. The CWS model allows for different (exogenous) regional discount rates, namely 1.5% in developed countries and 3.0% in developing ones. The huge differences among countries in terms of stage of development and access to financial markets justify this assumption. Higher discount rates for developing countries reflect both a higher degree of impatience and less efficient capital markets.

15. In the terminology of dynamic non-cooperative games, this is an 'open loop' Nash equilibrium. 'Closed loop' or 'feedback' Nash equilibria have also been introduced in dynamic core-stability analysis in Germain, Toint, Tulkens and de Zeeuw 2003, albeit with a simpler model. An extension to the CWS model is still awaiting.

16. These are of open loop nature as well.

17. The model runs under GAMS. All codes are available from the authors upon request.

Finally, transfers between countries are, as in Eyckmans and Tulkens (2003), *generalized GTT transfers*,[18] that is, a dynamic extension due to Germain, Toint and Tulkens (1997) of the Chander and Tulkens (1995–1997) transfers mentioned above.

3.2 Data set and calibration

The CWS model is calibrated on standard international databases. The key data and parameters value are gathered into the Appendix. All details are available in Gerard (2006, 2007). A special attention should be deserved to two key features that will have a clear influence on model's properties: population profiles and technological changes.

For population growth we use the 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. The time profiles of various regions become are 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 while it should be increasing in the USA, mainly because of immigration and fertility rates. In the Rest of the World, short-term population growth would be strong, but followed by a strong 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, the Former Soviet Union (FSU) and the Rest of the World (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.[19] Apparently, stringent industrial adjustments are in place that could yield sharp decreases in carbon intensities. This is particularly true for China and FSU. On the contrary, recent trends in Japan and ROW suggest slower carbon improvements.

4. STABILITY ANALYSIS OF COALITIONS

We now apply the different concepts of coalition stability to the numerical CWS model. Given the six regions and the 63 coalitions that can possibly form, denoted by S, we compute for each of them its worth W_S in the sense of

18. The formula, reproduced here as expression A.12 and A.13 in Appendix, is of the same structure as equation (1) in the text above.

19. 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.

the gamma-characteristic function, that is, at a Partial Agreement Nash Equilibrium of the model. More precisely, for each S we solve simultaneously the following $n - s + 1$ dynamic optimization problems:

- for the insider, $\forall i \in S$: $\max W_S = \sum_{i \in S} \sum_{t=0}^{T} \frac{Z_{i,t}}{(1+\rho_i)^t}$
- for the outsider, $\forall i \in N | S$: $\max W_i = \sum_{t=0}^{T} \frac{Z_{i,t}}{(1+\rho_i)^t}$

where each W_i is the value of the objective function A.1 of the CWS model as stated in Appendix, subject to the constraints A.2–A.11.

4.1 Core-stability

Let us focus first on the results for the cooperative approach as they appear in Table 1. In this 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 ($\Psi_S = \sum_{i \in S} \Psi_i$).

Checking Table 1 reveals two main results. First, without transfers the world efficient allocation, which needs the grand coalition to be achieved, is not core-stable: 18 smaller coalitions (out of 63) can improve upon it. Thus, the grand coalition without transfers cannot form. Second, with *GTT* transfers the world efficient allocation becomes core-stable. This result is of particular importance as it shows that achieving core stability of the world efficient allocation is possible.”

Table 1: 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

(continued)

Table 1: 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$) *(continued)*

key	$W(S)$	W_S^*	$W_S^* - W(S)$	(%)	Ψ_S	$W_S^* + \Psi_S$	$W_S^* + \Psi_S - W(S)$	(%)
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

(continued)

Table 1: 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$) *(continued)*

key	$W(S)$	W_S^*	$W_S^* - W(S)$	(%)	Ψ_S	$W_S^* + \Psi_S$	$W_S^* + \Psi_S - W(S)$	(%)
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

4.2 Internal-external stability

Table 2 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 main results as follows, distinguishing again between without and with transfers cases:

- Internal and external stability: very few coalitions pass the *IS* test (8 or 7 of them, out of 57[20]). 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.
- 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, and only 1 five-country coalition passes the test.

20. Here we exclude singletons.

However, many smaller coalitions do. More precisely, 10 four-country coalitions, out of 15, are PIS, and all the three-country and two-country coalitions are. In sum, only 5 coalitions (out of 63) are not PIS.

These results are in line with the main conclusion of the theoretical literature on IS-ES stability,[21] namely that no large coalitions can be stable in that sense. There is however the following novel interest with the present results: as this theoretical literature establishes its claim only for simple models with identical countries, it is shown here by an example that the thesis may also holds by and large in the case of a much more complex economic model and for non identical countries. On the question whether transfers can improve that stability, our mostly negative results do also confirm those obtained by Eyckmans and Finus (2004) and Carraro, Eyckmans and Finus (2006).

Table 2: Non cooperative stability properties satisfied by different coalitions

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

Coalition	*IS*	*ES*	*PIS*
USA,JPN			X
USA,EU	X	X	X
USA,CHN			X
USA,FSU			X
USA,ROW			X
JPN,EU			X
JPN,CHN			X
JPN,FSU			X
JPN,ROW	X		X
EU,CHN			X
EU,FSU			X
EU,ROW			X
CHN,FSU	X		X
CHN,ROW	X		X
FSU,ROW	X		X
USA,JPN,EU		X	X
USA,JPN,CHN			X
USA,JPN,FSU			X
USA,JPN,ROW			X
USA,EU,CHN		X	X
USA,EU,FSU		X	X
USA,EU,ROW		X	X
USA,CHN,FSU			X

(continued)

21. As initiated by Barrett (1994) and Carraro and Siniscalco (1993); Asheim et al. (2006) is in the same spirit.

Table 2: Non cooperative stability properties satisfied by different coalitions *(continued)*

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

Coalition	*IS*	*ES*	*PIS*
USA,CHN,ROW			X
USA,FSU,ROW			X
JPN,EU,CHN			X
JPN,EU,FSU			X
JPN,EU,ROW			X
JPN,CHN,FSU			X
JPN,CHN,ROW			X
JPN,FSU,ROW	X		X
EU,CHN,FSU			X
EU,CHN,ROW			X
EU,FSU,ROW			X
CHN,FSU,ROW	X		X
USA,JPN,EU,CHN		X	
USA,JPN,EU,FSU		X	X
USA,JPN,EU,ROW		X	
USA,JPN,CHN,FSU			X
USA,JPN,CHN,ROW			X
USA,JPN,FSU,ROW			X
USA,EU,CHN,FSU		X	
USA,EU,CHN,ROW		X	
USA,EU,FSU,ROW		X	
USA,CHN,FSU,ROW			X
JPN,EU,CHN,FSU			X
JPN,EU,CHN,ROW			X
JPN,EU,FSU,ROW			X
JPN,CHN,FSU,ROW			X
EU,CHN,FSU,ROW			X
USA,JPN,EU,CHN,FSU		X	
USA,JPN,EU,CHN,ROW		X	
USA,JPN,EU,FSU,ROW		X	
USA,JPN,CHN,FSU,ROW			X
USA,EU,CHN,FSU,ROW		X	
JPN,EU,CHN,FSU,ROW			
Grand coalition		irrelevant	

4.3 Core and internal-external stability compared

Considering the grand coalition N, we can report the following three results:

1. Without transfers, the world efficient allocation, that only the grand coalition can achieve, is lacking stability in both the core sense and the internal-external sense when computed with the CWS model.

2. By contrast, if transfers are introduced, the world efficient allocation achieved by *N* can be stabilized in the core sense, by means of *GTT* transfers within the grand coalition.
3. This is not possible in the internal-external sense, *i.e.* by means of *PIS* transfers.

The reason for this difference (GTT transfers work while PIS transfers do not) is in the logic that lies behind the two stability concepts: in the core case, stability of *N* is obtained from threatening the objecting parties to be deprived of any part in the surplus generated by the collective move to efficiency. By construction, this is always feasible. In the internal-external stability case, stability results from offering each country its free rider payoff; but there is no general assurance that this be always feasible: the surplus generated by the move to efficiency may be insufficient for ensuring that payoff to *all* countries. This depends upon characteristics of the computational model, such as, *e.g.* the distance in welfare terms between the Nash and Pareto solutions, that is, the size of the surplus.

As far as coalitions other than *N* are concerned, none of them can evidently be stable in the core sense because it is precisely the meaning of the core result that *N* with transfers can improve upon any of them. Concerning their stability in the internal-external stability sense, one finds in Tables 1 and 2 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 2) and those which could block in the core sense the efficient allocation without transfers (coalitions with a negative sign in column 4 of Table 1). 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 why 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, *N*, but also for smaller ones. One concept excludes small coalitions, whereas the other concept can be found to be satisfied with small coalitions.

5. STABILITY *VERSUS* 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 1 with the numerical results provided by the CWS model. 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: $I^W(S) = \dfrac{\sum_{i \in N}(W_i(S) - W_i^{Nash})}{\sum_{i \in N}(W_i^* - W_i^{Nash})}$,
- Environmental index: $I^E(S) = \dfrac{M_{2300}^{Nash} - M_{2300}(S)}{M_{2300}^{Nash} - M_{2300}^*}$,

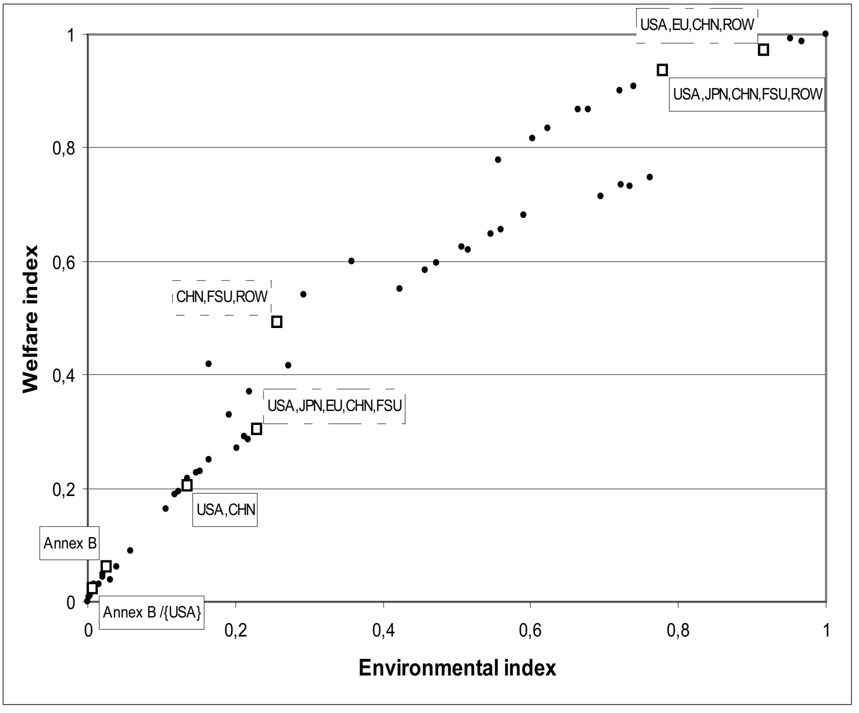
where $\sum_{i \in N} W_i(S)$ and $M_{2300}(S)$ are respectively the aggregate welfare and carbon concentration levels in 2300 under the corresponding coalition structure S. while "*" refers to the world efficient allocation (full cooperation) and "Nash" refers to the Nash case (no cooperation). An increasing 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 and the environmental performances of alternative coalition sizes.

Figure 1 displays many appealing results. First, it shows that different coalitions are able to provide similar outcome, either for welfare or environmental quality. Put differently, an improvement in the environmental quality does not necessarily goes with an improvement in welfare at the world level, and conversely. The outcome depends on the coalition. As an example, it is striking to see that a coalition formed by three countries, namely {CHN, FSU, ROW}, performs as well as a 5-country coalition in terms of environmental quality, namely {USA, JPN, EU, CHN, FSU}. Still, the former ranks much higher in terms of global welfare. It shows that a smaller coalition may perform better than a larger coalition. This result is even reinforced by the fact that the former coalition is internally stable while the latter cannot be stabilized. Another striking result is the performance of the Annex B coalition: it is almost similar to the Nash equilibrium.

Finally, two coalitions are of special interest because of their performance: {USA, EU, CHN, ROW} and {USA, JPN, CHN, FSU, ROW}. The for-

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



mer is quite close to the grand coalition. The latter is almost at the same welfare performance level but with a somewhat lower environmental index. How can this be explained? First, it must be noticed that the former can not be stabilized, while the latter is PIS. In other words, the former cannot form, while the latter can because it is beneficial to all parties. This makes a huge difference between the two in terms of political applicability. Second, the latter enlarges the coalition by inviting FSU and JPN, but puts the EU outside. By doing so, it makes the coalition PIS. In our model (as well as in many integrated models) the EU is known to have large climate damages. As a consequence, it asks for strong carbon emission reductions, which is costly for all coalition members. By putting the EU outside and inviting FSU and JPN, the coalition becomes potentially internally stable, the world welfare level is almost the same and the climate is better-off.

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

6. IS COALITION HOMOGENEITY DESIRABLE?

A common argument in the climate policy debate is that developed countries should engage themselves first, and developing countries would thereafter be invited to join the agreement and participate in the mitigation process. Although this argument seems reasonable on the ground of historical responsibilities, one may question its effectiveness in combating climate change.[22] This question has been partly addressed by McGinty (2007) who shows that the benefits from cooperation are greater when countries are heterogenous. Here, we go one step further by linking effectiveness with stability. We shall analyze 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:

- 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, all the 4 homogeneous coalitions involving FSU and developing-non-Annex B countries pass the *IS* test, and the homogenous coalition {USA, EU} is both internally and externally stable. On the other hand, 5 of the 7 internally stable coalitions are homogenous coalitions. Among these 5 homogenous IS coalitions, only one involve developed countries, USA or EU. The two heterogenous IS coalitions include JPN as developed-Annex B country, which is the least important emitter of the six regions.[23] So it seems that adding a large developed country to an homogenous coalition of developing country is detrimental to its internal stability.

It is sometimes argued that, for the sake of effectiveness, the big polluters of each category should be included in a coalition. In CWS, the two main polluters

22. This is the principle of ‘common but differentiated responsibilities’ of countries stated in the UN Framework Convention.

23. JPN is less important in terms of emissions than USA or EU.

in each category are USA or EU, on the one hand, and CHN or ROW on the other hand. It appears that none of the coalitions involving at least one of these big polluters is internally stable. Moreover, 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.

When the possibility of transfers is introduced, again stability seems to be enhanced by homogeneity. Indeed, it is striking to see that the 5 coalitions that are not PIS are all heterogenous ones. Those coalitions are large, as they gather 4 or 5 countries. Put differently, all the homogenous coalitions can be stabilized, but those coalitions are smaller. Interestingly, the Annex B coalition turns out to be more stable than the "Annex B without the USA" coalition.[24] Indeed, this latter coalition does not satisfy the *ES* property: this means that the United States would be better off by coming back to the Annex B coalition. Furthermore, no four-country (or more) coalitions that involve both the USA and the EU and at least one non-Annex B countries pass the *PIS* test.

The discussion about homogeneity *vs* heterogeneity can also be analyzed by using Figure 1. 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.

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

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 Appendix) in China in the forthcoming years, and the second one is the slope of the damage functions in all countries. They will be considered in the two first sub-sections. Then, we will pay some attention to the update of the CWS model, in particular in terms of carbon intensity profiles and population profiles between the version used in ET-03 and the current one. The question here is to see if updating the economic part of such a the model can alter our conclusions or not. This will be done in a last subsection. Sensitivity analyses with respect to the discount rate have not revealed important varying results as to the stability of alternative coalitions with respect to this parameter.

24. The so-called *Present Kyoto* coalition in CEF-06.

7.1 Carbon intensity in China

China is now the world largest carbon emitter. Still, in the CWS model carbon intensity and total factor productivity are calibrated and projected on the basis of past profiles, which yields a quite rapid—and too 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.

7.2 Slope of damage functions

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 Appendix) 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.

7.3 Economic update

In this paper we use an updated version of the CWS model initially presented in ET-03.[25] The update consists essentially in changes in the numerical value of several parameters of the optimization model (A.1)–(A.11), reflecting new assumptions on population growth and technological change. These have two main implications for the scenarios. First, world emissions are lower in the business-as-usual scenario than they were in the previous version of the model. Second, heterogeneity among countries is reinforced: national emission profiles are generally lower in all countries, in particular in China, but the USA experience higher emissions. Thus, the relative weight of countries in the global system is significantly changed, and so do the costs and benefits for each country of participating in a given climate agreement. The implications for our coalitional stability analyzes are as follows.

About the cooperative approach, the main economic theoretic point is to verify whether a gamma-core solution can also be found with the new values of the parameters, as was the case with the original ones.[26] The result happens to be positive. Here, as in the previous version, GTT transfers need to be used because, without them, the efficient solution is blocked by 18 coalitions (a number that was 14 previously). The concept of gamma-core thus appears to be robust to our updating. But the presence of four newly blocking coalitions may be seen as revealing an increased instability of the efficient allocation without transfers. This makes the transfers all the more necessary if efficiency is being sought in the international agreement.

As far as the non-cooperative approach is concerned, in both versions of CWS very few coalitions are internally stable (8 or 7 of them, out of 57). A few more coalitions (11, or 15, out of 56) are externally stable. No coalition passes both tests, except the couple {USA, EU} which does so only in the updated version. When transfers are introduced, 2 three-country coalitions that were not

25. The details of this update are reported in the discussion paper version of our article, Bréchet, Gerard, Tulkens (2007).

26. Remember that existence of a gamma-core solution is established analytically only for the usual basic models (linear and convex, respectively) of Chander and Tulkens 1995–1997, not for the CWS model.

stable in the first version become potentially internally stable (PIS) after the update, namely {USA, EU, CHN} and {JPN, CHN, FSU}. The number of four-country coalitions that are PIS remains the same in the two versions (10, out of 15).

Finally, as to the distinction between homogenous vs. heterogenous coalitions in relation with stability, we find that without transfers, while 6 of the 8 internally stable coalitions were heterogeneous coalitions in the earlier version, only two of these 6 heterogeneous coalitions still pass the *IS* test after the update. With transfers, homogeneity favors somewhat more the stability of coalitions in the updated version of CWS than in the original one.

8. CONCLUSION AND POLICY IMPLICATIONS

In the literature on international climate agreements, two alternative game theoretic approaches are used to discuss the stability of climate coalitions, which are based on two different stability concepts, namely "gamma-core" stability and "internal-external" stability. With the integrated assessment CWS model, this paper numerically compares and contrasts the results obtained from applying these two approaches. From a methodological viewpoint, it turns out that, in this model, transfers are required to ensure the stability of most coalitions whatever the concept used. But transfers are not equally successful to stabilize coalitions in either approaches because of the different logic that lies behind the two concepts. More precisely, while transfers can make the grand coalition stable in the gamma-core sense (which rests on the threat of failing to reach an agreement), this is never the case in the internal-external stability sense (which rests on offering compensation for resisting the temptation of free riding). Only smaller coalitions, where there is little to free-ride about, are found stable in this sense, sometimes with transfers. Moreover, we note that homogeneity among the members of a coalition appears to help the coalition's potential internal stability irrespective of its size. The global outcome in terms of aggregate welfare or environmental performance reached by small or homogeneous coalitions is far less attractive compared with the world efficient allocation that can be reached by the heterogeneous grand coalition only.

Policy-wise, these results support the view that environmental agreements which include a large number of countries are desirable both in terms of the countries' welfare as in terms of global environmental performance. In addition, stability in the gamma-core sense can be achieved only if the agreement includes all countries of the world, whereas stability in the internal-external sense can be achieved only among smaller numbers of signatories. Therefore, agreements including all countries, such as the Kyoto Protocol (before the withdrawal of the USA), are most desirable from the three points of view of welfare, environment, and stability.

As illustrated in the paper, the last property can be ensured by means of appropriately designed transfers of resources. These can take many forms, some of which are quite different from the lump sum ones used here. Among them, and most importantly, the transfers implied by a *cap and trade* scheme of the type established by the Kyoto Protocol do have all the stability properties required here for transfers—and a few more virtues as well.[27]

Finally, if for reasons other than those invoked above, a treaty involving the "grand" coalition of all countries cannot be signed and smaller coalitions are envisaged, the above simulations indicate that heterogeneity of composition matters more than size for the stability of a coalition.[28] Thus, promoting homogeneous coalitions, as is sometimes done, is not supported by our analysis if effectiveness is taken as a policy objective.

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27. For a full development of this point, which is often overlooked, see Chander, Tulkens, van Ypersele and Willems (2002). For an analysis applied to the EU unilateral strategy before Copenhagen, see Bréchet *et al.* (2010).

28. See Bréchet and Eyckmans (2010) for further analyzes about this point.

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9. APPENDIX

Statement of the CWS model. The index $i = 1, \ . \ . \ . \ n$ stands for region/country.

Objective functions

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

Constraints

$$Y_{i,t} = A_{i,t} K_{i,t}^{\alpha} L_{i,t}^{1-\alpha}$$

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

$$K_{i,t+1} = (1-\delta_K)^{10} K_{i,t} + 10 I_{i,t}, \text{ with } K_{i,0} \text{ given}$$

$$E_{i,t} = \sigma_{i,t}(1-\mu_{i,t}) Y_{i,t}$$

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

$$M_t +_1 = \bar{M} + \beta \sum_{j=1}^{n} E_{j,t} + (1-\delta_M)(M_t - \bar{M}), \text{ with } M_0 \text{ given}$$

$$F_t = 4.1\, ln(M_t/M_0)/ln(2)$$

$$T_t^0 = T_{t-1}^0 + \tau_3(\Delta T_{t-1} - T_{t-1}^0), \text{ with } T_0^0 \text{ given}$$

$$\Delta T_t = \Delta T_{t-1} + \tau_1(F_t - \lambda \Delta T_{t-1}) - \tau_2(\Delta T_{t-1} - T_{t-1}^0), \text{ with } \Delta T_0 \text{ given}$$

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

Solutions

- **Pareto efficient**:

$(\mu_{i,t}^*, I_{i,t}^*)_{\substack{i=1,\dots n \\ t=0,\dots T}}$ that solves:

Max $\sum_{t=0}^{T} \sum_{i=1}^{n} (A.1) = \sum_i W_i^*$, subject to (A.2)…(A.11).

- **Nash equilibrium**:

$(\mu_{i,t}^{NE}, I_{i,t}^{NE})_{\substack{i=1,\dots n \\ t=0,\dots T}}$ that solves, for each $i = 1, \dots n$:

Max $\sum_{t=0}^{T} (A.1) = \sum_i W_i^{NE}$, subject to (A.2)…(A.11), with

$E_{j,t} = E_{j,t}^{NE}, \forall j \neq i, \ t = 0, \dots T.$

• **Partial Agreement Nash equilibria *w.r.t.* any coalition** $S \in N$:

$(\mu^S_{i,t}, I^S_{i,t})_{\substack{i=1,\dots n \\ t=0,\dots T}}$ that solves:

Max $\sum_{t=0}^{T} \sum_{i=1}^{n} (A.1) = \sum_i W_i^S$, subject to (A.2)…(A.11) with $E_{j,t} = E^S_{j,t}, \forall j \notin S,\ t = 0, \dots T$, and $\forall i \notin S$, Max $\sum_{t=0}^{T} (A.1)$, subject to (A.2)…(A.11) with $E_{j,t} = E^S_{j,t}, \forall j \neq i, t = 0, \dots T$.

GTT transfers

$$\Psi_i = -(W_i^* - W_i^{NE}) + \pi_i\left(\sum_{j \in N} W_j^* - \sum_{j \in N} W_j^{NE}\right)$$

$$\pi_i = \left(\sum_{t=0}^{T} D_i' (\Delta T_t^*)/(1+\rho_i)^t\right) / \left(\sum_{j \in N} \sum_{t=0}^{T} D_j' \Delta T_t^*)/(1+\rho_j)^t\right)$$

Table I: 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 m^2)
ΔT_t	Temperature increase atmosphere (°C)
T_t^0	Temperature increase deep ocean (°C)
W_i	Welfare (billions 1990 US$)

Table II: 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
$\bar{M}$	Pre-industrial carbon concentration	590
M_0	Initial carbon concentration in 2000	783
ΔT_0	Initial temperature change atmosphere in 2000	0.622
T_0^0	Initial temperature change deep ocean in 2000	0.108

Table III: 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 IV: 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)	(%)

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