Cooperation on Climate Change under Economic Linkages: How the Inclusion of Macroeconomic Effects Affects Stability of a Global Climate Coalition

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ABSTRACT

Game-theoretic models of international cooperation on climate change come to very different results regarding the stability of the grand coalition of all countries, depending on the stability concept used. In particular, the core-stability concept produces an encouraging result that does not seem to be supported by reality. We extend the game-theoretic model based on this concept by introducing macroeconomic effects of emission reduction measures in multiple countries. The computable general equilibrium model DART and damage functions from the RICE model are used to quantify the theoretical model. Contrary to the classical model, we find that, under damages in the IPCC range, the core of the resulting cooperative game is empty and no stable global agreement exists. This is mainly due to fossil fuel exporting countries, which are negatively affected by lower fossil fuel prices resulting from emission reduction measures.

Keywords: Game theory, Cooperation, Climate change, Core, Stability, Macroeconomic effects

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1. INTRODUCTION

There is international consensus that significant global greenhouse gas (GHG) emission reductions are needed to prevent dangerous climate change. Since the early 1990s, the United Nations Framework Convention on Climate Change (UNFCCC) has tried to facilitate international cooperation on emission reductions. So far, the process has not resulted in a global agreement on ambitious reduction targets for major emitting countries that would result in adequate global emission reductions (IPCC, 2014b).

Economic analyses of international climate cooperation based on a non-cooperative game-theoretical framework and the internal and external stability concept theoretically predict a lack of global agreement. They find that a stable coalition of symmetric countries cooperating on climate change can only include a small number of countries and cannot effectively curb global GHG emissions (Barrett, 1994; Carraro and Siniscalco, 1998; Finus, 2003). When asymmetric countries are considered, a larger stable coalition can exist, but this coalition will only achieve little abatement (Pavlova and de Zeeuw, 2013). Financial transfers between regions are able to improve the situation somewhat, but they still cannot induce stability of the grand coalition (McGinty, 2007; Pavlova and

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de Zeeuw, 2013). Numerical applications largely support the bleak theoretical results (Bosello et al., 2003; Carraro et al., 2006; Nagashima et al., 2009; Bréchet et al., 2011; Dellink, 2011; Bosetti et al., 2013). Although stable coalitions consisting of more than half of all considered regions are possible, they are not able to reduce emissions to the global optimum (for a more detailed overview of the literature, see e.g. Hovi et al. (2015) and de Zeeuw (2015)).

A more encouraging theoretical result was provided by Chander and Tulkens (1995, 1997) and generalized by Helm (2001), using the core-stability concept of cooperative game theory. The authors show that under some standard assumptions on countries' cost functions,[1] and allowing for financial transfers between countries, it is possible to design an international agreement with a stable grand coalition (Chander and Tulkens, 1995). Specifically, Chander and Tulkens (1995, 1997) propose a particular transfer rule and show that the resulting imputation lies in the core of the game. Numerical studies applying the core-stability concept by Eyckmans and Tulkens (2003), Bréchet et al. (2011) and Dellink (2011)[2] validate those theoretic results of a stable grand coalition. This result is not influenced by the slope of the damage functions or an economic update of the model (Bréchet et al., 2011) and holds for a disaggregation into six world regions (Eyckmans and Tulkens, 2003; Bréchet et al., 2011) and 12 (Dellink, 2011).

In this paper, we investigate the reliance of the high degree of cooperation in the core-stability concept on the underlying assumptions of the model. More specifically, we generalize the modeling of consumption losses to incorporate international consumption effects of emission reduction measures. Current models are based on the assumption that a country's consumption loss due to emission abatement measures only depends on the country's domestic emissions. This approach neglects the fact that in a globalized world action in one country affects utility in other parts of the world. An example: the introduction of extensive energy efficiency measures in one country results in (i) a demand reduction for fossil fuels and (ii) cost reductions for the energy efficiency measures applied. Hence, other countries can be affected by changes in fossil fuel prices and technology cost changes. Further, competitiveness of firms is affected and hence changes in world trade arise.

The aspect of a less domestically oriented consumption function is particularly relevant in cases where global abatement activities are high, because such action causes fundamental technological and economic change on a global level. We therefore argue that the approach of taking purely domestic consumption functions might be appropriate for the calculation of the non-cooperative equilibrium, when abatement activities in all countries are rather small. When calculating the value of coalitions applying (ambitious) abatement targets, however, those international macroeconomic effects should be taken into account—an extension of the purely domestically oriented consumption functions used by Chander and Tulkens (1995, 1997) and Helm (2001).

Therefore, we modify the model by Chander and Tulkens (hereafter CT model) by changing the definition of the consumption function to include consequences of emission abatement in multiple countries. In a second step, we apply the global computable general equilibrium (CGE) model DART to quantify the consumption functions for regions and countries. Bringing together these consumption functions with damage functions taken from the RICE model (Nordhaus, 2010) allows us to provide the value function of the game. Subsequently, we calculate the core and the best partition of the game to check the stability of the grand coalition.

1. Monotonicity, differentiability, and convexity/concavity.

2. Eyckmans and Tulkens (2003) and Bréchet et al. (2011) apply the ClimNeg World Simulation Model, Dellink (2011) applies the STACO model.

To our knowledge no attempt has been made so far to include the international macroeconomic effects mentioned above into analyses applying the core-stability concept. While, for example, the WITCH model (Bosetti et al., 2013) includes macroeconomic effects, it has only been applied using the internal and external stability concept. The previous numerical analyses applying core-stability were based on models that did not include macroeconomic effects. Moreover, the incorporation of macroeconomic effects means that the utility functions may violate the assumptions used in the theoretical proof of a non-empty core in the CT model by Helm (2001). This paper may therefore also be seen as an attempt at a counter-example to this result, if assumptions about the form and dependence of functions are further relaxed.

Section 2 describes in detail the theoretical model by Chander and Tulkens, our modifications and the numerical models used for our calculations. Section 3 presents the results of the simulations. Section 4 discusses policy implications of our results. Section 5 concludes and offers an outlook for future work.

2. THE MODEL

The analyses in this paper are based on a game-theoretic framework. The basis for this framework is provided by the model of transfrontier pollution presented by Chander and Tulkens (1995, 1997). This model is briefly summarized in Section 2.1, followed by our extension of the model. Our approach on the quantification of the value function used within the theoretical framework is presented in Section 2.2. Several steps are necessary to derive the value function, including the application of the global CGE model DART to calculate countries' consumption functions and of the RICE model (Nordhaus, 2010) to calculate global damages.

2.1 Game-theoretic Model

2.1.1 The model by Chander and Tulkens (1995, 1997)

Let $\mathbf{N = \{1,\ldots,n\}}$ be the set of players representing the regions involved in the game. The CT model then consists of these components for all players $\mathbf{i \in N}$:

- Emissions $\mathbf{E_i}$
- Consumption function $\mathbf{C_i(E_i)}$, depending on a player's own emissions. This function is usually assumed to be monotonically increasing and concave.
- Damage function $\mathbf{D_i(E_N)}$, depending on global emissions $\mathbf{E_N = \sum E_i}$. It describes the damages caused by climate change in a region for a certain level of global emissions. This function is usually assumed to be monotonically increasing and convex.

Each player's utility is determined by the difference of consumption function and damage function. Therefore, it depends on the emissions of all other players, via the damage function. In order to determine the value function $\mathbf{v}$ of the game, it is assumed that a coalition $\mathbf{S \subseteq N}$ forms. Members of the coalition maximize joint utility of all coalition members.

$$\max_{(E_i)_{i\in S}} \sum_{i\in S} [C_i(E_i) - D_i(E_N)] \tag{1}$$

As the result of Equation (1) also depends on the emissions of players not in the coalition, called "outsiders", an assumption about the behavior of these outsiders is needed. The CT model uses the so-called γ-assumption, which states that outsiders maximize their individual utility, i.e. a deviation from the grand coalition causes remaining cooperation to break apart.[3] Consequently, it is not possible for one player or a coalition of players to maneuver itself outside a large remaining coalition, hence there are no free-rider incentives.

$$\max_{E_j}[C_j(E_j)-D_j(E_N)] \;\; \forall \; j \notin S \qquad (2)$$

Simultaneous utility maximization of the coalition and outsiders produces emission targets for each player.[4]

The CT model then defines the cooperative game by assigning the result of Equation (1) to the function **v(S)**, which represents the value of each coalition S. In cooperative game theory, a global agreement is represented by an imputation $(\mathbf{x_1,\ldots,x_n})$, a distribution of the value of the grand coalition, **v(N)**. The imputation is the vector of the monetary values that each player receives in the proposed agreement. Note that the optimization problem in Equation (1) results in a cost-effective division of emission reductions between coalition members. Therefore, in the context of the climate negotiations, an imputation can be realized by financial transfers, additional to globally cost-effective emission reductions and the resulting climate damages. These transfers can take the form of direct payments, emission allocations with redistribution of emission certificates in an international emissions trading scheme, or more indirect measures such as technology transfer.

To check the stability of a proposed imputation **x**, representing a global agreement, the imputation is compared to the value of each possible coalition.

$$\sum_{i \in S} x_i \geq v(S) \;\; \forall \;\; S \subset N \qquad (3)$$

An imputation is stable if no coalition can improve upon the agreement by rejecting it. Therefore, it is rational for all players to support the agreement.

The set of all imputations that satisfy Equation (3) is called the core of the cooperative game. If the core is empty, no stable agreement exists. Helm (2001) showed that the core in games with consumption and damage functions satisfying the assumptions mentioned above is always non-empty.

2.1.2 Modified consumption function

We adapt the consumption function of the CT model to be able to include the international macroeconomic effects mentioned in Section 1. In the extended CT model, the function no longer just depends on a player's own emissions, but rather on the vector of emissions of all players.

$$C_i = C_i(E), \;\; E = (E_1,\ldots,E_n) \qquad (4)$$

3. Chander (2007) provides a theoretical justification of the γ-assumption by showing that the assumed behaviour is an equilibrium of an infinitely repeated game. From a more applied point of view, the γ-assumption represents a unanimity rule for voting on global climate cooperation, similar to the UNFCCC process.

4. This concept is sometimes referred to as the Partial Agreement Nash Equilibrium (PANE).

This formulation ensures that emission abatement measures by one or multiple players can influence consumption of third players. The interaction occurs if the third player reduces emissions itself, as well as if it does not. The optimization problems are adjusted accordingly.

$$\max_{(E_i)_{i \in S}} \sum_{i \in S} [C_i(E) - D_i(E_N)] \tag{5a}$$

$$\max_{\mathrm{E_j}} [C_j(E) - D_j(E_N)] \ \forall \ j \notin \mathrm{S} \tag{5b}$$

In the formulation of the consumption function in the original CT model, the joint consumption function of a coalition was given by the sum of the consumption functions of the single players (singleton coalitions). In the new modified model, there is no direct link between the consumption functions of singletons and the joint consumption functions of larger coalitions, who control the emission levels of all players within the coalition and include international effects. Therefore, a fundamental assumption for the theoretical result of a non-empty core by Helm (2001), namely the direct additivity of consumption functions in a coalition, is violated in the new modified model. To check whether the core of the modified game remains non-empty in all cases is the main aim of the remainder of the paper.

Due to the high complexity of international macroeconomic effects, a detailed theoretical analysis of the modified model does not seem to be appropriate. Instead, we quantify the consumption functions with a numerical model, as outlined in the next section, without making prior assumptions about function form. Therefore, the assumptions about function form made by Helm (2001), namely monotonicity and concavity, might be violated by some consumption functions, as briefly highlighted in Section 3.1.

2.2 Quantification of the Game

2.2.1 Quantification of the value function

As outlined in Section 2.1, we calculate the utility of each region as the difference between consumption and damages. Data on consumption and damages are taken from two different models. For the calculation of the consumption function we use the global CGE model DART. The application of DART specifically allows covering the international macroeconomic effects described above and included in the modified CT model. For the calculation of the damage function we follow the approach by Nordhaus (2010).

As most impacts of climate change only become relevant over a longer time frame (IPCC, 2013), we apply a time period from 2013 to 2300 for our calculation of the value function.

Note that due to using two separate models instead of an integrated model, feedback effects from changes in the climate on the economic system are not included.

2.2.2 CGE model DART

The DART (Dynamic Applied Regional Trade) model[5] is a recursive dynamic CGE model of the world economy, covering multiple sectors and regions. Producers in each region minimize

5. For a more detailed description of the DART model, see the appendix of Weitzel et al. (2012) or https://www.ifw-kiel.de/academy/data-bases/dart_e.

Table 1: Regions in the Game-theoretic Model

Regions used in game-theoretic analysis	Countries or regions included
North America (NAM)	Canada, USA
Europe (EUR)	Europe
Australia/New Zealand (ANZ)	Australia, New Zealand
Japan (JPN)	Japan
Fossil Fuel Exporters (EXP)	Middle East, North Africa, Former Soviet Union
China (CHN)	China
India (IND)	India
Rest of the World (ROW)	Latin America, Pacific Asia, Africa

cost of production while one representative agent per region maximizes its consumption. The model covers all important market-based repercussions resulting from climate policies, such as changes in the terms of trade due to a reduced demand of fossil fuels. DART is calibrated to the GTAP dataset 8.1 (Narayanan et al., 2012) with the base year 2007 and is aggregated to 12 sectors. The electricity sector is further disaggregated into conventional (fossil based, thermal) generation and generation from nuclear, hydro, wind, solar and biomass; CCS is available as an option for electricity generation from gas and coal (Weitzel, 2010). The costs of technologies are endogenous in the model and change over time. For our game-theoretic analysis, we use eight world regions based on countries' similarities (see Table 1).

For this application the model is run up to 2050. In a baseline scenario that assumes no climate policy, the model is calibrated to follow emission projections of the World Energy Outlook (IEA, 2013) and GDP projections of the OECD Environmental Outlook (OECD, 2012). Marginal abatement cost curves are generated for all single regions (so-called singleton coalitions), for the grand coalition of all regions, and for all possible combinations of regions in between, resulting in a total of 255 coalitions. The curves are produced by implementing different emission reduction targets, ranging from 22% to 66% below the baseline in 2050, and observing the change in consumption over the time period 2013–2050. Emission reductions in the coalition region are achieved via a harmonized carbon tax, i.e. the target of the coalition region is achieved cost-efficiently. In this step it is assumed that no climate targets are enacted in regions outside of the coalition.

It should be noted that, as highlighted before, due to the incorporation of international macroeconomic effects as in Equation (4), the consumption functions for coalitions of more than one member do not directly result from the consumption functions of single regions.

MATLAB's *pchip* function is used to interpolate between the calculated emission reduction targets. It produces a piecewise cubic polynomial with continuous first derivative and preserves extrema and monotonicity of the data. The algorithm is based on Fritsch and Carlson (1980).

The DART model calculates consumption and emissions up to 2050. We use a simple procedure to extend the calculations to 2300. For baseline emissions, we extrapolate per capita emissions for each region to 2100 based on the linear trend of per capita emissions from 2030 to 2050. Population values are based on the scenario for medium fertility of the UN World Population Prospects (United Nations, 2012). This procedure leads to an emissions path similar to the Representative Concentration Pathway RCP8.5, which was used in the IPCC's Fifth Assessment Report (Collins et al., 2013). We then use the simple extension rule for RCP8.5 (Meinshausen et al., 2011) to extend the baseline emissions path to 2300. This means constant emissions from 2100 to 2150, followed by a linear reduction of annual emissions to values consistent with stabilized atmospheric concentration in 2250, and constant emissions afterwards. For emission reduction targets, we linearly extend the trend in the relative reduction amount below baseline from the period up to 2050. In subsequent years, absolute emissions are given by baseline emissions multiplied by the extrapolated relative reduction amount. The coalition is considered jointly, while the emissions of outsider regions are calculated individually. The reduction of annual emissions is stopped when a region or coalition reaches net-zero emissions.

The procedure for consumption is similar. Baseline consumption is extrapolated based on per capita consumption. Annual data from 2013 to 2300 is discounted and aggregated, resulting in the net present value (NPV) of baseline consumption.

To reflect the intergenerational nature of climate change, the discount rate is determined based on the Ramsey formula (Arrow et al., 2012). Accordingly, the discount rate applied to a specific year is calculated as the sum of the rate of pure time preference and the product of the elasticity of the marginal utility of consumption and the per capita growth rate of consumption up to the specific year. For the rate of pure time preference and the elasticity of the marginal utility of consumption, we use the median values from a recent survey of economists (Drupp et al., 2015), which are 0.5% and 1, respectively. The per capita growth rate of consumption up to a specific year is calculated from the baseline consumption extension procedure described above. The resulting discount rate starts at 3.3% and declines to 1.5% in 2300. This is in line with the discount rate path advocated by Gollier and Hammitt (2014).

The implementation of emission reduction targets results in a consumption loss. This loss is simulated with the DART model for the period 2013 to 2050. For later years, we assume that the consumption loss relative to the baseline stays constant at the value for 2050 for all years after 2050. This assumption balances increasing consumption loss due to more expensive mitigation technologies needed to reach low emission levels, with decreasing consumption loss due to the development and cost reduction of low-carbon technologies over time. However, it can be seen as a rather conservative assumption on consumption losses. For coalitions, the joint relative consumption loss of all members is taken. Population values beyond 2100 are based on the UN World Population to 2300 report (United Nations, 2004).

2.2.3 Damage function

For the regional damage functions, we use the Regional Integrated Climate-Economy (RICE) model.[6] We use the baseline of the RICE-2010 version of the model, as described in Nordhaus (2010). Calculation of the damages in each region for each year is a two-step process. In the first step, the temperature change caused by a given level of cumulative CO_2 emissions up to the specific year is taken from RICE. The resulting temperature changes range from 0.83°C to 6.61°C over the preindustrial level. This does not include a time component, i.e. the temperature change is the same if the same level of cumulative CO_2 emissions is reached in two different years.[7] In the second step, the temperature change is used to calculate the damages in each region. For regions that differ between our model and RICE, the values from the RICE model are disaggregated using 2013 GDP values from the World Bank indicator database (World Bank, 2014). The RICE

6. http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm

7. According to Collins et al. (2013, p. 1108), the amount of cumulative CO_2 emissions is a good indicator for the global temperature increase.

model gives damages as a fraction of gross output. We convert these fractions to absolute numbers using baseline consumption levels. RICE includes two types of damages: those caused by sea level rise and other damages. We include both types. This procedure generates absolute damages for each region and year up to 2300. The cumulative NPV of damages is then calculated using again the discount rate determined by the Ramsey formula, as in the method for consumption.

2.2.3.1 Damage scenarios

We implement three sets of damage scenarios. The damages given by the RICE model form the basis for the *default damages scenario*. These estimates are at the upper end of the range given by the IPCC (IPCC, 2014a).[8] In addition, we analyse two more damage scenarios: one scenario with damages only 50% as high as in the default damages scenario (*low damages scenario*), which is still significantly above the lower range given by the IPCC, and one scenario with damages twice as high as in the default damages scenario (*high damages scenario*).[9]

2.2.4 Game evaluation

The coalition and outsider regions choose their optimal emission level via the control variable of 2050 emission reduction targets below baseline. We find the equilibrium of emission reduction targets by successively calculating the best response of each region, starting with targets of one (meaning no reduction below baseline) for all regions. In this procedure, the coalition is treated as one entity, which controls a single joint emission reduction target. Best responses are calculated using the multi-level single linkage algorithm with low-discrepancy sequences by Kucherenko and Sytsko (2005). This is a global optimization algorithm, which uses multiple starting points for local optimizations. For the local optimization, we use the BOBYQA algorithm by Powell (2009). Both algorithms are supplied in the NLopt package (Johnson, 2014).

Due to runtime constraints with the DART model, we could not calculate consumption functions of outsider regions given a reduction target of a coalition. These functions are needed when calculating the best response of an outsider region. Instead, we use the consumption functions of the singleton coalitions, in which each region assumes that no other region introduces a reduction target, to calculate the best response emission reduction targets of outsider regions. Morris et al. (2012) show that this does not have a major impact on the optimal level of emission reductions. Rather, the consumption function reacts with parallel shifts up or down if another region reduces emissions. Therefore, this simplification does not have a considerable effect on optimal emission reduction targets in equilibrium. As the value function is determined by the sum of utility of coalition members, with no regard to the utility of outsiders, the value function is only slightly affected. Also, financial transfers between coalition members do not need to be explicitly considered, because the value of a coalition is defined over the sum of its members' utility.

The analysis of the resulting game focuses on the existence of a stable imputation, or, in other words, on the (non-)emptiness of the core of the game. Therefore, we calculate the **best partition** of the game. A **partition**

8. See Section 3.1 for details.

9. As we consider only one decision based on future discounted values and damages tend to occur later in time than consumption losses due to emission reduction measures, the reduction (increase) in damages in the low (high) damages scenario could also be viewed as an increase (decrease) in the discount rate.

$$P = \{S_1, \ldots, S_m\}$$
$$S_l \subseteq N, \quad \bigcup_{l=1}^{m} S_l = N, \quad S_k \cap S_l = \varnothing \quad \forall k,l \leq m \tag{6}$$

is a set of coalitions, in which each player is a member of exactly one coalition. That is, a partition combines distinct cases (i.e. coalitions) for different regions. The value of the partition is calculated as the sum of the values of the coalitions. Consequently, the best partition of the game is the partition with the highest value of all partitions. If the partition which only contains the grand coalition is not a best partition,[10] then the core of the game is empty, as the value of the grand coalition is not high enough to satisfy each coalition in the best partition.[11] In this case, we also calculate all other partitions with a higher value than the grand coalition. These are called **blocking partitions**.[12]

3. RESULTS

Results of the model are presented in two steps. In the first step, selected consumption functions from the DART model and the damage functions from the RICE model are presented, which serve as input for the game-theoretic model. The second step focuses on the results of the core-stability analysis. As benchmarks we briefly present the cases of no cooperation and full cooperation. All monetary values are provided as NPV, cumulated over the entire model time period, 2013–2300.

3.1 Consumption and Damage Functions

The application of the DART model (see Section 2.2.2) produces curves showing the change in consumption of each coalition for different 2050 emission reduction targets. Figure 1 shows these curves for all singleton coalitions. To allow for better comparability across regions, consumption changes are shown relative to each region's baseline consumption. Note that, while the emission target is based on a specific year, 2050, consumption uses cumulative NPV. Table A1 in the Appendix gives absolute baseline consumption for each region.

Most regions only experience a relatively small decline in consumption between 0 and 0.6% of GDP for reduction targets between 0 and 30% below baseline. The Fossil Fuel Exporters region EXP is an exception, as it experiences the highest consumption loss of all regions.

The consumption functions for almost all coalitions are monotonically increasing and concave. An exception for monotonicity is the coalition {JPN, IND}, which experiences a slight increase in consumption when reducing emissions by up to around 20%. Also, several coalitions including CHN are not concave for ambitious emission reduction targets. Hence, the two assumptions of the form of the consumption functions by Helm (2001) do no longer hold in these cases.

10. It is possible for a game to have multiple best partitions with identical value.

11. In the language of cooperative game theory, the game is not *cohesive*.

12. Note that per the definition of the core of a cooperative game, there is no "stability" requirement for coalitions in blocking partitions. Such a requirement would assume "farsighted" players (Chwe, 1994; Diamantoudi and Sartzetakis, 2002), i.e. players who evaluate several deviation steps before deciding on a possible deviation. In our model, the existence of one or multiple blocking partitions is merely used as a sufficient condition for the emptiness of the core and does not make a statement on the outcome of the game.

Figure 1: Consumption Functions for Singleton Coalitions (NPV of Consumption, Relative to Baseline)

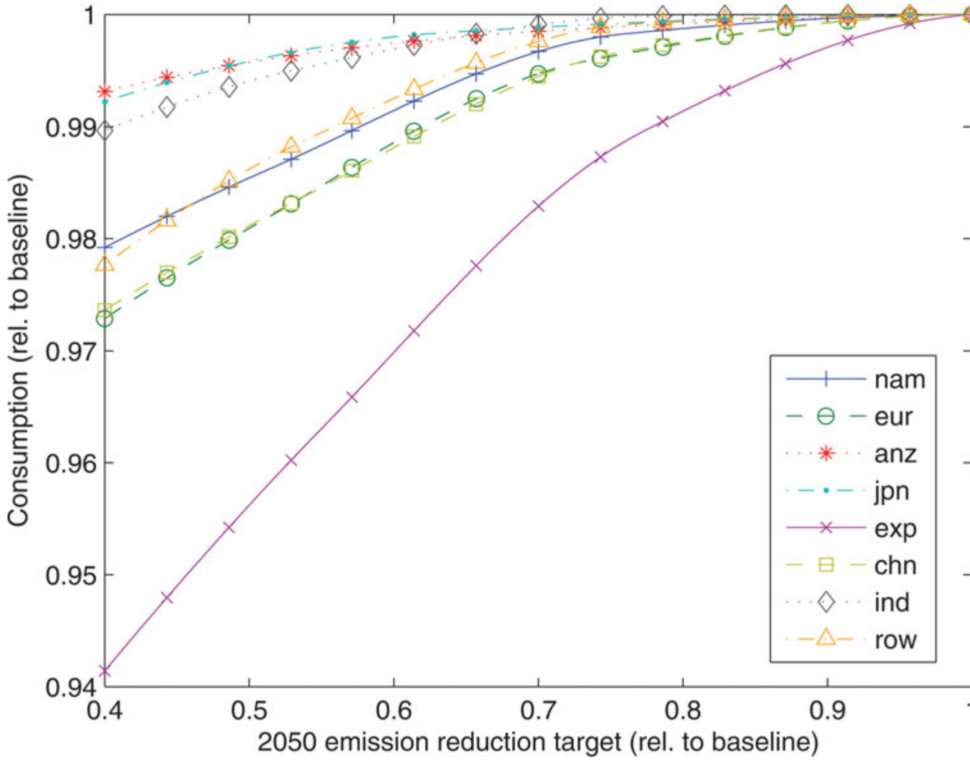


Figure 2 shows regional damages for a given temperature increase over the preindustrial level, relative to baseline consumption, in the default damages scenario. According to the projections, the lowest relative damages are expected to occur in the regions Australia / New Zealand, Japan and North America. The highest damages are projected for the regions Rest of the World, Fossil Fuel Exporters and China.

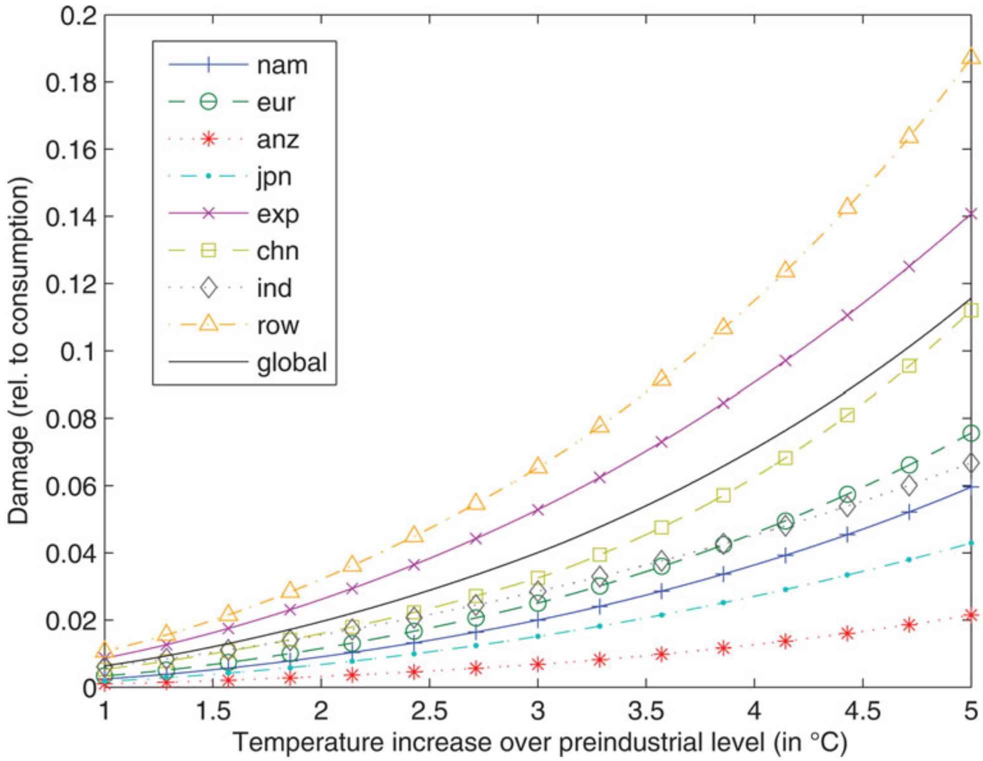
The figure also shows global relative damages, calculated as the average across all regions, weighted by regional consumption. For a temperature increase of 2°C, damages are 2.0% of consumption on a global level in the default damages scenario. This is at the upper end of the range given by the IPCC (IPCC, 2014a).

3.2 The Gains of Cooperation

In all damage scenarios, global cooperation leads to a substantial reduction in cumulative CO_2 emissions. Figure 3 shows the development of global emissions over time in the “All Singletons” case, where each region optimizes only its own utility, and in the case of global cooperation, where global utility is optimized. Emissions are shown for all damage scenarios. The baseline case without emission reduction measures in any region is shown for comparison.[13] The baseline case leads to a temperature increase of approximately 5.9°C in 2300 over the preindustrial level.

13. The baseline case can be interpreted as a scenario in which regions do not acknowledge the existence of damages caused by climate change.

Figure 2: Regional Damages Depending on Temperature Change in the Default Damages Scenario, Relative to Baseline Consumption



In the default damages scenario, the "All Singletons" case results in a global temperature increase in 2300 of 3.9°C with annual emissions peaking in 2068. For global cooperation, the emission peak is reached in 2037 and the emissions level is zero from 2117 onward, with a global temperature increase of 2.5°C in 2300.

In the low damages scenario, the "All Singletons" case produces a significantly higher temperature increase of 4.4°C in 2300. In case of global cooperation with low damages, annual emissions peak in 2057 and the emission level reaches zero in 2154. The result is a temperature increase of 3.1°C in 2300.

In the high damages scenario, the emission path in the "All Singletons" case is similar to the "Global Cooperation" case with low damages. Annual emissions peak in 2053 and the temperature increase in 2300 is 3.2°C. Global cooperation with high damages produces the most ambitious emission path, with a peak in 2023, an emission level of zero from 2089 onward, and a temperature increase of 2.0°C.

The differences in global and regional emission levels influence consumption, damages and total utility. Table 2 shows these values, in addition to CO_2 emissions and the resulting temperature increase at the end of the time period, as well as in 2100. For better readability, consumption and utility are shown as consumption *loss* and utility *loss*, compared to baseline consumption. All values are global, i.e. the sum of the values for all regions, and aggregated over the whole time period.

In all damage scenarios, damages are reduced by moving from the "All Singletons" case to global cooperation: from $343tn to $298tn (−13%) in the default damages scenario, from $202tn

Figure 3: Global CO_2 Emissions in the "All Singletons" and "Global Cooperation" Cases, for All Damage Scenarios

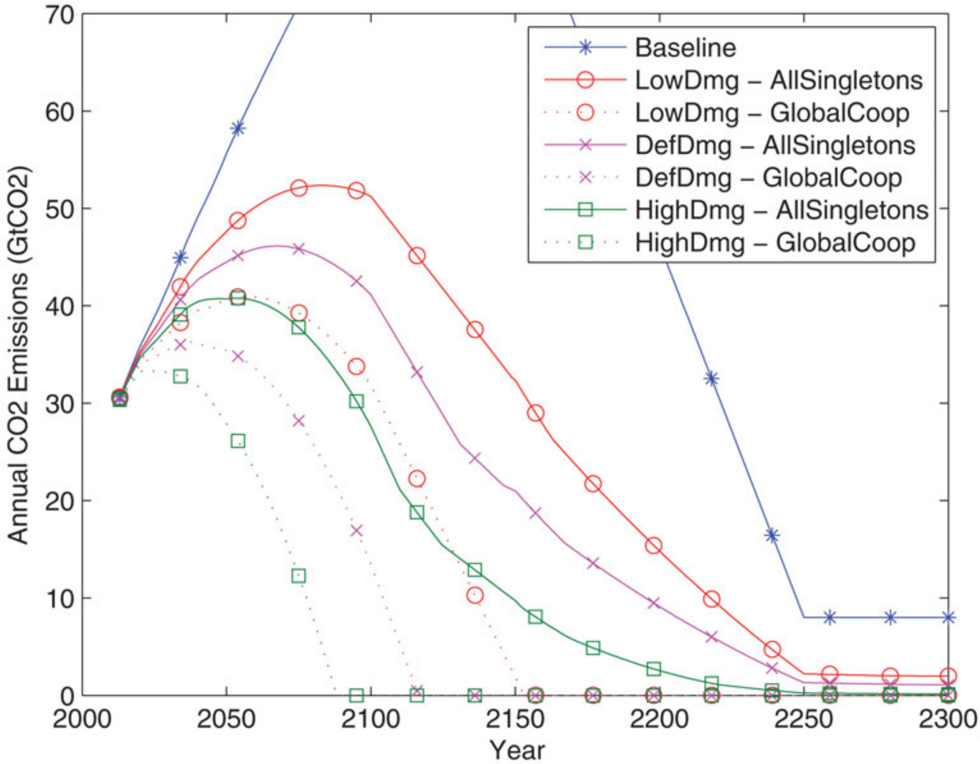


Table 2: Key Global Results in the Baseline, "All Singletons" and "Global Cooperation" Cases, for All Damage Scenarios (Monetary Values in Trillion 2007 US$)

	Cumulative CO_2 emissions ($GtCO_2$)	Temperature increase in 2100 (°C)	Temperature increase in 2300 (°C)	Consumption loss (NPV)	Damages (NPV)	Utility loss (NPV)
Low Damages						
Baseline	14,420	3.6	5.9	0	315.75	315.75
All Singletons	7,807	3.1	4.4	5.86	196.16	202.03
Global Cooperation	4,145	2.8	3.1	61.39	127.65	189.04
Default Damages						
Baseline	14,420	3.6	5.9	0	631.50	631.50
All Singletons	6,205	3.0	3.9	13.60	329.63	343.23
Global Cooperation	2,765	2.4	2.5	110.38	187.98	298.36
High Damages						
Baseline	14,420	3.6	5.9	0	1,263.00	1,263.00
All Singletons	4,401	2.7	3.2	31.88	516.56	548.44
Global Cooperation	1,804	2.0	2.0	180.49	272.60	453.09

to \$189tn (−6%) in the low damages scenario and from \$548tn to \$453tn (−17%) in the high damages scenario. Consumption losses due to emission reduction measures are small relative to absolute consumption (as shown in Figure 1). Global cooperation reduces consumption by \$96.78tn in the default damages scenario, by \$55.53tn in the low damages scenario and by \$148.61tn in the high damages scenario. The results of the optimization for the "All Singletons" and "Global Cooperation" cases are shown in Table 3. It displays the 2050 emission reduction target of the given coalition and its utility loss in equilibrium for all damage scenarios. The game-theoretic value of each coalition corresponds to the baseline consumption of each coalition member, minus the displayed utility loss. In the "All Singletons" case, the sum of the utility loss of the coalitions gives the utility loss of the partition.

We find that global cooperation in the default damages scenario increases utility by \$44.87tn compared to the "All Singletons" case, an increase of 0.6% of the absolute utility value. This corresponds to a net-avoidance of 14% of damages compared to the "All Singletons" case.

We also find that there is a large difference in the ambition level in the "All Singletons" case between different regions. In particular, China, India and Rest of the World realize relatively ambitious targets, even without cooperation. For India, this is the result of modest emission reduction costs, as seen in Figure 1. Rest of the World is the region with the highest relative damages of all regions and therefore reduces emissions in the "All Singletons" case by 32%, 28% and 39% in the default, low and high damages scenarios, respectively. China has the third highest relative damages and consequently also reduces emissions substantially, despite having the second highest emission reduction costs.

3.3 The Cooperative Game

The extreme cases "Global Cooperation" and "All Singletons" presented in the last subsection provide a standard against which we can compare other coalitions and partitions. As best partitions differ between scenarios, we discuss each damage scenario separately.

3.3.1 Default damages scenario

Table 4 shows selected partitions, including the best partition, and the respective targets and values of the member coalitions in the default damages scenario.

We find that the "Global Cooperation" partition is not a best partition of the game in the default damages scenario, as we find partitions with lower utility losses than the grand coalition. That is, we find the core of the game to be empty, contrary to the original CT model. In this scenario, a partition has the highest utility if it consists of the coalition of all regions except Australia / New Zealand (ANZ) and Japan (JPN), and ANZ and JPN as singleton coalitions. In total, utility loss of the best partition is \$297.30tn, compared to \$298.36tn in the grand coalition.

Our result arises, because a stable global agreement would have to cover against two cases simultaneously: the "All Singletons" case and the case of partial cooperation by a group of regions with high benefits from emission reductions, a *coalition of the willing*.

Consider first the region ANZ, a large exporter of fossil fuels, mainly coal. To illustrate its motivations, it is useful to look at the partition "All except ANZ", which is worse than the best partition, but still better than the "Global Cooperation" partition. When global utility is optimized in the grand coalition, global emissions in 2050 are 63.46% of baseline emissions. In the "All Singletons" case, the regionally optimized targets lead to a global average emission level of 79.95% of 2050 baseline emissions. Consequently, negative consumption effects for ANZ occur when mov-

Table 3: Utility of the "Global Cooperation" and "All Singletons" Cases in All Damage Scenarios (Utility Loss in Trillion 2007 US$)

	Low damages scenario		Default damages scenario		High damages scenario	
	2050 emission target (rel. to baseline)	**Utility loss of coalition or partition (NPV)**	**2050 emission target (rel. to baseline)**	**Utility loss of coalition or partition (NPV)**	**2050 emission target (rel. to baseline)**	**Utility loss of coalition or partition (NPV)**
Partition "Global Cooperation"	**72.57%**	**189.04**	**63.46%**	**298.36**	**50.05%**	**453.09**
N	72.57%	189.04	63.46%	298.36	50.05%	453.09
Partition "All Singletons"	**85.60%**	**202.03**	**79.95%**	**343.23**	**73.16%**	**548.44**
{NAM}	93.78%	16.99	85.93%	28.97	75.74%	45.86
{EUR}	97.45%	14.77	94.62%	24.89	88.34%	39.52
{ANZ}	100.00%	0.24	100.00%	0.40	100.00%	0.64
{JPN}	99.74%	1.25	99.42%	2.13	98.79%	3.35
{EXP}	98.48%	27.45	94.34%	47.41	81.76%	79.85
{CHN}	85.70%	19.58	75.53%	32.67	72.90%	48.27
{IND}	74.83%	10.98	71.57%	19.20	66.18%	31.83
{ROW}	72.32%	110.77	68.07%	187.56	61.22%	299.13

Table 4: Selected Partitions in the Default Damages Scenario

	2050 emission target (rel. to baseline)	Utility loss of coalition or partition (NPV, tn$2007)
Partition "Global Cooperation"	**63.46%**	**298.36**
N	63.46%	298.36
Partition "All except ANZ"	**63.59%**	**297.50**
N \ {ANZ}	63.25%	297.10
{ANZ}	100.00%	0.40
Partition "All except ANZ, JPN"	**64.95%**	**297.30**
N \ {ANZ, JPN}	64.23%	294.77
{ANZ}	100.00%	0.40
{JPN}	99.42%	2.13

ing from the "All Singletons" case to global cooperation, due to lower global fossil fuel demand and prices. The driver behind this finding is the assumption that regions expect an "All Singletons" outcome if they do not participate in the grand coalition. Consequently, ANZ would need to be compensated for its consumption loss to be motivated to join the grand coalition. This compensation would have to come from the *coalition of the willing*, in this partition consisting of all other regions. However, when this coalition optimizes its emission level, it does not need to incorporate the wishes of ANZ. This leads to a more ambitious emission reduction target of 63.25% in the *coalition of the willing*. While global emissions in the case of the *coalition of the willing* are still larger than in the grand coalition (global average target of 63.59%, compared to 63.46% in the grand coalition), the difference is rather small, because ANZ only has relatively few domestic emissions, compared to the *coalition of the willing*. Therefore, the *coalition of the willing* only experiences very small gains from moving to global cooperation. These additional gains are not large enough to offset the consumption loss of ANZ.

The motivation for JPN is different and stems from the fact that it experiences the second lowest damages from climate change, after ANZ. As the economic situation of ANZ causes global cooperation to be unstable, JPN now faces the choice between the "All Singletons" case and joining the *coalition of the willing* described above. Due to the low damages experienced by JPN, the cost of the additional emission reduction effort required by a *coalition of the willing* outweighs the reduction in damages. Consequently, JPN also blocks global cooperation and the best partition is "All except ANZ, JPN".

It should be noted that the economic effects described above for ANZ also apply to the Fossil Fuel Exporters region EXP. However, this region also experiences the second highest damages from climate change. Therefore, the damage reduction caused by global cooperation outweighs the loss of fossil fuel export revenue for EXP.

The blocking partitions shown in Table 4 are not all blocking partitions that exist in the default damages scenario. In total, four such partitions exist, all consisting of ANZ and/or JPN as blocking regions, in addition to a *coalition of the willing* of the remaining regions.

In this default damages scenario, the difference in utility loss between global cooperation and the best partition is quite small. This is further underscored by the small number of blocking partitions. The next section shows that a reduction of damages increases both the utility deficit of global cooperation and the number of blocking partitions.

Table 5: Selected Partitions in the Low Damages Scenario

	2050 emission target (rel. to baseline)	Utility loss of coalition or partition (NPV, tn$2007)
Partition "Global Cooperation"	**72.57%**	**189.04**
N	72.57%	189.04
Partition "All except ANZ"	**72.73%**	**187.44**
N \ {ANZ}	72.48%	187.20
{ANZ}	100.00%	0.24
Partition "All except ANZ, JPN"	**73.30%**	**184.18**
N \ {ANZ, JPN}	72.75%	182.69
{ANZ}	100.00%	0.24
{JPN}	99.74%	1.25
Partition "All except ANZ, JPN, CHN"	**75.41%**	**183.95**
N \ {ANZ, JPN, CHN}	72.62%	163.00
{ANZ}	100.00%	0.24
{JPN, CHN}	83.41%	20.71

3.3.2 Low damages scenario

Table 5 shows selected partitions, including the best partition, in the low damages scenario. We find that "Global Cooperation" is not the best partition of the game and hence again the core of the game is empty. The best partition comprises ANZ as a singleton, a coalition of JPN and CHN, and a *coalition of the willing* of the remaining regions. Utility loss in the best partition is $183.95tn, compared to $189.04tn in the case of global cooperation. This difference is substantially larger than in the default damages scenario.

The behaviour of ANZ is caused by the same effects described in the default damages scenario. JPN again sees no benefit in joining the *coalition of the willing*, due to its low damages, compared to other regions. CHN's behaviour can be explained by the consumption loss due to emission reductions. For CHN, this is the third-highest of all regions (see Figure 1). Therefore, CHN also does not benefit from joining the *coalition of the willing*. However, as CHN does already reduce its emissions by roughly 15% in the "All Singletons" case, it can cooperate with JPN to better distribute these emission reductions. This reduces the joint consumption loss of CHN and JPN, as JPN has low emission reduction costs.

In total, we find 80 blocking partitions in the low damages scenario, a substantial increase over the four blocking partitions in the default damages scenario.

3.3.3 High damages scenario

Table 6 shows selected partitions, including the best partition, in the high damages scenario. We find that—in contrast to the other two damage scenarios—"Global Cooperation" is the best partition of the game in the high damages scenario and that the core of the game is not empty, in line with the original CT model. Table A2 in the Appendix shows one core-stable imputation.

The different outcome in this high damages scenario is driven by high gains from cooperation, which are induced by the relatively high damages. Both the inclusion of JPN and the inclusion of ANZ into the *coalition of the willing* without those two regions lead to a gain in utility. While both regions have only low damages compared to other regions, their damages in this scenario are high enough that even they benefit from a move from "All Singletons" to "Global Cooperation".

Table 6: Selected Partitions in the High Damages Scenario

	2050 emission target (rel. to baseline)	Utility loss of coalition or partition (NPV, tn$2007)
Partition "Global Cooperation"	**50.05%**	**453.09**
N	50.05%	453.09
Partition "All except ANZ"	**50.39%**	**454.24**
N \ {ANZ}	49.93%	453.60
{ANZ}	100.00%	0.64
Partition "All except ANZ, JPN"	**51.58%**	**458.68**
N \ {ANZ, JPN}	50.59%	454.69
{ANZ}	100.00%	0.64
{JPN}	98.79%	3.35
Partition "All except ANZ, JPN, CHN"	**59.34%**	**484.84**
N \ {ANZ, JPN, CHN}	54.71%	432.91
{ANZ}	100.00%	0.64
{JPN, CHN}	72.57%	51.29

However, the economic effects which drove the results in the low and default damages scenarios are still apparent in the emission targets of the high damages scenario. The target in the case of "Global Cooperation" (50.05%) is still less ambitious than the preferred targets of the remaining coalition, when ANZ is excluded (49.93%). This means that, while ANZ prefers "Global Cooperation" to "All Singletons", it still favours a less ambitious target than the other regions. Therefore, to include ANZ in the joint target, the target becomes less ambitious. Nevertheless, these economic effects are outweighed by the high gains from cooperation in the high damages scenario.

3.3.4 Basic model without international effects

The previous subsections showed that our model can produce a game with empty core in some circumstances. This is in contrast to the original CT model, which always produces games with non-empty core. To show that this is not an artefact of the specific set up of the numerical model, we also analyse the core of the game if we do not take international effects of emission reductions into account. For that, an alternative version of the model is constructed, based only on the singleton consumption functions. The resulting model thus replicates the assumption of the original CT model that the joint consumption function of a coalition is given by the sum of the domestic consumption functions. Table 7 shows the results for the "All Singletons" case, the grand coalition and the selected partitions shown in prior sections. Consistent with the theoretical result by Helm (2001) and previous numerical applications of the core stability concept (Eyckmans and Tulkens, 2003; Bréchet et al., 2011; Dellink, 2011), we find that the core of this game is non-empty in all damage scenarios. Consequently, we conclude that our deviating results in the model with modified consumption functions are driven by this modification.

4. POLICY IMPLICATIONS

Our results imply that, under the assumption that damages from climate change are not higher than the range given by the IPCC, it is not possible to design a straightforward global climate agreement, based on emission reduction targets and including all countries, under the UNFCCC. This is true even if all countries assume that there will be no coalition without them as a member, i.e. they neglect the existence of free-riding incentives. In our model, a global agreement is blocked

Table 7: Selected Partitions in the Basic Model without International Effects (Utility Loss in Trillion 2007 US$)

	Low damages scenario		Default damages scenario		High damages scenario	
	2050 emission target (rel. to baseline)	Utility loss of coalition or partition (NPV)	2050 emission target (rel. to baseline)	Utility loss of coalition or partition (NPV)	2050 emission target (rel. to baseline)	Utility loss of coalition or partition (NPV)
Partition "Global Cooperation"	**69.35%**	**152.87**	**62.38%**	**253.91**	**50.65%**	**410.90**
N	69.35%	152.87	62.38%	253.91	50.65%	410.90
Partition "All except ANZ"	**69.69%**	**154.03**	**62.77%**	**256.43**	**51.11%**	**416.10**
N \ {ANZ}	69.41%	153.79	62.43%	256.03	50.65%	415.47
{ANZ}	100.00%	0.24	100.00%	0.40	100.00%	0.64
Partition "All except ANZ, JPN"	**70.20%**	**155.30**	**63.49%**	**259.12**	**51.99%**	**421.31**
N \ {ANZ, JPN}	69.59%	153.80	62.75%	256.59	51.01%	417.32
{ANZ}	100.00%	0.24	100.00%	0.40	100.00%	0.64
{JPN}	99.74%	1.25	99.42%	2.13	98.79%	3.35
Partition "All except ANZ, JPN, CHN"	**73.92%**	**176.68**	**67.36%**	**288.03**	**58.50%**	**468.18**
N \ {ANZ, JPN, CHN}	70.31%	155.65	64.49%	252.96	53.66%	416.11
{ANZ}	100.00%	0.24	100.00%	0.40	100.00%	0.64
{JPN, CHN}	84.45%	20.79	75.28%	34.67	72.38%	51.43
Partition "All Singletons"	**85.60%**	**202.03**	**79.95%**	**343.23**	**73.16%**	**548.44**

Note: Values for the individual regions under the "All Singletons" partition are identical to those presented in Table 3.

by the consumption loss of a major fossil fuel exporter, who would experience revenue losses due to lower fossil fuel prices in a world with ambitious global GHG abatement. All blocking countries assume that without their agreement no cooperation will take place at all, leaving them better off when not joining the coalition.

For the set of remaining countries, which we refer to as *coalition of the willing*, this situation presents two options. The first option is to stick to the idea of a global agreement under the UNFCCC and provide incentives for all countries to join. This would mean compensating the fossil fuel exporters for their consumption losses. Such compensation for the impacts of "response measures" is an essential demand by oil exporting countries, represented in the group of Like-Minded Developing Countries (LMDC), in the UNFCCC negotiations (LMDC, 2014). However, the results of our model indicate that such compensation measures would not be rational from the perspective of the *coalition of the willing*, as the additional avoided damages are not enough to make up for the consumption loss. As compensatory measures are not rational from an economic perspective, the incentive to compensate and incentivize blocking countries to join the coalition would have to come from other political reasoning. Fairness principles often discussed in the context of burden sharing, such as historic responsibility for the climate problem and the ability to pay for the solution, are one example. Countries could also be motivated by the aspiration to avoid a large temperature increase and the accompanying risk and regionally differentiated impacts. In addition, the required compensation amount is small compared to total consumption (see Table A1 in the Appendix). Therefore, if the decision is not based purely on a benefit-cost analysis of GHG abatement but other arguments are taken into account, the *coalition of the willing*, or parts of it, could reasonably incentivize blocking countries to join the global climate agreement.

The second option for the *coalition of the willing* is to abandon the UNFCCC process and try to consummate an agreement among this coalition. This option would not be as environmentally effective as a global agreement, but could be close to it, depending on the exact specification of the coalition. Non-global "climate clubs" have been proposed as a solution for the climate problem in the literature (Eckersley, 2012; Weischer et al., 2012; Nordhaus, 2015) and initiatives exist for certain sectors and/or gases.[14] Note that we cannot make an assessment about the stability of such a *coalition of the willing* with the theoretical framework applied here. In contrast to a proposed global agreement under the UNFCCC, there are no clearly defined members of a climate club. This means that free-riding incentives exist and each country would try to be on the outside of a preferably large club. Such games should therefore be analyzed using a different theoretical framework such as e.g. the internal and external stability concept.

Although our pessimistic result might seem to be caused solely by the ANZ region, the effects driving the result might be more impactful than the model is able to depict. Take the Fossil Fuel Exporters region, which also experiences large economic effects from global emission reductions. However, it does not cause a blocking partition, because it has the second highest damages of all regions and therefore benefits from global cooperation. However, the high damage estimate for this region is largely driven by the Middle East and North Africa and might not apply to Russia and other Former Soviet Union countries. These countries with high economic losses from global emission reduction measures and low climate damages might cause further blocking partitions in a model with higher regional disaggregation.

14. For example, the REDD+ Partnership supports measures to reduce emissions from deforestation, and the Climate and Clean Air Coalition is focused on short-lived GHGs. See Weischer et al. (2012) for an overview of climate clubs.

Nevertheless, our model implies that high gains from cooperation reduce blocking incentives and make a stable global agreement seem possible. Therefore, the promotion of the positive effects of emission reduction measures and further research in this area might improve the prospects of a global agreement.

5. CONCLUSIONS

We argue that a main weakness of earlier analyses on coalition stability stems from the fact that consumption functions are usually assumed to depend on domestic reductions only, while this is clearly not the case in a globalized world. Therefore, we extend the model by Chander and Tulkens (1995, 1997) to include international macroeconomic effects of emission reduction measures in multiple regions and quantify the new value function by applying two models, the DART model and the RICE model.

Contrary to the original theoretical paper and previous numerical applications, we find that, under the assumption that climate damages are in the IPCC range, the grand coalition in this setting is not stable. In the best partition of our default damages scenario, Japan and the fossil fuel exporting region Australia / New Zealand act as singletons, while a *coalition of the willing* of the remaining regions agrees on a joint emission reduction target. Australia / New Zealand stands to lose a substantial part of its fossil fuel export revenue, if global emission reduction measures are implemented and fossil fuel prices fall as a result. Therefore, as long as the region believes that it can block international cooperation by not signing off on a global agreement, it has no incentive to join an agreement, which does not include adequate compensation. This effect is amplified in a scenario with lower damages.

In contrast, under higher damages, no blocking partition exists and a stable global agreement is possible. While the economic effects mentioned above are still apparent, the high gains from cooperation, due to higher damages, outweigh all other effects in this scenario.

Our results point to alternative ways forward, if blocking partitions exist. The *coalition of the willing* of non-blocking countries can make the decision to compensate the blocking regions for their loss of consumption in the case of global cooperation. Such a decision would not be rational from the perspective of a pure benefit-cost analysis based on climate damages avoided and consumption loss, but might be reasonable if other factors such as historic responsibility or risk aversion are included. Alternatively, the *coalition of the willing* could terminate the quest for a global agreement and form a climate club outside of the UNFCCC. If designed properly, such an agreement might include very broad participation (Hovi et al. 2015).

Our model could be improved in a number of ways. It does not include a full feedback of the optimization of emission levels to the consumption side, in the way that integrated assessment models do (Leimbach et al., 2010; Nordhaus, 2010; Bosetti et al., 2013). Also, the model is static, meaning that the decision on the optimal emission level is only taken once. A dynamic version of the model could include decisions each year or every few years (de Zeeuw, 2008). In addition, a higher number of world regions is needed for a detailed analysis of countries' blocking incentives. Furthermore, despite the long time frame, the model does not include uncertainty about the future values of the consumption and damage functions (Dellink and Finus, 2012; Barrett, 2013; Finus and Pintassilgo, 2013). These issues are left for further research.

APPENDIX

Table A1: NPV of Cumulative Baseline Consumption for Each Region in Trillion 2007 US$

Region	Consumption (NPV)
NAM	1,471.4
EUR	1,110.4
ANZ	69.2
JPN	176.4
EXP	850.8
CHN	845.3
IND	630.1
ROW	2,557.7
Global	7,711.1

Table A2: Core-stable Imputation in the High Damages Scenario, in Utility Loss (NPV, Trillion 2007 US$)

Region	Allocated amount
NAM	39.90
EUR	33.56
ANZ	0.64
JPN	3.35
EXP	58.99
CHN	27.42
IND	10.97
ROW	278.27

Note: the imputation was found by manual allocation of the surplus of the grand coalition, beginning with the "All Singletons" case and adjustment based on coalitions with an incentive to deviate. It is just one example of infinitely many core-stable imputations of this game.

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