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The Role of Proactive Adaptation in International Climate Change Mitigation Agreements

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Abstract

This paper investigates the role of proactive adaptation in international mitigation coalition formation. Adaptation is introduced into a three stage cartel game of coalition formation. We analytically derive the optimal level of mitigation and proactive adaptation for the singletons and coalition members. We introduce the AD-STACO model which is constructed based on the STACO model, which is an applied three-stage cartel formation model with 12 heterogenous regions. Simulating all possible coalitions (4084) and checking for internal and external stability, we investigate how different levels of proactive adaptation will affect the payoffs in Grand coalition and the incentives to freeride. We examine which stable coalitions are found with different levels of proactive adaptation and whether regions can gain from overadaptation in the best performing stable coalition. We find that though payoffs increase in the Grand coalition with lower adaptation, incentives to leave increase. Coalition members can increase their payoffs through overadaptation.

1 Introduction

Game theoretical analyses are used to study the formation and stability of International Environmental Agreements (IEAS) on climate change. In this analysis we apply non-cooperative game theory, assuming that regions act in rational self-interest and there is no supranational authority to impose obligations on regions. An agreement needs to be *self-enforcing* (McEvoy and Stranlund 2009) to be successful (Hoel 1992). A self enforcing agreement should be stable. A coalition is considered stable if it adheres to both internal and external stability (d'Aspremont et al. 1983; Barrett 1994; Hoel 1992). Internal stability holds when no member region within the coalition wishes to leave the coalition. External stability holds when no non-member region outside the coalition wishes to join the coalition. In the literature it is found that only small coalitions or coalitions with few benefits are stable.

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IEAs focus on mitigation. Through adaptation, however, regions can also decrease the level of climate change damages they face. Through adjustments in social or economic systems regions can moderate potential damages or benefit from opportunities associated with climate change (Smit et al. 2001). An important difference between these two measures is that mitigation is a public good whereas adaptation is a private good.

In the literature on IEAs adaptation is not explicitly considered, but implicitly included in the damage function; or not considered at all. In fact, the only cases where it is mentioned are in Barrett (2008) and Zehaie (2009). Barrett assumes that players first choose whether or not to join a coalition after which they set their adaptation levels. As adaptation is chosen after the coalition formation process it will have no effect on the process as any threats of higher (or lower) levels of adaptation will not be credible.

Zehaie (2009) studies the strategic role of adaptation in a two-stage two-player model where regions in the first stage of the game invest in adaptation and in the second stage choose their mitigation levels. He finds that adaptation can have a strategic role when the two regions do not cooperate and when the two regions cooperate on mitigation only. Increased irreversible investments in adaptation in one region decreases the need for mitigation in that region, increasing the level of mitigation in the second region. There are several limitations to the Zehaie (2009)'s study. Firstly, he only considers two regions, whereas any climate coalition would include many players. Secondly, he does not consider how adaptation will affect the coalition formation and stability. Thirdly, he does not consider a sharing rule for the benefits of the mitigation cooperation. Fourthly, though he can show theoretically that adaptation can have a strategic effect, whether this is in fact possible in practice remains undetermined. For overinvestment of proactive adaptation to be worthwhile the benefits need to outweigh the costs. Parameter estimates of adaptation and mitigation costs and benefits are needed to understand if in fact adaptation can strategically affect mitigation choices. Finally, Zehaie, like Barrett, treats adaptation as a homogeneous issue, without considering the varying forms of adaptation and the roles they can play. In this paper we address these issues.

Based on their timing, adaptation measures can be categorised as either proactive (*anticipatory*) or *reactive*. Proactive adaptation refers to adaptation measures taken before climate change occurs. These measures are often large scale and irreversible. Reactive adaptation takes place in reaction to climate change where costs and benefits are felt simultaneously. To illustrate these different forms of adaptation we use an example. Heat and droughts associated with climate change will cause increasing amounts of crops to fail. To limit the losses both reactive and anticipatory adaptation can be applied. Reactive adaptation options include using more water (where irrigation systems are in place), changes to other more heat resistant crop types or changing the planting times of the crops. Proactive adaptation measures include investments in irrigation systems or investments in the development of different more heat resistant crop types. Adaptation investments which are irreversible, such as proactive adaptation, limit the amount of climate change damages for a region far into the future. An adaptation capital is built up of which the benefits will be reaped in the future. Such an investment changes the damages of climate change for a region thereby changing its business as usual damages and mitigation level. This may give a region a strategic advantage in an IEA game.

Adaptation as described in Barrett (2008) that takes place after the coalition formation process or can be adjusted after the formation process is comparable to reactive adaptation. Irreversible adaptation investments as described in Zehaie (2009) are comparable to the proactive (stock) adaptation. We distinguish between these two forms of adaptation in our analysis of mitigation coalition formation. Reactive adaptation will have no effects on the coalition formation process and we can implicitly include this adaptation in the damage function.

We present a three-stage non-cooperative cartel game of coalition formation, where in the first stage the level of proactive adaptation is chosen. In the second stage (the coalition formation stage) regions choose whether to join a unique coalition or not. The third stage of the game is a transboundary mitigation game, where mitigation and reactive adaptation levels are set to maximise pay-offs. In this stage the coalition acts as a single player maximising coalition benefits. The model can then be solved for the optimal levels of proactive adaptation and mitigation using backward induction. An analytic solution can, however, only be found given a coalition.

We, therefore, introduce an applied model (AD-STACO) which incorporates adaptation into the existing STACO model. This model checks all possible coalitions (4084) between 12 geo-political regions for external and internal stability to find stable coalitions. We use this model to examine the effects of different levels of proactive adaptation. Regions will need to set their level of adaptation beforehand without the knowledge of which coalition will be formed. Thus, though the model does not include uncertainty there is uncertainty over which coalition will form.

Applying AD-STACO, we first study what effects the different levels of adaptation will have on the incentives to withdraw from the Grand Coalition (GC) . Secondly, we study the best performing stable coalition and investigate whether over-adaptation or under-adaptation by a single region can be used to increase its payoffs.

In the second section we introduce our three-stage game theoretical model. Using backward induction the optimal level of proactive adaptation and mitigation are found for both coalition members and non-members. In the third section a numerical model (AD-STACO) is introduced which incorporates adaptation into the existing STACO model. The fourth section presents our results and the final section concludes.

2 Model

In this paper, we interpret IEA formation as a coalitional game between heterogeneous regions. We model this interaction as an extensive form game played in three stages. In the first stage regions choose their proactive adaptation levels simultaneously. Given this in the second stage regions choose whether to join a coalition or not. Here coalition is understood as a binding agreement, where multi-coalitions are not possible. In the final stage regions set their mitigation levels. The three stages are referred to as:

1. Proactive adaptation stage (protection)

2. Coalition formation stage (ratification)

3. Transboundary pollution game (mitigation)

There is a finite set of players (regions) $|N| \geq 3$. If there is a coalition with signatories, $S \subseteq N$, if there is no coalition, $S = \emptyset$. Regions are denoted by i where $i \in N$.

If a region acts as a singleton it maximises its individual net benefits, i.e. minimises the sum of its individual climate change damages, adaptation costs and mitigation costs. Signatories maximise joint net benefits of all agreement members. As the coalition acts as one player and as all singletons are individual players there are $|N| - |S| + 1$ players in the transboundary pollution game. By using backward induction we can analyse our three-stage game. Therefore, the stages of our game will be described backwards.

Stage 3: The transboundary pollution game In this stage the levels of proactive adaptation p_i are fixed and the agreement of stage 2 has become binding for the signatories $S \subseteq N$. Each player i then sets its level of mitigation q_i simultaneously, where $q_i \in [0, \bar{e}_i]$, where $\bar{e}_i$ is the regional business as usual (BAU) emissions. The mitigation benefits for each player depend on the total level of global mitigation. Where total mitigation is given as the sum of all individual mitigation efforts; $q = \sum_{i \in N} q_i$. Climate change costs consist of the sum of residual damages, adaptation costs and mitigation costs. The residual damages (which implicitly include optimal reactive adaptation) are given by: $D_i(q, p_i) = d_i \cdot (\bar{e} - q) \cdot (1 - p_i)$, where $\bar{e}$ represents the business as usual level of global emissions, p_i denotes the individual level of proactive adaptation ($p_i \in [0, 1]$), and $d_i > 0$ is a parameter that represents the marginal damages of climate change. Proactive adaptation decreases the regional damages of climate change. Proactive adaptation can therefore decrease the benefits of mitigation and vice versa; increased mitigation decreases the marginal benefits of adaptation. Proactive adaptation levels are given in this stage as they are set in the first stage of the game. The associated adaptation costs are region specific and (strictly) convex and assumed to be $PC_i = \frac{1}{2} \cdot a_i \cdot p_i^2$, where $a_i > 0$. The costs associated with mitigation also vary between regions and are denoted by $MC_i = \frac{1}{2} \cdot m_i \cdot q_i^2$, where $m_i > 0$.

The benefits of adaptation and mitigation are the avoided damages, which are given as the BAU damages minus the actual damages, assuming that in the BAU case proactive adaptation is zero and no mitigation measures are taken. We can now write the payoffs of each player i of climate change policies:

$$\begin{aligned} W_i(q, p_i) &= B_i(q, p_i) - MC_i(q_i) - PC_i(p_i) \\ &= d_i \cdot (\bar{e}) - d_i \cdot (\bar{e} - q) \cdot (1 - p_i) - \tfrac{1}{2} \cdot m_i \cdot q_i^2 - \tfrac{1}{2} \cdot a_i \cdot p_i^2 \end{aligned} \quad (1)$$

The payoffs to each player (the coalition and the non-signatories) are a function of the unique coalition formed. Each coalition is associated with a unique optimal level of proactive adaptation and mitigation for each player. We can now restate the payoffs of abatement and adaptation ($W_i(q, p_i)$ from equation 1) as a function of the coalition formed. Here we assume that optimal mitigation levels are adopted as these are a function of the coalition formed. We find the payoffs as a function of others and regional mitigation for non-signatories :

$$V_i(S) = d_i \cdot (\bar{e}) - d_i \cdot (\bar{e} - q^*(S)) \cdot (1 - p_i^*(S)) - \frac{1}{2} \cdot m_i \cdot q_i^*(S)^2 - \frac{1}{2} \cdot a_i \cdot p_i^*(S)^2. \quad (2)$$

The coalition payoffs represents the value of the coalition, i.e. the sum of climate policy benefits minus policy costs over all coalition member regions:

$$V_S(S) = \sum_{i \in S} V_i(S). \quad (3)$$

In our model the gains of the coalition are shared among its members using the optimal sharing rule as proposed by Weikard (2009). We use a sharing rule where the coalition benefits are shared according to each region's benefits if they choose not to join the coalition, i.e.

$$V_i = \frac{V_i(S_{-i})}{\sum_{j\in S} V_j(S_{-j})} \cdot V_S. \tag{4}$$

Here there is a coalition S with members j. Member i chooses to join the coalition or not. If the region i chooses to leave, the coalition left is denoted as S_{-i}. The benefits region i would receive outside the coalition are denoted as $V_i(S_{-i})$. Hence the larger a region's outside option, the larger its share of coalition payoffs will be.

An optimal sharing rule will guarantee internal stability of a coalition whenever that is at all feasible, i.e. whenever the coalition payoff equals or exceeds the sum of the outside option payoffs. If a coalition is internally stable under some arbitrary sharing rule, then it is stable under an optimal sharing rule (Eyckmans and Finus 2004; Weikard 2009). For this reason we apply an optimal sharing rule.

Stage 2: Coalition formation stage The second stage of the game is the coalition formation stage. Each region $i \in N$ has a choice to either join a unique IEA or not, as any player may join this game, it is an open membership game. Each region i thus has a binary strategy space; $\sigma_i \in \{0,1\}$. $\sigma_i = 1$ implies a choice to join the unique IEA; $\sigma_i = 0$ implies the choice to not join.

Stage 1: Proactive adaptation stage In the first stage regions set their levels of proactive adaptation affecting their benefits function by reducing the gross damages associated with a certain level of climate change and hence mitigation. Here p_i represents the amount of adaptation in an individual region as a fraction of damages reduced by adaptation and $p_i \in [0,1]$. In this stage each region i, chooses a level of investment in proactive adaptation that maximises its own benefits given the expected actions by others.

3 Analysis of Optimal Proactive Adaptation in Mitigation Strategies

Stage 3 We first look at the last stage of the game, where the mitigation level is chosen. As the level of proactive adaptation is chosen in the first stage, a level mitigation can be chosen in the third stage given the level of proactive adaptation. In the final stage a region is either a singleton or a coalition member, depending on its choice in the second stage. We will first discuss the case of a singleton.

A singleton maximises its own benefits given the level of others mitigation. In that case q_i is chosen to maximise V_i, which is given as the benefits of climate change policies (adaptation and mitigation) minus the costs. This is given by Equation 1:

$$W_i(p_i, q) = d_i \cdot (\bar{e}) - d_i \cdot (\bar{e} - q) \cdot (1 - p_i) - \frac{1}{2} \cdot m_i \cdot q_i^2 - \frac{1}{2} \cdot a_i \cdot p_i^2. \tag{1}$$

In the last stage of the game a level of mitigation q_i is chosen given the level of adaptation chosen in the first stage. Note that we do not consider coalition formation just now, i.e. the coalition S is given at this stage. The optimal level of mitigation for a singleton in the third stage for a given level of proactive adaptation can then be derived using the first order condition:

$$\frac{\partial W_i}{\partial q_i} = d_i \cdot (1 - p_i) - m_i \cdot q_i = 0, \qquad i \notin S. \tag{5}$$

Here $d_i \cdot (1-p_i)$ represent the marginal benefits of mitigation, i.e. the avoided marginal residual damages and $m_i \cdot q_i$ represents the marginal costs. The marginal benefits of mitigation are thus decreasing in the level of proactive adaptation. The optimal level of mitigation is given by:

$$q_i^* = \frac{d_i}{m_i} \cdot (1-p_i), \qquad i \notin S. \tag{6}$$

Equation 6 states that, for singletons, every level of proactive adaptation chosen in the first stage is associated with a particular level of optimal mitigation chosen in the third stage. Furthermore the level of mitigation increases with the damage parameter d_i and decreases with the costs of mitigation m_i and the level of proactive mitigation p_i.

When a region is a coalition member it will choose its mitigation level as to maximise coalition payoffs. These benefits are given as the sum of the individual benefits of all coalition members:

$$\begin{aligned} W_S(q,p) &= \textstyle\sum_{i\in S} W_i(q,p_i) \\ &= \textstyle\sum_{i\in S} \left(d_i \cdot p_i \cdot \bar{e} - d_i \cdot q_i \cdot (1-p_i)\right) \quad - \sum_{i\in S}\left(\frac{1}{2}\cdot m_i \cdot q_i^2\right) - \sum_{i\in S}\left(\frac{1}{2}\cdot a_i \cdot p_i^2\right). \end{aligned} \tag{7}$$

Maximising this with respect to regional abatement we find;

$$\frac{\partial W_s}{\partial q_i} = \sum_{j\in S}\Big(d_j \cdot (1-p_j)\Big) - m_i \cdot q_i = 0, \tag{8}$$

$$q_i^* = \frac{\sum_{j\in S} d_j \cdot (1-p_j)}{m_i} = \frac{\sum_{j\in S\setminus\{i\}} d_j \cdot (1-p_j)}{m_i} + \frac{d_i \cdot (1-p_i)}{m_i}. \tag{9}$$

Comparing equations 6 and 9, we can see that the optimal level of mitigation of a coalition member will be higher than for the singleton. In the singleton case only the benefits of mitigation (avoided damages) to the singleton were considered. In the case of the coalition member the benefits to all other coalition members are considered in addition. Furthermore, the optimal level of mitigation for a coalition member will increase in the coalition size.

Stage 2 In the coalition formation stage a Nash equilibrium is given by a vector of ratification decisions $(\sigma_i)_{i\in N}$ such that no single region would prefer to change its decision. A coalition S a stable coalition if the strategy profile $(\sigma_i)_{i\in N}$ that corresponds to S is a Nash equilibrium. A coalition is stable if it is both internally and externally stable (d'Aspremont et al. 1983). A coalition is internally stable if and only if for all $i \in S$ it holds that $V_i(S) \geq V_i(S_{-i})$ and externally stable if $V_j(S) \geq V_j(S_{+j})$. Given the large number of asymmetric regions in this game, the number of possible coalitions is large. We cannot derive analytically for each coalition whether it is stable or not, but will use our applied model in Section 4. We move on to the first stage of the game and solve the model for a given coalition.

Stage 1 Now we can turn to the first stage of the game to find the optimal level of proactive adaptation. A region's optimal level of proactive adaptation will depend on two factors, firstly the global level of mitigation and secondly whether and in which coalition the region will be. Hence for each coalition there is a unique optimal level of adaptation for members and non-members. As the agreement only refers to mitigation decisions, in the adaptation decision in the first stage, each region will maximise its own benefits. At this stage there are no obligations to other (future) members of the coalition. We first assume that mitigation in the third stage is given, later we define the level of mitigation for each coalition, in terms of the level of proactive adaptation.

Optimising equation 1 with respect to the level of proactive adaptation leads to the optimal level for singletons:

$$\frac{\partial W_i}{\partial p_i} = d_i(\bar{e}-q) - a \cdot p_i = 0, \qquad i \notin S. \tag{10}$$

$$p_i^*(S) = \frac{d_i(\bar{e}-q)}{a_i}, \qquad i \notin S. \tag{11}$$

However when a region is a coalition member its level of proactive adaptation will affect the value of the coalition as well as the regions share of the coalition benefit. A coalition member's share of the coalition value is given by $V_k(S)$, this was defined in Equation 3. The coalition member will set his proactive adaptation level to maximise this. Hence, the following first order condition must hold:

$$\frac{\partial W_k(S)}{\partial p_k} = \frac{\partial V(S)}{\partial p_k} \cdot \frac{\partial \left(\frac{V_k(S_{-k})}{\sum_{j\in S} V_j(S_{-j})} \right)}{\partial p_k} = 0, \qquad k \in S. \tag{12}$$

Assuming:

$$\frac{\partial \sum_{j\in S} V_j(S_{-j})}{\partial p_k} = 0, \tag{13}$$

we have:

$$\frac{\partial V(S)}{\partial p_k} \cdot \frac{\partial V_k(S_{-k})}{\partial p_k} \cdot \frac{1}{\sum_{j\in S} V_j(S_{-j})} = 0. \tag{14}$$

furthermore:

$$\frac{\partial V(S)}{\partial p_k} = \frac{\partial \sum_{j\in S} V_j(S)}{\partial p_k} + \frac{\partial V_k(S)}{\partial p_k} \tag{15}$$

$$\frac{\partial V_k(S)}{\partial p_k} = d_k \cdot \bar{e} - d_k \cdot q(S) - a_k \cdot p_k \tag{16}$$

$$\frac{\partial \sum_{j\in S} V_j(S)}{\partial p_k} = \frac{\partial \sum_{j\in S} V_j(S)}{\partial q} \cdot \frac{\partial q}{\partial p_k} = \sum_{j\in S} d_j(1-p_j) \cdot -\frac{d_k}{m_j} \tag{17}$$

Resulting in:

$$\frac{\partial W_k(S)}{\partial p_k} = \left(d_k \cdot \bar{e} - d_k \cdot q_S - a_k \cdot p_k + \sum_{j\in S} d_j(1-p_j) \cdot -\frac{d_k}{m_j} \right) \cdot (d_k \cdot \bar{e} - d_k \cdot q_{S-k} - a_k \cdot p_k) = 0. \tag{18}$$

$$p_k^* = \frac{\left(\sum_{j\in S} d_j(1-p_j) \cdot \frac{-1}{m_j} \right) \cdot (d_k \cdot \bar{e} - d_k \cdot q_{S-k} - 1)}{a_k \cdot d_k \cdot \bar{e} \cdot q_{S-k}} + \frac{d_k \cdot q_S - d_k \cdot \bar{e}}{a_k} \tag{19}$$

Where q_S is the total level of emissions, given the coalition S, which can be written in terms of p_i, where regions denoted by f are singletons and regions denoted by j are coalition members.

$$q_S^* = \sum_{f\in N\setminus\{S\}} \frac{d_f}{m_f} \cdot (1-p_f) + \sum_{j\in S} \frac{\sum_{j\in S} d_j \cdot (1-p_j)}{m_j} \tag{20}$$

$$q^*_{S-k} = \sum_{f \in N \setminus \{S\}} \frac{d_f}{m_f} \cdot (1 - p_f) + \sum_{j \in S \setminus \{k\}} \frac{\sum_{j \in S} d_j \cdot (1 - p_j)}{m_j} \tag{21}$$

Thus we find a unique level of proactive adaptation given the other regions' levels of proactive adaptation for both the singleton and coalition member in a specific coalition. This problem is too complex to study further in an analytical framework. Hence we develop the AD-STACO model in the next section to run empirical simulations of coalitions.

4 The AD-STACO Model

The original STACO model consists of a two-stage, non-cooperative game of coalition formation. The AD-STACO model adds an additional stage to the STACO model which takes place before the two stages of STACO. These three stages are in essence identical to those described in Section 3. This first stage is the proactive adaptation stage where a level of proactive adaptation is chosen based on the expectation of which coalition will form. Investments in adaptation will decrease the residual damages associated with climate change in the future. The second stage is the coalition formation stage and the third the trans-boundary pollution game.

The welfare of the regions in the model is based on a payoff function, which represents the discounted net benefits from mitigation (i.e. mitigation efforts) and adaptation over the model horizon. We assume that undiscounted benefits in each period depend not only on the current global mitigation level but also on global mitigation in previous periods through reduced concentrations of CO_2 and correspondingly lower gross damage levels; in contrast, mitigation costs only depend on current mitigation levels within the region. The level of proactive adaptation is set in the first stage but the costs and benefits of adaptation are felt each period throughout the planning horizon.

We refer to the situation where none of the regions choose to join the coalition as "All Singletons;" (AS) the associated optimal mitigation paths are an open loop Nash equilibrium. In the "Grand Coalition,Ä (GC)ù, all regions cooperate and global marginal mitigation costs and benefits are equated achieving the social optimum. If no region can receive a higher payoff by diverging, i.e. by unilaterally changing its strategy, the coalition structure is called stable. Thus a coalition is stable if it adheres to internal stability and externally stability.

Emission permit trading is incorporated in the model to allow for transfers among regions in the coalition, such that emission permits can be traded only among signatories. The transfers imply that if a region reduces its emissions more than required for achieving the assigned emission permit level, the region can sell permits to other signatories. The price of a permit is endogenous and equals marginal mitigation costs (as a result of the cost-benefit analysis). Emission trading in the model ensures that the global optimum will be achieved and creates a tool to incorporate the sharing rule of a coalition. We apply two different allocation schemes:

1. No permit trading, where each year the distribution of permits follows from the actual emissions; i.e. no transfers are allowed.

2. Incentive allocation, where permits are allocated according to an "optimal" transfer scheme that maximises potential participation in the international agreement (Carraro et al. 2006; Fuentes-Albero and Rubio 2010; McGinty 2007; Weikard 2009).[1]

4.0.1 Calibration of the AD-STACO Model

The original STACO model was introduced in Finus et al. (2006) and has been updated and extended to a forward-looking specification by Nagashima et al. (2009). A detailed description of the specification of the STACO model is given in Dellink et al. (2009). The STACO model includes twelve world regions; USA (USA), Japan (JPN), European Union - 15 (EU15), other OECD regions (OOE), Eastern European regions (EET), former Soviet Union (FSU), energy exporting regions (EEX), China (CHN), India (IND), dynamic Asian economies (DAE), Brazil (BRA) and the rest of the world (ROW). The planning horizon in the model consists of 100 years, ranging from 2011 to 2110. This ensures a proper reflection of the long-term aspects of climate change, while the period for which the international agreement holds is limited. Essentially, in 2010 the signatories strike an agreement that sets their mitigation path until 2110, while taking into account all future benefits and costs from that mitigation path. Future costs and benefits are discounted at a regional discount rate, based on region-specific GDP growth rates and a pure rate of time preference that is assumed to be equal across regions (cf. the Ramsey rule). Data from the EPPA model (Paltsev et al. 2005) is used to calibrate regional BAU emission and GDP paths in the STACO model.

Benefits from mitigation represent avoided damages, which in turn depend on global atmospheric temperature change. The climate system is approximated by a linear system of three equations (for concentrations, radiative forcing and atmospheric temperature increase, respectively) assuming exogenous forcing from non-CO_2 greenhouse gases and ignoring the non-linear feedbacks between the atmosphere and the oceans. The original damage function is calibrated such that global damages are calibrated separately from regional damage shares. This is not restrictive given the assumption in STACO of linear benefits and it allows for the direct calibration of marginal global benefits from mitigation, for which much better information exists than for regional damage estimates (Nordhaus 2008). The mitigation cost function follows estimates of the EPPA model by Ellerman and Decaux (1998).

Furthermore, exogenous technological progress is assumed implying an annual reduction of marginal mitigation costs that is relatively small for the developed regions (USA, JPN, EU15, OOE, EET, FSU) and twice as high for the other regions; this provides an approximation of the reduction in marginal mitigation costs between 2010 and 2050 as projected by Morris et al. (2008).

The AD-STACO model recalibrates the STACO damage function into a damage function consisting of two forms of damages. The model equations of AD-STACO are given in the appendix. We assume there are damages that can be combated through proactive adaptation and damages that can be combated by reactive adaptation. The net damages in the STACO model are split into stock (proactive) damages and flow (reactive) damages based on the empirical assessment of Agrawala et al. (2010). As reactive adaptation has

[1] The incentive-based grandfathering scheme distributes emission permits proportional to the outside option payoff as described in Equation 3.

Region	v_1	Gross stock damages	Net flow damages	AS adaptation level	GC adaptation level
USA	0.88	0.42	0.64	0.39	0.37
JPN	1.15	0.74	0.41	0.52	0.50
EU15	1.01	0.47	0.57	0.38	0.36
OOE	0.57	0.31	0.71	0.45	0.42
EET	0.43	0.27	0.77	0.52	0.49
FSU	0.42	0.21	0.81	0.40	0.38
EEX	0.68	0.33	0.69	0.39	0.38
CHN	0.97	0.43	0.60	0.36	0.35
IND	1.53	0.47	0.55	0.25	0.24
DAE	1.28	0.47	0.55	0.30	0.29
BRA	0.77	0.39	0.66	0.41	0.39
ROW	1.21	0.44	0.64	0.30	0.29

Table 1: Parameter values of AD-RICE, where the cost and benefit parameters are given as a fraction of the original net damages

no effect on the coalition formation process, this form adaptation can be implicitly included in the damage function. As we have shown in de Bruin et al. (2009a) and de Bruin et al. (2009b). this will not affect the mitigation decision in a first best world. Hence the flow damage part of the damage function represents the net flow damages assuming optimal flow adaptation. The stock part of the damage function is given by the stock gross damages which can be reduced through proactive adaptation. The level of proactive adaptation is set in the first period for all periods, the costs and benefits of which are felt in each period of the planning horizon. The costs and benefits of proactive adaptation are calibrated based on the empirical estimates of AGA where each region has a unique proactive adaptation potential and adaptation cost function. We assume a quadratic proactive adaptation cost function for each region; $pc_{it}(p_{it}) = a_{1i} \cdot p_{it}^2$.

Table 1 gives the adaptation cost parameter estimates for the various regions. In this paper we focus on three levels of adaptation, which we refer to as AS adaptation, GC adaptation and no adaptation. These levels refer to the optimal level of proactive adaptation in the All Singletons case and the optimal proactive adaptation level in the Grand Coalition case. Both these levels are presented in Table 1. These levels of optimal adaptation refer to the optimal levels assuming there are no strategic advantages of proactive adaptation by coalition members.

5 Results

5.1 Analysis of the Grand Coalition

The chosen level of proactive adaptation will affect the payoffs of regions in the GC and the incentives of regions to remain in the GC. We examine two (extreme) levels of proactive adaptation, in which all regions choose the same level of adaptation. Firstly, assuming that all regions simultaneously choose the AS level of proactive adaptation, i.e. the optimal level of proactive adaptation given that no coalition will form (AS).

This is the highest credible level of adaptation as it coincides with the adaptation level associated with the highest possible temperature in the model, i.e. the temperature when there is no mitigation cooperation. Secondly, assuming that all regions simultaneously set their level of proactive adaptation at the GC level, i.e. the optimal level given the formation of the GC. This is the lowest credible level of proactive adaptation as it coincides with the lowest temperature in the model (when there is global cooperation in mitigation).

Table 2 shows the difference in payoffs between the Grand Coalition and the All Singletons case for each region with optimal transfers and with no transfers. A positive number in the table entails that a region is better off in the Grand Coalition than in the case of All Singletons.

Region	GC adaptation no transfers	AS adaptation no transfers	GC adaptation optimal transfers	AS adaptation optimal transfers
USA	7021	6996	6067	6052
JPN	8495	8449	7230	7212
EU15	7985	7946	6591	6571
OOE	865	863	932	929
EET	183	185	357	356
FSU	1622	1619	1718	1713
EEX	470	472	714	712
CHN	-753	-724	1267	1268
IND	754	757	1035	1033
DAE	413	415	621	620
BRA	439	438	402	400
ROW	1635	1632	1723	1717
Global	29130	29048	28657	28583

Table 2: Payoffs in the Grand Coalition with optimal transfers and without transfers in NPV over the time horizon (100 years) in billion US

When there are no transfers between regions, two regions are not better off in the Grand Coalition compared to no coalition. These regions are EET and CHN. As these regions have low marginal abatement costs they will have high levels of mitigation in the Grand Coalition. When no transfers take place these regions cannot be compensated for their high levels of mitigation by other regions. In the case of no transfers some regions have a higher gains from the Grand Coalition when adapting at the GC level compared to AS level the and others not. The regions that are worse off when GC adaptation is chosen are EET, CHN, EEX and DAE. These regions have relatively low marginal abatement costs and hence in the Grand Coalition, these regions will have high abatement levels to compensate other regions' damages. If regions over-adapt, by applying the AS level of adaptation, their damages will decrease resulting in a lower optimal level of global abatement. Hence low abatement cost regions are better off when all regions over-adapt. In the case of optimal transfers all regions are better off in the Grand Coalition GC adaptation is globally optimal.

When regions choose to adapt at the AS level, the difference in payoffs between the Grand Coalition and All Singletons case decreases. This is a logical consequence as the payoffs in the All singletons case are maximised when AS adaptation is applied and the Grand coalition payoffs are maximised when GC adaptation is applied.

Region	GC adaptation no transfers	AS adaptation no transfers	GC adaptation optimal transfers	AS adaptation optimal transfers
USA	-22	-26	933	919
JPN	-161	-151	1105	1086
EU15	-377	-374	1017	1001
OOE	212	209	144	142
EET	230	226	55	55
FSU	362	356	266	262
EEX	353	348	110	108
CHN	2212	2182	192	190
IND	439	432	158	156
DAE	304	299	96	94
BRA	24	23	62	61
ROW	354	347	266	262

Table 3: The incentives of regions to withdraw from the GC, in NPV over the time horizon (100 years) in billion US$

The incentive of a region to withdraw from the GC is given by the difference between a regions outside option payoffs and its GC payoffs. These incentives are given in Table 3. In the case of no transfers, the payoffs of USA, JPN and EU15 are higher in the GC, than in their outside options (i.e. have negative incentive to withdraw); all others are better off withdrawing. The coalition surplus is thus not large enough to pay all regions their outside option payoff, making the GC unstable. JPN and EU15 have lower incentives to stay in the GC when AS adaptation is applied than when GC adaptation is chosen. This is due to the decreased abatement under GC adaptation, leading to lower payoffs for these regions in the GC. These regions both have high damage levels and would benefit in a coalition without transfers, where they would not have to compensate other regions for their mitigation efforts. Other regions have a higher incentive to remain in the GC when AS adaptation is applied as this results in lower mitigation commitments in the GC for these regions. In the case of optimal transfers, a lower level of proactive adaptation (GC adaptation) will lead to higher abatement commitments in the GC. This, in turn, increases the free rider incentives of regions and hence the incentives of regions to withdraw from the coalition. Even though all regions unanimously prefer the GC level of adaptation in the GC (per definition), applying GC adaptation will in fact increase the incentives of regions to withdraw from the coalition.

5.1.1 Analysis of Stable Coalitions

The stable coalitions that form will depend on the level of proactive adaptation chosen in the first stage. Here we compare the stable coalitions found when regions simultaneously and uniformly set their proactive adaptation at either AS or GC levels. We only examine the case of optimal transfers. The ten best performing coalitions are given in 4. The performance of a coalition is measured by the NPV of global payoff increases as compared to the AS case. This is given as a percentage of gains from cooperation, i.e. global payoffs in excess of the All Singletons global payoff. The best performing stable coalition found in

AD-STACO[2] is the coalition between USA, EET, CHN, IND and DAE achieving some 48% of NPV of the gains of the Grand Coalition. This coalition is stable when either AS adaptation or GC adaptation. All of the ten best performing coalitions include either CHN, EU15 or USA, these being the regions who contribute the most to the gains from the cooperation (see Table 2). These mayor players form a coalition with other regions (e.g. EET, EEX, IND, DAE, ROW, FSU,OOE) and compensate them for their mitigation efforts.

USA, EET, CHN, IND, DAE (48%)
EU15, EET, CHN, IND, DAE (47%)
USA, EET, EEX, CHN, DAE, BRA (46%)
USA, CHN, IND, BRA (45%)
USA, EEX, CHN, IND (44%)
EU15, EET, EEX, CHN, DAE, BRA (44 %)
USA, OOE, EET, EEX, CHN (44%)
EU15, OOE, EEX, CHN, DAE (44%)
USA, FSU, EEX, CHN (43%)
USA, CHN, DAE, ROW (43 %)

Table 4: Ten best performing stable coalitions

GC adaptation	**AS adaptation**
EU15, EET, FSU, EEX, DAE (18%)	JPN, EU15, CHN (35%)
JPN, EET, FSU, EEX (11%)	USA, IND, BRA, ROW (20%)
JPN, EET, EEX, ROW (11%)	EU15, FSU, IND, BRA (13%)
JPN, OOE, EET, DAE, BRA (9%)	JPN, OOE, EET, DAE (8%)
	JPN, OOE, DAE, BRA (6%)
	JPN, OOE, EET, BRA (5%)

Table 5: Unique stable coalitions to the different levels of adaptation, where the performance of the coalition is given between brackets

The stable coalitions that are found with the two levels of adaptation are similar, but there are some differences. When regions choose the AS level of adaptation more stable coalitions form (173 versus 171). This is because as the benefits of cooperation decrease (when more adaptation takes place) they are more likely to be stable (Barrett 1994). However, several stable coalitions form in the case of GC adaptation that do not form in the case of AS adaptation, as GC adaptation increases the damages of regions, increasing their incentives to join a coalition. The stable coalitions unique to each adaptation level, are given in Table 5.

Examining Table 5, we can for example see that the coalition between JPN, OOE, EET and BRA is stable when AS adaptation is applied but not when GC is applied. In contrast, the coalition between JPN, OOE, EET, DAE and BRA is stable with GC adaptation but not when AS adaptation is applied. When adaptation decreases DAE wants to join the coalition between JPN, OOE, EET and BRA making it externally unstable.

[2] Note that in STACO, the best performing coalition is that between EU15, EET, EEX, CHN and IND achieving slightly higher performance than the coalition between USA, EET, CHN, IND and DAE (Nagashima et al. 2009). However, when explicitly including adaptation and setting it at either the GC, AS level or at the level optimal in this specific coalition, this coalition becomes unstable.

This is because as adaptation decreases the damages in DAE increase to such a degree that it becomes worthwhile for DAE to join the coalition. The same is valid for BRA where the coalition between JPN, OOE, EET and DAE becomes externally unstable under GC adaptation as BRA wishes to join it. Furthermore, when adaptation is lower, a coalition is stable between three of the main players, i.e. JPN, EU15 and CHN. This coalition is not internally stable in the GC case as the damage levels in JPN and EU15 are too high, resulting in high levels of mitigation for CHN. CHN has an incentive to leave this coalition and free ride on the others' mitigation. However, when the damages of JPN and EU15 are limited through a higher level of adaptation the coalition becomes beneficial to CHN and hence the coalition is stable in the AS case.

5.2 Analysis of the Best Performing Stable Coalition

To get a better understanding of the strategic role that proactive adaptation can play, we now consider what effects a unilateral divergence of coalition members would have on their payoffs in the best performing stable coalition (the coalition between USA, EET, CHN, IND and DAE). Firstly, we examine the case where regions, when deciding their level of adaptation in the first stage of the game, adapt at the GC level. Secondly, we assume that regions in the first stage expect that no coalition will form and adapt at the AS level.

Diverging region	**Diverging region payoffs**	**Coalition payoffs excluding diverging region**	**Coalition payoffs**	**Singletons' payoffs**	**Global payoffs**
USA*	0.26	-0.15	0.12	-0.09	-0.03
JPN	0.13	*na*	-0.01	0.05	0.03
EU15	0.09	*na*	-0.02	0.02	0.01
OOE	0.12	*na*	0.00	0.00	0.00
EET*	0.12	0.00	0.00	0.00	0.00
FSU	0.14	*na*	0.00	0.01	0.00
EEX	0.18	*na*	0.00	0.00	0.00
CHN*	0.57	-0.03	0.06	-0.02	0.00
IND*	0.36	-0.01	0.03	-0.01	0.00
DAE*	0.25	0.00	0.01	-0.01	0.00
BRA	0.25	*na*	0.00	0.00	0.00
ROW	0.16	*na*	-0.01	0.01	0.00

Table 6: The difference in payoffs in percentage in the case of unilateral over-adaptation (AS by diverger and GC by others) for the best performing coalition, where coalition members are denoted by *

Looking at the first case, i.e. when a singleton unilaterally increases its proactive adaptation to the AS level while the other regions' adaptation remains at the GC level. We refer to this as unilateral over-adaptation. Table 6 presents the changes in payoffs in the best performing stable coalition for the diverging region, for all coalition members excluding the diverging region, for all coalition members, for all singletons and for all regions (global payoffs). Examining the case of unilateral over-adaptation by a singleton, we see that over-adaptation results in higher payoffs for the diverging singleton. The diverging region increases its adaptation level and reduces its mitigation level, while the mitigation of others remains

Diverging region	USA	EET	CHN	IND	DAE
USA	0.15	-0.29	-0.23	-0.30	-0.28
EET	-0.01	0.12	0.00	0.00	0.00
CHN	-0.09	-0.08	0.52	-0.08	-0.08
IND	-0.04	-0.04	-0.03	0.34	-0.04
DAE	-0.02	-0.02	-0.01	-0.02	0.24

Table 7: Percentage change in outside option payoffs due to unilateral over-adaptation (AS by diverger and GC by others)

the same, on balance increasing its payoffs. The payoffs to the other players, and thus also to the coalition decrease as the mitigation level of the diverging region has decreased. The total singletons payoffs increase due to the diverging region's increased payoffs. The total global effect is in most cases negligible, but in the case of larger regions (JPN and EU15) slightly positive. Note that though global payoffs increase in the case of divergence by (JPN and EU15), environmentally the world is worse off as less mitigation is undertaken.

When a coalition member diverges and over-adapts, this region again benefits, for the same reasons as above. The benefits of divergence are, however, larger for coalition members than singletons. By over-adapting a diverging coalition member can increase its outside option payoffs, as shown in Table 7. By increasing its outside option payoffs, it increases its share in the division of the coalitional surplus of coalition members. In this way, due to the sharing rule of the coalition, the diverging region can increase its coalition payoffs. From Table 6 we see that the payoffs of the other coalition members decrease while total coalition payoffs increase. Furthermore, when a coalition member diverges, total singleton payoffs decrease as the mitigation level in the coalition will decrease. In the case of a divergence by USA the negative effect on other regions outweighs the positive effect for USA and the global payoffs decrease. USA is a major player with high damages, increasing its adaptation by diverging will decrease the level of mitigation in the coalition to such a degree that global benefits decrease.

The results for under-adaptation and over-adaptation are symmetric in this specification and coalition.[3] In the case of unilateral under-adaptation, the diverging region sets adaptation at GC while all other regions set their adaptation at the AS level. When a region diverges, its payoffs decrease. As mitigation levels remain the same a reduction in adaptation decreases the diverging region's payoffs. As the diverging region applies more mitigation to compensate for the lower level of adaptation, all other regions benefit.

5.2.1 Sensitivity Analysis

In this section we undertake a sensitivity analysis of our results. We first examine the potential role of strategic over-adaptation. We then set proactive adaptation at the level optimal for singletons in the best

[3] This result is due to the fact that the best performing coalition is roughly halfway between the AS and the GC in terms of gains and our model is linear. Therefore, any diversions from the optimum in either way will have symmetric effects. Thus the unilateral benefits of over-adaptation are the same as the costs of unilateral under-adaptation. Furthermore, the effect on other regions' payoffs is symmetrical.

performing stable coalition (PSC level) and examine what effect that will have on the best performing coalition stability and the results concerning over and under-adaptation.

Diverting region	Diverting region payoffs	Coalition payoffs excluding diverting region	Coalition payoffs	Singletons' payoffs	Global payoffs
USA*			*not stable*		
JPN	-16.35	*na*	-0.11	-6.74	-4.79
EU15	-12.33	*na*	-0.20	-4.29	-3.09
OOE	-9.96	*na*	-0.03	-0.45	-0.33
EET*	-9.84	-0.01	-0.38	-0.06	-0.15
FSU	-6.39	*na*	-0.05	-0.51	-0.37
EEX	-8.28	*na*	-0.04	-0.30	-0.22
CHN*	-6.41	-0.38	-1.25	-0.29	-0.57
IND*	-5.36	-0.10	-0.66	-0.17	-0.32
DAE*	-8.51	-0.03	-0.60	-0.10	-0.25
BRA	-8.09	*na*	0.00	-0.15	-0.11
ROW	-8.23	*na*	-0.09	-0.72	-0.54

Table 8: Differences in payoffs in percentage in the case of unilateral extreme over-adaptation: all regions apply GC adaptation, diverting region applies 150% of AS adaptation, where coalition members are denoted by *

Global	USA*	JPN	EU15	OOE	EET*	FSU	EEX	CHN*	IND*	DAE*	BRA	ROW
-3.27	3.57	-0.67	-13.94	-1.42	-1.32	-1.80	-1.48	-1.10	-1.17	-1.18	-1.34	-1.53

Table 9: Differences in payoffs in percentages between new best performing coalition (with unilateral extreme over-adaptation of US) and original best performing coalition

In Table 8 the payoffs of a unilateral divergence to 150% of the AS level are given. In this case regions over-adapt by a large amount. The extra costs of adaptation outweigh the benefits of increased coalition payoffs and decreased mitigation for most regions. Over-adaptation furthermore will result in lower mitigation levels by the diverting regions, which has a negative effect on the payoffs of all regions. When USA diverges the best performing coalition is no longer stable as the USA has no incentive to join this coalition anymore. The new best performing coalition is then that between EU15, EET, CHN, IND and DAE. The new coalition includes EU15 in the place of USA. Hence the burden of compensating the low mitigation cost regions for their mitigation efforts in the coalition will shift from US to EU15. The differences in payoffs compared to the previous best performing coalition are given in 9. All other regions are worse off due to the decreased level of mitigation, were specifically the EU15 looses with a payoff decrease of 13.9 % .The payoffs for USA increase by nearly 3.6 %. Hence by setting its proactive adaptation level extremely high, the USA can influence the coalition formation process and cause a new best performing coalition to form which is more beneficial to the USA.

The assumption that regions either choose AS or GC adaptation is somewhat ad hoc. We therefore, now look at what the effects are of unilateral divergence when other regions adapt to the level optimal in the best performing coalition. When the level of proactive adaptation is chosen which is optimal for the level of temperature change in the best performing coalition (BSC level), this coalition remains stable, and indeed best performing. This level of proactive adaptation is the level which a singleton would choose given the best performing stable coalition. Hence expecting that the best performing coalition will form and adapting accordingly will result in the best performing stable coalition to indeed be stable. We assume that coalition members set their level of adaptation to be optimal for the degree of temperature change associated with that coalition, i.e. they do not consider the secondary benefits of changes in coalition benefits and their share therein, but choose their adaptation level as a singleton would given this coalition. The rationale for this assumption is that at stage 1, regions cannot be sure which coalition will emerge in stage 2. Again one region at a time diverges to either a higher level of adaptation, AS adaptation or a lower level of adaptation, GC adaptation.

Diverting region	**Diverting region payoffs**	**Coalition payoffs excluding diverting region**	**Coalition payoffs**	**Singletons' payoffs**	**Global payoffs**
USA*	0.06	-0.05	0.02	-0.03	-0.01
JPN	0.01	*na*	0.00	0.00	0.00
EU15	0.01	*na*	-0.01	0.00	0.00
OOE	0.02	*na*	0.00	0.00	0.00
EET*	0.02	0.00	0.00	0.00	0.00
FSU	0.03	*na*	0.00	0.00	0.00
EEX	0.04	*na*	0.00	0.00	0.00
CHN*	0.16	0.00	0.01	-0.01	0.00
IND*	0.10	0.02	0.01	0.00	0.00
DAE*	0.06	0.01	0.00	0.00	0.00
BRA	0.06	*na*	0.00	0.00	0.00
ROW	-0.13	*na*	0.01	-0.01	0.00

Table 10: The difference in payoffs in percentage in the case of unilateral over-adaptation (AS by diverter and PSC by others), where coalition members are denoted by *

Table 11 shows the changes in payoffs when regions unilaterally under-adapt. Here the results do not are similar to the results of Table 5 and of similar magnitude.

In Table 10 the effects on payoffs of unilateral over-adaptation are given, assuming other regions adapt at the best performing stable coalition level. The results for the payoffs of the diverting regions are similar to the previous results of Table 6. However, these effects are smaller as the divergence, i.e. the difference between the divergers' adaptation and the other regions' adaptation is less. Here divergence by a coalition member has ambiguous effects on the payoffs of other coalition members.

Diverting region	Diverting region payoffs	Coalition payoffs excluding diverting region	Coalition payoffs	Singletons' payoffs	Global payoffs
USA*	-0.20	0.10	-0.10	0.06	0.02
JPN	-0.12	*na*	0.01	-0.04	-0.03
EU15	-0.08	*na*	0.01	-0.02	-0.01
OOE	-0.10	*na*	0.00	0.00	0.00
EET*	-0.10	0.00	0.00	0.00	0.00
FSU	-0.11	*na*	0.00	-0.01	0.00
EEX	-0.14	*na*	0.00	0.00	0.00
CHN*	-0.41	0.02	-0.04	0.02	0.00
IND*	-0.27	0.01	-0.02	0.01	0.00
DAE*	-0.19	0.00	-0.01	0.01	0.00
BRA	-0.19	*na*	0.00	0.00	0.00
ROW	-0.13	*na*	0.01	-0.01	0.00

Table 11: The difference in payoffs in percentage in the case of unilateral under-adaptation (GC by diverter and PSC by others), where coalition members are denoted by *

6 Conclusion

This paper investigated the role of proactive adaptation in mitigation coalition formation. Game theory literature has studied the formation and stability of coalitions, but does not include adaptation in these analyses. This paper introduces adaptation into a three stage cartel game of coalition formation. Adaptation can be divided into two categories, namely reactive and proactive (anticipatory) adaptation. Reactive adaptation takes place after climate change occurs and hence any threat of higher or lower levels of adaptation will not be credible. Proactive adaptation, on the other hand, takes place before climate change occurs and before coalition formation and hence can change the payoff function for a region and its position in a coalition. Proactive adaptation may thus have an effect on coalition formation and stability.

In this paper we, firstly, analytically derived the optimal level of mitigation and proactive adaptation for both the singletons and coalition members. We can, however, only determine these levels for a given coalition. We therefore introduced the AD-STACO model which is constructed based on the STACO model but includes a proactive adaptation decision. This model combines game theory and Integrated Assessment Modelling to create an applied three-stage cartel formation model. This model consists of 12 heterogenous regions and simulates all possible coalitions (4084) and checks all coalitions for internal and external stability.

Using AD-STACO we, secondly, investigated how different levels of adaptation will affect the Grand Coalition (where all members join the coalition) payoffs. We first assumed two levels of adaptation for illustrative purposes, namely GC adaptation and AS adaptation. GC adaptation refers to the optimal level of proactive adaptation for singletons associated for singletons with the Grand Coalition temperature path. AS adaptation refers to the level of optimal proactive adaptation in the All Singletons case (i.e. when no coalition is formed). We found that when no transfers take place low abatement cost regions such as CHN and EET will benefit more when all regions adapt at the AS level as opposed to the GC level, whereas other regions do not. The reason is straightforward: with higher adaptation levels these regions have to mitigate less. With optimal transfers the benefits of the Grand Coalition can be shared across regions and low marginal abatement cost regions can be compensated for their high levels of abatement. Hence in the case of optimal transfers all regions are better off when GC adaptation is applied.

Thirdly, the incentives to withdraw from the Grand Coalition were examined. Though payoffs are higher when GC adaptation is applied in the Grand Coalition, incentives to withdraw are also higher than in the AS case. As adaptation decreases, mitigation in the coalition will increase resulting in higher mitigation costs for coalition members and hence higher incentives to withdraw from the Grand Coalition.

Fourthly, we examined how the different levels of proactive adaptation (AS and GC) will affect the stable coalitions formed. We saw that with higher levels of adaptation, the damages of regions are limited, making specific coalitions stable. On the other hand lower levels of adaptation increase damages, giving incentives to certain regions to cooperate whose damages were too low with high adaptation.

Fifthly, we examined the best performing stable coalition and what strategic effect proactive adaptation may have. A coalitions performance is measured in the percentage of the gains from cooperation captured by the coalition. The best performing stable coalition in the AD-STACO model is the coalition between USA, EET, CHN, DAE and IND, achieving 48% of the potential cooperation gains. We investigated the effect of unilateral over-adaptation assuming that all regions adapt at the GC level and one region diverts to the AS level. We saw that diverting regions benefit from this, while all other regions lose (due to the lower mitigation level in the diverting region). Furthermore, the increased benefits of diverging coalition members are higher than those of singletons as a coalition member can increase its outside option payoff by over-adaptation, this in turn increasing its share of the coalition benefits.

When we assumed all regions adapt at the AS level and one coalition member diverts to the GC level, hence under-adapts, we saw the opposite effects: the diverting region loses, and the others all gain. When assuming that the other regions set their level of adaptation to the optimal level for the best performing stable coalition, we saw roughly the same results but the effects were of a smaller magnitude.

Furthermore we found that certain countries can influence the stability of the best performing stable coalition, by going beyond the credible level of adaptation and over-adapting extremely. When USA extremely over-adapts (150% of AS adaptation) the best performing stable coalition is no longer stable and hence will not form. The new best performing stable coalition creates larger benefits for USA, where EU15 takes the place of USA and hence the burden of compensating mitigation efforts by other coalition members. USA can thus extremely over-adapt to ensure the formation of a larger coalition, thereby increasing its gains.

The main conclusions of this paper are that adaptation will affect both the incentives to join the Grand Coalition and the stable coalitions. Furthermore, excessive adaptation can be strategically applied by regions to gain higher (coalition) payoffs. This is done at the cost of the other members. Though these effects are small, they nonetheless show that proactive adaptation can affect coalition formation.

There are several limitations to this analysis. Firstly, we only investigate several level of proactive adaptation (and only unilateral divergences) and do not identify a Nash equilibrium where each region optimises its proactive adaptation given the expected outcome of the second stage of the game.. This next step is left for later research. Secondly we do not consider uncertainty in our model. Thirdly, our results are dependent on our parameter estimates which are based on the limited empirical literature on the costs and benefits of adaptation and mitigation. This work would benefit from better estimates on the exact effects of climate change, adaptation and mitigation.

6.A AD-STACO model equations

Payoff function (objective function)

$$\max \pi_i(p_1,...,p_T,q_1,...,q_T) = \sum_{t=1}^{T} \left\{ (1+r_{it})^{-t} \cdot \left(b_{it}(p_t,q_t) - mc_{it}(q_{it}) - pc_{it}(p_{it}) \right) \right\} \quad (22)$$

$\forall i \in N$ with $q_t \equiv \sum_{i=1}^{N} q_{it}$ and $r_{it} \equiv \rho + \eta \cdot \dot{y}_{it}$

Stock of CO_2

$$M_t\left(M_{t-1},q_t\right) = (1-\delta_M)\cdot M_{t-1} + \gamma_M \cdot \sum_{i=1}^{N} \left\{ \bar{e}_{it} - q_{it} \right\}; M_0 = \overline{M_{2010}} \quad (23)$$

Radiative forcing

$$F_t\left(M_t\right) = \gamma_F \cdot M_t + \overline{F\,non\,CO_{2t}} \quad (24)$$

Temperature change

$$T_t\left(T_{t-1},F_t\right) = (1-\delta_T)\cdot T_{t-1} + \gamma_T \cdot F_t; T_0 = \overline{T_{2010}} \quad (25)$$

Gross damages

$$gd_{it}(T_t) = \theta_i \cdot (\gamma_D \cdot T_t) \cdot \overline{Y_{it}} \quad (26)$$

Residual damages

$$rd_{it}(p_{it},T_t) = gd_{it}(T_t)\cdot(1-p_{it}) \quad (27)$$

Benefits of mitigation

$$mb_{it}(p_{i1},...,p_{it},q_t) = \sum_{s=t}^{\infty} \left\{ (1+r_{is})^{t-s} \cdot \left(rd_{is}(p_{is},q_t=0) - rd_{is}(p_{is},q_t) \right) \right\} \quad (28)$$

Mitigation costs

$$ac_{it}(q_{it}) = \frac{1}{3}\cdot\alpha_i\cdot(1-\varsigma)^t\cdot q_{it}^3 + \frac{1}{2}\cdot\beta_i\cdot(1-\varsigma)^t\cdot q_{it}^2 \quad (29)$$

Adaptation costs

$$pc_{it}(p_{it}) = a_i \cdot p_{it}^2 \tag{30}$$

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