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Climate Agreement**

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Coalition Formation under Uncertainty: The Stability Likelihood of an International Climate Agreement

Summary

Results derived from empirical analyses on the stability of climate coalitions are usually very sensitive to the large uncertainties associated with the benefits and costs of climate policies. This paper provides the methodology of Stability Likelihood that links uncertainty about benefits and costs of climate change to the stability analysis of coalitions in a stochastic, empirical setting. We show that the concept of Stability Likelihood improves upon the robustness and interpretation of stability analysis. Our numerical application is based on a modified version of the climate model STACO. It turns out that the only non-trivial coalition structure with a relatively high Stability Likelihood (around 25 percent) is a coalition between the European Union and Japan, though quantitative results depend especially on the variance in regional benefits from abatement.

Keywords: Climate change, Coalition formation, International environmental agreements, Uncertainty

JEL Classification: C79, H87, Q54

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1. Introduction

There are many obstacles that prevent the formation of effective international environmental agreements (IEAs) as well as high participation. Two of the most important obstacles are free-riding and uncertainty.

First, IEAs aim at providing a public good and therefore most countries face strong free-rider incentives. Typically, for each region it is more profitable if other regions cooperate, while own abatement activities are kept at a low level. How free-riding undermines successful formation of IEAs has been studied extensively using game theoretical models, as in Hoel (1992), Cararro and Siniscalco (1993) and Barrett (1994) and also in empirical climate models such as Botteon and Carraro (1997, 1998), Tol (2001), Bosello *et al.* (2003), Eyckmans and Finus (2005), and Finus *et al.* (2005). A main conclusion of this literature is that stable coalitions improve only marginally upon the non-cooperative outcome because either stable coalitions are small or the abatement level that can be sustained in larger coalitions is very low. However, regardless of the specific model, all of these papers determine stable coalitions in a deterministic setting.

Second, the uncertainties surrounding the future impacts of climate change are large, complicating the formation of an agreement of joint action. In particular, the benefits from abatement that arise in the distant future are highly uncertain, but also abatement costs are not fully known. These issues are highlighted in Roughgarden and Schneider (1999), Tol (2002) and Tol (2005). This implies that decisions on climate strategies must be made without full knowledge of their impacts. However, regardless of how uncertainty is captured in these papers and what this means for optimal abatement strategies, success can only be evaluated if free-rider incentives are also included in the analysis.

The novel contribution of our paper is that it brings both strands in the literature together. It illustrates a methodology to calculate the stability of all possible coalition structures in a stochastic, empirical setting. Our concept of Stability Likelihood (SL) determines the *likelihood* that a coalition structure is stable, taking into account the uncertainty of the model parameters. That is, we model uncertainty via probability functions on parameter values and therefore can directly evaluate the robustness of results and the validity of qualitative conclusions. This contrasts with deterministic coalition models that can only compute whether a coalition is stable or not. This is often not innocuous for at least two reasons. First, in a deterministic setting coalitions are either stable or unstable, even though differences in payoff between equilibrium and deviation strategies are very small. Small changes in parameter values, which are not accurately known, can invalidate the conclusions. Second, uncertainty in parameter values is only indirectly accounted using sensitivity analyses, where each analysis is itself subject to the first problem.

We apply the SL-concept to a two-stage cartel formation game that has been widely used in the literature (cf. Finus *et al.*, 2005). In the first stage, countries decide whether to participate in an IEA for reducing greenhouse gases and in the second stage they choose their abatement strategies. Generally, there can be uncertainty in both stages. More precisely, when (i) deciding on participation there can be uncertainty regarding climate impacts and abatement costs; and (ii) hence also about other players' participation strategies; and when (iii) choosing the abatement level there can be uncertainty regarding climate impacts and abatement costs. We consider the first option. This means that countries face uncertainty regarding the parameter values of the benefit and cost functions when deciding on participation, but choose their optimal abatement level after learning the “true” values in the second stage. The stability likelihood (SL) concept therefore identifies the probability that regions took the correct participation decision. We leave the last two options for further research that may make use of results obtained for instance in Ulph and Maddison (1997), Na and Shin (1998), Ulph (2004), Baker (2004) and Kolstad (2005).

In Section 2, we present our model of coalition formation and introduce the concept of stability likelihood. Section 3 discusses the calibration of the model, including the distribution functions used for the uncertain model parameters. Section 4 presents and discusses result of our stability analysis. Section 5 concludes.

2. The model of coalition formation

Consider a set of N heterogeneous players, each representing a region of the world. In the first stage, regions decide whether to become a member of an international agreement (IEA) or to remain an outsider. Announcement $c_i = 1$ means “Region i joins the coalition” and announcement $c_i = 0$ “Region i remains an outsider”; a coalition structure c is described by announcement vector $c = (c_1, \dots, c_N)$. The set of players that announce 1 are coalition members and is denoted as $k = \{i \mid c_i = 1, \forall i = 1, \dots, N\}$.

In the second stage, regions choose their abatement levels. This leads to abatement vector $q = (q_1, \dots, q_N)$. The payoff of an individual region i , $\pi_i(q, b)$ depends on abatement vector q (and hence on the strategy of all regions, due to the public good nature of abatement) and on a vector of model parameters b .

We solve the game backwards assuming that strategies in each stage must form a Nash equilibrium. For the second stage, this entails that abatement strategies form a Nash equilibrium between coalition k and the remaining non-signatories. That is,

$$[1] \quad \begin{aligned} \sum_{i \in k} \pi_i(q_k^*, q_{-k}^*, b) &\geq \sum_{i \in k} \pi_i(q_k, q_{-k}^*, b) \quad \forall q_k \quad \text{and} \\ \pi_i(q_k^*, q_i^*, q_{-i}^*, b) &\geq \pi_i(q_k^*, q_i, q_{-i}^*, b) \quad \forall q_i \end{aligned}$$

where q_k is the abatement strategy vector of coalition k , q_{-k} the vector of all regions not belonging to k , q_i the strategy of non-signatory i , and q_{-i} the strategy vector of all other non-signatories except i . An asterisk denotes equilibrium strategies. Computationally, this implies that non-signatories ($i \notin k$) that announced $c_i = 0$ will choose their abatement strategies so as to maximize their individual payoff $\pi_i(q, b)$, whereas all signatories ($i \in k$) that announced $c_i = 1$ jointly maximize the aggregate payoff of their coalition $\sum_{i \in k} \pi_i(q, b)$, taking the abatement strategies of all other regions as given. Strategically, this means that the behaviour of non-signatories towards all other regions is selfish and non-cooperative; signatories behavior is cooperative towards their fellow members, but non-cooperative towards outsiders. Economically, this means strategies are group (but not globally) efficient within coalition k . Hence, the equilibrium economic strategy vector q^* corresponds to the classical “social or global optimum” if coalition k comprises all countries, *i.e.* the grand coalition forms, and corresponds to the classical “Nash equilibrium” if coalition k comprises only one member or is empty. Thus, any inefficiency stems from the fact that k is not the grand coalition.

Since in the context of our empirical model the equilibrium abatement vector q^* is unique for every coalition structure c and a given set of parameters b (see the proof in Olieman and Hendrix 2004), we can construct a vector of optimal payoffs for every coalition structure c , $v_i(c, b) \equiv \pi_i(q^*, b)$.

We now turn to the first stage. Also in the first stage, strategies form a Nash equilibrium. That is, no signatory that announced $c_i = 1$ should have an incentive to change its announcement to $c_i' = 0$ (internal stability) and no non-signatory that announced $c_i = 0$ should want to announce $c_i' = 1$ instead (external stability). For our purposes, this condition can be summarized compactly by the payoff stability indicator function $f(c, b)$, which assigns the value 1 to a stable announcement vector (*i.e.* stable coalition) and the value 0 to an unstable announcement vector (*i.e.* unstable coalition):

$$[2] \quad f(c, b) = \begin{cases} 1 & \text{if } (v_i(c, b) - v_i(c', b) \geq 0) \text{ for all } |c - c'| = 1 \text{ and for all } i = 1, \dots, N \\ 0 & \text{else} \end{cases}$$

The function $f(c, b)$ will take on the value 1 if for all regions the payoff for announcement c is higher than, or equal to, the payoff associated with alternative announcements c' . These alternatives are constructed by changing the announcement of

one player at a time: $|c - c'| = 1$ is only true if the vector c' differs from vector c in one element.

In a deterministic model parameter b may be based on estimation but is treated as given. In contrast, we construct a stochastic model by replacing the deterministic parameter b with stochastic variable \mathbf{b} which is characterised by probability space (B, \mathcal{B}, \Pr) and probability density function $g(b)$. Consequently, function $f(c, \mathbf{b})$ becomes a Bernoulli variable, meaning that we can assign a likelihood to the event that $f(c, \mathbf{b}) = 1$.

The stability likelihood of coalition structure c is defined as $SL = \Pr\{f(c, \mathbf{b}) = 1\}$ which equals $\int_B f(c, b) \cdot g(b) db$. Assuming that $f(\cdot)$ is a correct representation of reality, we can interpret SL as the probability that coalition structure c can be claimed stable.

Given the complexities of the model, we cannot find an analytical solution for SL, and therefore resort to numerical calculations. The stability likelihood is calculated using a Monte Carlo sampling technique: we generate M samples b_m from \mathbf{b} ; based on these

samples we can estimate the stability likelihood with $\hat{SL} = \frac{1}{M} \sum_{m=1}^M f(c, b_m)$ that has an

estimated variance of $\frac{1}{M-1} (\hat{SL}(1 - \hat{SL}))$.

A more detailed discussion of the stability likelihood concept and computation methods can be found in Olieman and Hendrix (2004).

3. Calibration of the model

3.1. Introduction

In this section, the calibration of the empirical model, called STACO (STAbility of Coalitions) is described. For more detailed information on the model and calibration procedure, see Dellink *et al.* (2004) and Finus *et al.* (2005). The model comprises benefit and cost functions for twelve world regions: USA (USA), Japan (JPN), European Union (EEC), other OECD countries (OOE), Eastern European countries (EET), former Soviet Union (FSU), energy exporting countries (EEX), China (CHN), India (IND), dynamic Asian economies (DAE), Brazil (BRA) and "rest of the world" (ROW). The philosophy behind the construction of the model comprises two items. First, the model must be simple enough to allow for sufficient samples to be calculated

within reasonable time¹. Second, the model should still reflect important results and features of integrated assessment models in terms of overall magnitudes of global emissions and concentration, abatement costs from regional abatement and benefits from global abatement over some time period. Therefore, the model focuses on carbon dioxide, but the exogenous level of other greenhouse gases is included in the calibration of the benefit function (*cf.* Nordhaus, 1994). The analysis calculates the net present value of a stream of net benefits starting in 2010 and covering a time period of 100 years in order to capture the long-run effects of global warming. We model a one-shot cartel game and analyse only single deviations. The model is a simple version of an integrated assessment model and hence results should only be interpreted as a numerical example. Nonetheless, we believe that our numerical example illustrates the usefulness of SL as an indicator, as we include the best available information on the probability density functions of the model parameters.

3.2. *Elements of the empirical model*

The payoff function of region i is given by:

$$[3a] \quad \pi_i = \sum_{t=1}^T (1+r)^{-t} (B_{it}(q_t) - AC_{it}(q_{it}))$$

where T denotes the time horizon, $t=2011, \dots, 2110$; r is the discount rate; B_{it} are benefits from global abatement ($q_t = \sum_{i=1}^N q_{it}$); and AC_{it} are abatement costs from individual abatement q_{it} .

The payoff function is calculated as the net present value of a stream of net benefits from abatement between 2010 and 2110 and thus reflects discounted avoided damages minus discounted abatement costs. Regional abatement costs are a function of the level of individual abatement by region i , while regional benefits depend on global abatement efforts.

Assuming stationary abatement strategies ($q_{it} = q_i/100$), benefits in year t can be expressed as a function of global abatement over the entire period. Furthermore, we consider that the stock of CO_2 can be approximated by a linear function of emissions and that damages are linear in the stock of CO_2 .² It follows that annual benefits from reduced emissions are also linear in the level of abatement:

¹ We need around 40,000 samples to get sufficient accuracy in the estimate of SL. This implies around 2 billion calculations of optimal regional abatement and payoff levels (40,000 times 12 regions times 4096 possible coalitions).

² The details of this approximation are given in Dellink *et al.* (2004).

$$[4a] \quad B_t(q) = \varphi_t \cdot q$$

where φ_t denotes marginal benefits in period t from total abatement over the entire period. This parameter also includes the effects of limited retention of GHGs in the atmosphere and decay of the stock of GHGs over time. As abatement in period t will lead to benefits in all periods from t onwards, these marginal benefits are time-dependent.

Discounted total benefits, $TB(q)$, are then expressed as

$$[4b] \quad TB(q) = \gamma \cdot q$$

where γ represents discounted marginal benefits in \$/ton carbon equivalents and is calculated as $\gamma = \sum_{t=2011}^{2110} (1+r)^{-t} \cdot \varphi_t$.

Regional benefits are assumed to be a share of global benefits from abatement:

$$[4c] \quad TB_i(q) = s_i \cdot TB(q) = s_i \cdot \gamma \cdot q$$

where s_i is the share of total benefits for region i .

For the specification of the abatement cost function, estimates of the EPPA model are used (Ellerman and Decaux, 1998). They assume an annual abatement cost function for region i of the following form:

$$[5a] \quad AC_{it}(q_{it}) = \frac{1}{3} \cdot \alpha_i \cdot (q_{it})^3 + \frac{1}{2} \cdot \beta_i \cdot (q_{it})^2$$

For the total abatement costs of region i , $TAC_i(q_i)$ the same functional form is used, summed over the entire time horizon. Assuming stationary strategies and a constant discount rate, as in the case of benefits, the total abatement cost function becomes

$$[5b] \quad TAC_i(q_i) = \rho \cdot \left(\frac{1}{3} \cdot \alpha_i \cdot (q_i)^3 + \frac{1}{2} \cdot \beta_i \cdot (q_i)^2 \right)$$

$$\text{with } \rho = \sum_{t=2011}^{2110} (1+r)^{-t}$$

Taken together, the payoff function can be written as:

$$[3b] \quad \pi_i = TB_i(q) - TAC_i(q_i).$$

Generally, all model parameters are uncertain. However, we have insufficient information to fully estimate the probability density functions of all parameters at a regional level. A more advanced meta-analysis of published and unpublished estimates would require a study of its own and therefore is beyond the scope of the current paper. Hence, we consider only uncertainty in the benefit and cost parameters γ , s_i , α_i and

β_i . Other parameters such as emissions in 2010, the decay rate of greenhouse gases and the discount rate are assumed known with certainty. Calibration of emissions and concentrations is based on the widely known DICE-model by Nordhaus (1994). The discount rate r is set at 2% per year.

3.3. Global Benefit Function

The distribution function for the global level of benefits (γ) is based on a recent study by Tol (2005). The probability density function for peer-reviewed studies as presented by Tol can be closely mimicked by a 2-sided exponential function. This function is described by four pieces of information: (i) the 5 percentile point; (ii) the value where the two sides of the exponential function are separated (assuming this is above the 5 percentile point); (iii) the cumulative probability density at this separation value; and (iv) the 95 percentile point (assuming this is above the separation value). The first piece of information is given by the value that corresponds to a cumulative probability of 5%; this value equals -9 \$/ton, implying a strictly positive probability that benefits from abatement are negative. The point of separation between both sides of the function is given by the mode and equals 5 \$/ton; the associated cumulative probability density is 13%. Finally, the point on the right side of the function is given by the 95% cumulative probability density and equals 245 \$/ton. These numbers are summarised in Table 1 and the corresponding histogram of all drawn samples is shown in Appendix I.³ This distribution function implies that there is a probability of around 9 percent that the benefits of abatement are zero or negative; if this is the case, the optimal abatement quantities are zero, and regions are indifferent to cooperation.

Table 1. Characteristics of the 2-sided exponential distribution function for the global benefit function (γ).

	Value
5% density	-9 \$/ton
mode	5 \$/ton
density at mode	13%
95% density	245 \$/ton

3.4. Regional Benefit Shares

The distribution function for the regional benefit shares (s_i) is based on insights from a study by Tol (2002), though this source does not provide sufficient information on the

³ Note that the mean value of this function (77 \$/ton) differs from the value (37 \$/ton) used in Finus *et al.* (2005).

functional form of the distribution function of these shares. We opt for a gamma distribution that can handle the lower bound of the shares such that no region receives a negative share of the benefits. Moreover, as the shares can vary between zero and one and the mean value is typically close to zero, the distribution function should be skewed, as is the case for a gamma distribution. As the choice for a gamma distribution function may to some extent seem arbitrary, we will subject it to a sensitivity analysis in section 4.3.

The mean values used for the regional shares are the values reported in the deterministic setting of the STACO model, which are in turn based on Fankhauser (1995) and Tol (1997). Standard deviations are based on expert judgement, using in particular Tol (2002). Typically, standard deviations are of the same order of magnitude as mean values, and are lower for OECD countries than for the other regions. The regional numbers are represented in Table 2; for a better understanding, the corresponding histograms for the USA and China are shown in Appendix I.

Table 2. Characteristics of the gamma distribution function for the share parameters in the benefit function (s_i).

Region	Lower bound	Mean	Standard deviation
USA	0	0.2263	0.1414
JPN	0	0.1725	0.1078
EEC	0	0.2360	0.1475
OOE	0	0.0345	0.0216
EET	0	0.0130	0.013
FSU	0	0.0675	0.0675
EEX	0	0.0300	0.0300
CHN	0	0.0620	0.0620
IND	0	0.0500	0.1000
DAE	0	0.0249	0.0498
BRA	0	0.0153	0.0306
ROW	0	0.0680	0.1360

After the samples of the regional shares are drawn, all shares are scaled up or down to force the sum of shares to unity. This implies that the regional shares do not strictly follow the gamma distribution and the resulting variance in the shares is smaller than in

the original gamma distribution.⁴ Though rescaling is not a necessary condition for the working of the model, the restriction on the sum of shares is enforced to avoid an impact of variations in this parameter on global benefit levels. The consequences of this specification will be investigated in a sensitivity analysis in section 4.3.

3.5. Abatement Cost Functions

The regional abatement cost function contains two parameters (α_i and β_i), which cannot be assumed to be independent. Typically, empirical studies report only variations in the marginal abatement costs without providing information on how the slope and curvature of the MAC function vary. Therefore, we assume the functional form of the abatement cost curves to be given, and vary the level of marginal abatement costs per region in the simulations. This implies that both parameters in the abatement cost functions move simultaneously and in the same direction.

Table 3. Characteristics of the normal distribution for the parameters in the abatement cost function (α_i and β_i).

Region	α_i		β_i	
	Mean	St. dev.	Mean	St. dev.
USA	0.00050	0.00006	0.00398	0.00050
JPN	0.01550	0.00194	0.18160	0.02270
EEC	0.00240	0.00030	0.01503	0.00188
OOE	0.00830	0.00104	0.00000	0.00000
EET	0.00790	0.00198	0.00486	0.00122
FSU	0.00230	0.00058	0.00042	0.00011
EEX	0.00320	0.00080	0.03029	0.00757
CHN	0.00007	0.00002	0.00239	0.00060
IND	0.00150	0.00038	0.00787	0.00197
DAE	0.00470	0.00118	0.03774	0.00944
BRA	0.56120	0.14030	0.84974	0.21244
ROW	0.00210	0.00053	0.00805	0.00201

⁴ More information on the impact of this rescaling on the probability density function can be obtained from the authors upon request.

We assume a normal distribution function; the mean is based on the deterministic version of the STACO model, which is in turn based on Ellerman and Decaux (1998). The normal distribution is chosen as there seems no reason to assume a skewed distribution. The standard deviation for the abatement cost parameters are based on information in the IPCC report of 2001 (Metz *et al.*, 2001). Due to lack of regional information, the standard deviation is calibrated to 12.5 percent of the mean for OECD regions and 25 percent for non-OECD regions. Hence, the variation in abatement costs is typically much smaller than the variation in benefits for most regions. The key inputs for the normal distribution are shown in Table 3 and for USA and China the corresponding probability density functions are illustrated in Appendix I.

4. Results

Using the confidence intervals and distribution functions described above, we calculate the Stability Likelihood (SL) of all 4096 possible coalition structures. The results of this simulation are reported and discussed in Section 4.1. Section 4.2 investigates an alternative scenario with lower probability of extreme observations for the benefits from abatement, by adoption much stricter bounds on the distribution function of the global benefit parameter. These stricter bounds are chosen such that the mean value of global benefits coincides with the deterministic value for global benefits used in Finus *et al.* (2005), thereby allowing a direct comparison between the deterministic and stochastic settings. Section 4.3 briefly discusses the results of some sensitivity analyses on the uncertainty of the various parameters and the associated distribution functions. All simulations are carried out with a confidence interval of 95% on the second digit of SL ($\sigma_{SL} = 0.0025$).

4.1. Results for the base specification

Table 4 presents the main results for those coalition structures that have the highest SL and for the Grand Coalition.

Note that the stability of the All-Singletons structure is not uniquely defined. If all regions announce $c_i = 0$, then $SL=1$ by definition. However, if all regions announce $c_i = 0$ except one, then SL may be lower, because external stability is no longer automatically guaranteed. In this case, the highest SL is obtained if JPN announces $c_i = 1$ and all other regions $c_i = 0$ with $SL=0.40$. That is, the likelihood that none of the other regions wishes to join JPN is 40%. In the All-Singletons structure abatement efforts amount to only 70 Gton per century, or an annual abatement of 5.8 percent of global emissions in 2010. This leads to a discounted payoff of almost 8.8 trillion US\$ over the century.

Table 4. Results for selected coalition structures (mean values).

Coalition	SL (fraction)	Strict SL (fraction)	Total abatement (Gton)	Abatement (% of emissions)	Total payoff (bln \$)
All-Singletons	Undefined	undefined	69.4	5.8%	8775
JPN,EEC	0.24	0.15	74.5	6.2%	9251
USA,JPN	0.15	0.06	79.1	6.6%	9663
USA,EEC	0.14	0.05	84.7	7.1%	10090
JPN,BRA	0.12	0.02	69.7	5.8%	8824
JPN,ROW	0.11	0.02	76.7	6.4%	9613
EEC,ROW	0.11	0.01	79.2	6.6%	9835
JPN,IND	0.10	0.01	78.0	6.5%	9773
JPN,FSU	0.10	0.01	75.8	6.3%	9475
EEC,BRA	0.10	0.01	70.1	5.9%	8857
EEC,FSU	0.10	0.01	78.4	6.6%	9699
Grand coal.	0.09	0	326.3	27.3%	27360

The Grand Coalition would lead to much larger abatement efforts and a higher global payoff than no cooperation, as the gains of cooperation are fully reaped. However, the Grand Coalition has a low SL. In fact, the Grand Coalition is only stable when there are no benefits to be reaped from abatement, *i.e.*, when the global benefit parameter is zero or negative. In such cases, the optimal abatement level is zero, and regions are indifferent to cooperation. In the calculation of SL, this is interpreted as stable. Therefore, Table 4 also reports “Strict SL”, which equals SL minus the probability that regions are indifferent to cooperation (“probability of indifference”).

Only a few non-trivial coalition structures have a positive strict SL. All these coalition structures are small and improve only little over the All-Singletons structure. This shows the important information the SL-concept provides that cannot be obtained in a deterministic setting. For instance, in the deterministic STACO model analysed in Finus *et al.* (2005), no stable non-trivial coalition could be found for the base parameter values. Only if the global benefit parameter is raised by 20 percent a coalition of Japan and European Union turns out to be stable. In the stochastic setting, we obtain the probability that this coalition structure is stable, given the uncertainty of the benefit and abatement cost parameters: in 24 percent of the samples this coalition structure turns out to be stable (15 percent if the stability condition is strict).

The regional results for the coalition of Japan and European Union are given in Table 5. Though the standard deviations of the abatement levels are rather big, there is a probability of more than 90% that abatement levels are strictly positive, implying that the implicit distribution function for abatement levels is right-skewed. Though they are not part of the coalition, the largest abatement efforts are carried out by China and the USA. These regions have strong incentives to unilaterally reduce their emissions because of relatively low marginal abatement costs compared to their marginal benefits.⁵ For Japan and the European Union, marginal abatement costs are equal to the sum of marginal benefits of this coalition, reflecting the first order condition implied by the assumption of joint welfare maximisation of coalitions as explained in section 2.⁶

Table 5. Regional results for coalition JPN and EEC.

Region	Total abatement (Gton)		Abatement (% emis)	Total payoff (bln \$)		MAC (\$/ton)	MB (\$/ton)	Incentive (bln \$)
	Mean	Standard deviation	Mean	Mean	Standard deviation	Mean	Mean	Mean
USA	20.31	16.01	8.4%	2050	4313	17.6	17.3	-247
JPN	2.83	2.68	5.1%	1650	3525	31.7	13.3	-79
EEC	12.29	9.15	8.8%	2043	4213	31.7	17.9	-12
OOE	2.30	1.71	3.7%	369	817	2.9	2.8	-127
EET	1.14	1.20	2.2%	141	406	1.1	1.1	-145
FSU	5.64	5.11	5.6%	670	1712	5.4	5.3	-221
EEX	1.40	2.01	1.2%	312	850	2.5	2.4	-206
CHN	21.02	24.19	8.9%	611	1739	4.9	4.8	-1282
IND	3.30	5.59	5.2%	441	1647	3.6	3.5	-289
DAE	0.81	1.80	2.0%	245	1008	1.9	1.9	-167
BRA	0.03	0.08	0.2%	151	636	1.2	1.2	-11
ROW	3.42	5.54	4.9%	568	2117	4.7	4.6	-227

⁵ This is in line with the arguments put forward by the Bush administration: the USA will not ratify the Kyoto protocol, but will carry out abatement efforts in its own interest.

⁶ For singletons, the equality between regional MAC and regional MB holds for samples where marginal benefits are nonnegative, but not necessarily for the mean values. Similarly, regional MAC equals coalitional MB for coalition members only at the level of individual samples with nonnegative marginal benefits.

The last column in Table 5 shows the mean incentive to change membership: for example, if the USA were to join the coalition of Japan and European Union, its mean payoff would be reduced by 247 bln \$. Similarly, Japan and European Union would have a lower payoff of 79 and 12 bln \$, respectively, if they were to leave the coalition. It turns out that the mean values for the incentive to change membership are negative for all regions. Thus, a model that only looks at mean values would come to the conclusion that this coalition is both internally and externally stable. But the corresponding SL is only 24%, implying that in three quarter of all samples the coalition is unstable. This clearly illustrates the importance of using a more sophisticated stability indicator, such as SL, when the probability density functions of the model parameters are strongly skewed.

The relationship between the samples of global marginal benefits and the corresponding global abatement levels is illustrated in Figure 1 for the All-Singletons structure. For samples with negative marginal benefits, optimal abatement levels are zero. For positive marginal benefits, there is a clear positive correlation between the marginal benefits and abatement levels, but the relation is not linear: as marginal abatement costs increase quadratic in abatement levels, higher marginal benefits lead to a less than proportional increase in abatement levels.

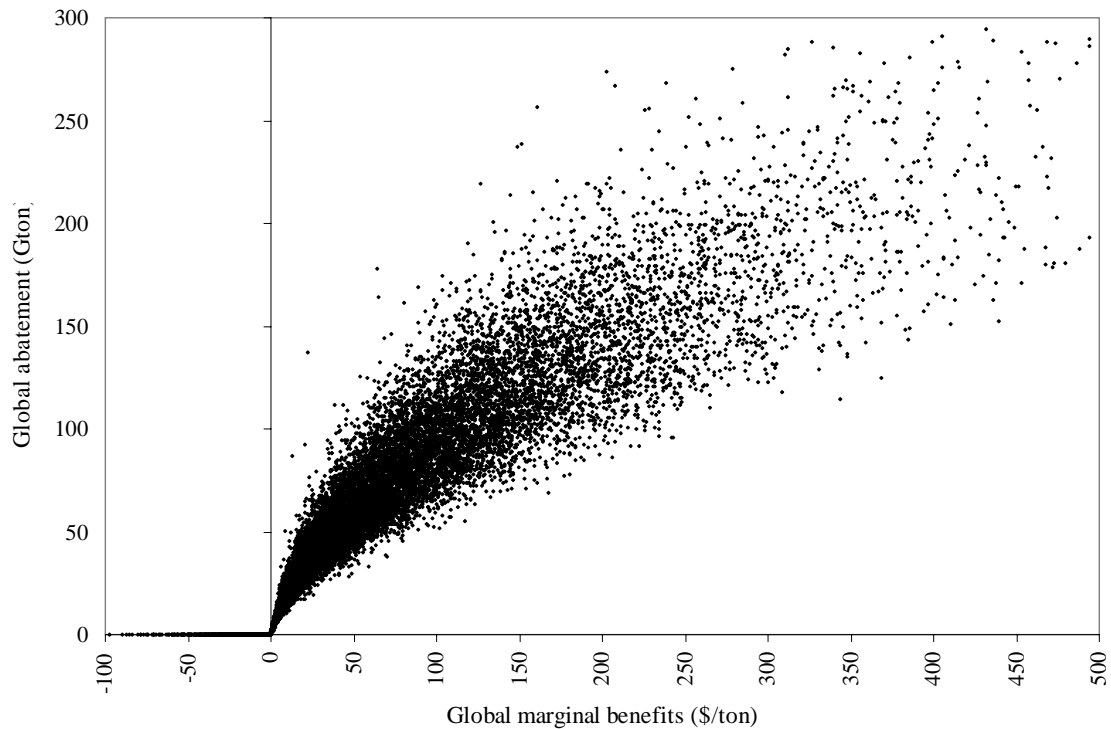


Figure 1. Relationship between global marginal benefits and global abatement levels for the All-Singletons structure.

The graph clearly shows the dispersion in global marginal benefits that is generated by the distribution function and the resulting dispersion in optimal global abatement levels. The bulk of samples produce global marginal benefits between 0 and 200 \$/ton, with corresponding optimal abatement levels of less than 200 Gton over the century, though outliers may have a value of more than 800 \$/ton for marginal benefits, while abatement levels can be up to 400 Gton.

As we may recall, stability of a coalition structure comprises internal and external stability. The internal SL, *i.e.* the Stability Likelihood when considering only internal stability, of the coalition between Japan and the European Union is somewhat larger than the ‘total’ SL (0.33 vs. 0.24), as shown in Table 6.⁷ This implies that in some samples, the coalition structure is internally stable, but one or more other regions wish to join this coalition, making it externally unstable. For most samples (67 %), however, this coalition structure is not internally stable.

Table 6. Internal stability likelihood (ISL) and SL of selected coalition structures.

Coalition	ISL	SL	Coalition	ISL	SL
JPN,EEC	0.33	0.24	FSU,CHN	0.22	0.09
USA,EEC	0.33	0.14	OOE,EET	0.22	0.09
OOE,EEX	0.29	0.09	EET,EEX	0.22	0.09
OOE,FSU	0.28	0.09	USA,OOE	0.20	0.09
OOE,CHN	0.28	0.09	EET,FSU	0.19	0.10
USA,JPN	0.27	0.15	EEC,FSU	0.19	0.09
EEX,CHN	0.24	0.09	OOE,DAE	0.19	0.09
EET,CHN	0.24	0.09	OOE,IND	0.18	0.09
FSU,EEX	0.23	0.09	OOE,ROW	0.18	0.09
USA,FSU	0.23	0.10	Grand coalition	0.09	0.09

In the vast majority of the coalition structures, including all coalition structures with 4 coalition members or more, there is at least one region that wishes to leave the coalition and ISL equals SL. Thus, internal stability can be identified as the main problem in achieving larger and more ambitious coalitions.⁸

⁷ Note that the singleton coalition structures are internally stable by definition; hence, their ISL equals unity.

⁸ Many large coalitions have an external SL of almost 1; the external SL of coalition {JPN,EEC} equals 0.64.

4.2. Results for the alternative specification with lower mean global benefits

It is clear that the probability density function used for global marginal benefits is of crucial importance for the results of the analysis. Moreover, estimates of future benefits from abatement are widely acknowledged to be highly uncertain. Therefore, we carry out an alternative simulation with a different assumption on the global benefit parameter γ . Table 7 shows results assuming that the 5 percentile point is set to 0 \$/ton and the 95 percentile point is set to 110 \$/ton. This implies that extreme values are rare and that the mean value for global marginal benefits is reduced from 77 to 37 \$/ton. This lower mean is in line with the value for global marginal benefits used in the deterministic setting in Finus *et al.* (2005).

Table 7. Results for selected (non-trivial) coalition structures (mean values) using smaller bounds on global benefit parameter γ .

Coalition	SL (fraction)	Strict SL (fraction)	Mean total abatement (Gton)	Total payoff (bln \$)
All-Singletons	undefined	undefined	44.5	2520
JPN,EEC	0.20	0.15	47.9	2660
USA,JPN	0.11	0.06	51.2	2790
USA,EEC	0.10	0.05	55.2	2929
JPN,BRA	0.07	0.02	44.7	2532
JPN,ROW	0.07	0.02	49.5	2774
EEC,ROW	0.06	0.01	51.2	2844
JPN,IND	0.06	0.01	50.3	2819
EEC,BRA	0.06	0.01	45.0	2543
JPN,FSU	0.06	0.01	49.1	2738
EEC,IND	0.06	0.01	52.1	2894
Grand coal.	0.05	0.00	225.8	8353

For all coalition structures, the SL is lower than in the base specification. This is partly due to the lower probability of negative marginal benefits (this probability is reduced to 5%) and partly due to the fact that mostly positive outliers of marginal benefits are removed from the model. The ranking (in terms of SL) of the different coalition structures is largely unchanged, implying that the level of global marginal benefits changes only the quantitative results, but not qualitative conclusions.

The lower benefits clearly reduce optimal abatement levels. In the All-Singletons structure, global abatement levels drop from around 70 Gton per century to 45 Gton. It is obvious that the reduction in mean marginal benefits does not translate into a proportional reduction in mean abatement levels (*cf.* Figure 1). This is due to the non-linear nature of the model: the quadratic marginal abatement cost functions imply that lower marginal benefits lead to less than proportionately lower abatement levels. The lower benefits and abatement levels also lead to lower pay-offs (2.5 trillion \$ versus 8.8 trillion \$ in the base specification).

These quantitative results for the alternative specification are roughly comparable to the results of the deterministic setting (*cf.* Finus *et al.*, 2005). They found that none of the coalition structures is stable, but that the coalition of the European Union and Japan is stable when the global benefit level is raised by at least 20 percent. In the stochastic setting, this translates into an SL for this coalition structure that is higher than all others, but well below unity.

4.3. Results of the sensitivity analyses

In order to shed light on the robustness of our previous conclusions, a series of sensitivity analyses have been carried out. The main results of alternative assumptions regarding the uncertainty of the main model parameters are reported in Table 8. A second set of sensitivity analyses concerns the functional forms used in the simulations, and is reported in Table 9.

Table 8. Stability Likelihood of selected coalition structures under different model specifications.

Coalition	Base specification	No uncertainty w.r.t. s_i	No uncertainty w.r.t. γ	No uncertainty w.r.t. α_i, β_i
JPN,EEC	0.24	0.63	0.17	0.24
USA,JPN	0.15	0.09	0.07	0.15
USA,EEC	0.14	0.09	0.06	0.14
JPN,BRA	0.12	0.09	0.02	0.11
JPN,ROW	0.11	0.09	0.02	0.11
EEC,ROW	0.11	0.09	0.02	0.10
JPN,IND	0.10	0.09	0.01	0.10
JPN,FSU	0.10	0.09	0.01	0.10
EEC,BRA	0.10	0.09	0.01	0.10
EEC,FSU	0.10	0.09	0.01	0.10
Grand coal.	0.09	0.09	0	0.09

The general result that emerges from these sensitivity analyses is that although the levels regional abatement levels and payoffs depend on several model parameters, the sensitivity of the value of SL is much smaller. Essentially, the value of SL depends crucially on two elements: (i) the variance in regional benefit shares (s_i), and (ii) the variance and level of the global benefit level (γ), but only through changes in the probability of negative benefits. Reducing the uncertainty with respect to the regional benefit shares from the model greatly reduces the variability of stability over the different coalitions. Thus, when regional benefit shares are known, it becomes much easier to predict which regions have incentives to collaborate and which don't: only the coalition structure of Japan and European Union has an SL that is higher than the probability of indifference.

Table 9. Stability Likelihood of selected coalition structures under different model specifications.

Coalition	Base specification	Normal distribution s_i	Normal distribution γ	Gamma distribution α_i, β_i	$\sum s_i$ varies from unity
JPN,EEC	0.24	0.26	0.32	0.24	0.24
USA,JPN	0.15	0.13	0.24	0.15	0.15
USA,EEC	0.14	0.14	0.23	0.14	0.14
JPN,BRA	0.12	0.09	0.20	0.11	0.11
JPN,ROW	0.11	0.09	0.20	0.11	0.11
EEC,ROW	0.11	0.09	0.20	0.10	0.11
JPN,IND	0.10	0.06	0.20	0.10	0.10
JPN,FSU	0.10	0.07	0.20	0.10	0.10
EEC,BRA	0.10	0.08	0.19	0.10	0.10
EEC,FSU	0.10	0.08	0.19	0.10	0.10
Grand coal.	0.09	0.01	0.19	0.09	0.09

For the ranking of the different coalition structures in terms of their SL, we get an even stronger result: in all simulations, the same structures emerge as the most stable. In all cases the coalition of Japan and European Union has the highest SL, followed by USA and Japan and USA and European Union. Thus, we can conclude that SL provides a highly robust indicator of the stability of climate coalitions.

Finally, the impact of rescaling regional benefits to sum to unity is investigated by removing this assumption from the model. Thus, global benefit levels vary not only

with the variations in the global benefit parameter, but also with the sum of the regional shares. It turns out that this assumption is not of major significance: the results remain very similar to the base specification.

5. Discussion

This paper investigates the formation and stability of coalitions on an international climate agreement. We introduce a methodology to calculate the stability of all possible coalition structures in a stochastic, empirical setting. The concept of Stability Likelihood (SL) provides a notion of stability that conveys much more relevant information than the ordinary binary outcome: stable / unstable.

The numerical application shows that the SL concept contributes to a better understanding of stability of coalition structures under uncertainty. The results suggest that for most possible climate coalition structures there is at least one region that is better off by changing its actions, thereby making these structures unstable. This includes important coalition structures such as the coalition of industrialised countries and the Grand Coalition. The lack of stability holds for the wide range of possible values for regional abatement costs and benefits, as described by the respective probability distribution functions. Only when benefits from abatement are zero or negative (calibrated to be around 9 percent in the base specification), *i.e.* when climate change does not pose a problem, will regions be indifferent to signing an agreement. In such cases, the optimal abatement levels will be zero, regardless of coalition formation. Consequently, there is only a limited number of coalition structures with a SL larger than the probability of indifference.

The non-trivial coalition structure with the highest SL is the coalition of Japan and the European Union, with an SL equal to 24 percent. This relatively low number stresses the difficulties in striking an international environmental agreement. In fact, the highest Stability Likelihood (40 percent) is achieved when Japan takes the initiative to participate in a small coalition, as none of the other regions is willing to join Japan.

It is important to note that the coalition structures with relatively high SL hardly improve over the All-Singletons case: abatement efforts are only slightly higher than when there is no international collaboration at all. If coalition structures are stable, they are small and only marginally improve upon the All-Singletons case in terms of global welfare, global emissions and concentrations, confirming the results of the deterministic literature.

The gains from co-operation that are at stake in the case of global warming are large according to our model. This is not only true for the absolute amount of global net benefits in the global optimum (Grand Coalition Structure), but also when this number is put in perspective to net benefits in the All-Singletons case. The conclusion can be

drawn that additional mechanisms have to be included in the international negotiations to overcome the large free rider incentives; such additional mechanisms could take the form of a scheme for international transfers or issue linking.

The calculated SL of the different coalition structures is robust in terms of the distribution functions used, the variance in regional abatement costs and the global level of benefits from global abatement, but sensitive to the variance in the regional distribution of benefits. Unfortunately, regional benefits from abatement are very uncertain, and international research on adaptation and damage costs is still in its infancy. Therefore, it is of utmost importance to get better information on this issue.

There are many ways in which the analysis above can be ameliorated. First, better estimates of the variance on regional benefits may be obtained via a meta-analysis of the existing literature, similar to what Tol (2005) did for global benefits. Secondly, the empirical model used to calculate the regional payoffs can be extended to a fully-fledged computable general equilibrium model. Together, these two extensions will improve the empirical validity of the numerical example. Thirdly, asymmetric information and learning may give more insight in the actual position of individual players in the international negotiations. Finally, the analysis can be extended to decision making under uncertainty, *e.g.* by using utility functions to describe risk-aversion of players. Nonetheless, the current application already shows that many relevant results and interpretations can be obtained by investigating the Stability Likelihood of coalition structures.

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Appendix I. Histograms for the uncertain model parameters

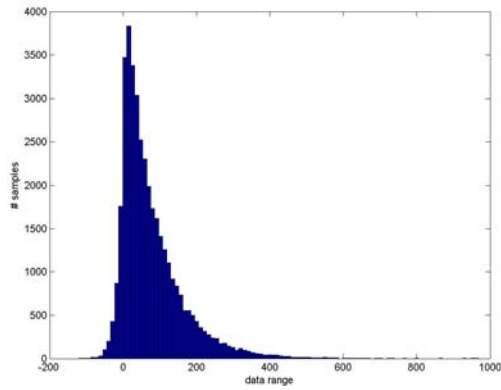


Figure A.1. Histogram for the global benefit parameter (γ).

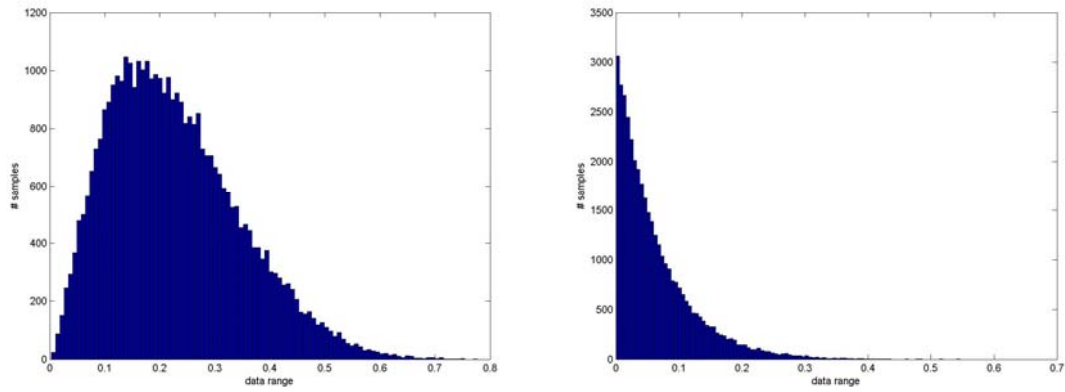


Figure A.2. Histogram for the regional benefit parameters (s_i) for USA and China, respectively.

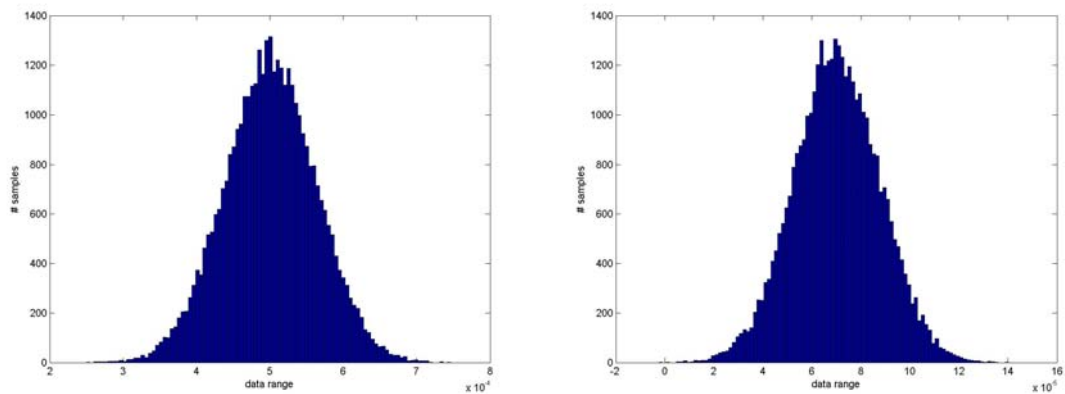


Figure A.3. Histogram for the regional abatement cost parameter (α_i) for USA and China, respectively.

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- (lxv) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications” organised by Fondazione Eni Enrico Mattei and sponsored by the EU, Milan, September 25-27, 2003
- (lxvi) This paper has been presented at the 4th BioEcon Workshop on “Economic Analysis of Policies for Biodiversity Conservation” organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003
- (lxvii) This paper has been presented at the international conference on “Tourism and Sustainable Economic Development – Macro and Micro Economic Issues” jointly organised by CRENoS (Università di Cagliari e Sassari, Italy) and Fondazione Eni Enrico Mattei, and supported by the World Bank, Sardinia, September 19-20, 2003
- (lxviii) This paper was presented at the ENGIME Workshop on “Governance and Policies in Multicultural Cities”, Rome, June 5-6, 2003
- (lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference “The Future of Climate Policy”, Cagliari, Italy, 27-28 March 2003
- (lxx) This paper was presented at the 9th Coalition Theory Workshop on "Collective Decisions and Institutional Design" organised by the Universitat Autònoma de Barcelona and held in Barcelona, Spain, January 30-31, 2004
- (lxxi) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications”, organised by Fondazione Eni Enrico Mattei and Consip and sponsored by the EU, Rome, September 23-25, 2004
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- (lxxvii) This paper was presented at the Workshop on Infectious Diseases: Ecological and Economic Approaches held in Trieste on 13-15 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics.

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