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Information disclosure and dynamic climate agreements: Shall the IPCC reveal it all?

Sareh Vosooghi [a,*], Alejandro Caparrós [b,c]

[a] University of Oxford, Department of Economics, Manor Road, Oxford, OX1 3UQ, United Kingdom
[b] Durham University, Department of Economics and Finance, Durham, DH1 3LB, United Kingdom
[c] Spanish National Research Council (CSIC), Madrid, Spain

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ABSTRACT

This paper examines the role of public information communication in dynamic self-enforcing climate agreements. We consider a framework with implicit contracts but also a dynamic coalition formation context. In a stochastic game, where the social cost of Greenhouse Gasses (GHG) is an unknown random variable, an information sender, such as the Intergovernmental Panel on Climate Change (IPCC), controls the release of verifiable information about the unknown state variable to the countries. The *equilibrium* communication strategy of the IPCC takes a threshold form, above which the IPCC reveals all the information available, even if it hurts the prospect of approaching the socially optimum level of emissions. The case where the IPCC remains silent, below the threshold, vanishes as the sender gets perfectly informed about the underlying social cost.

1. Introduction

Climate change is one of the main problems faced by humanity and it is by now clear that global cooperation is needed to mitigate human-induced climate change (Stavins et al., 2014). However, climate change is also a problem in which uncertainty is prevalent (Masson-Delmotte et al., 2018). Although the physical basis of climate change is now well established, there is wide disagreement among economists about the magnitude of the social cost of GHG.[1] In this context, the role of the Intergovernmental Panel on Climate Change (IPCC) has been key to shape international climate change policy. Its recent 'Global warming of 1.5 °C' report has been particularly influential (Masson-Delmotte et al., 2018). The IPCC regroups a significant share of the leading scientists working on climate change and it summarises and assesses the information available on climate change. The IPCC prepares reports to inform the governments of the world and it is supposed to be 'policy-relevant but not policy prescriptive'. Hence, it does not propose a precise course of action, as governments are supposed to do this. Instead, it clarifies the underlying science of the problem, including its underlying economics.

The questions that we are asking is as follows: does the IPCC always convey all the information that it has? If this is not always the case, and an institution meant to inform the public has under some circumstances incentives to withhold information, the suspicions

* Corresponding author.
E-mail addresses: sareh.vosooghi@economics.ox.ac.uk (S. Vosooghi), alejandro.caparros@durham.ac.uk (A. Caparrós).

[1] According to the recent survey and meta-analysis by Wang et al. (2019), the range of estimates varies from 13.36 to 2386.91 dollars per ton of CO_2, with a mean of 54.70 dollars per ton of CO_2 (see also Nordhaus, 2014).

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of some country leaders in the reports produced by the IPCC could be justified,[2] especially because the goals of individual countries would not necessarily be aligned with the social-planner-like goal assigned to the IPCC in this paper.

To answer this question, we build a stochastic dynamic public-good game where the countries, by contributing to GHG emission abatement, try to mitigate the losses from climate damages. There is uncertainty about the social cost of GHG. At the beginning of the game, the IPCC receives private information regarding the true value of this parameter, although this information is not necessarily perfect. We assume that, as a UN body, the IPCC's ultimate goal is to bring the world's climate policy to the social optimum.[3] We further assume that the IPCC cannot fabricate messages, as this would be verifiable by a third party and would lead to severe punishment, in this case to a loss of prestige and reputation of the organisation and the scientists involved. Hence, we focus on 'verifiable' information disclosure regarding the social cost of GHG by the IPCC. In order to internalise the global externality, the countries try to internationally coordinate their emission abatement decisions. We consider two alternatives, as detailed below, either countries can sign an implicit agreement or they can form climate coalitions. Finally, countries choose their emission abatement levels consistent with their agreement (if any).

If the IPCC were perfectly informed about the underlying state variable, we confirm that the sender cannot suppress any information (the standard unravelling result in information economics, see Milgrom (1981) or Grossman (1981)). However, in a complex problem like climate change there is no reason to assume that the IPCC is perfectly informed. If the IPCC is not perfectly informed, there is a clearly defined threshold above which the IPCC has to reveal all the information in the unique equilibrium, while it remains silent below this threshold. For the case where revealing the true information brings the outcome of the game closer to the social optimum, the IPCC always reveals the true value, as expected. For the case where revealing information hurts the prospect of approaching the outcome of the countries' interaction to the social optimum, the IPCC *sometimes* chooses to be silent. This latter possibility vanishes as the IPCC becomes increasingly informed about the uncertain social cost and chooses full revelation in all cases.

In our analysis we assume that the IPCC has to decide whether or not to disclose a particular piece of information. This assumption is particularly suited for modelling the work of the IPCC, as its mandate is to review and assess the literature on climate change, not to produce new research. Hence, scientists in the IPCC can only decide whether or not they are going to include in their assessment the results of a particular published article. Although in modelling terms we assume that the IPCC receives *private* information, it is fair to accept that the information obtained by the IPCC is not truly private, as it is based on scientific publications. Thus, a more adequate interpretation is that the IPCC has to decide whether or not to use its megaphone to inform (or not) policymakers, and the general public, about a particular piece of information, which is known to the scientific community, i.e. the IPCC is effectively deciding which information to pass on to the policymakers.

As already mentioned, we consider two very different frameworks: one where countries can sign implicit agreements, under the assumption that the punishment for not following the internationally agreed path will be reversion to business-as-usual (BAU), and a coalition formation setting, where if one country abandons an international agreement the remaining countries will continue cooperating.[4] In other words, we consider what is probably the harshest punishment that is *feasible* in practical terms among countries but also the weakest possible punishment. Analysing the conditions for the revelation of information in the latter framework is particularly relevant, as the literature on coalition formation has shown that learning may have negative impacts in the context of climate change (see the next section for details). The results detailed above are qualitatively similar in both frameworks, although the channels through which they occur are different.

The remainder of the paper is organised as follows. Section 2 discusses our contribution in relation to the literature; while Section 3 presents the framework and two benchmarks. Then, the model is analysed under the two frameworks of the implicit agreement and the coalitional agreement in Sections 4.1 and 4.2, respectively. We then examine the role of learning and the information communication by an information sender in Section 5, and check the robustness of our results to alternative assumptions in Section 6. Section 7 concludes and discusses some directions for future research. For proofs, we refer the reader to the Appendix.

2. Related literature

The economics of climate change and IEA has been extensively studied in recent decades. Here we are interested in game theoretic approaches and especially in non-cooperative analyses of IEAs.[5] Most authors in the field believe that in the absence of a supra-national authority, the agreements should be self-enforcing, although there are different interpretations of what this means.

One strand of the literature focuses on implicit agreements that can be sustained with a threat of a reversion to a punishment path (Long, 2011, reviews the literature on dynamic renewable games). To name a few, Dutta and Radner (2009), using dynamic climate change models, characterise the set of subgame perfect equilibrium emissions given reversion to BAU and reversion to the

[2] Donald Trump, the President of the US, accused climate scientists of having a political agenda after the release in 2018 of the Global warming of 1.5 °C report, see https://www.bbc.com/news/world-us-canada-45859325.

[3] Scientists taking part in the IPCC are nominated by countries, but only a subgroup of them is finally selected by the IPCC bureau. The selected scientists produce their reports almost without any government intervention and only the 'Summary for Policymakers' is formally discussed with government representatives. As scientists participating in the IPCC see themselves as representing science and not particular governments, it is reasonable to assume that their goal is to minimise the gap between the world's climate policy and the social optimum.

[4] The possibility of leaving an agreement without expecting a reversion to BAU appears to be adequate for international environmental agreements, as countries rarely break up an agreement because one country leaves; for example, when Canada abandoned the Kyoto Protocol, the agreement did not break up.

[5] See Finus and Caparrós (2015) for a collection of the most relevant articles on this topic.

worst equilibrium. Dutta and Radner (2006, 2012) derive the set of sustainable equilibria given BAU reversion, in models which allow technological change and capital accumulation, respectively. This branch of the literature focuses on deterministic models, and we introduce learning and information communication to this strand of implicit climate agreements.

Another set of papers use a coalition formation framework to analyse IEAs, typically assuming that only one coalition (IEA) can form. Here, if a country considers abandoning an agreement, it expects that the remaining countries will continue cooperating at their optimal level, but without any form of retaliation. This assumption was originally proposed in the context of cartel formation and was introduced in the IAE literature on coalition (agreement) formation by Carraro and Siniscalco (1993) and Barrett (1994). Given the dynamic nature of our model, the closest precedent can be found in Battaglini and Harstad (2016), which generalises the internal and external-stability concept of coalition formation to a dynamic setting (see also Rubio and Ulph, 2007).

Out of the vast literature on coalition formation and IEAs, the most relevant papers for our analysis are those focused on learning. The most cited paper in this strand is Na and Shin (1998) which discusses negotiations for coalition formation in a static model of three countries. This paper has been extended by many authors. The earlier literature generally concluded that there is an adverse effect of learning on abatement efforts (Na and Shin, 1998). However, Kolstad (2007) and Finus and Pintassilgo (2013), who have more general models, show that this effect of learning is not a general rule. (In terms of the impact of learning on outcome, our results are in line with the two last papers just mentioned, as different cases may arise.) All this literature deals with uncertainty in perfect (and complete) information setups, where learning is perfect, so that no uncertainty remains. Uncertainty is resolved either after countries decide about their membership in the IEA, 'no learning', or before membership decisions have been taken, 'full learning' (Kolstad and Ulph, 2008; Finus and Pintassilgo, 2013, analyse what they call 'partial learning', but this scenario refers to perfect learning that occurs after membership decision have been taken and before abatement decisions are taken). We generalise these analyses in two directions. First, we allow learning to be imperfect, i.e. countries can hold interior posterior beliefs and the transmission of information can be noisy. We also consider a situation in Section 6.3, where the imperfect learning by countries is due to imperfect learning by the sender. Secondly, by adding an information sender to an IEA game, signals and learning become endogenous, and we find the equilibrium learning outcome of the interaction of countries and the information sender under the two IEA settings discussed above.

Caparrós and Péreau (2017) is another paper with links to the analysis presented here, as they analyse the role of a mediator, or a facilitating agency, in promoting cooperation. This is done in a gradual coalition formation context where the multilateral bargaining process is explicitly modelled. However, their mediator only governs the time that elapses between negotiations and offers, and has, therefore, no control over the transmission of information.

The role of asymmetric information in IEA has been analysed in Caparrós et al. (2004), Jakob and Lessmann (2012), Slechten (2020) and others. In these papers, information transmission is part of the strategic behaviour of the countries, while here we do not study asymmetric information across the countries, but between the information sender and the countries.

The paper is also related to the literature studying contributions to public goods in the presence of uncertainties (Gradstein et al., 1992 and 1993), although in this literature the focus is on the impact of uncertainty on the interrelated decisions of the agents, and not on the role of an information sender. Closer to our paper is the broad literature on transmission of information by an informed sender, and more specifically the verifiable-disclosure literature. In contrast to the cheap-talk or 'soft-information' literature, here we examine the communication of 'hard information'. Thus we assume any false revelation by the information sender can be detected and severely punished. Classic papers in this strand of literature are Milgrom (1981) and Grossman (1981), which show that the sender cannot withhold any information in equilibrium if s/he is perfectly informed (the 'unravelling' result).

Shin (1994, 2003), Okuno-Fujiwara et al. (1990) and Milgrom (2008) generalise the verifiable disclosure analysis to situations in which the sender is potentially not informed either, showing that the information sender may withhold information under certain circumstances in this context. These papers typically analyse interactions between a seller (sender) and a buyer, and discuss the potential role of liability rules or direct regulation by the government (the central planner). We extend their results to a dynamic public-good game. In our case the central planner is not regulating the sender, as the sender is essentially the central planner. Yet, even in this context we find that the sender withholds information under some circumstances. We also show that this holds in a framework with reversion to BAU and also in a coalitional formation framework, despite the fact that many relevant results do not hold in both settings. This requires showing the relation between learning and abatement in our context, which was not obvious given the results on learning in a coalition formation framework discussed above.

Finally, in Section 6.3 we move away from the framework reviewed in Milgrom (2008) and discuss the implications of using a Bayesian persuasion framework á la Kamenica and Gentzkow (2011) in our context. We study a situation where the sender at the stage of setting it communication strategy does not have any private information about the social cost, and can never observe the true social cost perfectly. But by gathering information, the sender can acquire more precise information, which it can eventually communicate to the countries. Although there is not a unique equilibrium strategy is such a case, we show that full revelation of the state can be one of the equilibrium strategies and that in any case the sender never gains from communication.

3. The model

Countries, indexed $i \in N$, choose their emission abatement levels, q_{it}, where time index is $t = 0, 1, 2, \dots$ and the set of countries is $N \equiv \{1, 2, \dots, n\}$. Their abatements contribute to a reduction in the total stock of GHG in the next period. The stock of GHG has the following equation of motion,

$$Q_{t+1} = \delta Q_t + \Psi - \sum_i q_{it} \tag{3.1}$$

where Q_t is the GHG in period t, $(1-\delta)$ is the rate of decay of GHG, and $0<\delta<1$. Assume the initial level of GHG, Q_0, is given. Furthermore, Ψ is the unabated emission of GHG, and we assume it is a constant over time. By $\mathbf{q}_t=(q_{1t},q_{2t},\dots,q_{nt})$, where $q_{it}\in \mathrm{IR}_+$, we refer to the vector of pollution abatements undertaken by the countries and it can be interpreted as an investment in abatement technologies, green technologies, or reforestation to reduce the emission of GHG. In fact, $\Psi-\sum_i q_{it}$ is the actual emission level, and $\mathbf{q}_t$ can be targeted quantitatively by the countries in a climate mitigation policy. From this point on, we refer to q_{it} as the abatement level.

In the dynamic game, where the stock of GHG changes over time, the countries minimise their expected discounted loss function, which is additive separable in the total stock of GHG, and the private cost of abatement. The flow loss function is

$$\Pi_{it}=C(q_{it})+\gamma Q_t \tag{3.2}$$

where $C(.)$ refers to the private cost of emission abatement, which is independent of i. In addition, γ is the marginal social cost of GHG, in the literature it is also known as the cost ratio parameter.[6] We assume that the choice variable q_i belongs to intervals in IR_+. Furthermore, the common discount factor is $0<\beta<1$.

Similar to most stochastic IEA literature, we focus on uncertainty about the marginal social cost of GHG, representing the uncertainty about the costs of catastrophic events caused by climate change and the global warming consequences.

Assume that in period zero nature draws a random $\gamma\in\Gamma$ for all countries from one commonly-known distribution from $[0,1]$. Countries know that the stochastic state variable is constant, but they do not observe its true realisation.

The countries have a public belief about the value of the marginal social cost of GHG, $\mu(\gamma)$, which leads to their common expectation about it, $\mathbb{E}_\mu(\gamma)$. At the beginning of the game, and in the absence of any communication, $\mathbb{E}(\gamma)$ is the public prior about γ, which is simply its mean and is common knowledge.

Moreover, we assume that $C(.)$ is a strictly increasing and strictly convex function, with $C(0)=0$. In other words, $C'(.)>0$, also $C''(.)>0$. Therefore, $C'^{-1}(.)$ is a function.[7]

The assumptions detailed above imply additive separability and linearity of the equation of motion of GHG and the loss function. This is fairly standard in the climate-change literature, and provides a tractable framework.

We assume that the countries at the end of each period observe the individual actions, so the deviations can be detected unambiguously, and it is a perfect-monitoring repeated game. There is no private information, and public history includes all past actions and the initial value of GHG. For simplicity, it is assumed that the countries take action simultaneously, hence we abstract from any social learning or any leader–follower interactions within each period.

In our infinite-horizon game, the equilibrium concept that we use is Perfect Bayes Nash equilibrium (PBNE).[8]

As already mentioned, we consider two settings. In the first setting, countries sustain PBNE payoffs such that deviations are punished by a reversion to BAU. By BAU abatement, we refer to equilibrium strategies where all countries choose best response to each others abatement strategies in each history. We label this setting as the 'implicit- contract' setting. In the second setting, countries enter into an agreement by joining a climate coalition. The agreement specifies that the members of the coalition will determine their abatement levels cooperatively; the duration of the agreement is also determined endogenously.

Before moving to a detailed presentation of the two settings, we derive two benchmarks which are relevant in both settings.

3.1. *The socially-optimal abatement*

A potential social planner would choose a sequence of $\{q_{it}\}_{t=0}^{\infty}$ to minimise the discounted sum of the losses of all countries, that is

$$\sum_{t=0}^{\infty}\beta^t\sum_i x_i[C(q_{it})+\mathbb{E}_\mu(\gamma)Q_t] \tag{3.3}$$

such that the equation of motion in (3.1) holds. In addition, $x_i>0$ for every i, and it signifies weight of country i in the social welfare, where the weights are normalised such that $\sum_i x_i=n$, so we refer to x_i as the Pareto share of country i.

The solution to this problem is referred as the socially-optimal abatement, $\mathbf{q}^s$. The problem has a recursive structure and the standard dynamic programming tools can be applied. The socially optimal level of abatement, q_i^s is

$$q_i^s=C'^{-1}(\frac{\beta B^s}{x_i}) \tag{3.4}$$

where $B^s=\frac{n\mathbb{E}_\mu(\gamma)}{1-\beta\delta}$. Also, with a utilitarian social planner, i.e. if $x_i=1$ for all i, then there is a unique 'symmetric' solution such that $q_i^s=q^s$ for all i. However, in a general approach, we allow for asymmetric weights in the social loss function, to capture the potential asymmetry of importance of countries in international arena by factors which are not captured in our model.

[6] If the flow loss function is $\hat{\Pi}_{it}=\hat{a}_iC(q_{it})+\hat{b}_iQ_t$, then $\Pi_{it}\equiv\frac{\hat{\Pi}_{it}}{\hat{a}_i}$ and the cost-ratio parameter is $\gamma_i\equiv\frac{\hat{b}_i}{\hat{a}_i}$.

[7] Na and Shin (1998) and Finus and Pintassilgo (2013), assume $C(q_{it})=\frac{q_{it}^2}{2}$. They study coalition formation in static and two-period models, respectively.

[8] In a finite-horizon model, using backward induction, and given the loss is increasing in the abatement level, in the last period, zero abatement is the dominant action for all countries. So, independent of whether one deviates in the previous period or not, they will choose zero abatement in the last period. Therefore, there is no credible punishment available and non-interestingly no history-dependent strategy can sustain a positive amount of abatement.

Given the assumptions about the private abatement cost function, $\mathbf{q}^s$ is unique, for any given Pareto share, x_i. The policy is stationary and independent of the stock of GHG.[9]

Let us define the 'Pareto frontier' as $\{\mathbf{q} \mid \mathbf{q} = \mathbf{q}^s$, for all $x_i > 0$, for all $i \in N$, where $\sum_i x_i = n\}$.[10] In general and given any symmetric or asymmetric Pareto share, the resultant Pareto frontier is a hypersurface of dimension n.

3.2. The BAU abatement

Taking the action of the others as constant and minimising their own loss, obtains the BAU abatement, $\overline{\mathbf{q}}$. Choosing the BAU abatement, in every history is the history-independent strategy of the game and it is a Markov perfect equilibrium (MPE). In other words, when the other countries use history-independent strategies, a country's best response is also history independent, so it is an equilibrium for every country to take the BAU abatement in every history. Again the solution is unique and the BAU abatement level, $\overline{q}_i$ is

$$\overline{q} = C'^{-1}(\beta\overline{B}) \tag{3.5}$$

where $\overline{B} = \frac{\mathbb{E}_\mu(\gamma)}{1-\beta\delta}$. In addition, under the assumption of public belief, $\overline{\mathbf{q}}$ is a *symmetric* equilibrium.

Moreover, by restricting attention to the history-independent strategies, the reaction functions of the countries are independent of each other's abatements. In other words, the BAU solution, as a history-independent strategy, is a dominant strategy. Indeed, the uniqueness of the BAU solution is a result of the orthogonality of reaction functions at $\overline{\mathbf{q}}$. This property relies on marginal benefit and marginal cost of abatement being independent of stock of pollution.

Since $C(.)$ is increasing and strictly convex, the inverse of its first derivative is an increasing function as well. Therefore, q^s is strictly larger than $\overline{q}$, for all parameter values. This is because under BAU each country fails to take into account the positive externality of its own abatement.

4. Self-enforceable IEAs

4.1. Implicit contract

4.1.1. The set of sustainable abatement levels as PBNE

In this section, we derive the set of expected payoffs and associated abatement levels which can be sustained as PBNE payoffs when deviations are punished by reversion to the BAU abatement from the next period. This provides us with the first dynamic IEA setting for our analysis, and so we examine the relevant properties of this set. Reversion to BAU is not the worst punishment, but seems to be the strongest punishment that can be feasible in practice.[11]

Here, we derive the incentive-compatibility constraint of adopting a general stock-independent abatement level, $\mathbf{q} = (q_1, q_2, \dots, q_n)$.

Lemma 1. *The loss of abating according to* $\mathbf{q}$*, can be sustained as a PBNE loss, by the trigger-type stationary strategy profile of playing* q_i *at all subgames at which there has not been a deviation from* $\mathbf{q}$ *in the past, and playing* $\overline{q}_i$ *otherwise, if for all* i

$$C(q_i) + \beta A - \beta B q_i \leq C(\overline{q}_i) + \beta\overline{A} - \beta\overline{B}\overline{q}_i \tag{4.1}$$

where B*,* A *and* $\overline{A}$ *are constants defined in the Appendix.*

Moreover, the minimum sustainable abatement level is clearly the BAU abatement. This implies that the Individual-Rationality constraint of countries is satisfied too.

In order to verify the set of sustainable abatement levels as PBNE abatements, let us define IC_i as the combination of abatement levels which are incentive-compatible for country i, given the trigger strategy specified above,

$$IC_i \equiv \{\mathbf{q} \mid C(q_i) + \beta A - \beta B q_i - C(\overline{q}_i) - \beta\overline{A} + \beta\overline{B}\overline{q}_i \leq 0\} \tag{4.2}$$

Because of the strict convexity of $C(q_i)$, $C(q_i) + \beta A - \beta B q_i - C(\overline{q}_i) - \beta\overline{A} + \beta\overline{B}\overline{q}_i$ is strictly quasi convex, and thus set IC_i is strictly convex. In addition, we define set IC_i^0 for every i as

$$IC_i^0 \equiv \{\mathbf{q} \mid C(q_i) + \beta A - \beta B q_i - C(\overline{q}_i) - \beta\overline{A} + \beta\overline{B}\overline{q}_i = 0\} \tag{4.3}$$

Indeed IC_i^0 is a level set such that (4.1) binds for country i, and it is strictly convex. For any country i, any combination of abatements $\mathbf{q} \geq \overline{\mathbf{q}}$, which are on the lower contour sets inside IC_i^0 satisfy the incentive-compatibility of country i. Let us call these combinations of abatements D_i for i, and the intersection of all D_i sets D. Indeed, adoption of any abatement level $\mathbf{q}$ in the closure of D is a PBNE abatement strategy and the resulting loss sustains a PBNE loss under the threat of BAU reversion.

[9] This is also seen by Dutta and Radner (2009).

[10] Indeed, it is the set of abatements which correspond to the Pareto frontier in the loss space. An example of the Pareto frontier of two countries with quadratic private cost is plotted in Fig. 1.

[11] See Dutta and Radner (2009) for more discussion on the set of SPE of emission levels.

Let us call the derivative of $\frac{dq_i}{dq_j}$ along IC_i^0 the marginal rate of compliance of country i with country j, MRC_{ij} for any $j \neq i$. In fact, MRC_{ij} is the amount of increase in q_i which is incentive-compatible for country i, following an infinitesimal increase in the abatement of country j, where other coordinates are constant. In the Appendix it is shown that IC_i^0 for all i at the BAU level of abatements are orthogonal.

It has already been discussed that D is non-empty because $\overline{\mathbf{q}}$ is the minimum abatement level and always sustains a PBNE by the threat of BAU reversion. The following proposition shows that for all parameter values of the model, the countries can sustain levels of abatement which are strictly larger than the BAU.

Proposition 1. *Set D is non-singleton, for any $\beta > 0$.*

Intuitively, the orthogonality of IC_i^0 for all countries at the BAU level implies that at the least incentive-compatible policy level, i.e. at $\mathbf{q} = \overline{\mathbf{q}}$, for any $j \neq i$, when country j increases its abatement level, the amount which country i can increase its abatement and is incentive compatible for i itself is more than the increase in q_i in order to keep country j incentive compatible, i.e. $MRC_{ij} > MRC_{ji}$. This guarantees the existence of some larger level of abatement which is incentive-compatible for all countries.

We are not restricting the equilibrium of the symmetric game to necessarily be symmetric, as symmetric countries can sustain asymmetric levels of abatement in set D.

4.1.2. Equilibrium selection from the set of sustainable PBNE under the threat of BAU

Given Proposition 1, at two levels of abatement the incentive compatibility constraints of all countries bind. One is the BAU abatement (the minimum sustainable point) and the other one is the maximum sustainable abatement, say $\hat{\mathbf{q}}$. Similar to the BAU abatement, the maximum sustainable abatement belongs to IC_i^0 of each country. In fact, beyond some certain level of abatements, for each i its gains and its losses of abating according to $\hat{q}_i$, versus the BAU level, will be equal.

Lemma 2. *$\hat{\mathbf{q}}$ is finite.*

Again, although we are not imposing any symmetry restriction on the equilibrium abatements, with the assumption of public belief, $\hat{\mathbf{q}}$ is symmetric.

Any abatement in set D can be an equilibrium and if countries agree on it, they will not deviate from it. Among the range of incentive-compatible abatements, the countries choose an equilibrium which minimises their joint long-run loss function. Explicitly,

Assumption 1. Under the implicit-contract setting, the countries minimise their joint expected loss.

Assuming that for the joint loss function, the countries use the same weights as the social planner, i.e. the Pareto shares, the countries minimise (3.3) over the set D. For the symmetric game, the chosen abatement level, $\mathbf{q}^c$, is unique for n countries.

If the Pareto frontier crosses set D, and $\mathbf{q}^s \in D$, then $\mathbf{q}^c = \mathbf{q}^s$. However if for a given Pareto share, $\mathbf{q}^s \notin D$ (where the Pareto frontier may or may not have intersection with D), then the countries choose an abatement level on the boundary of D (as a corner solution). In other words, if $\mathbf{q}^s$ is not incentive compatible for i, but it is for some $j \neq i$, then $\mathbf{q}^c \in IC_i^0$ such that (3.3) is minimised.[12] Let us call such an equilibrium abatement $\mathbf{q}^B$, referring to the boundary solution.[13] Note that $\mathbf{q}^B$ includes $\hat{\mathbf{q}}$, for example if the Pareto frontier does not have any intersection with set D. Thus, in general, $\mathbf{q}^c \in \{\mathbf{q}^s, \mathbf{q}^B\}$. If the game is symmetric, i.e. if $x_i = 1$ for all i, then $\mathbf{q}^c$ is symmetric as well.

Fig. 1 illustrates an example for two countries, 1 and 2, where $\mathbf{q}^s \notin D$. Let $x_1 \ll x_2$ (using a quadratic cost function for concreteness[14]). First, note that in the two-dimensional space of abatements, the hypersurfaces of IC^0 are reduced to curves and the hyperplanes of BAU are two orthogonal lines. The shaded area is set D, formed by the intersection of the two sets D_1 and D_2. Also, it is clear that at $\overline{\mathbf{q}}$, the IC^0 of two countries are tangential to the line of the BAU abatement of the other country, where $MRC_{1,2} \to \infty$ and $MRC_{2,1} = 0$. Thus, strictly convex IC^0 of the two countries have two intersections, $\overline{\mathbf{q}}$ and $\hat{\mathbf{q}}$. In addition, the Pareto frontier (P.F in the figure), which is different combinations of $\mathbf{q}^*$ as Pareto shares vary, is here a hyperbola above the BAU lines. Because it is assumed that $x_1 \ll x_2$, $q_1^s \gg q_2^s$, and as drawn $q_1^s \notin D_1$. In other words, in this example it is assumed that country 1 cannot sustain the social optimum. Therefore, the chosen equilibrium, $\mathbf{q}^c$, is a boundary policy, denoted on the diagram as $\mathbf{q}^c = \mathbf{q}^B$, and it belongs to IC_1^0, where here $q_2^c > q_2^s$.

[12] This implies that it may happen that country j should abate more than q_j^s, however as long as it is incentive compatible for j, they agree on an abatement which minimises the joint loss. This is because of the strict quasi-convexity of the optimal loss function of the social optimum problem, defined in the Appendix as $V^s(Q_t)$.

[13] See Fig. 1 for an example of this case.

[14] Assume $C(q_i) = \frac{q_i^2}{2\varphi}$, where φ is an exogenous parameter affecting the private abatement cost and $0 < \varphi \leq 1$. If $\gamma_i = \gamma$ for both countries, then $q_i^s = \frac{2\beta\gamma\varphi}{x_i(1-\beta\delta)}$, $\overline{q}_i = \frac{\beta\gamma\varphi}{1-\beta\delta}$ and $\hat{q}_i = \frac{\beta\gamma\varphi(2\beta+1)}{1-\beta\delta}$.

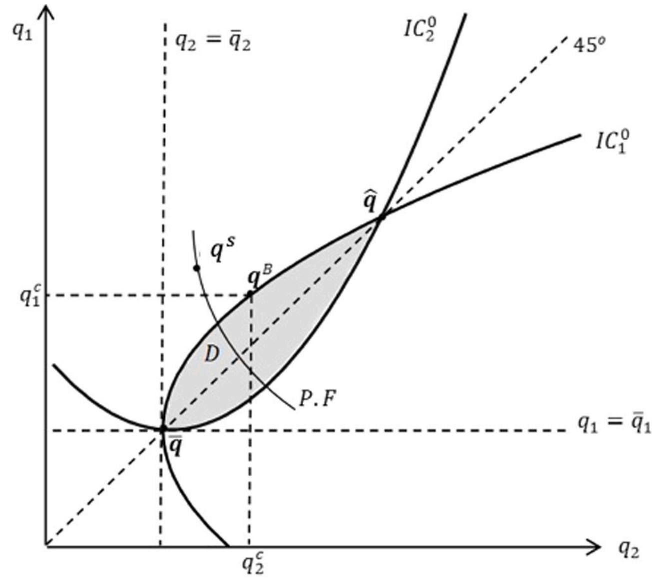

Fig. 1. Equilibrium selection of two countries with asymmetric Pareto shares.

4.1.3. Comparative statics and dynamics with respect to the public belief

According to our model, levels of abatements depend on the functional form of private cost, the discount factor, the decay rate of GHG, and the expected marginal social cost of GHG. All policy levels are increasing in β, δ and γ. Furthermore, as discussed before, MRCs of any two countries depend on these parameters as well. Thus, the set D, which depends on MRCs in addition to the distance of the minimum and maximum sustainable abatements, is positively related to these parameters.

Among all these factors, in the literature on climate change, the social cost of carbon or GHG has received the most attention,[15] and this paper focuses on communication of public information about it. Therefore, in this section, first, we provide some comparative static results specifically for the expected marginal social cost of GHG, $\mathbb{E}_\mu(\gamma)$, on the social optimum, and the BAU abatement.

Given the strict convexity of private cost, $C'^{-1}(.)$ is a strictly increasing function. Therefore, $\frac{\partial q_i^s}{\partial \mathbb{E}_\mu(\gamma)}$ and $\frac{\partial \bar{q}}{\partial \mathbb{E}_\mu(\gamma)}$ are always positive. Thus, as the marginal cost of GHG increases, the Pareto frontier shifts upward and the countries are required to abate more in order to sustain the socially optimal level. This implies that $\mathbf{q}^s$ after the increase in $\mathbb{E}_\mu(\gamma)$ is not sustainable as a PBNE, if it was not sustainable before the increase in $\mathbb{E}_\mu(\gamma)$. Furthermore, $\frac{\partial q_i^s}{\partial \mathbb{E}_\mu(\gamma)} > \frac{\partial \bar{q}}{\partial \mathbb{E}_\mu(\gamma)}$.[16]

Finally, here we examine the comparative dynamics of the stock of GHG with respect to the expectation of the cost-ratio parameter. Given the equation of motion of GHG in (3.1), there is a unique long-run equilibrium (steady-state) of GHG, $\tilde{Q} = \frac{\Psi - \sum_i^n q_i}{1-\delta}$, where q_i is the level of abatement in the long run abatement strategy. The general solution to the difference equation of (3.1) is $Q_t = \delta^t Q_0 + (1-\delta^t)\tilde{Q}$. Recall that $0 < \delta < 1$, thus the stock of GHG converges smoothly to the long-run $\tilde{Q}$, and because $\lim_{t\to\infty} Q_t = \tilde{Q}$ for any Q_0, the stock has global stability. It is plausible to assume that $Q_0 < \tilde{Q}$, thus Q_t over time increases smoothly and converges to $\tilde{Q}$. To check the comparative dynamics of the GHG with respect to the expected marginal social cost of GHG, assume that the countries select a level of abatement, which is increasing in the expected marginal social cost of GHG. Because the abatement levels affect the steady-state of GHG, after the increase in the expected marginal social cost of GHG, and therefore the abatement levels, the long-run steady-state, $\tilde{Q}(\mathbb{E}_\mu(\gamma))$, decreases. Hence, if the current level of stock, Q_t, is above the new steady-state, then the stock along a decreasing convergence path converges to its long-run level. Conversely, the stock increases over time, if it is below the new steady-state.

4.2. Coalition formation

4.2.1. Stages, timing and stability

We introduce now the possibility to form a coalition, building on the deterministic model of Battaglini and Harstad (2016), which provides a dynamic version of the cartel-formation game, widely considered as the workhorse model for the analysis of IEA

[15] It can be argued that the persistence rate of GHG may have a similar importance for policy implications, but, at least in our model, the marginal effect of γ on abatement levels is larger than δ. Furthermore, the scientific basis of δ is better known, while γ is an economic-climate variable and currently there are more uncertainties about it and as stated before, the focus of this paper is on information and learning about the marginal social cost of GHG.

[16] For the quadratic example of $C(q_i) = \frac{q_i^2}{2\varphi}$, actions are linearly increasing in $\mathbb{E}_\mu(\gamma)$.

(Finus and Caparrós, 2015). As most of the literature, see Section 2, we study a single-coalition game, where a subset of countries may join a climate coalition, M, of size $m \leq n$. The coalition formation is reversible and the countries are allowed to renegotiate. The timing of the model is now as follows. In period $t = 0$, the countries receive the public signal, and each period (including period $t = 0$) is divided into three stages. At the coalition formation stage, if there exists no coalition, every country $i \in N$ independently and simultaneously decides whether to become a member of a new coalition, M, while the remaining countries, $N \backslash M$, remain independent. At the negotiation stage, the coalition members first negotiate the duration of the agreement T and the abatement q_{it} that each member of coalition $i \in M$ will perform for all $t \in \{0, 1, \dots, T\}$. Following the standard approach, we assume that the coalition members determine their abatement levels by maximising the aggregate welfare of the coalition, assuming further that, within the coalition, losses are split according to a share w_i for each country, such that $\sum_i w_i = m$. Finally, at the abatement stage every nonparticipant $i \in N \backslash M$ simultaneously and independently chooses its abatement, while the coalition members abate as they had agreed in the negotiation stage. If an agreement already existed at the start of the period, the first two stages are skipped.

Countries assume that if one country leaves the agreement, there will be no retaliation in the form of reversion to BAU. Instead, the remaining countries will abate at the level that is optimal for them (off-the-equilibrium path). This assumption implies that we check a unilateral deviation at the membership stage, i.e. we are looking for the Nash equilibrium strategies at the membership stage. The conditions that no country has an incentive to leave the agreement and that no additional country has an incentive to join it, are known as the internal–external stability and were originally proposed in the context of cartel formation. Although we only consider one-step deviations in the membership stability, there is farsightedness in the abatement strategies in the sense that if a country leaves the coalition, other members will update their abatement actions to a new optimal level in the next period.

We solve the model by backward induction. The non-participants are singletons who take the actions of others as given. This leads to their orthogonal reaction functions and hence their dominant-strategy BAU abatement, while their losses depend on the total stock of GHG, and in turn on the size of formed coalition and its members' abatements. The following lemma determines the equilibrium abatement level of a coalition M^* (the proof can be found in the Appendix):

Lemma 3. *In the coalition formation setting, equilibrium abatement by every member of a coalition of size m^* is given by:*

$$q_{it}^{m^*} = q_i^{m^*} = C'^{-1}\left(\frac{\beta B(m^*)}{w_i}\right) \tag{4.4}$$

where

$$B(m^*) = \frac{m^* \mathbb{E}_\mu(\gamma)}{1 - \beta\delta} \tag{4.5}$$

This shows that a country which has a larger share in the coalition's aggregate loss, abates less than others. If the countries in the coalition are symmetric and have an equal weight, i.e. $w_i = 1$, then they will have symmetric abatements, where $q_i^{m^*} = q^{m^*}$. Therefore, the selected abatement vector of all countries can be shown by $\mathbf{q}^c \in \{\mathbf{q}^{m^*}, \overline{\mathbf{q}}\}$. In addition, as the number of members of the coalition increases, the abatement levels of all members increase. In other words, a larger coalition internalises more of the externality relative to a smaller coalition. Furthermore, it can be verified that if in a period only a coalition of singletons forms, where $m = 1$, the abatements of all countries reduce to the BAU level; and if the grand coalition forms, where $m = n$, the countries choose the socially-optimal level of abatement.

Again, here the abatement levels agreed upon by the coalition members are time-independent (specially independent of T), and they do not depend on the total number of countries, n, either. Therefore, the equilibrium loss function of the coalition members is the same for any length of the agreement(s), as long as $m = m^*$. Their loss indeed depends on both n and m, but the duration of agreements does not affect it. This is the main intuition behind the next lemma which determines the optimal duration of the agreement, T^*. The choice of the duration will depend on the size of the current coalition and on the expectation on what will happen if a country leaves it.[17]

Lemma 4. *In the coalition formation setting, a coalition of size m finds it optimal to contract for $T(m)$ periods, where*

$$T(m) = \begin{cases} 1 & \text{if } m < m^* \\ \{1, 2, \dots, \infty\} & \text{if } m = m^* \\ \infty & \text{if } m > m^* \end{cases} \tag{4.6}$$

and m^* is the size of the equilibrium coalition, M^*.

As mentioned above, if $m = m^*$ any duration of the equilibrium agreement is optimal; while if $m > m^*$ there should be no incentive to renegotiate the length of the agreement. If $m < m^*$, by increasing T under such a situation, the continuation loss of the coalition members increases, implying that they should renegotiate next period. In other words, when one country deviates and abandons an agreement, the duration is set to only one period, because the country is expected to join the equilibrium agreement again in the next period and the loss will be lower. Thus, countries remaining in the coalition reduce their abatement level to $q_i^{m^*-1}$, but only for one period. Note that the (off-equilibrium path) punishment period is endogenous here, and it implies the weakest possible

[17] The proof of Lemma 4 closely follows Battaglini and Harstad (2016), and so it is omitted here.

punishment, and in this sense, the two settings of implicit contracts (with the BAU punishment) and the coalition-formation that we consider represent extreme situations regarding the punishment paths.

This, in turn, leads to the next lemma on the membership strategies. When deviating, e.g. at period t, player i reduces its cost to $C(\bar{q}_{it})$ for one period and based on Lemma 4 will return to the coalition of size m^* the next period, but that changes the future path of Q_t permanently.

A member of the coalition, $i \in M^*$ in period t does not leave the coalition if:

$$\mathbb{E}_\mu V(Q_t^*(m^*, T^*)) \leq \left[C(\bar{q}_{it}) + \mathbb{E}_\mu(\gamma) Q_t\right] + \sum_{\tau=t+1}^{\infty} \beta^{\tau-t} \left[C(q_{i\tau}^{m^*}) + \mathbb{E}_\mu(\gamma) \overline{\overline{Q}}_\tau\right], \tag{4.7}$$

where $\overline{\overline{Q}}_{t+1}$ is the GHG stock in the period following the deviation. Let us define Λ as the difference in the total stock of GHG between the deviation scenario and the case with no deviation, i.e. $\Lambda \equiv Q_{t+1}(m^*, T(m^*)) - \overline{\overline{Q}}_{t+1}$, where $Q_{t+1}(m^*, T(m^*))$ denotes the emission path for a succession of agreements (coalitions) of size m^* and duration $T(m^*)$ (as defined in Lemma 4). Indeed, Λ is the difference in the net emissions in year t between the two scenarios. In other words,

$$\Lambda = \left(\Psi - \sum_{k=1}^{n-m^*} \bar{q}_{kt} - \sum_{j=1}^{m^*} q_{jt}^{m^*}\right) - \left(\Psi - \sum_{k=1}^{n-m^*+1} \bar{q}_{kt} - \sum_{j=1}^{M^*-1} q_{jt}^{m^*-1}\right) \tag{4.8}$$

$$= q_{it}^{m^*} - \bar{q}_{it} + \sum_{j=1}^{m^*-1} \left(q_{jt}^{m^*} - q_{jt}^{m^*-1}\right) \tag{4.9}$$

or, if the countries in the coalition are symmetric in the sense that $w_i = 1$, then Λ simplifies to:

$$= q_{it}^{m^*} - \bar{q}_{it} + (m^* - 1)\left(q_{it}^{m^*} - q_{it}^{m^*-1}\right). \tag{4.10}$$

Recall that the equilibrium net emissions at any future time are independent from the stock in our model. Thus, at any period $\tau > t$, the new path $\overline{\overline{Q}}_\tau$ can be written as $\overline{\overline{Q}}_\tau = Q_\tau(m^*, T(m^*)) + \delta^{\tau-t-1}\Lambda$.

Given this fact, condition (4.7) simplifies to the following rule to determine the equilibrium size of the coalition:

Lemma 5. *In the coalition formation setting, M^* is an equilibrium coalition if*

$$C(q_{it}^{m^*}) - C(\bar{q}_{it}) \leq \frac{\mathbb{E}_\mu(\gamma)\beta\Lambda}{1 - \beta\delta} \text{ for all } i \in M^* \tag{4.11}$$

The proof is in the Appendix; and intuitively, a coalition can only be stable if what members would gain from leaving the coalition (the reduction in the short-run cost shown at the LHS of condition (4.11)), is less than or equal to the discounted value of the long-run impact of the reduced abatements and hence the increased GHGs in our infinite-horizon model (the RHS of condition (4.11)).

4.2.2. Comparative statics with respect to the public belief

Parallel to the implicit-agreement setting, here, we examine the effect of an increase in the expected marginal social cost of GHG on the abatements and the stability of the climate coalition.

If the expected marginal social cost of GHG increases, the abatement levels of the members of the coalition, and that of the nonparticipants increase. This result shows the potential role of learning and information transmission about this parameter even on the free riders. More importantly, an increase in $\mathbb{E}_\mu(\gamma)$ can affect the internal stability condition in (4.11).

Proposition 2. *Assume $w_i = 1$ for all i. If the expected marginal social cost, $\mathbb{E}_\mu(\gamma)$, increases, the deviation from the climate coalition becomes less attractive.*

Therefore, if $\mathbb{E}_\mu(\gamma)$ increases, by increasing the long-run impact of deviation more than its short-run gains, the sufficient condition of coalition stability becomes less binding, i.e. it is satisfied more easily. Therefore, the members of a coalition find the deviation less worthwhile.

Condition (4.11) indeed determines m^*, and although an increase in $\mathbb{E}_\mu(\gamma)$ affects the deviation incentives, we are conscious that changing the public belief may or may not affect the coalition size because it depends on the functional form of the cost.[18]

5. Communication about the social cost of GHG

In both IEA settings, we showed that in the absence of any communication and given the prior belief, the countries may not be able to achieve the socially-optimum level of abatements.

Assume that the countries, by receiving a public signal, can learn about the state variable. By learning, we mean that the countries receive (or do not receive) a public signal and update their prior belief according to the Bayes rule. From the comparative-static

[18] For example, with the specific but conventional quadratic cost function, $C(q_i) = \frac{q_i^2}{2\varphi}$, or an exponential cost function, $C(q_i) = e^{q_i}$, the internal stability conditions and therefore the size of stable coalition are independent of the belief, but this is not a general result.

exercise, we have already highlighted how the chosen abatement level of countries changes as $\mathbb{E}_{\mu}(\gamma)$ varies. Based on Proposition 2, the membership condition depends on the state variable, so in our model, the communication of information has a direct affect on the coalition formation, in addition to its effect on the selected abatement levels and indeed the aggregate loss of the countries.

In this section, we examine an information-transmission game between the IPCC, as an information sender, and the countries. We make three main assumptions here: first, we assume that the information communication is verifiable by a third party and any fabrication of information is credibly punished. Second, similar to Shin (1994), Okuno-Fujiwara et al. (1990) and Milgrom (2008), we suppose that the countries believe that the sender may not necessarily learn the state. However, in contrast to them, here we have a dynamic public good game among the receivers, who interact either in implicit contracts or in coalitions. Lastly, we restrict attention to situations that communication of information happens only once and that is at the beginning of the game. This is not without loss of generality, but for the moment it is sufficient to investigate the possibility of affecting the abatement levels with disclosure of verifiable public information. In Section 6.1 we find the optimal time of communication.

We assume that the information sender tries to affect the beliefs of the countries in order to induce a particular action, i.e. an abatement level which has the minimum distance from the true socially optimal level. In addition, we assume that gathering information and communication are costless for the sender. Also, once the information is provided publicly, acquiring it is free for the countries.

Suppose at the beginning of period $t = 0$, the information sender may privately observes the true social cost of GHG: the sender receives signal $r = \gamma$ with probability θ, and $r = \phi$ with probability $1-\theta$. Signal $r = \phi$ implies that the sender does not learn anything. If the sender does not learn, it cannot certify it. And, the countries never know what signal the sender has privately observed about the social cost. Furthermore, assume $0 < \theta \leq 1$ and that its value is common knowledge. As discussed in the introduction, in our context 'privately observed' means observed by the scientific community represented by the IPCC but not known to policymakers and the general public. The (degenerate) belief of the sender is not known by the countries, and they do not learn about the true state, in the absence of the sender. In other words, their only source of information is the sender. Furthermore, payoffs of both parts are common-knowledge, and so, the sender knows the common prior and the countries payoff functions and the equation of evolution of GHG.

Given the verifiable disclosure assumption, the information sender can never report any false information, so it is constrained to a certain set of strategies. In this subsection, we focus on a binary information strategy, where at the beginning of the game, after having privately observed signal r, the sender decides whether to reveal the state or not. Let $\alpha(.)$ denote the probability of sending a fully revealing signal to the countries, given the information of the sender. More specifically, the information strategy of the sender is a map, $\alpha : \{\Gamma, \phi\} \to \{0, 1\}$, where $\alpha(.) = 1$ refers to revealing the true state, and $\alpha(.) = 0$ denotes being silent. The sender, conditional on observing the state and choosing the strategy of revealing it, sends a precise public signal $y = \gamma$. Let $y \in Y$, where the set of public signals is Y, and $Y = \Gamma$. Furthermore, the information strategy and the set of signals are given to the sender and they are not choice variables.

Then at the end of period $t = 0$, before any membership or abatement decision, the countries given the information action of the sender and (possibly) the signal realisation, update their common prior to a posterior, $\mu(\gamma \mid \alpha)$.

The flow loss of the sender can be written as:

$$v(\mathbf{q}^c(\mu), \{\Gamma, \phi\}) = \begin{cases} \|\mathbf{q}^c(\mu) - \mathbf{q}^s(\gamma)\| & \text{if sender observes } \gamma \\ \|\mathbf{q}^c(\mu) - \mathbf{q}^s(\mathbb{E}(\gamma))\| & \text{if sender observes } \phi \end{cases} \tag{5.1}$$

and the sender chooses an optimal communication strategy which minimises its loss subject to the constraint that any signal (if any) is truthful. Note that $v(.)$ indirectly depends on the posterior beliefs of the countries about the state of the world, through their chosen abatement levels. Furthermore, the beliefs of the sender and the countries do not necessarily coincide, so the social optimum as the bliss point of the sender is not a function of the countries' beliefs, and clearly, if the sender does not know the state, the best approximation for $\mathbf{q}^s(\gamma)$ is $\mathbf{q}^s(\mathbb{E}(\gamma))$.

As shown in previous sections, the abatement solutions of the countries are stationary. Thus, after the update of their beliefs in period zero, the countries work out their constant level of abatements for all future periods. Hence, the objective function of the sender is simply $\sum_{t=0}^{\infty} \beta^t \|\mathbf{q}^c(\mu) - \mathbf{q}^s(.)\| = \frac{1}{1-\beta} \|\mathbf{q}^c(\mu) - \mathbf{q}^s(.)\|$.

The following two lemmas can be directly concluded:

Lemma 6. *If the sender does not know the state, the unique equilibrium verifiable communication is $\alpha_e(\phi) = 0$.*

Therefore, our main question is whether the sender may ever choose to suppress information (if it knows the state) in order to increase the abatement levels.

Lemma 7. *Suppose $\mathbf{q}^s(\gamma) \in D(\gamma)$ in the implicit contract setting, or $n = m^*$ in the coalition formation setting, then if the sender observes the state for any $\gamma \in \Gamma$, $\alpha_e(\gamma) = 1$ is the unique equilibrium disclosure strategy.*

In other words, if the countries, knowing the true state, can sustain the socially optimal payoff, then by the full revelation of the state, the sender can obtain its bliss point. We know from the Revelation Principle in information economics that anything that can be implemented as an equilibrium can be achieved with truthful revelation. Given this result, henceforth we are going to restrict attention to cases where the countries under neither the no-learning nor the full-learning scenario can sustain the socially-optimum abatement. This allows us to focus the attention on the theoretically more interesting results. However, we believe also that this is more reasonable and relevant to today's climate change problem. Formally, we impose the next three assumptions:

Assumption 2. Under the implicit-contract setting, for any $\gamma \in \Gamma$, $\mathbf{q}^s(\mathbb{E}(\gamma)) > \hat{\mathbf{q}}(\mathbb{E}(\gamma))$, $\mathbf{q}^s(\gamma) > \hat{\mathbf{q}}(\gamma)$.

From Assumption 1 we know that the countries select the Pareto-superior abatement levels, therefore from the set of self-enforceable abatements, D, they prefer abatement levels which are closer to the social optimal levels. Given Assumption 2, this implies that under both full-learning and no-learning scenarios, $\mathbf{q}^c = \hat{\mathbf{q}}$.[19]

Assumption 3. In the coalition formation setting, $n > m^*$.

In the coalition setting, we know that $\mathbf{q}^c = \{\mathbf{q}^m, \bar{\mathbf{q}}\}$, so if $n > m^*$, then immediately it holds that for any $\gamma \in \Gamma$, $\mathbf{q}^s(\mathbb{E}(\gamma)) > \mathbf{q}^c(\mathbb{E}(\gamma))$, $\mathbf{q}^s(\gamma) > \mathbf{q}^c(\gamma)$.

Finally, we assume that in both settings, the countries cannot achieve the *true* socially-optimum abatement with their *prior belief*, no matter how optimistic or pessimistic they are:

Assumption 4. $\mathbf{q}^s(\gamma) > \mathbf{q}^c(\mathbb{E}(\gamma))$.

Although the assumption is written in terms of abatement levels, it restricts the realisation of the social cost parameter.[20] Furthermore, it implicitly implies that $0 \ll \gamma < 1$, in other words that the social costs of carbon is significant. This ensures that the externality of abatement is relevant in our analysis for any realisation of the random variable. Although it is not without loss of generality to look at cases where Assumption 4 holds, we think that assuming that countries would abate more with their priors than what is socially optimal with the true value, or that the value of the social cost of carbon is infinitesimally close to zero, is not relevant for today's climate problem.

As already noted, it is an incomplete information game and the solution concept that is used is PBNE. We are interested to check whether the game can have any pooling equilibrium, where different types of senders choose the action of being silent and lead to no learning or partial learning by the countries.

The PBNE strategies consist of functions $\mu(\gamma \mid \alpha(.))$, $\mathbf{q}^c$, and $\alpha(.)$ such that (i) the posterior belief of the countries is consistent with the Bayes rule; (ii) in the implicit-contract setting, $\mathbf{q}^c$ is an incentive-compatible level of abatement of the countries, and in the coalition setting, the coalition members jointly choose their $\mathbf{q}^m$, while the free riders choose $\bar{\mathbf{q}}$. (Furthermore, in both settings, given the corresponding updated beliefs, $\mathbf{q}^c$ satisfies sequential rationality and hence is a best response to $\alpha(.)$); and (iii) $\alpha(.)$ minimises the loss of sender and is a best response to $\mathbf{q}^c$. The unique PBNE is characterised as follows:

Proposition 3. *There is a unique PBNE such that,*

if the sender does not learn the social cost of GHG, then $\alpha_e(\phi) = 0$,

if the sender learns the social cost of GHG, there is a threshold $\bar{\gamma}_e = (1 - \frac{1}{\theta}) + \frac{1}{\theta}\sqrt{(1-\theta)}$, *above which* $\alpha_e(\gamma) = 1$ *and below which* $\alpha_e(\gamma) = 0$.

in the implicit-contract setting, $\hat{\mathbf{q}}(\mu(\gamma \mid \alpha(.))) \in D$ *is the incentive-compatible level of abatement,*

in the coalition formation setting, $\mathbf{q}^c(\mu(\gamma \mid \alpha(.)))$

$$= \begin{cases} \mathbf{q}^m(\mu(\gamma \mid \alpha(.))) & \text{if } i \in m \\ \bar{\mathbf{q}}(\mu(\gamma \mid \alpha(.))) & \text{if } i \notin m \end{cases} \tag{5.2}$$

The proof is in the Appendix. To develop the intuition, let us first consider the case in which the sender always learns the state, i.e. $\theta = 1$. Then, given that the abatement strategies are increasing in the social cost of GHG, if the sender knows that $\mathbb{E}(\gamma) \leq \gamma$, it chooses to reveal the state, and sends the precise public signal $y = \gamma$. Accordingly, the countries update their prior belief to a common posterior belief, denoted by $\mu(\gamma \mid \alpha(\gamma) = 1, y = \gamma) = 1$, which leads to selection of $\mathbf{q}^c(\gamma)$.

On the contrary, if the sender was informed that $\mathbb{E}(\gamma) > \gamma$, then it would prefer to completely hide its awareness of the state, and leave the countries with their prior belief. However, if it chooses to be silent, then the countries obtain more information relative to their prior belief. In fact, the countries know that the sender prefers a higher level of abatement which is closer to the social optimum. So, to the countries, which prefer the fully revealing strategy, the silence of the sender reveals to them that $\mathbb{E}(\gamma) > \gamma$. Hence, the countries truncate the distribution of social cost from above, which gives rise to $\mathbb{E}(\gamma \mid \alpha(\gamma) = 0) < \mathbb{E}(\gamma)$. Truncating continues and in equilibrium they end up at a situation where $\bar{\gamma}_e = 0$. In fact, because the difference of expected loss of the sender from the two strategies is monotone in the true social cost of GHG, the equilibrium strategy of the sender has a threshold form with respect to γ, and if $\theta = 1$ the threshold is equal to the minimum element of Γ. In other words, if ex-ante an informed sender has two choices, revealing the true state or being silent, then in equilibrium it must fully disclose the true state, and this is independent of whether the prior public belief is more optimistic or pessimistic about the true social cost of GHG. Hence, $\mu(\gamma \mid \alpha(\gamma) = 1, y = \gamma) = 1$ and $\alpha(\gamma) = 1$. This is the 'unravelling' result of Milgrom (1981) and Grossman (1981).

However, in our model the sender does not necessarily learn the state. Let us consider the case where $0 < \theta < 1$. If the sender does not disclose any information, to the countries with probability $1 - \theta$ it has not learnt anything and with probability θ, the

[19] With the quadratic cost function and $n = 2$, $q_i^s = \frac{2\beta\gamma\varphi}{x_i(1-\beta\delta)}$, and $\hat{q}_i = \frac{\beta\gamma\varphi(2\beta+1)}{1-\beta\delta}$. Therefore assumption $q_i^s > \hat{q}_i$ holds if and only if $x_i < \frac{2}{2\beta+1}$, for all i, which implies that the countries are not sufficiently patient to sustain the socially-optimal loss.

[20] For the quadratic cost example, it is equivalent to assuming $\gamma > \frac{2x_i\beta\mathbb{E}(\gamma)+x_i\mathbb{E}(\gamma)}{2}$ in the implicit contract setting, and equivalent to assuming for all i, $\gamma > \frac{x_i m\mathbb{E}(\gamma)}{2}$ in the coalition formation setting.

sender knows that $\gamma < \mathbb{E}(\gamma)$. Accordingly, $\mathbb{E}(\gamma \mid \alpha(.) = 0)$ is a weighted average of the countries' prior, $\mathbb{E}(\gamma)$, and $\mathbb{E}(\gamma \mid \gamma < \bar{\gamma})$. Hence, their reasoning leads to a positive threshold but less than their prior, i.e. $0 < \bar{\gamma}_e < \mathbb{E}(\gamma)$.

Finally, note that the equilibrium remains robust if the sender chooses between reporting ϕ and sending 'any' truthful signal about the social cost parameter. For example, assume the sender observes $\gamma = k$, and can choose between reporting ϕ and truthfully reporting an interval $\gamma > k$. But there is a separating equilibrium where a sender who has observed a social cost k', such that $k' > k$, would report $\gamma > k'$. i.e. any sender which had observed a higher state, would want to distinguish itself. Therefore, the sceptical conjecture of the countries in equilibrium leads to interpretation of any signal on interval $\gamma > k$ as $\gamma = k$.

For our model with imperfect learning by the sender, the following Corollary specifies the five possible cases that can result from the unique equilibrium specified in Proposition 3, depending on the relationship between the prior beliefs of the countries and the true value of γ.

Corollary 1. *The unique PNBE defined in Proposition 3 yields the following cases, depending on the relationship between the prior beliefs of the countries and the true value of γ. If*

(i) $\mathbb{E}(\gamma) = \gamma$, then there is neither a gain nor a loss from communication.

(ii) $\gamma > \mathbb{E}(\gamma) > \bar{\gamma}_e$, then the sender reveals the true social cost of GHG, and the countries choose higher abatement levels and potentially form a larger coalition, which were not achievable with their prior information.

(iii) $\mathbb{E}(\gamma) > \gamma > \bar{\gamma}_e$, then full revelation is the unique equilibrium outcome and the countries choose lower abatement levels and potentially a smaller coalition relative to the case with their prior belief.

(iv) $\mathbb{E}(\gamma) > \bar{\gamma}_e > \gamma$, then the sender does not reveal any information.

(v) the sender does not learn the state variable, then the sender is silent.

Let us briefly discuss and compare the outcomes in Corollary 1. Case (i) is not particularly relevant, as for a γ belonging to a continuum, this situation is a zero-probability event. Case (ii) is probably the most relevant case in real-life negotiations, as in this case the IPCC uses its information to convince countries that climate change is more severe than what they initially thought. Cases (iii) and (iv) are the most interesting ones in terms of information disclosure. In case (iii) the IPCC has to reveal the information that it has available, despite the fact that countries will abate less as a consequence of the revelation. Note that whenever the sender does not disclose any information, in equilibrium the countries' conjecture about the social cost of GHG is the threshold value, i.e. $\mathbb{E}(\gamma \mid \alpha_e(\gamma) = 0) = \bar{\gamma}_e$. Hence, the sender strictly gains from revelation relative to being silent, as countries would reduce their abatement even further if the IPCC remains silent. On the contrary, in case (iv) the sender does not reveal any information and gains from suppression relative to full revelation. In this case, the true value of γ implies that countries will abate more with the threshold value than what they would knowing the true value. Finally, in case (v) gain or loss of the sender would not be a question. As the sender cannot fabricate information, the sender does not have any choice other than being silent (see Lemma 6). Thus, silence is not strategic in such a case.

There are a couple of additional points worth highlighting. First, given that in a game with an information sender keeping the countries at their prior is not possible in cases (ii), (iii), and (iv), the equilibrium communication strategy of the sender leads to Pareto-superior outcomes, relative to choosing the rival communication strategy. In other words, the equilibrium communication strategy leads to relatively higher welfare and makes the deviation less attractive.

Second, case (iv) is the only case where the sender is silent while it knows the state variable. But, as θ increases, less information is suppressed in equilibrium ($\bar{\gamma}_e$ decreases), and in the limit as θ converges to one, the model predicts the full-disclosure outcome for all states. Parameter θ captures the sender's ability to learn about the social cost of GHG, and factors such as research funding and scientific support by the countries can affect it. The literature on stochastic IEAs takes learning of the countries exogenously, by comparing the outcome of full-learning and no-learning, while we endogenise it here by introducing the information sender. However, learning of the sender is taken exogenously here, and we do not model how θ can be changed. We have assumed that the policymakers representing the countries are rational and sophisticated and they interpret any missing information in the most sceptical way. Thus it can be assumed that in a potential pre-game phase, if the countries could affect the sender's learning, they would have incentive to choose $\theta = 1$, to ensure attaining full revelation of the social cost by the sender. This would yield a lower threshold, $\bar{\gamma}_e$.

6. Robustness

In this section we check the robustness of our results to variations in our assumptions. To keep the problem tractable, in each one of the subsections below we relax one assumption, but we simplify the problem in another dimension. To simplify, we focus on a perfectly informed sender, i.e. $\theta = 1$, where we have shown above that full revelation is the outcome (the unravelling result). However, similar arguments could be used to extend the more subtle results obtained for $\theta < 1$.

6.1. Delay in communicating

In the previous analyses, we assumed that the sender sends the signal at the beginning of the game. Now we show that, even if the option to delay was available, the sender would be interested in sending the information immediately.

Specifically, in either binary or noisy signalling games, assume the sender, after observing the state γ, sets $\alpha(\gamma) = 1$ in $t = 0$, but has the option of delaying sending signal $y = \gamma$, from period $t = 0$ to a finite time $t = T'$, where T' is a positive integer. The result of the equilibrium time of communication is provided in the next proposition.

Proposition 4. *In equilibrium the sender sends the precise public signal at the beginning of the game, immediately after observing the social cost of GHG.*

Although the expected loss of countries is a function of the total level of GHG in each period, Q_t, in our linear model, the level of abatements and coalition decisions are independent of the stock, and after learning the state, the chosen strategies are independent of Q_t in both scenarios of learning in period 0 and T'. As explained, the countries select their incentive-compatible strategies given their belief about the social cost of GHG. Hence, the countries prefer to immediately update their beliefs and adjust their strategies based on the true γ.

From the expected loss of the sender, it is clear that if $\mathbb{E}(\gamma) \leq \gamma$, then the sender prefers to send out the signal in $t = 0$, as well. In other words, if initially the countries are more optimistic about the social cost of GHG, the sooner the countries receive the signal and increase their level of abatements, the better.

Conversely, assume that $\mathbb{E}(\gamma) > \gamma$, where the sender prefers to delay the communication of the true social cost of GHG. But the countries, as soon as they experience delay in receiving the signal, will realise that ex-ante they are abating more than necessary. Although the long-run level of GHG is lower under the prior belief, i.e. $\tilde{Q}(\gamma) > \tilde{Q}(\mathbb{E}(\gamma))$, and in each period $t < T'$, the lower Q_t under no learning leads to a lower level of loss, $V^*(Q_t)$, delay reveals that $\mathbb{E}(\gamma) > \gamma$, thus for the countries $\mathbf{q}^c(\mathbb{E}(\gamma))$ is not incentive compatible any more. Therefore, the countries truncate the distribution of beliefs, and as a best response to delay, they decrease their selected abatement to $\mathbf{q}^c(\frac{\mathbb{E}(\gamma)}{2})$. Assuming that $\mathbf{q}^c(\frac{\mathbb{E}(\gamma)}{2}) < \mathbf{q}^c(\gamma)$, the sender will send the signal in $t = 0$.

6.2. A noisy signal

As discussed in the introduction, the most appropriate interpretation of our main assumption is that the IPCC chooses between remaining silent or including a particular piece of information in its reports, and in particular in the Summary for Policymakers, to make it available for decision makers. Informally, we now consider the possibility that the IPCC includes a piece of information in the report, but in a 'messy' or noisy manner, so that there is a chance that policymakers will not get the message. Technically, in this sub-section we generalise the communication strategy to a non-binary information strategy, focusing on the case where the sender always learns the state.

Let us examine a similar game, but assuming that $\alpha(\gamma)$ is not necessarily degenerate and can admit any value between $[0, 1]$. In other words, we adjust the choices of the sender such that it is constrained to sending a signal which is equal to the true value with probability $\alpha(\gamma) \in [0, 1]$.

After the sender privately observes the true state, it chooses $\alpha(\gamma)$ as its information strategy which specifies the probability of revealing the true state, γ, while with probability $1 - \alpha(\gamma)$ the sender sends a random draw from Γ, which is indeed sending a meaningless signal. Hence, $\alpha(\gamma)$ is the precision of the public signal. We refer to this strategy as the noisy signalling strategy. Then the sender sends a signal $y \in Y$, according to the chosen strategy. Given the information strategy, $\alpha(\gamma)$, and the observed signal, y, countries update their common prior belief. Subsequently, in the coalition setting, the countries decide about their membership and details of their agreement, and in both IEA settings, they choose an abatement level.

The objective functions of the sender and countries are the same as in the last section. As before, what matters for the countries is the conditional expected value of the social cost parameter, $\mathbb{E}(\gamma \mid \alpha(\gamma), y)$. Hence, the continuation losses of the countries and the resulting abatement levels all depend on the precision of the public signal. Furthermore, let Assumptions 1–4 be satisfied here as well.

The sender chooses an optimal precision which minimises its long-run loss function and is the best response to the strategy of the countries. The unique PBNE of the game is as follows, and the proof is in the Appendix,

Proposition 5. *The posterior belief of $\mu(\gamma \mid \alpha_e(\gamma) = 1, y = \gamma) = 1$, and strategies of $\mathbf{q}^c(\gamma)$ and $\alpha_e(\gamma) = 1$ constitute the unique PBNE of the game with noisy signals such that,*

in the implicit-contract setting, $\hat{\mathbf{q}}(\gamma) \in D$ is the incentive-compatible level of abatement,

in the coalition formation setting, $\mathbf{q}^c(\gamma)$

$$= \begin{cases} \mathbf{q}^m(\gamma) & \text{if } i \in m \\ \bar{\mathbf{q}}(\gamma) & \text{if } i \notin m \end{cases} \tag{6.1}$$

Hence, if a perfectly informed sender has access to a randomisation device to select between either revealing the true social cost of GHG or sending a meaningless signal, and to induce agents to adjust their profile of abatement such that the sum of sender's discounted loss is minimised, in equilibrium, it reduces the noise of public information to zero and provides the countries with as precise as possible information.

6.3. No perfect learning by the sender and noisy signal

We now consider the possibility that the sender 'never' learns the state perfectly. Thus the signal would never be equal to the true social cost with probability one, but with an interior probability $\alpha(. \mid \gamma)$. The sender chooses the set of signals and their precision, i.e. $\alpha(. \mid \gamma)$. This probability distribution over the signals could be interpreted as setting up a research proposal. The IPCC generally relies on published literature, where the verifiable information framework discussed above is more appropriate. However, it also generates some new research, mainly by combining the results from different models.[21] Thus, the IPCC selects the models that will go into the analysis. Although it does not know the results beforehand, it may know that selecting (information strategy) a particular model A has a different probability of 'bad news' (as a possible signal) than selecting model B.

The timing is as follows: at the beginning of the game, when the sender does not know anything about the state of social cost of carbon, it chooses a proposal (i.e. information strategy, $\alpha(.\mid\gamma)$), and commits to it.[22] Then the sender acquires information about the social cost of carbon based on the proposal (though never learns the state perfectly), and finally the sender communicates the outcome as a public signal, y.

This analysis departs from the verifiable-disclosure approach discussed above, where the sender was perfectly informed about the social cost of GHG with a given probability (which could be one). However, it relates to the strand of Bayesian persuasion literature, with the seminal paper of Kamenica and Gentzkow (2011). In a companion paper, Vosooghi (2017) generalises their information communication framework to the coalition formation and IEAs, in a binary-action setting. Here, the action space (the abatement space) is a continuum. Thus if the belief of the countries changes, the abatement levels continuously respond to it, and the sender can indirectly select any abatement level from the continuum space. Furthermore, due to different payoff structures, here we derive different equilibrium communication strategies.

Bayesian persuasion analysis with continuum action and state spaces can be complicated. In this section, to simplify the analysis, we assume that the state is binary, i.e. $\Gamma = \{\gamma_h, \gamma_l\}$, where $\gamma_l < \gamma_h$, and both parameters belong to $(0, 1)$. With the binary state space we can simplify notation: let μ be the probability of $\gamma = \gamma_h$, and let p be the prior belief about such a state.

The countries after receiving the public signal update their prior belief according to the Bayes rule. So, each signal y induces a posterior probability $\mu_y(\gamma)$. Thus, an information strategy, by setting a probability distribution over signals, induces a probability distribution over the posterior beliefs.

As in previous sections, the action of countries and subsequently the flow loss of the sender depend on $\mu_y(\gamma)$. Since at the stage of communication of the research strategy, the sender does not know the state, and the belief of the countries after communication is going to be μ, the flow loss of the sender is $\nu(\mathbf{q}^c(\mu)) = \|\mathbf{q}^c(\mu) - \mathbf{q}^s(\mu)\|$. About this payoff function, note that in contrast to the verifiable disclosure, here, there is no case in which after gathering information the sender could not learn the social cost at all where at best it was relying on the prior of the countries. Furthermore, in this subsection relaxing Assumptions 2–4 does not affect our analysis. Given that the countries face a probability distribution over their updated beliefs, the expected loss of the sender is,

$$\mathbb{V}(\mathbf{q}^c(\mu)) \equiv \mathbb{E}_\mu \nu(\mathbf{q}^c(\mu)) = \mathbb{E}_\mu \|\mathbf{q}^c(\mu) - \mathbf{q}^s(\mu)\| \tag{6.2}$$

Kamenica and Gentzkow (2011) show that the only constraint that the sender's communication need to satisfy is the law of total probability, i.e. the expected posterior beliefs must be equal to the prior belief. This is also known as the Bayes Plausibility rule.[23] They show that given the commitment power of the sender, and the Bayes Plausibility, the Revelation Principle holds. In other words, the sender by sending signal y recommends an action and the countries knowing that they have the 'right' belief, follow the recommendation. Thus there is no scepticism about the sender's communication.

Because the Revelation Principal holds, there is a one-to-one map between the signal and the induced belief of the countries. So by choosing the precision of signals (the probability distribution over signals), the sender indeed directly selects the probability distribution over the beliefs of the countries. And, by sending a public signal after the research procedure (which is based on the set research strategy), one of these beliefs is induced.

To characterise $\mathbb{V}(\mu)$ we need to know how the various levels of abatement respond to a change in the countries belief. To fix ideas, here, we focus on the quadratic cost function, $C(q_i) = \frac{q_i^2}{2\varphi}$, where actions linearly increase in μ. It turns out that the expected loss of the sender, $\mathbb{V}(\mathbf{q}^c(\mu))$ in $(\mu, \mathbb{V})$–space is a linear and increasing function in the probability of γ_h. This observation leads to the following result:

Proposition 6. *Assume $C(q_i) = \frac{q_i^2}{2\varphi}$. If the sender can never learn the social cost parameter perfectly, and has commitment power, the equilibrium communication strategy is not unique. The full revelation of the state is one of the equilibrium strategies. The sender never gains from any communication and persuasion.*

We relegate the proof to the Appendix. Intuitively, the sender should always follow the Bayes Plausibility rule. Thus depending on the prior belief of the countries, it selects two posterior beliefs for the countries which contain their prior belief, and sets any probability distribution over these posterior beliefs that satisfies the law of total probability.

The full revelation of the state can be an equilibrium if the sender can observe the state. Observing the state after setting and committing to the chosen information strategy, does not change the results. It is only important that initially the sender is uninformed.

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[21] For example, the recent Atlas that combines visually the results of different models. See https://interactive-atlas.ipcc.ch/.

[22] As it becomes clear later, the commitment assumption is important to ensure that the Revelation Principle holds and the countries follow the sender's recommendation.

[23] See the Appendix for more detail.

6.4. Asymmetric countries

Our main model assumes that all countries are identical (although weights for the central planner problem and the shares inside the coalition were potentially different). We now explore the impact of asymmetries, retaining the verifiable disclosure assumptions on the information communication side. There are at least two relevant questions that arise once countries are asymmetric, one is whether the sender would vary its communication strategy when faced with heterogeneous agents, and another question is which type of countries will join the coalition.

The latter is obviously only relevant in a coalition formation framework, but it has not been properly analysed in this literature. The reason is that there are multiple equilibria and that different coalitions are possible, without a clear procedure to determine which ones are more likely. Thus, which countries are actually joining the coalitions is a coordination problem that is not studied in this literature.

Battaglini and Harstad (2012) argue, not formally, that 'with some types of heterogeneity, it may be natural to order the countries according to their benefit from an IEA, and this ordering of countries may serve as a natural focal point for the composition of the equilibrium coalition, suggesting that the coordination problem (of who should participate and who should not) is a problem that is likely to be overcome in reality.' This argument applies to our framework too.

Our model follows most of the IEA literature on coalition formation, which do not model the extensive-form bargaining of countries in coalition formation. In an extensive-form bargaining model of climate negotiation it can be assumed that a coalition forms if an initial proposer makes an acceptable offer to a group of countries (Caparrós and Péreau, 2017). The identity (here the social cost or any source of heterogeneity) of the proposer would be an important factor in determining the composition of the equilibrium coalition. The ordering of initial proposers, which is determined by a so-called protocol and is typically assumed to be exogenously given, would be a key factor. Although certainly relevant, incorporating this into the analysis would modify our model substantially and we leave this for further research.

In any case, the former question is probably more relevant in our context, as our paper focuses on the role of an information sender. To analyse this issue, in this section we study a situation where the countries are not symmetric in terms of their marginal cost of GHG, assuming that there are only two countries in the IEA, i.e. that $I = 2$.[24] Note that the question whether the sender would change its communication strategy can already be addressed with two countries, with the additional advantage that there is effectively no difference between the implicit contract and the coalition formation settings with two countries.

Distributional uncertainty in the literature of stochastic IEAs refers to a situation where the realised values of state for different countries do not coincide, and each country has a different unknown cost-ratio parameter γ_i drawn from one commonly-known distribution. Distribution and level uncertainty means that there exists a distribution Γ_i for every country i, and the marginal social costs of GHG are random draws from these known independent distributions (the level of cost-ratio parameters of different countries may coincide, though they are from different distributions). For both situations, as long as the signals are publicly observed by all countries and the (expected value of) distribution(s) is (are) known, the analysis of level and distributional uncertainty will be similar to distributional uncertainty. Here we look into the more general case of distribution and level uncertainty, and again we assume that both state variables are distributed on bounded domains of [0,1].

At the beginning of the game, nature draws two independent values for the two countries from the two commonly known distributions of Γ_i for each $i \in \{1, 2\}$.

All derivations are generalised to the case of level and distributional uncertainty, and the incentive-compatibility constraints for sustaining abatements greater than BAU levels as a PBNE by threat of BAU reversion, are the same as (4.1). The definitions such as IC_i^0, D, MRC_{ij}, are the same here. Proposition 1 is also applied directly, as its proof is independent of the asymmetry of marginal social cost of GHG. In addition, still $\mathbf{q}^c \in \{\mathbf{q}^s, \mathbf{q}^B\}$. Note that here $\overline{\mathbf{q}}$ and $\hat{\mathbf{q}}$ are not necessarily symmetric, although if $x_1 = x_2$, the social optimum, $\mathbf{q}^s$, is symmetric. In addition,

$$\begin{aligned}\frac{dq_1^s}{d\mathbb{E}_\mu(\gamma_1)} &= \frac{\partial C'^{-1}}{\partial(\frac{\beta B^s}{x_1})}.\frac{\beta}{(1-\beta\delta)}\\ \frac{dq_1^s}{d\mathbb{E}_\mu(\gamma_2)} &= \frac{\partial C'^{-1}}{\partial(\frac{\beta B^s}{x_1})}.\frac{\beta x_2}{x_1(1-\beta\delta)}\end{aligned} \tag{6.3}$$

Thus, if $x_1 < x_2$, then $0 < \frac{dq_2^s}{d\mathbb{E}_\mu(\gamma_1)} < \frac{dq_2^s}{d\mathbb{E}_\mu(\gamma_2)} = \frac{dq_1^s}{d\mathbb{E}_\mu(\gamma_1)} < \frac{dq_1^s}{d\mathbb{E}_\mu(\gamma_2)}$. In other words, the social-optimal level of abatement of country 1 is relatively more sensitive to the expected marginal social cost of GHG in country 2, which has a greater weight in the social loss function.

Now let us consider the game between an informed information sender and the countries, with level and distributional uncertainty. Assume that in period $t = 0$, the sender observes the states, and announces the chosen $\alpha_i(\gamma_1, \gamma_2)$ of each country publicly. Therefore, both countries receive $\alpha_1(\gamma_1, \gamma_2)$, and $\alpha_2(\gamma_1, \gamma_2)$, and if specified by the information strategy, afterwards they both observe the two signal realisations of y_1 and y_2. The sender's problem is minimising

$$\|\mathbf{q}^c(\mathbb{E}(\gamma_1 \mid \alpha_1(\gamma_1,\gamma_2), y_1), \mathbb{E}(\gamma_2 \mid \alpha_2(\gamma_1,\gamma_2), y_2)) - \mathbf{q}^s(\gamma_1,\gamma_2)\| \tag{6.4}$$

[24] This assumption guarantees the uniqueness of $\hat{\mathbf{q}}$, and therefore $\mathbf{q}^c$.

where the choice variables are $\alpha_1(\gamma_1,\gamma_2)$, and $\alpha_2(\gamma_1,\gamma_2)$. Also assume that Assumption 2 is generalised to this case. Thus, $\mathbf{q}^c = \hat{\mathbf{q}}$ under any belief, furthermore, the sender strictly prefers higher levels of abatement. The following proposition is directly generalised from Propositions 3–5.

Proposition 7. *The posterior beliefs of* $\mu(\gamma_1 \mid \alpha_1(\gamma_1,\gamma_2) = 1, y_1 = \gamma_1) = 1$*, and* $\mu(\gamma_2 \mid \alpha_2(\gamma_1,\gamma_2) = 1, y_2 = \gamma_2) = 1$ *and strategies of* $\hat{\mathbf{q}}(\gamma_1,\gamma_2) \in D(\gamma_1,\gamma_2)$*,* $\alpha_1(\gamma_1,\gamma_2) = 1$ *and* $\alpha_2(\gamma_1,\gamma_2) = 1$ *constitute the unique PBNE of the game with either binary or noisy signals. Furthermore, in equilibrium public signals of* y_1 *and* y_2 *are sent in* $t = 0$*.*

In other words, given the assumed information structures, a sender always fully reveals the true state to asymmetric countries. Again the result is independent of whether one or both countries are more optimistic or pessimistic about the true marginal social cost of GHG. Furthermore, it can be deduced that the sender cannot choose the country with which to communicate the information strategy, as any strategy other than the full revelation of the state is off the equilibrium path.

7. Conclusion

This paper presents and discusses a framework to examine the role of public information in dynamic self-enforcing IEAs on climate change. In modelling the IEA, we have analysed the two alternative approaches proposed by the literature. The first approach analyses the possibility of coordination among the countries through implicit climate agreements, where the countries revert to the BAU policy if one country deviates from the agreed path of abatement; we consider this to be the harshest feasible punishment, although technically harsher punishments may be available. On the other hand, the second approach, which drives the literature on coalition formation and IEAs, assumes that if one player deviates, the remaining countries will continue cooperating, at an updated level of abatement.

In our stochastic model, where the social cost of GHG is an unknown random variable, we derive sensitivity analysis on the emission abatement effort of countries with respect to changes of the public belief (which is taken from a continuum set in our model). Furthermore, with our relatively general functional forms, we show that incentives of climate coalition members are linked to their belief: the higher the expected marginal social cost, the lower the deviation incentives.

In our model, an information sender, such as the IPCC, can control the release of verifiable information about the unknown state variable to the countries. Relative to the literature, where the focus is on comparative static of full-learning and no-learning scenarios in static coalition games, one of the most noteworthy contributions of our study is that we derive the equilibrium learning outcome endogenously in our dynamic games, in the two frameworks discussed above. We show that the communication takes a simple threshold-form strategy.

Our result shows that there is a threshold for the marginal social cost of GHG above which the IPCC has to reveal the information, while it remains silent below this threshold. Thus, answering the question in the introduction, if the true value of the social cost of carbon is more than the countries expectation, communication increases the abatement effort from countries, and the IPCC always reveals the true value. Also, if the true values is slightly smaller than that expectation by the countries, the IPCC reveals the information even though this moves the abatement effort of countries away from the social optimum. The reason is that the countries would reduce their efforts even more if they did not know the true value. Hence, climate deniers do not need to fear a strategic silence in this case. However, if the true value is clearly below the value believed by the countries, i.e below the threshold detailed above, then the IPCC best serves its goal of bringing the world closer to the social optimum by being silent, as countries will stay closer to the social optimum with their original beliefs. In any case, it is unlikely that the true value is 'clearly' below the expectations of countries in real-life. Furthermore, the possibility of the sender's silence vanishes as the sender gets perfectly informed about the underlying social cost. Thus, countries can obtain full and truthful disclosure of information by increasing their research efforts to ensure that scientists in the IPCC (and other climate scientists) get perfectly informed. Our findings depend on a number of simplifying assumptions. In Section 6 we have shown that relaxing several of our key assumptions will probably not change our results. However, we have left other relevant extensions for future research. In the coalition formation setting our results follow the tradition of examining internal and external stability. As a possible pathway for future research, using farsighted membership strategies over time (taking into account stability to more than one-step deviations) and across the coalition structure (examining coalitional deviations in addition to unilateral deviations) can provide more insight into the membership strategies of the countries in the climate coalitions.

Finally, studying private communication of information with players in a coalition game, where the countries decide about the membership decisions based on their (potentially) asymmetric private information can be another future research direction. Such a setting would involve second-guessing information of other countries, across the players and within the coalition. Although such an extension can provide interesting theoretical contributions, it is probably not particularly relevant when the focus is on the IPCC, as its report are published online.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. The socially optimal abatement level

The Bellman equation of the social planner problem is

$$V^s(Q_t) = \min_{q_{it}}\{\sum_i x_i[C(q_{it}) + \mathbb{E}_\mu(\gamma)Q_t] + \beta\mathbb{E}_\mu V^s[Q_{t+1}]\} \tag{A.1}$$

where Q_{t+1} is given by Eq. (3.1), and $V^s(Q_t)$ is the optimal loss function of the socially-optimal abatements.

Because the flow loss, $\prod_{it}$, is a continuous and strictly convex function, also the set $\{(Q_t, Q_{t+1}) : Q_{t+1} = \delta Q_t + \Psi - \sum_i q_{it}, q_{it} \in \mathbb{R}_+\}$ is convex and compact, $V^s(Q_t)$ is differentiable, strictly increasing and strictly convex. Hence, the set of optimal controls is non-empty and single-valued.

Using the guess and verify method, it can be guessed that the optimal loss function has a form of $V^s(Q_t) = A^s_{it} + B^s_{it}Q_t$.[25] Hence, from the first-order condition of the abatement level, the solution in Eq. (3.4) is obtained. To verify the coefficients, by plugging the guess into the Bellman equation, it turns out to be

$$V^s(Q_{t-1}, S_{t-1}) = \max\{\sum_i x_i[C(q_{it}) + \mathbb{E}_\mu(\gamma)Q_t] + \beta\mathbb{E}_\mu A^s_{it} + \beta\mathbb{E}_\mu B^s_{it}Q_{t+1}\} \tag{A.2}$$

The first-order condition of q_{it} gives $B^s_i = B^s = \frac{\sum_i x_i\mathbb{E}_\mu(\gamma)}{1-\beta\delta} = \frac{n\mathbb{E}_\mu(\gamma)}{1-\beta\delta}$. Hence the socially optimal abatement is independent of t. By substituting B^s in Eq. (A.2), one can verify A^s_{it} as

$$A^s_i = \frac{\sum_i x_i C(q^s_i) + \beta B^s(\Psi - \sum_i q^s_i)}{1-\beta} \tag{A.3}$$

Appendix B. The BAU abatement level

The Bellman equation of the BAU problem of country i is

$$\overline{V}_i(Q_t) = \min_{q_{it}}\{[C(q_{it}) + \mathbb{E}_\mu(\gamma)Q_t] + \beta\mathbb{E}_\mu\overline{V}_i[\delta Q_t + \Psi - q_{it} - \sum_{j\neq i} q_{jt}]\} \tag{B.1}$$

where $\overline{V}_i(Q_t)$ is the optimal loss function of BAU policy. If the optimal loss function has a form of $\overline{V}_i(Q_t) = \overline{A}_{it} + \overline{B}_{it}Q_t$, from the first-order condition of abatement level, the reaction function of country i is $C'(\overline{q}_{it}) - \beta\overline{B}_{it} = 0$, and the BAU abatement in Eq. (3.5) is obtained. Again, in order to verify the coefficients, after substituting the guess in the Bellman equation, it turns out to be

$$\overline{V}_i(Q_t) = \min_{q_t}\{[C(q_{it}) + \mathbb{E}_\mu(\gamma)Q_t] + \beta\mathbb{E}_\mu\overline{A}_{it} + \beta\mathbb{E}_\mu\overline{B}_{it}[\delta Q_t + \Psi - q_{it} - \sum_{j\neq i} q_{jt}]\} \tag{B.2}$$

The first-order condition of q_i gives $\overline{B} = \frac{\mathbb{E}_\mu(\gamma)}{1-\beta\delta}$. Hence, by substituting $\overline{B}$ and $\overline{q}$ for all i in Eq. (B.2), one can verify $\overline{A}_{it}$ as

$$\overline{A} = \frac{C(\overline{q}) + \beta\overline{B}(\Psi - \sum_i \overline{q})}{1-\beta} \tag{B.3}$$

Appendix C. The incentive-compatibility constraint for following a constant level of abatement in every period under the punishment of BAU reversion

The total loss of following the stationary strategy of q_i, for every i, is denoted by $V(Q_t)$. As an optimal loss, q_i is the solution to the following Bellman equation:

$$V_i(Q_t) = \min_{q_{it}}\{[C(q_{it}) + \mathbb{E}_\mu(\gamma)Q_t] + \beta\mathbb{E}_\mu V_i[\delta Q_t + \Psi - q_{it} - \sum_{j\neq i} q_{jt}]\} \tag{C.1}$$

The iteration of the loss function shows that it is linear in the level of GHG. In Section 4.1.1, we denoted it as $V(Q_t) = A_i + B_iQ_t$ for any stationary strategy. Choosing any abatement strategy above the BAU, results in a lower stock of GHG in future and a lower $V(Q_t)$. But this higher level of abatement is bounded by the countries incentive-compatibility constraint.

[25] The guess can be obtained by iteration of the loss function for a few times.

Any unilateral deviation from the constant targeted level of $\mathbf{q}$ will be punished by reverting to the BAU abatement from the following period. Every country i computes the resultant geometric series of GHG, and the short-run and long-run losses of following the constant abatement, q_i in every period. Country i compares $V(Q_t)$ with the optimal loss of deviation path.

If the following condition holds for every country i, then the corresponding loss of abating according to $\mathbf{q}$, can be sustained as a PBNE loss, by the trigger-type stationary strategy profile of playing q_i at all subgames at which there has not been a deviation from $\mathbf{q}$ in the past, and playing $\overline{q}_i$ otherwise. The incentive compatibility constraint (as a sufficient condition) for every i is[26]

$$\begin{aligned} &C(q_{it}) + \mathbb{E}_\mu(\gamma)Q_t + \beta\mathbb{E}_\mu[V(\delta Q_t + \Psi - q_{it} - \sum_{j\neq i} q_{jt})] \leq \\ &C(q_{it}^{BR}) + \mathbb{E}_\mu(\gamma)Q_t + \beta\mathbb{E}_\mu[\overline{V}_i(\delta Q_t + \Psi - q_{it}^{BR} - \sum_{j\neq i} q_{jt})] \end{aligned} \tag{C.2}$$

where q_i^{BR} is the best-response level of abatement to $\sum_{j\neq i} q_j$, and $\overline{V}(Q_{t+1})$ denotes the optimal continuation loss of the BAU strategy. The sufficient condition can be simplified to

$$\begin{aligned} &C(q_i) + \mathbb{E}_\mu(\gamma)Q_t + \beta\mathbb{E}_\mu[A + B(\delta Q_t + \Psi - \sum_i q_i)] \leq \\ &C(q_i^{BR}) + \mathbb{E}_\mu(\gamma)Q_t + \beta\mathbb{E}_\mu[\overline{A} + \overline{B}(\delta Q_t + \Psi - q_i^{BR} - \sum_{j\neq i} q_j)] \end{aligned} \tag{C.3}$$

In order to find q_i^{BR}, it is sufficient to take the derivative with respect to q_i from the right-hand side of the inequality in (C.3), which is the short-run and long-run payoff of deviation, and by equating it to zero, it will be obtained that $q_i^{BR} = \overline{q}$. Indeed, as explained, because there is no interaction in the reaction functions, the stationary strategies of other countries, i.e. q_j for all $j \neq i$, only affect the level of GHG, but best responses are independent.

Given this result, the IC constraint in (C.3) can be further simplified to

$$C(q_i) + \beta A - \beta B q_i \leq C(\overline{q}_i) + \beta\overline{A} - \beta\overline{B}\overline{q}_i \tag{C.4}$$

and this condition should hold for all countries.

Appendix D. Proof of Proposition 1

With the linear functional form of $V(Q_t)$, it is simple to see that

$$A = \frac{C(q) + \beta B(\Psi - \sum_i q)}{1-\beta} \tag{D.1}$$

By total differentiation from (4.1), i.e. along one IC_i^0, MRC_{ij} is derived as:

$$\left.\frac{dq_i}{dq_j}\right|_{IC_i^0} = \frac{\beta^2 B}{C' - \beta B} \tag{D.2}$$

Therefore, MRC_{ij} is increasing in the discount rate, β, the expected marginal social cost of GHG, $\mathbb{E}_\mu(\gamma)$, and the persistence rate of GHG, δ. Furthermore, it is decreasing in C'. Similarly, MRC_{ji} is

$$\left.\frac{dq_i}{dq_j}\right|_{IC_j^0} = \frac{C' - \beta B}{\beta^2 B} \tag{D.3}$$

In addition, at $\mathbf{q} = \overline{\mathbf{q}}$, MRC_{ij}, i.e. the derivative in (D.2), is infinite. While at $\mathbf{q} = \overline{\mathbf{q}}$, MRC_{ji} is zero. Hence, $MRC_{ij} = \frac{1}{MRC_{ji}}$, for any $j \neq i$, which implies that at $\mathbf{q} = \overline{\mathbf{q}}$, IC_i^0 is orthogonal to IC_j^0. Furthermore, recall that the reaction functions of the BAU problem, $C'(\overline{q}) - \beta\overline{B}$, for all countries, are orthogonal to each other. But since $\overline{B} = B$, and given the definition of MRC_{ij} in (D.2), the vector of partial derivative of MRC_{ij} is orthogonal to the hyperplane of $q_i = \overline{q}_i$, and therefore tangent to the hyperplane of $q_j = \overline{q}_j$.[27]

Furthermore, because the level sets of IC_i^0 for all i, are strictly convex, there is another unique fixed point, where the symmetric level hypersurfaces IC_i^0 for all i cross each other. Hence, D, as the intersection of strictly convex sets, is itself a convex and non-singleton set. □

[26] Note that both sides of the inequality are the losses of one country.

[27] As an example, see Fig. 1 for $n = 2$.

Appendix E. Proof of Lemma 2

This is already shown in the proof of Proposition 1, and it is a direct result of the strict convexity of private cost, $C(q_i)$ for all i. To find the maximum sustainable abatement, it is sufficient to solve for $\hat{\mathbf{q}}$ in n equations of binding incentive compatibility constraints, for all i,

$$C(\hat{q}_i) + \beta A - \beta B\hat{q}_i \leq C(\bar{q}_i) + \beta\overline{A} - \beta\overline{B}\bar{q}_i \tag{E.1}$$

The RHS of the equality is a constant, and for the symmetric game a unique non-trivial $\hat{\mathbf{q}}$, which is strictly greater than the BAU level, solves the system. □

Appendix F. Proof of Lemma 3

The members of a coalition of size m^* and length T^* jointly agree on abatement levels. Hence the aggregated loss function at any period t for any equilibrium T^* can be written as:

$$V^M(Q_t(m^*,T^*)) = \min_{q_{it}} \left\{ \sum_{i\in M} w_i \left[C(q_{it}) + \mathbb{E}_\mu(\gamma)Q_t\right] + \beta\mathbb{E}_\mu V^M(Q_{t+1}(m^*,T^*)) \right\} \tag{F.1}$$

Using again the guess and verify method, we guess that the continuation value function can be written in the form $V^M(Q_t(m^*,T^*)) = A_{it}(m^*,n) + B_{it}(m^*,n)Q_t$. Optimality condition calls for:

$$\frac{\partial V^M(Q_t(m^*,T^*))}{\partial q_{it}} = 0 \ \Rightarrow w_i C'(q_{it}^{m^*}) = \beta B_{it}(m^*,n) \ \ \forall i \in M \tag{F.2}$$

yielding

$$q_{it}^{m^*} = C'^{-1}\left(\frac{\beta B_{it}(m^*,n)}{w_i}\right). \tag{F.3}$$

To find the coefficients we write:

$$V^M(Q_t(m^*,T^*)) = \min_{q_{it}} \left\{ \sum_{i\in M} w_i \left[C(q_{it}) + \mathbb{E}_\mu(\gamma)Q_t\right] + \beta\mathbb{E}_\mu A_{it}(m^*,n) + \beta\mathbb{E}_\mu B_{it}(m^*,n)\left(\delta Q_t + \Psi - \sum_{i\in N} q_{it}\right)\right\} \tag{F.4}$$

which implies $B_{it}(m^*,n) \equiv \sum_{i\in M} w_i\mathbb{E}_\mu(\gamma) - \beta\delta B_{it}(m^*,n)$, or

$$B(m^*) = \frac{\sum_{i\in M} w_i\mathbb{E}_\mu(\gamma)}{1-\beta\delta} = \frac{m^*\mathbb{E}_\mu(\gamma)}{1-\beta\delta}. \tag{F.5}$$

and $A_{it}(m^*,n) \equiv \sum_{i\in M} w_i C(q_{it}) + \beta A_{it}(m^*,n) + \beta B(m^*)\left(\Psi - \sum_{i\in N} q_{it}^*\right)$, or

$$A_{it}(m^*,n) = \frac{\sum_{i\in M} w_i C(q_{it}^*) + \beta B(m^*)\left(\Psi - \sum_{i\in N} q_{it}^*\right)}{1-\beta}. \tag{F.6}$$

Due to the linearity in the model, in equilibrium, the abatements are stock-independent, so the optimal continuation loss function depends on constant abatements. □

Appendix G. Proof of Lemma 5

The equilibrium continuation value for every member i of a coalition of size m^* can be written as:

$$V(Q_t^*(m^*,T^*)) = \left[C(q_{it}^{m^*}) + \mathbb{E}_\mu(\gamma)Q_t\right] + \sum_{t=1}^{\infty}\beta^t\left[C(q_{it}^{m^*}) + \mathbb{E}_\mu(\gamma)Q_t^*(m^*,T^*)\right]. \tag{G.1}$$

If player i leaves, then the coalition would have a size of $m = m^* - 1$ and from Lemma 4 we know that $T^* = 1$, thus player i is expected to join again in the next period. This is similar to checking a one-shot deviation. The deviation is not beneficial for i if:

$$V(Q_t^*(m^*,T^*)) \leq \left[C(\bar{q}_{it}) + \mathbb{E}_\mu(\gamma)Q_t\right] + \sum_{\tau=t+1}^{\infty}\beta^{\tau-t}\left[C(q_{i\tau}^{m^*}) + \mathbb{E}_\mu(\gamma)\overline{\overline{Q}}_\tau\right], \tag{G.2}$$

where $\overline{\overline{Q}}_\tau = Q_\tau(m^*,T(m^*)) + \delta^{\tau-t-1}\Lambda$ for any period $\tau > t$ as described in Section 4.2. Using the expression for Λ given in (4.8), the condition for internal stability in (G.2) simplifies to

$$C(q_{it}^{m^*}) - C(\bar{q}_{it}) \leq \frac{\mathbb{E}_\mu(\gamma)\Lambda}{\delta}\sum_{t=1}^{\infty}\beta^t\delta^t \text{ for all } i \in M \tag{G.3}$$

This further simplifies to Eq. (4.11). One can also show that the external stability condition, that no player wants to join the coalition, holds for any $m^* \geq 2$, as the free-riders always gain more in this model. □

Appendix H. Proof of Proposition 2

By assuming $w_i = 1$ for all i, partial derivative of the LHS of (4.11) with respect to $\mathbb{E}_\mu(\gamma)$ is:

$$C'(q_i^{m^*})\frac{\partial q_i^{m^*}}{\partial \mathbb{E}_\mu(\gamma)} - C'(\bar{q}_i)\frac{\partial \bar{q}_i}{\partial \mathbb{E}_\mu(\gamma)} \tag{H.1}$$

while the partial derivative of the RHS of the inequality is:

$$\frac{\beta}{1-\beta\delta}\Lambda + \frac{\beta \mathbb{E}_\mu(\gamma)}{1-\beta\delta}\left[\frac{\partial q_i^{m^*}}{\partial \mathbb{E}_\mu(\gamma)} - \frac{\partial \bar{q}_i}{\partial \mathbb{E}_\mu(\gamma)} + (m^*-1)(\frac{\partial q_i^{m^*}}{\partial \mathbb{E}_\mu(\gamma)} - \frac{\partial q_i^{m^*-1}}{\partial \mathbb{E}_\mu(\gamma)})\right] \tag{H.2}$$

By substituting for $q_i^{m^*}$ and $\bar{q}_i$ in $C'(.)$ functions in the LHS derivatives, it is easy to verify that the terms in the LHS appear on the RHS too, but the derivative of the RHS has an extra term:

$$\frac{\beta}{1-\beta\delta}\left[\Lambda - (m^*-1)\mathbb{E}_\mu(\gamma)\frac{\partial q_i^{m^*-1}}{\partial \mathbb{E}_\mu(\gamma)}\right] \tag{H.3}$$

If the term in the brackets is positive, then by increasing $\mathbb{E}_\mu(\gamma)$ the RHS of (4.11) increases more than its LHS, implying that the internal stability condition would be more slack (the deviation is less attractive). Using (4.10), the bracket can be rewritten as:

$$q_i^{m^*} - \bar{q}_i + (m^*-1)(q_i^{m^*} - q_i^{m^*-1}) - (m^*-1)\mathbb{E}_\mu(\gamma)\frac{\partial q_i^{m^*-1}}{\partial \mathbb{E}_\mu(\gamma)} \tag{H.4}$$

Equivalently,

$$\left.\frac{\Delta q_i^{m^*}}{\Delta m^*}\right|_{\Delta m^*=m^*-1} + (m^*-1)\left.\frac{\Delta q_i^{m^*}}{\Delta m^*}\right|_{\Delta m^*=1} - (m^*-1)\mathbb{E}_\mu(\gamma)\frac{\partial q_i^{m^*-1}}{\partial \mathbb{E}_\mu(\gamma)} \tag{H.5}$$

Or

$$\left.\frac{\Delta C'^{-1}(\frac{\beta\mathbb{E}_\mu(\gamma)m^*}{1-\beta\delta})}{\Delta m^*}\right|_{\Delta m^*=m^*-1} + (m^*-1)\left.\frac{\Delta C'^{-1}(\frac{\beta\mathbb{E}_\mu(\gamma)m^*}{1-\beta\delta})}{\Delta m^*}\right|_{\Delta m^*=1} - (m^*-1)\mathbb{E}_\mu(\gamma)\frac{\partial C'^{-1}(\frac{\beta\mathbb{E}_\mu(\gamma)(m^*-1)}{1-\beta\delta})}{\partial \mathbb{E}_\mu(\gamma)} \tag{H.6}$$

which is non-negative for any $\gamma \in (0,1)$ and its marginal changes. □

Appendix I. Proof of Proposition 3

Starting from the last subgame of $t = 0$, and given the results of equilibrium selection of the countries in the implicit-contract and the coalition-game settings, also Assumptions 1–4, given their updated belief the countries choose $\mathbf{q}^c$ as specified in Proposition 3. About the information strategy, there are two cases:

(I) $\theta = 1$: By contradiction, assume that by choosing to be silent, the sender could block the transmission of information. So, let $\alpha'(\gamma)$ denote such a strategy. Then the sender compares the expected losses of $\alpha'(\gamma) = 1$, and $\alpha'(\gamma) = 0$. Let us denote the difference of expected losses by $Dif(\gamma) \equiv \|\hat{\mathbf{q}}(\gamma) - \mathbf{q}^s(\gamma)\| - \|\hat{\mathbf{q}}(\mathbb{E}(\gamma)) - \mathbf{q}^s(\gamma)\|$. Because $\mathbb{E}(\gamma)$ is constant, $Dif(\gamma)$ is strictly monotone in γ. Furthermore, $Dif(\gamma) \le 0$ iff $\hat{\mathbf{q}}(\gamma) \ge \hat{\mathbf{q}}(\mathbb{E}(\gamma))$ iff $\gamma \ge \mathbb{E}(\gamma)$. This leads to the threshold-form strategy of

$$\alpha'(\gamma) = \begin{cases} 1 & \text{if } \gamma \ge \bar{\gamma} \\ 0 & \text{if } \gamma < \bar{\gamma} \end{cases} \tag{I.1}$$

where $\bar{\gamma} = \mathbb{E}(\gamma)$. Therefore, if $\mathbb{E}(\gamma) < \gamma$, then $\alpha'(\gamma) = 1$ and the strategies specified in the proposition are all best response, and it would lead to $\mu(\gamma \mid \alpha(\gamma) = 1, y = \gamma) = 1$.

While if $\alpha'(\gamma) = 0$, the countries realise the threshold-form strategy of the sender and they speculate that $\mathbb{E}(\gamma) > \gamma$. In other words, they optimally truncate the distribution of random variable γ to support $(0, \bar{\gamma})$. Thus the best response of the countries implies

$$\mathbb{E}(\gamma \mid \gamma < \bar{\gamma}) = \frac{\int_0^{\bar{\gamma}} \gamma d\gamma}{Pr(\gamma < \bar{\gamma})} \tag{I.2}$$

which is strictly less than $\bar{\gamma}$.[28] Hence, the sender's strategy of $\alpha'(\gamma)$ is not a best response to the countries' strategy. The same reasoning applies to a situation where the sender chooses a strategy with threshold stated in (I.2), etc. Therefore, the unique PBNE threshold of the sender coincides with the minimum element of Γ, implying that in equilibrium for all $\gamma \in \Gamma$, the sender chooses $\alpha(\gamma) = 1$, and the conjecture of the countries about the threshold is correct in equilibrium, i.e. $\mathbb{E}(\gamma \mid \alpha(.) = 0) = \bar{\gamma}_e = 0$.

(II) $0 < \theta < 1$: If the sender does not learn anything, Lemma 6 holds. Again, similar to the case of $\theta = 1$, the countries conjecture that if the sender learns the state, it must have a threshold-form strategy, as specified in (I.1). Now if the sender is silent, the countries know that there are two possible reasons behind it, either the sender has not learnt anything or it is suppressing information:

[28] For a uniform distribution, $\mathbb{E}(\gamma)$ equals $\frac{1}{2}$, and $\frac{\int_0^{\bar{\gamma}} \gamma d\gamma}{Pr(\gamma<\bar{\gamma})} = \frac{\bar{\gamma}}{2}$, which is equal to $\frac{1}{4}$.

$Pr(\alpha(.) = 0) = 1 - \theta + \theta Pr(\gamma \le \bar{\gamma})$ which is equal to $1 - \theta + \theta\bar{\gamma}$. Accordingly, to them $\mathbb{E}(\gamma \mid \alpha(.) = 0)$ is a weighted average of their prior and $\mathbb{E}(\gamma \mid \gamma < \bar{\gamma})$,

$$\begin{aligned}\mathbb{E}(\gamma \mid \alpha(.) = 0) &= \frac{1}{2}\left(\frac{1-\theta}{1-\theta+\theta\bar{\gamma}}\right) + \left(\frac{\theta\bar{\gamma}}{1-\theta+\theta\bar{\gamma}}\right)\frac{\int_0^{\bar{\gamma}} \gamma d\gamma}{\bar{\gamma}} \\ &= \frac{1-\theta+\theta(\bar{\gamma})^2}{2(1-\theta+\theta\bar{\gamma})}\end{aligned} \tag{I.3}$$

Let us label $h(\bar{\gamma}) \equiv \mathbb{E}(\gamma \mid \alpha(.) = 0)$. The countries use their updated belief as the best guess about the threshold, so it is indeed their best response function, and in equilibrium it must be $h(\bar{\gamma}) = \bar{\gamma}$. It is easy to verify that the equation has a unique fixed point: first, $\frac{\partial h(\bar{\gamma})}{\partial \bar{\gamma}} = 0$ gives the unique solution of $\bar{\gamma}_e = (1 - \frac{1}{\theta}) + \frac{1}{\theta}\sqrt{(1-\theta)}$. In addition, $\frac{\partial^2 h(\bar{\gamma})}{\partial \bar{\gamma}^2} > 0$ for all $\bar{\gamma}$. Second, $h(\bar{\gamma} = 0) = \frac{1}{2}$ and $h(\bar{\gamma} = 1) = \frac{1}{2}$. The equation of $h(\bar{\gamma})$ is indeed similar to a conventional average cost of convex cost function in microeconomic theory, where the 45° line (analogous to a marginal cost) crosses through its minimum. Finally, it is easy to check that $h(\bar{\gamma} = \bar{\gamma}_e) = \bar{\gamma}_e$ as required, and the sender does not have any incentives to deviate from the equilibrium strategies. □

Appendix J. Proof of Proposition 5

The countries in the implicit-contract and the coalition formation settings, given Assumptions 1–4, and given their updated belief, choose $\mathbf{q}^c$ as specified in Proposition 5. By contradiction, assume that the sender can use a noisy signalling strategy, $\alpha''(\gamma) < 1$. Let us assume that it is possible, with probability $1 - \alpha''(\gamma)$, to exactly leave the countries with their prior belief to achieve the best outcome as if the sender was not informed about the state. This implies that $\mathbb{E}(\gamma \mid \alpha''(\gamma), y) = \alpha''(\gamma)y + (1 - \alpha''(\gamma))\mathbb{E}(\gamma)$. Hence, the posterior belief of the countries is a convex combination of their signal (as the true state) and the prior expectation. Because the optimal abatements are strictly increasing in beliefs, any induced solution $\mathbf{q}^c(\mathbb{E}(\gamma \mid \alpha''(\gamma), y))$ is also a convex combination of $\mathbf{q}^c(y)$ and $\mathbf{q}^c(\mathbb{E}(\gamma))$. Then the best response of the sender is as follows. If $\mathbb{E}(\gamma) \le \gamma$, then the separating PBNE specified in the proposition, constitutes best response for all players, as no one has any incentive to deviate. However, if $\mathbb{E}(\gamma) > \gamma$, the sender optimally, chooses $\alpha''(\gamma) = 0$ to minimise its loss function. But this is similar to Proposition 3 if $\theta = 1$, where the sender has a threshold strategy and knowing that the sender is biased to higher levels of abatement (given Assumptions 1–4), if the countries observe $\alpha''(\gamma) = 0$, they truncate the distribution of social cost of GHG from above. So, they will have a posterior expectation which is strictly less than $\mathbb{E}(\gamma)$, and they select an abatement $\mathbf{q}^c$, which is strictly less than $\mathbf{q}^c(\mathbb{E}(\gamma))$. Therefore, $\alpha''(\gamma) = 0$ is not a best response to the selected $\mathbf{q}^c$. Similarly, no other $\alpha(\gamma) < 1$ can be a best response to the countries' strategy. The only best-response abatements and signalling strategy are where the posterior beliefs of the countries lead to $\mathbb{E}(\gamma \mid \alpha''(\gamma), y) = \gamma$ and $\mathbb{E}(\gamma \mid \alpha = 0) = \bar{\gamma}_e = 0$. Hence, the sender has no choice other than setting $\alpha(\gamma) = 1$, and countries choose $\mathbf{q}^c(\gamma)$. □

Appendix K. Proof of Proposition 6

With binary state variable it is optimal to choose a binary signal space. Let $Y = \{l, h\}$, where $y = l$ recommends a lower level of abatement and $y = h$ recommends a higher level of abatement. Hence, $\mu_h \equiv pr(\gamma_h \mid \alpha(.); y = h)$. Furthermore, let τ be the total probability of μ_h.

Since each posterior belief is associated with an expected payoff $\mathbb{V}(\mu_y)$, every information strategy (i.e. probability distribution over signals, and thus over posteriors) is associated with an expected payoff of $\tau\mathbb{V}(\mu_h) + (1-\tau)\mathbb{V}(\mu_l)$. This reduces the problem of the sender to

$$\begin{aligned} &Min_\tau \quad \tau\mathbb{V}(\mu_h) + (1-\tau)\mathbb{V}(\mu_l) \\ &\text{subject to} \quad \tau\mu_h + (1-\tau)\mu_l = p \end{aligned}$$

where the constraint is the Bayes Plausibility condition.[29] Aumann and Perles (1965) and Kamenica and Gentzkow (2011) show that the solution to the above problem can be found by finding the infimum of the convex hull of graph of $\mathbb{V}(\mu)$ in $(\mu, \mathbb{V}(\mu))$-space. Let us label the lower enclosure of the convex hull of graph of $\mathbb{V}(\mu)$ as $V(\mu)$. In other words,

$$V(\mu) = \inf_\tau [\tau\mathbb{V}(\mu_h) + (1-\tau)\mathbb{V}(\mu_l) \mid \tau\mu_h + (1-\tau)\mu_l = p] \tag{K.1}$$

The sender chooses a randomisation (using τ) over two posterior beliefs such that they satisfy the Bayes Plausibility and they minimise its expected loss.

We prove Proposition 6 in two steps: first, we show that under the quadratic cost assumption, $\mathbb{V}(\mu)$ is a linear function in $(\mu, \mathbb{V}(\mu))$-space. Secondly, we show $V(\mu)$ is also linear and coincides with $\mathbb{V}(\mu)$. Then, we derive the optimal information communication policy.

To derive $\mathbb{V}(\mu)$ in $(\mu, \mathbb{V}(\mu))$-space, note that since the countries are symmetric and the message is public, we can focus on q^c of a representative country. With the binary distribution, it is clear that there is a one-to-one map between μ and $\mathbb{E}_\mu(\gamma)$, as $\mathbb{E}_\mu(\gamma) = \mu\gamma_h + (1-\mu)\gamma_l$. Now if μ changes, from the comparative static analysis in Section 4.1.3, we can say that there is a one-to-one map between the belief of the countries about the social cost, μ, and their abatement level too: as μ increases, the abatement level increases over its continuum range. We showed that different levels of abatement react differently to the change in belief,

[29] If Bayes Plausibility holds, τ is also equal to the total probability of signal $y = h$, i.e. $\alpha(y = h)$.

for instance $\frac{\partial q_i^s}{\partial \mathbb{E}_\mu(\gamma)} > \frac{\partial \bar{q}}{\partial \mathbb{E}_\mu(\gamma)}$, but all abatement levels change in the same direction. With the quadratic cost assumption, the actions respond linearly to the change in their belief with respect to the social cost of carbon. First consider a case where $\mathbf{q}^c < \mathbf{q}^s$. As μ increases, $\mathbf{q}^s$ increases linearly, and any chosen abatement level such that $\mathbf{q}^c < \mathbf{q}^s$ increases linearly too, but at a lower rate. Given this, the difference between $\mathbf{q}^c$ and $\mathbf{q}^s$ increases as the belief about γ_h increases. Considering the flow loss of the sender, $v(\mathbf{q}^c(\mu))$, we can establish a mapping between μ and $\mathbb{V}(\mu)$: as μ increases, $\mathbb{V}(\mu)$ linearly increases over $\mu \in [0,1]$. Now consider a case where $\mathbf{q}^c > \mathbf{q}^s$. As, μ increases both $\mathbf{q}^c$ and $\mathbf{q}^s$ linearly increase, but now $\mathbf{q}^c$ increases at a greater rate. Again, the distance of the level of abatement diverges as μ increases. Thus, $\mathbb{V}(\mu)$ is again a linear and increasing function. This completes the first step of the proof.

To derive $V(\mu)$, note that the lower enclosure of the convex hull of $\mathbb{V}(\mu)$ in $(\mu, \mathbb{V}(\mu))$-space connects the minimum of $\mathbb{V}(\mu)$ at $\mu = 0$ to its maximum at $\mu = 1$. Hence, $V(\mu)$ is also a linear function and coincides with $\mathbb{V}(\mu)$.[30]

Now we can read off the optimal information policy from the derived graph of $V(\mu)$ to find the PBNE. The sender in selecting the beliefs needs to ensure that the Bayes Plausibility rule is satisfied. Thus the sender chooses two posterior beliefs on two sides of the prior belief, p, such that $V(\mu)$ is minimised and at those beliefs $\mathbb{V}(\mu) = V(\mu)$. But along all $\mu \in [0,1]$, $\mathbb{V}(\mu)$ and $V(\mu)$ coincide. Therefore, there is no unique equilibrium strategy: any two Bayes Plausible beliefs on two sides of p can construct the equilibrium posterior beliefs, including the two fully revealing beliefs of $\mu = 0$ and $\mu = 1$ (if the sender could observe the state). All such equilibrium strategies lead to the expected loss of $V(p)$ for the sender. In addition, because $\mathbb{V}(\mu) = V(\mu)$ for all beliefs, the sender never gains from communication. Furthermore, the probability of τ is not uniquely determined, and as long as $\tau\mu_h + (1-\tau)\mu_l = p$, the two posterior beliefs constructs an equilibrium strategy. □

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[30] In $(\mu, \mathbb{V}(\mu))$-space, the curvature of $\mathbb{V}(\mu)$ is not characterised with a general cost function, and it depends on the response of various abatement levels to the change in μ.