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Strategic incentives for climate geoengineering coalitions to exclude broad participation

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Abstract

Solar geoengineering is the deliberate reduction in the absorption of incoming solar radiation by the Earth's climate system with the aim of reducing impacts of anthropogenic climate change. Climate model simulations project a diversity of regional outcomes that vary with the amount of solar geoengineering deployed. It is unlikely that a single small actor could implement and sustain global-scale geoengineering that harms much of the world without intervention from harmed world powers. However, a sufficiently powerful international coalition might be able to deploy solar geoengineering. Here, we show that regional differences in climate outcomes create strategic incentives to form coalitions that are as small as possible, while still powerful enough to deploy solar geoengineering. The characteristics of coalitions to geoengineer climate are modeled using a 'global thermostat setting game' based on climate model results. Coalition members have incentives to exclude non-members that would prevent implementation of solar geoengineering at a level that is optimal for the existing coalition. These incentives differ markedly from those that dominate international politics of greenhouse-gas emissions reduction, where the central challenge is to compel free riders to participate.

Keywords: geoengineering, international environmental agreements, game theory, climate modeling, climate coalitions

 Online supplementary data available from stacks.iop.org/ERL/8/014021/mmedia

1. Introduction

Intentionally reducing the amount of sunlight that reaches Earth's surface through the use of stratospheric aerosols may have potential for mitigating some effects of global warming [1]. Even if solar geoengineering is implemented uniformly across the globe, the regional effects would be geographically heterogeneous [2–4]. Thus, the preferred

amount of reduction in solar intensity likely would vary from region to region [5, 6]. Moreover, if a decision were made somehow to move ahead with the deployment of an intentionally introduced stratospheric aerosol layer, some regions might prefer a cooling or warming relative to the current climate, creating complicated problems in setting the global thermostat. In addition, several modeling studies have demonstrated that if solar geoengineering is used to compensate for rising greenhouse-gas concentrations and is then stopped abruptly, very rapid warming can occur [4, 7]. Thus, if solar geoengineering is ever implemented, stopping suddenly poses a threat. The magnitude of this threat, like any



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risk, depends not only on the consequences if it is realized but also its likelihood of occurrence.

The theory of International Environmental Agreements (IEA) is the most common way to analyze the characteristics of environmental coalitions (see [8] for a recent survey of the literature). In the most common variant of the game, coalitions are formed in a one shot ‘open membership’ game where actors choose whether or not to join a coalition and coalition members maximize their joint benefits. Due to the free riding nature of the climate change mitigation game, self-enforced global coalitions are not a likely outcome (see [9] and [10]), but participation in the global coalition can be expanded through side payments [11] or through credible threats of reciprocation [12].

Barrett (2008) proposes that while the mitigation game is one of cooperation, the solar geoengineering game is one of coordination in which the only relevant decision is how to divide the costs of SRM, as would be done with an asteroid defense system [13]. However, unlike a defense asteroid system where there are two outcomes: success or failure, outcomes of the implementation of solar geoengineering are not binary. The heterogeneity of the physical climate response to solar geoengineering generates heterogeneity in preferences for the level of implementation. Therefore, given the very low direct costs associated with solar geoengineering, the only reason to cooperate in such a game is to gain political viability. In this type of exclusion game, only players that prefer to form a coalition with each other are able to do so, and players that are not wanted in a coalition cannot enter.

Here we evaluate the incentives to implement solar geoengineering and illustrate that the strategic effects of solar geoengineering are appropriately characterized by an exclusive, rather than open membership, coalition game. We use the game to assess the potential for inequitable and unstable regimes to emerge in a world where coalitions attempt to counteract climate change with climate engineering. In the scenarios examined, climate models are assumed to correctly predict the future and damage is parameterized in terms of regional temperature and precipitation changes only, and do not consider other, possibly formidable, risks. Direct costs of geoengineering, such as those to sustain a fleet of airplanes to implement geoengineering [18], are assumed to be negligible relative to damages from climate change. Albeit simple, this model captures some of the essential interactions that could occur in a world that is seriously considering climate engineering.

Under the model of player welfare used here, large coalitions can be sustained due to the low costs of solar geoengineering and large benefits associated to its implementation. If geoengineering coalitions were formed through an ‘open membership game’ typical to the characterization of climate change mitigation agreements, a grand coalition would always form. (A ‘grand coalition’ is one in which all players are members.) With negligible costs of participation, players can only benefit from having input into the setting of the global thermostat. Conversely, the result of an exclusion game is a ‘public good club’ [19], where ‘public good’ describes the fact that all regions will benefit (or

lose) from geoengineering regardless of coalition membership statuses and ‘club’ describes the fact that only the members of the coalition have a say on where to set the thermostat.

In this context, multiple coalitions are likely to appear around different preferred amounts of solar geoengineering. In contrast to mitigation games, however, multiple coalitions cannot take action. The climate outcome associated with mitigation is proportional to the sum of the contribution of all parties. With solar geoengineering, only one amount can be implemented that affects the global outcome. Therefore, among all the possible coalitions, only the one with the majority power share is implemented. The methodology we use to solve the model is similar in spirit to early work on political coalition formation (e.g. [14] and [15]) in which (as with solar geoengineering) the goal is to achieve political viability with minimum compromise.

2. The game

2.1. Definitions

The following terminology is employed throughout the rest of the paper. We list it here for ease of explanation.

Damages: the socio-economic impacts of anthropogenic climate change.

Benefits: reduction in damages due to the deployment of a solar geoengineering system at some specified level. Benefits are negative if solar geoengineering deployment harms a country or region.

Majority coalition: a coalition holding more than 50% of world power. These coalitions cannot be defeated by more powerful coalitions.

Stable coalitions: in these coalitions no member has an incentive to leave the coalition for another.

Winning coalition: a stable majority coalition. By definition only one winning coalition can exist for any given configuration of the game.

Setting the global thermostat: implementing a specific amount of solar geoengineering—in our model a globally uniform perturbation to stratospheric aerosol optical depth.

Surplus benefits: net benefits for a given coalition above and beyond the sum of benefits each coalition member expects to receive from its next-best possible coalition option (the surplus benefit for a given coalition member may be negative).

2.2. Rules and assumptions of the game

The game takes place in two stages. During the first stage players choose their memberships and the winning coalition is formed. In the second stage, the winning coalition acts as a single actor to maximize the benefits of geoengineering to all coalition members. Players outside the coalition do not make decisions in this second stage.

To implement solar geoengineering, the actors deploying it need some minimum assemblage of international power. This power could take the form of egalitarian, military

or economic power. Here we contrast power regimes that are proportional to population and economic output. (The additional cases of military spending and a combined international power index are considered in supplementary material available at stacks.iop.org/ERL/8/014021/mmedia.)

We assume that the solar geoengineering system is deployed in a way that produces a uniform optical depth of sulfate aerosols, and thus there is only one degree of freedom. Individual actors optimize their own benefit and coalitions have one decision: how to set the global thermostat.

The cost to a coalition of a region joining the coalition is the reduction of benefits of solar geoengineering attainable if the existing members could choose the knob setting alone; the benefit to the party joining the coalition is the reduction in that party's climate damage resulting from a knob setting that is closer to that party's preferences. In this thermostat setting game transfers of surplus benefits within a coalition are distributed in proportion to the power that is held by each coalition member.

In the real world, parties to such coalition formation would likely be countries, or closely integrated blocks of countries such as the European Union. However, for simplicity, here we consider coalitions of 22 Giorgi regions [16]; Giorgi regions are often used to analyze global climate model results at the regional level (eg, [17]). As with countries, these regions have different amounts of power, prefer different amounts of solar geoengineering deployment (i.e., different 'knob' settings), and have different rates of benefit loss with departure of the knob from their preferred setting. Thus, the mechanics of the model would remain unchanged if countries were used instead of climatic regions, although the quantitative results may change.

We compare the outcomes of the exclusion game to an open membership coalition game. In this game each region evaluates its payoffs in a coalition including and excluding itself. With no direct costs in the model, the region can only benefit from joining the grand coalition and so it does. The region's benefits are equal to its payoffs in a global coalition which excludes it, plus its share of the grand coalition surplus, distributed power proportionately, as with exclusive coalition surpluses. Transfers in the open membership coalition game are relatively small, but not negligible (see supplementary figure S1 available at stacks.iop.org/ERL/8/014021/mmedia). In particular, coalition members that are attractive in the exclusion game—because they have near-median preferences and are relatively damage insensitive to changes in the amount of geoengineering—also benefit disproportionately in the open membership game from surplus sharing in the grand coalition.

2.3. Model of climate response and damages

We apply our coalitions game using data from physical climate model simulations of global warming and solar geoengineering, and a climate damage function that is similar to those used in classic integrated assessment models (e.g., RICE). Each player, in our case regions, has three relevant distinct characteristics that influence its

preferences and affinities in the formation of coalitions: g^* , the preferred amount of geoengineering; s , marginal sensitivity to changes in geoengineering; and p , the power a region holds. The 'thermostat setting', g_i^* , is the amount of solar geoengineering, implemented in the physical climate model as a modification of stratospheric aerosol optical depth, at which player i experiences its minimum regional damages. Damages in some regions increase markedly as the difference between the preferred and actual amount of solar geoengineering implemented increases, while damage in other regions is relatively insensitive to the amount of solar geoengineering implemented—therefore each player typically has a different marginal sensitivity, s , to changes to the knob setting. Finally, p , is the amount of power a given player possesses in negotiations relative to the others. As mentioned above, in the examples considered here, this may be the player's gross domestic product (GDP), population or military strength.

Previous work has demonstrated how g^* varies from region to region in climate model simulations and how the spread of regional values of g^* increases with the amount of greenhouse-gas driven climate change for which solar geoengineering is compensating [6]. In the series of 'one shot' club-formation games we simulate for this example, we assume that the 22 regions analyzed in Ricke *et al* [6] would each like to stabilize their annual mean temperature and precipitation as close to the recent past as possible. (For our purposes, the baseline is the first decade of the 21st century.) We assume that, if the coalition so decides, solar geoengineering can be implemented starting in 2015 and negotiations among club members only will determine the setting of the global thermostat for the next ten years. In each subsequent decade, negotiations begin anew, and determine a new thermostat setting for the next ten years.

In order to implement solar geoengineering, a coalition of regions must represent more than 50% of a power criterion. In the calibrated example, we test how various power criteria, change the results of the coalitions game, emphasizing population versus GDP.

In the game, regional benefits depend on how well solar geoengineering restores regional temperature and precipitation, approximated by:

$$T_i(G) = T_{0i} - \kappa_{Ti}G \quad (1)$$

$$P_i(G) = P_{0i} - \kappa_{Pi}G \quad (2)$$

where T_{0i} and P_{0i} are temperature and precipitation changes in region i without climate engineering, normalized by the amount of variability in that region (see [6] for further details). G is the level of solar geoengineering implemented globally. κ_{Ti} and κ_{Pi} capture the region-specific temperature and precipitation responses to solar geoengineering. (Notice that no restrictions are given to these parameters; they can be positive or negative.)

In most integrated assessment models and conventional representations of regional damages under anthropogenic climate change, damage functions are parameterized as a function of global temperatures. This simplification is made under the assumption that climatological indicators that are actually important to regional impacts, such as changes

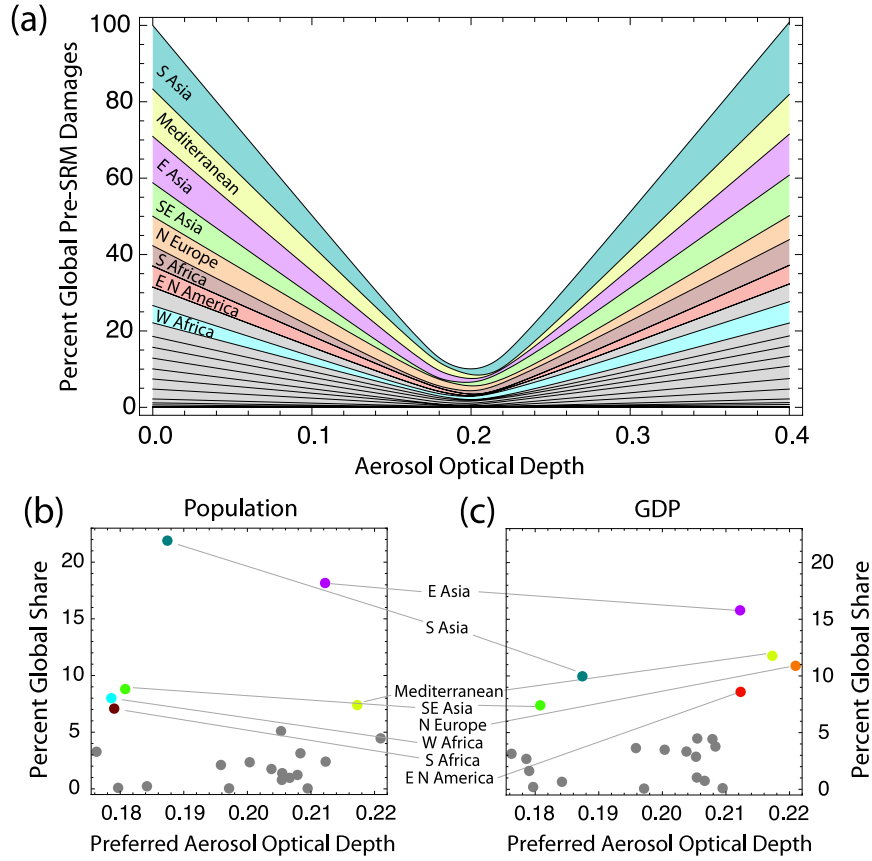


Figure 1. Regional damage as per cent of net global damage in the absence of solar geoengineering, and aerosol optical depths preferred by each region. (a) shows damages from climate change in 2070 as a function of aerosol optical depth, with regional shares partitioned and sorted by amount of pre-geoengineering damages. (b) and (c) show the share of global population and GDP in 2070, respectively in the 22 regions with the top 6 regions for each power metric labeled.

in local temperature, precipitation and soil moisture, are generally correlated with global temperatures in a consistent way. With the implementation of solar geoengineering, this approach does not suffice because with geoengineering-stabilized global temperatures, if other anthropogenic forcings continue to increase, regional temperature and precipitation (among other indicators) will continue to change, albeit in a different manner than without geoengineering. As such, the representation of regional (or even global) damages in a geoengineered climate requires a more complex functional form.

In this analysis we estimate damages as a function of combined variability-normalized regional temperatures and precipitation:

$$D_i(G) = \delta_i * \sqrt{(T_i^2 + P_i^2)} / \sqrt{T_i(0)^2 + P_i(0)^2} \quad (3)$$

where δ_i is an estimate of the sensitivity of climate damage in each region to the amount of climate change in that region.

Formally, D_i in equation (3) is a sum of all damages as calculated for each RICE region in a given Giorgi region:

$$D_{\text{giorgi}}(G) = \sum_{i=1}^N \frac{\delta_i((T_{0i} - \kappa_{Ti}G)^2 + (P_{0i} - \kappa_{Pi}G)^2)^\gamma}{(T_{0i}^2 + P_{0i}^2)^\gamma}. \quad (4)$$

See supplementary text S1 (available at stacks.iop.org/ERL/8/014021/mmedia) for details on the derivation of coefficient δ_i . The exponent, γ , which defines the convexity of the damage function is set at one for the results presented below. See supplementary text S3 (available at stacks.iop.org/ERL/8/014021/mmedia) for note on the form of the damage function.

The incentive structure of the game and its results appear insensitive to the choice of climate damage function, but the specific configuration of the winning coalition may change dramatically. Figure 1(a) shows the regional damage as a function of the amount of solar geoengineering in 2070 (near the end of the game series) as a percentage of the global no-SRM climate damages. Panels (b) and (c) show the projected regional shares of global population and GDP for the same decade.

2.4. Model of coalition formation and competition

A set of potential coalitions is generated for each power scheme and decade using a variation of a greedy algorithm solution to the knapsack problem; each region is used as the coalition seed member in turn. The coalition set is evaluated using a standard sequential bargaining approach to determine payoffs and a winning coalition. (See supplementary text S2 for details (available at stacks.iop.org/ERL/8/014021/mmedia).)

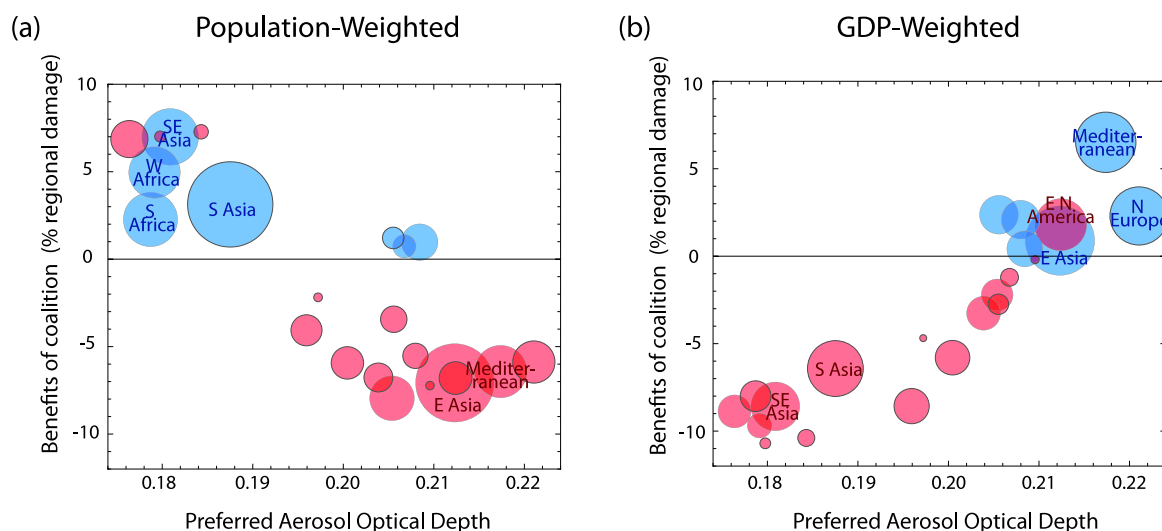


Figure 2. The benefits of exclusive coalition-implemented solar geoengineering relative to open membership by region in 2070. Benefits are displayed as per cent regional climate damages reduced, for coalitions formed under different power metrics. Regions are plotted by preferred amount of solar geoengineering (x-axis), with members of the winning coalition in blue and non-members in red. The size of each bubble is proportional to regional power. (a) Illustrates the results for a population-weighted power scheme and (b) shows the results for a GDP-weighted power scheme.

3. Results

The results of our game simulations show the maximum achievable benefits regions can gain by acting strategically to form exclusive clubs; this necessarily imposes damages on non-members relative to their preferences but in the cases examined here provides them with benefits relative to the zero geoengineering case. We present the outcomes of the exclusion games relative to a globally optimal open membership implementation of geoengineering, in which a grand coalition sets the thermostat to maximize global benefits (and distributes those benefits as described in section 2).

Figure 2 shows the regional results of two exclusive coalition games in 2070 relative to the open membership game, comparing power schemes based on population versus GDP. With the population power index, the winning coalition is one centered around South Asia, while the GDP power index yields a coalition of East Asia and Europe. In both cases these coalition configurations represent the potential coalition in which all coalition members received the highest payoffs relative to all other offered memberships (or non-memberships), including the option of joining the grand coalition that would form in the absence of exclusion.

As illustrated in figure 2, by forming an exclusive coalition, winning coalition members increase their benefits from geoengineering by 1–7% over what they would achieve in the grand coalition that would form in the absence of exclusion. In the simulations presented here, all regions benefit by deployment of solar geoengineering at the level of any other regions preference, but benefits to a region are less than what could be attained with deployment at level closer to that regions preference. Benefits to regions that are excluded from a winning coalition are often but not always less than the benefits that would be attained under a grand coalition. Many regions excluded from the winning coalition

have benefits that are up to 10% less than would be attained under the grand coalition. However, some regions excluded from the winning coalition (such as Eastern North American in the GDP-weighted game) still benefit from exclusive coalition because the exclusive coalitions implements a level of geoengineering closer to that region's preference than would the grand coalition.

In our game, we find that different assumptions and majority criteria lead to different coalitions, but in all cases and at any time:

- (i) many potential coalitions would have incentive to implement solar geoengineering, thus, if a majority coalition were to fall apart due to some exogenous factor, another would have incentive to take its place;
- (ii) the amounts of solar geoengineering that any given coalition would implement are similar enough that a change in the majority coalition from one implementing higher-than-average solar geoengineering to another implementing lower-than-average solar geoengineering, or vice versa, would not result in rapid climate change; and
- (iii) the differences between the effects of solar geoengineering as implemented by an exclusive coalition and those at the global optimum are dwarfed in comparison to the differences between solar geoengineering and no-solar geoengineering.

When the game is played through six decades with the population or GDP power criteria, membership in the winning coalitions varies dramatically from decade to decade (see figures 3(c) and (d)). While the results presented in figure 2 imply that changes in coalitions could have a large impact on the amount of solar geoengineering implemented and its global effects, all of the differences between cases

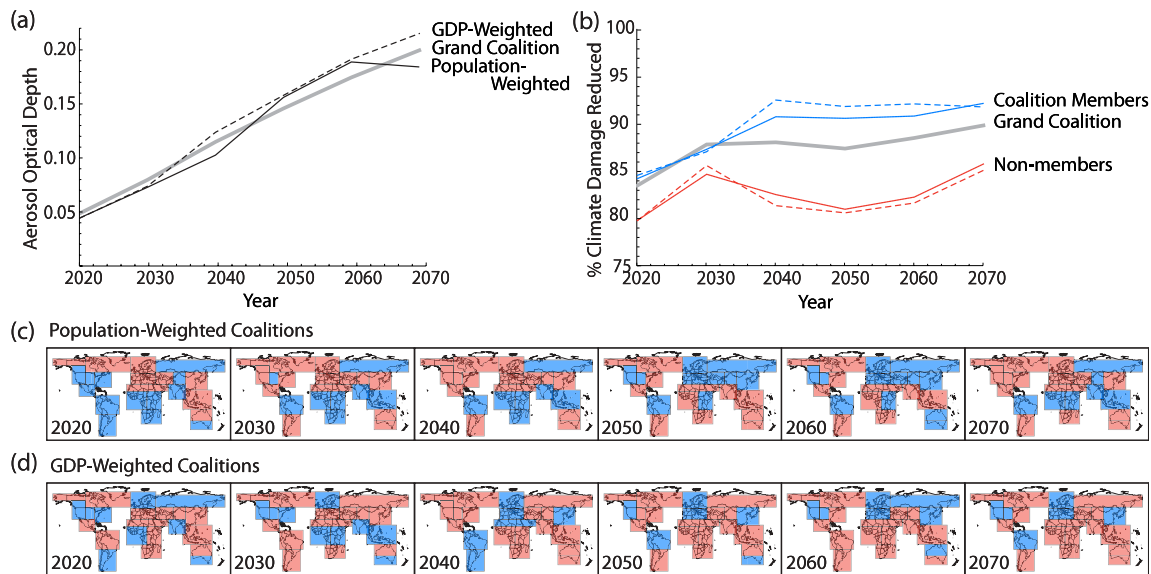


Figure 3. Comparison of results under a grand coalition versus exclusive coalition for population and GDP power criteria over 6 decades of solar geoengineering implementation. (a) shows how the amount of solar geoengineering (in units of stratospheric aerosol optical depth, AOD) implemented by an exclusive coalition under a population-weighted power scheme (solid) or a GDP-weighted power scheme (dashed), compared to the open membership (grand) coalition (thick gray); (b) shows how the winning coalition members (in blue) and non-members (in red) reduce their damages from climate change using solar geoengineering compared to reductions for the grand coalition (thick gray). (c) and (d) show the regional membership of the winning coalitions in each decade.

result in relatively minor reductions in net global benefit. Figure 3(a) shows the amount of solar geoengineering implemented over time by the winning coalitions compared to the global optimum and 3(b) shows the impact of the coalition implementation on damages for coalition members non-members. On average, even ‘losers’ in the coalition game have damages from climate change reduced by well over 70%.

4. Discussion

We have shown how the heterogeneity in physical effects of solar geoengineering creates economic incentives for exclusive solar geoengineering implementation agreements. Despite the low direct costs associated with stratospheric geoengineering, the best current understanding of its implementation suggests it would require the continuous actions implemented through visible infrastructure [18]. It is unlikely that a unilateral implementation scheme contrary to the interests of much of the world could get far underway without intervention from harmed world powers. A more likely possibility is a strategic multilateral implementation through an exclusive ‘club’ that increases benefits to members at the expense of those excluded. If the option of a global coalition is accounted for in formulating a system of intracoalitional transfers, the game presented here always produces a stable and powerful coalition in which all coalition members benefit from excluding other parties. Our characterization of climate damages assumes that all players benefit from reducing or eliminating regional changes to temperature and precipitation, but this may not be true. If regional responses to solar geoengineering are more diverse, incentives to exclude will grow.

Nonetheless, a number of factors would favor an inclusive approach to future agreements to implement solar geoengineering. First, direct and indirect costs of an exclusive agreement would provide incentives to broaden coalitions. We neglect direct costs in our model because they are expected to be modest for this technology. Gains from exclusion, however may also be quite modest, in particular when geoengineering is first implemented and the amount of climate damages that can be prevented or reversed are small. Indirect costs, such as penalties or sanctions by excluded parties, may provide additional incentive to avoid exclusionary policies and thus would tend to favor formation of a grand coalition.

Perhaps even more than costs, the fickle outcomes of negotiations present an incentive to consider advocating open membership. The idealized game we present is based on detailed climate model results, and it illustrates that even small shifts in relative payoffs and power balances can lead to dramatic changes in the membership of a winning coalition. In a game where winners reap modest gains at unknown costs, a player with foresight may recognize significant advantages to the institutionalization of inclusivity. With institutionalized inclusivity, parties assure that they will not be excluded from future coalitions.

Our results reflect a highly simplified model of preferences in which regions act to simultaneously stabilize temperature and precipitation at early 20th century values with the goal of minimizing climate damage. The result is an implementation of solar geoengineering that maximizes the climate benefits among coalition members at the expense of non-members. However, for the climate model simulations and climate damage functions considered here, all players in the game benefit from some level of solar geoengineering

and compared to a no-solar geoengineering alternative, the differences between distribution of benefits under a grand coalition and exclusive coalitions are relatively small.

The fundamental characteristics of winning climate engineering coalitions described here would not be affected by different choices of damage function or a more complex representation of physical and political path dependences. Sufficient heterogeneity of climate outcomes and damages are the only requirements to incentivize exclusivity. The use of some other damage function would alter the preferred amount of solar geoengineering. For example, different damage functions could potentially be developed that account for effects such as stratospheric ozone destruction or sea-level rise. These different damage functions could produce markedly different quantitative results for the preferred 'knob setting', perhaps leading to winning coalitions that choose to forego solar geoengineering completely. In addition, while the games illustrated are played consecutively across decades, our model assumes that political alliances and regional climate states between decades are independent, a significant simplification of the real world. In the climate model we use, only about half of the global temperature response is realized by ten years after a change in radiative forcing, and this lag is not explicitly reflected in our model of damages and decadal timescale decision making.

While considerable research has been focused on the large potential damages associated with abrupt termination of solar geoengineering, the risks associated with such a scenario depend not only on these damages but also the likelihood that such a termination would occur. Under an exclusive coalitions model of international agreements to geoengineer, if one coalition breaks down, another is ready and eager to take its place. As the potential harm from termination grows (i.e., as the amount of greenhouse-gas forcings being compensated for with geoengineering increases), so too do the incentives to avoid this termination among all potential coalitions. In addition, the requirement that a winning coalition must meet the majority power criterion (and therefore be impervious to the challenge of a competing coalition) keeps volatility in the geoengineering forcing trajectory low, even if coalition membership changes dramatically.

Divorced from other considerations, the strategic behavior of players in a global thermostat game is best represented by a public goods club. In reality, however, the politics of solar geoengineering would not occur in a void. Solar geoengineering preferences do not necessarily align with previously existing political blocks. Other considerations beyond climate damage, such as maintaining good economic and political relations with other regions would certainly influence decisions about inclusivity of solar geoengineering coalitions. Factoring in any influences beyond those of the physical climate system would tend to move coalitions toward universal membership, i.e., the formation of a grand coalition. The extent to which geoengineering clubs choose exclusivity versus open membership in real world scenarios will depend on the costs of geoengineering, the form of regional climate damage functions and the players' expected costs of exclusion (or inclusion) unassociated with climate considerations. Given

the relatively small gains associated with exclusivity for most players in our configuration of the global thermostat setting game, however, incentives for a broad coalition may be high.

Climate change mitigation and solar geoengineering present very different incentives for cooperation and exclusion. Mitigation results in low coalition participation due to free riding. There is incentive to broaden coalitions to reduce the cost to each party of achieving climate benefits. In contrast, for geoengineering, low coalition participation is the result of exclusive behavior by coalition partners. There is incentive to exclude willing allies in order to maximize the climate benefit among the winning coalition members. Hence, the governance institutions required to ensure equity are quite different for geoengineering than climate change mitigation. It has been argued that the requirement for broad participation may be a hindrance in achieving agreements to reduce global greenhouse-gas emissions [20]. For geoengineering, however, institutionalizing inclusiveness—that is, agreeing that anyone who wants to participate in a coalition to geoengineer can—may be a simple and effective way to ensure the global thermostat is not controlled by a few at the expense of others.

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