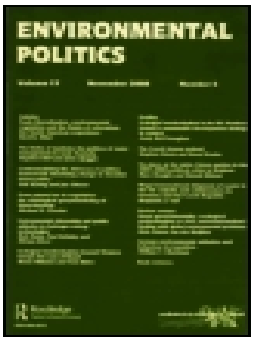

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Highly decentralized solar geoengineering

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ABSTRACT
Nonstate actors appear to have increasing power, in part due to new technologies that alter actors' capacities and incentives. Although solar geoengineering is typically conceived of as centralized and state-deployed, we explore highly decentralized solar geoengineering. Done perhaps through numerous small high-altitude balloons, it could be provided by nonstate actors such as environmentally motivated nongovernmental organizations or individuals. Conceivably tolerated or even covertly sponsored by states, highly decentralized solar geoengineering could move presumed action from the state arena to that of direct intervention by nonstate actors, which could in turn, disrupt international politics and pose novel challenges for technology and environmental policy. We conclude that this method appears technically possible, economically feasible, and potentially politically disruptive. Decentralization could, in principle, make control by states difficult, perhaps even rendering such control prohibitively costly and complex.

KEYWORDS Climate change; solar geoengineering; solar radiation management; nonstate actors; governance

> [Our] satellite will collect data about pollution that is warming the planet. We will put that data in the hands of people who can make simple fixes that will change the course of global warming in our lifetime.
>
> – Fred Krupp (2018), President, Environmental Defense Fund

Introduction

In April 2018, the Environmental Defense Fund (EDF) announced its intention to launch a satellite to monitor the emissions of methane, a potent greenhouse gas whose sources and quantities are not fully understood. Similarly, another set of nonprofit organizations, with a grant from Google's philanthropic arm, announced their intention to use satellites to measure and publicly report greenhouse gas emissions from the world's

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largest power plants (Arnone 2019). While environmental groups have rapidly grown over the years and have had outsize impact on environmental policies, the satellite announcement adds a new dimension to their work. Nonstate actors, such as nongovernmental organizations and philanthropists, have a long history of giving large grants to provide local public goods such as libraries, research, and land preservation, especially in the United States (Bremner 1988). More generally, nonstate actors are recognized as having increasing power in international political domains. However, the direct provision of global public goods – such as launching satellites for scientific monitoring – has traditionally been the responsibility of national governments, usually through international cooperation (Risse 1995, Falkner 2003). Even then, global public goods are usually undersupplied relative to the social optimum. Meanwhile, in a world of more multi-billionaires, growing transboundary and other environmental challenges, and, in some corners, an apparent retreat of the state, such nonstate actions – philanthropic or not – appear ever more likely (Giridharadas 2018).

Nonstate actors are recognized as having increasing power and influence in international politics – spanning the gamut from private actors (Sending and Neumann 2006, Green 2013) to international bureaucracies (Jinnah 2014). Nonstate provision of global public goods can also extend to individuals, which have received less scholarly attention. However, decentralized, loosely coordinated groups of individuals have been quite important in the climate change context. For example, tens of thousands of environmentally motivated individuals spend ~10–100 annually on voluntary greenhouse gas emissions offsets. The capacity of decentralized individuals to provide public goods and to affect international politics, therefore, deserves more scholarly attention.

Technology is an increasingly important enabler of nonstate actors' growing importance in international politics. This seems especially true for decentralized technologies, that is, those used by many geographically dispersed actors who are not coordinated, or only loosely so. In recent years, attention has focused on the role of social media in enabling nonstate action. For example, the outbreaks of unrest in the Middle East, North Africa, and Eastern Europe in 2009 through 2011 have been called 'Twitter Revolutions' (Parmelee and Bichard 2011). Other novel decentralized technologies could directly amplify nonstate actors' capacities to intervene in world politics. For example, direct cash transfer technologies, such as GiveDirectly, enable individuals and other nonstate actors to bypass states foreign aid mechanisms in making contributions to the global poor (Blattman and Niehaus 2014).

Here, we consider a radical way in which nonstate actors could use a new technology – solar geoengineering – to provide a global public good and, in the process, influence and potentially disrupt domestic and international (climate) politics. Solar geoengineering, most prominently in the form of sulfate aerosols deliberately injected into the lower stratosphere, could be effective in reducing climate change, global and rapid in its impacts, technically possible, and inexpensive in its direct implementation costs (Keith 2000, Royal Society 2009, National Research Council 2015).[1] This set of characteristics – despite the technology's clear imperfections and controversial nature – has raised the prospect of one or a few actors, possibly even nonstate actors, deploying solar geoengineering, independent of any consensus among the international community. Such deployment might happen in an uncoordinated fashion, possibly with large detrimental climatic and environmental outcomes. With sufficient international governance efforts, it could also happen with a level of coordination among states to monitor and guide desirable climatic outcomes. Regardless of the level of coordination assumed – or hoped for – solar geoengineering proposals have, until now, relied on relatively centralized (that is, interventions by a few coordinated actors, or only one) deployment systems, using, for example, fleets of specially modified aircraft (Smith and Wagner 2018).

Here we go a step further and introduce what we argue is a technologically possible, economically feasible, and potentially politically disruptive way in which solar geoengineering could be deployed. Numerous unmanned high-altitude balloons, launched in highly decentralized yet potentially coordinated fashion, could have outsized impact on the world's climate. Highly decentralized solar geoengineering, provided by many nonstate actors, such as environmentally motivated individuals, nongovernmental organizations, or possibly commercial firms, and quietly tolerated or perhaps covertly sponsored by states, is a possible scenario that has yet to be considered in governance proposals. We also argue that such a decentralized deployment scenario could disrupt international relations and pose novel challenges for technology and environmental policy. Decentralization may also make oversight and control by democratic states difficult, perhaps even prohibitively costly and complex.

The remainder of this discussion is organized as follows. In the next section, we explain the basic landscape of centralized solar geoengineering as conceived in the existing literature. We then lay out a new scenario, that of decentralized non-state actor deployment. Finally, we analyze the feasibility of such a scenario along three dimensions: technology and coordination; economics and incentives; and governance and politics.

Centralized solar geoengineering

Largely in response to insufficient global greenhouse gas emissions abatement and adaptation efforts, some scientists and others have looked toward direct, large-scale technological interventions to reduce climate change.

One such category of 'geoengineering' is solar geoengineering, in which a small portion of incoming solar radiation would be deliberately reflected or otherwise blocked to cool the planet. The basic principle has been known for decades and was the one response mentioned in the first U.S. government report on anthropogenic climate change (President's Science Advisory Committee 1965). However, the possible deployment of – and even research into – solar geoengineering was subject to a decades-long global taboo, primarily because many see it as a distraction from what is clearly necessary to address climate change: aggressively reducing greenhouse gas emissions and, ultimately, excess atmospheric greenhouse gas levels (Lin 2013, Reynolds 2015, Wagner and Merk 2018). The publication of a speculative essay by Nobel Laureate Paul Crutzen that highlights the moral quandary of *not* researching solar geoengineering substantially weakened this taboo (Crutzen 2006), and the field has seen a steady increase in research ever since (Lawrence and Crutzen 2017).

The leading proposed method of deploying stratospheric aerosols is inspired by large volcanic eruptions, whose ash and sulfuric droplets linger in the atmosphere, scattering a small fraction of sunlight and cooling the planet. Humans could mimic this by injecting a fine aerosol or a precursor thereof into the stratosphere. This could be done through various delivery systems, such as high-altitude balloons or perhaps fleets of specially designed aircraft (Smith and Wagner 2018). Importantly, the Intergovernmental Panel on Climate Change (IPCC) recently concluded that stratospheric aerosol injection could '*with high agreement* […] limit warming to below 1.5°C' (IPCC 2018, p. 350), an ambitious goal that otherwise appears out of reach.

Solar geoengineering's characteristics, especially the inexpensive nature of a global intervention, pose a distinct set of problems. Although solar geoengineering, like emissions abatement, is technically a non-excludable public good, a single actor's benefits could be greater than that actor's direct costs. Thus, in contrast to abatement's 'free-rider' collective action problem of suboptimal provision, the main challenge here is that of 'free drivers' injecting too much material into the stratosphere too early (Schelling 1996, Barrett 2008, Victor 2008, Wagner and Weitzman 2012, Weitzman 2015).

The vast majority of considered solar geoengineering deployment scenarios has focused on state action (e.g., Parson 2014, Horton and Reynolds 2016, Jinnah 2018). Within this discourse, most attention has been dedicated to problematic unilateral deployment, either by a hegemonic country or a so-called rogue state. Some scholars have discussed possible minilateral governance (Benedick 2011, Lloyd and Oppenheimer 2014). Others envision global consensus on deployment through, for example, the United Nations General Assembly or a specialized multilateral agreement with widespread participation (Zürn and Schäfer 2013). Along these lines, the IPCC report states also:

> There is *robust evidence* but medium agreement for unilateral action potentially becoming a serious [solar geoengineering] governance issue … An equitable institutional or governance arrangement around [solar geoengineering] would have to reflect views of different states and be multilateral because of the risk of termination, and risks that implementation or unilateral action by one state or organization will produce negative precipitation or extreme weather effects across borders. (IPCC 2018, p. 347)

Consequently, a central question in academic and policy debates has been how to constrain premature and/or unilateral solar geoengineering and to responsibly govern deployment by a larger group of state actors (e.g., Pasztor 2017, Reynolds 2019, Stavins and Stowe 2019), with prominent calls for 'immediate polycentric governance' (Nicholson *et al.* 2018).

However, the present factor limiting solar geoengineering's consideration and governance is the *absence* of state action. Besides modest research funding by a handful of states (Necheles *et al.* 2018), none are (as of yet) meaningfully moving forward with actual policy, research, or development, let alone deployment. For one reason, solar geoengineering might presently seem too hypothetical or uncertain. Second, those decision-makers most concerned with climate action and most likely to support solar geoengineering might wish to be seen as fully dedicated to emissions cuts. Third, politicians might be worried about opposition from some environmentalists, who are often opposed to the idea, or about fueling international distrust. Lastly, some leaders might see no feasible means through which solar geoengineering's use could be effectively and legitimately governed. Thus, while its problem structure points toward possible premature deployment by 'free drivers', solar geoengineering's present politics indicate suboptimal and insufficient governance action and research (Horton and Reynolds 2016).

Non-state actors that become concerned about the risk of inadequate progress in solar geoengineering might therefore consider taking action into their own hands. A first step would be funding research. Indeed, a substantial portion of financial support for solar geoengineering research is currently philanthropic, especially in the United States (Necheles *et al.* 2018). Centralized non-state deployment is also possible, at least in principle. Victor (2008, p. 324) describes how a wealthy 'self-appointed protector of the planet,' whom he memorably names 'Greenfinger' after a James Bond villain, might undertake this out of a desire to counter dangerous climate change. Although this attention-catching scenario has been invoked to highlight the difficulty of governing solar geoengineering, the few scholars who have considered – albeit briefly – a non-state deployment scenario usually argue that it seems unlikely (Bodansky 2013, Parson and Ernst 2013, Reynolds *et al.* 2017).[2]

Despite a steady rise of private actors in global environmental governance (Green 2013), states will likely consider large-scale climatic alterations to be their exclusive prerogative. States in whose territory non-state actors might deploy centralized solar geoengineering would either oppose it themselves or come under external pressure to end the activity. Bodansky (2013, p. 548), for example, says that a threat of private solar geoengineering would be treated like terrorism and controlled by a combination of police and military action. Parson and Ernst (2013) further highlight the fairly high technological requirements of sustained centralized climatic intervention through solar geoengineering. Meanwhile, although solar geoengineering might be cheap in terms of climate change economics, it is far from costless. A rough calculation of a hypothetical deployment ramp puts the total price tag for the first 15 years at just over $30 billion, increasing thereafter (Smith and Wagner 2018). That is inexpensive with respect to emissions abatement and especially climate change impacts. It also compares favorably to many states' overall and military budgets, but it is still expensive in terms of billionaires' personal wealth, suggesting that deployment by a single non-state actor seems to be an unrealistic scenario (Reynolds *et al.* 2017). However, such centralized non-state deployment is not the only possible scenario involving non-state actors.

Highly decentralized solar geoengineering

The literature to date has focused on centralized unilateral and minilateral solar geoengineering deployment by both state and non-state actors, as well as multilateral deployment by states. Yet it has neglected the possibility of decentralized deployment conducted by non-state actors. This is an understandable consequence of current conceptualizations of delivery systems, which focus on specialized aircraft, multi-kilometer tethered hoses, rockets, and artillery requiring large capital investments and specialized expertise. There could, however, be significantly smaller-scale technologies available, such as, for example, unmanned high-altitude balloons, for which technical and financial barriers to entry have greatly decreased in recent years. Hobbyists have launched balloons, costing ~25–50, that can carry ~5–10 kilograms (kg) to heights above 20 kilometers (km) (e.g., Ganapati 2010). Similar balloons are readily available online. Their payload could include a few kilograms of sulfur dioxide (SO_2) or some other aerosol precursor, either in a separate delivery device or mixed with the balloon's lifting gas itself. The balloons themselves could then be designed to 'fail' at a specified air pressure, which would roughly correspond with altitude.

While there are many possible ways in which such a technology could play out – with balloons only representing perhaps the simplest, currently available technology – any such highly decentralized implementation would

Table 1. Categorization of solar geoengineering deployment by type and number of entities involved in deployment.

	Approximate order of magnitude of actors deploying solar geoengineering			
Character of deployers	1	~10	~100	>~1,000
State	Unilateral	Minilateral	Multilateral	n/a
Non-state	'Greenfinger'	Moderately decentralized solar geoengineering		Highly decentralized solar geoengineering
Possible means of delivery	Newly designed aircraft (deployment costs ~1.4/kg SO_2)[a]			Small balloons (~5/kg SO_2)[b]

[a] Rough estimates suggest costs of around 1,400 per ton of sulfur dioxide (SO2) deployed, carried into the stratosphere in form of sulfur and burned *in situ* (Smith and Wagner 2018).
[b] At a cost of ~25–50 for a small balloon carrying ~5–10 kg of SO_2.

dramatically expand the options available for solar geoengineering implementation. Possible sets of solar geoengineering deployers can now be conceptualized along two dimensions: number of actors and their state or non-state character (Table 1).

Like individual actions that emit greenhouse gases or reduce them, a single balloon would not alter the global climate. Yet such balloons could be feasibly deployed by the many thousands or even millions, perhaps coordinated and/or supported by entrepreneurs, campaigners interested in reducing climate change, states, or by other vested interests.

Unmanned high-altitude balloons are significantly less cost-effective than centralized delivery mechanisms. But at ~5 per kg SO_2 delivered, such balloons are only around four times more expensive than a centralized program using high-altitude aircraft (Table 1). Other, more effective materials could be developed in the future, which would reduce the number of balloons needed. While this is clearly not cost-effective compared to other possible solar geoengineering methods, it compares favorably to serious emissions abatement efforts, and most definitely compared to unmitigated climate change impacts, the costs of which are of the order of trillions of US dollars annually. Furthermore, because solar geoengineering is expected to indirectly remove atmospheric carbon dioxide (CO_2), primarily by slowing carbon cycle feedback, the highly decentralized variant still shares the characteristic of its centralized one, in that it could remove more CO_2 per dollar than tackling emissions directly (Keith *et al.* 2017). Although cost-effectiveness is an unlikely primary motivation, a low barrier to action is necessary for highly decentralized solar geoengineering to be plausible.

Feasibility and political consequences

In this section, we analyze the feasibility and possible political consequences of decentralized solar geoengineering by non-state actors. We do so by considering three dimensions: technology and coordination; economics and incentives; and governance and politics.

Technology and coordination

There are plenty of challenges, the first set of which is technical. For example, the amount of helium necessary to lift enough SO_2 to lower global average temperatures appreciably would be greater than current world supply. Yet that alone may not be a limiting factor. For one, there is significant potential to expand global helium supply, primarily as a byproduct of natural gas extraction. Its price elasticity of supply might thus be low. Furthermore, the lifting gas may not need to be helium, with hydrogen a possibly abundant, albeit technically more challenging alternative. Meanwhile, another challenge might be that the balloons themselves could have significant negative environmental impacts. All of this, of course, is highly speculative. The main point is simply that it appears technically possible – sufficiently so for someone to attempt to explore the methods more closely, and to unearth additional challenges and possible solutions in the process. In the end, a technically feasible delivery mechanism may not involve balloons at all. Even rail guns, which can shoot small loads long distances at the cost of an electric charge, might provide a possible alternative.

In addition to technical challenges, the process would require considerable funding and coordination to achieve desirable climatic and environmental outcomes. Crucially, such coordination need not be supplied by states. Without coordination, deployment activities would be poorly distributed spatially or temporally, and consequently ineffective or counterproductive (Jones *et al.* 2017). Here, decentralized online platforms could both match 'buyers' – those who wish to financially support the activity – and 'sellers' – those who wish to undertake it – as well as inform actors when, where, and how they should (not) deploy. Distributed ledger technologies (e.g. blockchain) and crowdfunding could help provide an incentive-compatible coordinating mechanism. They could also, if necessary, help evade state control (or enable states to evade responsibility) and enable remote deployment. Indeed, one could think of highly decentralized non-state solar geoengineering as 'crowdsourced'. At the same time, this could make the platform potentially vulnerable to hacking, manipulation, and the projection of power, both non-state and state.

Importantly, our estimates are based on using SO_2, which is presently the leading candidate substance for aerosol injection because of extant knowledge from volcanic eruptions. In the future, more effective substances could be discovered or developed. For example, fine solid alumina particles seem to be twice as reflective (Weisenstein *et al.* 2015). This could reduce the required number of balloons or other decentralized interventions, possibly greatly so.

One notable advantage of highly decentralized solar geoengineering may be the deployment system's resilience. A serious concern regarding solar geoengineering is that if it were to suddenly and permanently end under conditions of elevated atmospheric greenhouse gas concentrations, then the previously suppressed climate change would manifest rapidly, and dangerously so (Matthews and Caldeira 2007, Parker and Irvine 2018, Rabitz 2019). More deploying actors and locations would allow it to be more resistant to such rapid and sustained termination.

Economics and incentives

Incentives differ widely for possible highly decentralized non-state deployment on the one hand and a state-sponsored scenario on the other. Non-state actors' incentives rest heavily on their internal motivation to provide a global public good.[3] We assert only that some people – perhaps a substantial number – are willing to take actions that are costly in terms of money, time, and effort, provided that they believe that the actions would support sustainability or some other goal that they normatively desire. This is presently evident in greenhouse gas emissions offsets (Bumpus and Liverman 2008, Green 2011), donations to environmental causes, and costly environmental actions more broadly (Brulle 2000). There is no *ex ante* reason why environmentally minded individuals and other non-state actors would not likewise voluntarily act or pay to contribute to decentralized solar geoengineering (Buck 2012, pp. 266–7).

Yet there are important differences between highly decentralized solar geoengineering and emissions offsets. Even though the latter rest on individuals' intrinsic motivation, both states and institutions support individuals in doing so. That goes for environmental organizations as much as for companies such as airlines encouraging individuals to voluntarily pay more to offset their emissions. If states and other institutions actively discourage individuals from engaging in highly decentralized solar geoengineering, they surely could. Thus, it remains uncertain whether a large enough number of individuals would be motivated to act. A hundred million balloons launched in a given year, each releasing ~10 kg of SO_2 at heights of around 20 km, would lower global average temperature in the subsequent year by ~0.1°C. We suggest three scenarios in which a significant number of individuals and other non-state actors could contribute to decentralized solar geoengineering.

First and most generally, individuals could see it as helping prevent and reduce climate change. Returning to the comparison with emissions offsets, tens of thousands of people spend small sums (~10–100) in an effort to offset greenhouse gas emissions and prevent climate change (Bumpus and Liverman 2008). Such action is tightly linked to a belief in the importance of climate change (Jacobsen 2011). Meanwhile, offsets' total effects are limited at best, with a substantial body of literature (e.g., Green 2011) and increasing media coverage (e.g., Song 2019) questioning their effectiveness and the wisdom of encouraging the offsetting of emissions instead of preventing them in the first place. The cost effectiveness of solar geoengineering – even when highly decentralized – in reducing climate change is at least 2 or 3 orders of magnitude greater, which could reduce barriers to action among some environmentally motivated individuals and nongovernmental organizations. Furthermore, although solar geoengineering does not directly change greenhouse gas concentrations, it could indirectly reduce them through carbon cycle feedback (Keith *et al.* 2017). Highly decentralized solar geoengineering might, thus, even be cost-effective when solely viewed through the 'offset' lens (Lockley 2016). Moreover, solar geoengineering climatic effects occur quite quickly, while offsets – which rely mostly on forestry and other land use practices – are slow.

A second scenario involves non-state actors engaging in decentralized solar geoengineering to try to catalyze greater state action. They would aim not to have direct impacts but instead to engage in a type of civil disobedience (Morton 2015, pp. 348, 391). Some groups might seek to disrupt climate policies – both with the intention of catalyzing them or by hoping to provoke a backlash against solar geoengineering and to stop further action. The non-state actors could even call for centralized solar geoengineering itself. Through such disobedience, the non-state actors might aim to change the 'facts on the ground' regarding solar geoengineering. Even small-scale, decentralized interventions could be powerful catalysts for broader action, with analogies from nuclear to cyber security (Nye 2011).

The third scenario is one of covert sponsorship by a state or other powerful actor. A highly vulnerable state could wish to protect itself from climate change in the face of continuing insufficient greenhouse gas emissions abatement. Although it might possess the financial resources to implement centralized solar geoengineering on its own, the state's leadership might realize that any such unilateral effort by a non-hegemonic state would likely be met with international political, diplomatic, and military responses. Thus it could choose to secretly bankroll a clandestine decentralized program, leveraging perceptions of vulnerability and environmental activism throughout the world. Alternatively, a wealthy environmentally motivated individual or nongovernmental organization could covertly support the endeavor.

Biotechnology may offer an analogy. Some new, powerful techniques could be used for conservation purposes. For example, gene drives can genetically alter entire wild populations, with desired results including their local extinction (National Research Council 2016). They could be used to eradicate invasive alien species, a leading driver of biodiversity loss (Rode *et al.* 2019), something which is under consideration in New Zealand and elsewhere (Dearden *et al.* 2018). Although many established actors in conservation biology have resisted the use of these and related techniques, a younger cohort, inspired by 'eco-radicals', sees tools such as possible DIY gene drives and cloning as necessary conservation interventions. In this context, 'one person's vigilante could be another person's savior' (Kuiken 2017, p. 109). DIY solar geoengineering would surely be in a similar situation, with some highly supportive and personally active, while others would be vocally opposed to any such efforts.

All such activities might seem contrary to current politics in which 'deeper' and 'greener' environmentalists presently tend to oppose solar geoengineering (Corner *et al.* 2013). However, much of this appears linked to the high-technology, centralized nature of solar geoengineering as it is currently imagined. In contrast, a highly decentralized non-state form could turn this image on its head and might, thus, appeal to egalitarian-minded environmentalists.[4] To some degree, this change is already evident in attitudes about biotechnology and conservation (Island Conservation 2018). Some active environmental organizations could come to embrace highly decentralized non-state solar geoengineering, just as they have offsets.

Ultimately, we conclude that highly decentralized non-state solar geoengineering, while clearly speculative, is *economically feasible* and, ultimately, conceivable.

Governance and politics

Finally, we assess the governance and potential politics of decentralized solar geoengineering. Given states' interests and capabilities, might they try to suppress and end decentralized solar geoengineering? If so, could they? It seems clear that if states wanted to suppress – if not end – decentralized solar geoengineering, they could, although doing so might be both complex and intrusive. In contrast to centralized solar geoengineering, the sources of its decentralized variant would be more difficult to detect and especially to control and prevent entirely. That said, states could reduce such activity domestically by regulation. For example, commerce in high altitude balloons, helium, and SO_2 could be tightly controlled, and remote surveillance could detect many launches. Yet, given the globalization of communication and commerce, as well as the small scale of each deployment action, highly decentralized solar geoengineering would be difficult to eradicate altogether, as eradication would require high degrees of international agreement, cooperation, and domestic action. Nonstate actors, meanwhile, could actively try to circumvent detection and regulation by moving abroad or offshore. Regardless, such international dynamics appear to be potentially highly complex and to require substantial coordination among governments. Together, this complex politics and potentially intrusive regulation of decentralized nonstate solar geoengineering implies that it could be *politically disruptive*.

All that might change if highly decentralized solar geoengineering is, in fact, quietly tolerated or covertly sponsored by states. Even if the international community were to agree on political and legal agreements to eradicate highly decentralized solar geoengineering, some states could hinder or delay domestic enforcement. This could especially be the case with those most vulnerable to climate change impacts and/or resistant to aggressive emissions abatement. In fact, some 'petrostates', primarily those located in the Middle East, might fall into both categories (Ricke *et al.* 2018).

In this sense, hypothetical efforts to combat highly decentralized solar geoengineering would resemble, in some ways, efforts to control the distribution of illicit drugs, which states have agreed through treaties to prohibit. Yet tens of thousands of tons of drugs are nevertheless produced, internationally transported, and consumed annually (United Nations Office on Drugs and Crime 2018). A large majority of raw substances for cocaine and heroin come from Colombia and Afghanistan, respectively. Their governments' records in international cooperation to end their production are mixed, at best, which can be explained by the domestic economic benefits and international political leverage that it provides. Decentralized solar geoengineering, too, might provide both for some states. While nonstate deployment, thus, might be politically unlikely except when used by small groups to be disruptive, state-tolerated or sponsored highly decentralized solar geoengineering may well be a scenario with which to reckon.

Conclusions

Climate policy governance is complex for multiple reasons, often manifesting as overlapping institutions and governance mechanisms (Keohane and Victor 2011). Extant suggestions of centralized solar geoengineering at once simplify some aspects of governance, given the smaller number of possible actors, yet could also add further complications to governance discussions (Victor 2008, Parson 2014, Jinnah 2018, Reynolds 2019). Decentralization of solar geoengineering deployment may make governance even more difficult. Numerous motivated disparate individuals or other non-state actors could, through highly decentralized solar geoengineering, have impacts on global environmental conditions and on governance in novel ways (Wapner 1996, Josselin and Wallace 2001, Green 2013). States seeking to eradicate such efforts might need to resort to highly intrusive enforcement mechanisms. One or more states tolerating or even sponsoring decentralized solar geoengineering may make international governance all the more complex.

Highly decentralized solar geoengineering is a speculative, suboptimal response to anthropogenic climate change, yet as we argue above, it appears at once *technically possible* and *economically feasible*. Regardless of whether most states, or only powerful ones, would condemn it, they would likely find complete eradication to be difficult, especially if the activity is quietly tolerated or covertly sponsored by one or more states. It could thus be *politically disruptive*. These scenarios might not be likely, but their mere possibility and potentially disruptive nature point to the imminent need for including highly decentralized solar geoengineering in governance discussions.

Notes

1. Solar geoengineering is variously known as 'albedo modification,' 'climate engineering,' 'solar radiation management,' and 'solar radiation modification' – the latter two often abbreviated as 'SRM.'
2. While not directly involved in deployment, non-state actors are indeed active in governing solar geoengineering. See, e.g., Zelli *et al.* (2017).
3. We mean 'good' in the sense of a product that some people desire, not in any normative sense. See Weitzman (2015) on public '*gob*s' that are normatively neither good or bad.
4. Eckersley (1992) made this point about decentralized, non-state governance in general.

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