Designing a scenario of unilateral climate intervention

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Author contributions

All authors devised the research plan. All authors contributed to the writing of the manuscript.

Conflict of Interest

None.

Data Availability and Code Availability

The data used in this research is publicly available. The military expenditure data is available via the Stockholm Peace Research Institute (https://www.sipri.org/databases). The economic data is available from the World Bank Data Bank (https://databank.worldbank.org/). The climate data is available from the World Bank Climate Knowledge Portal (https://climateknowledgeportal.worldbank.org/).

Abstract

Climate change is causing increasingly alarming global impacts, such as rising temperatures and more severe storms. Despite this, current multilateral initiatives and agreements to systematically reduce greenhouse gas emissions are completely incommensurate with the scale of the problem. Thus, we explore the potential that some unilateral actor, finding present and near-future climate changes intolerable, may seek to respond to these changes through its own deliberate intervention in the climate. Focusing specifically on stratospheric aerosol injection (SAI), which is the dispersal of reflective particles in the stratosphere to reflect some of the sun's energy away from Earth, we seek to identify the characteristics of states that might be most likely to modify the climate without broad international consensus. We develop a framework of geopolitically-relevant conditions that progressively reduce the number of candidate states, with the aim of identifying plausible unilateral SAI initiators. These conditions consider the state's capacity to deploy SAI, variability in states' motivations to change their local climates, the confidence that a deployment could be sustained and might produce the intended effects, and the state's insensitivity to global condemnation, should the international community disapprove of this action. We provide a detailed explanation of each of these conditions along with discussion of potential candidate states. Our results highlight a concentration of states meeting all or most of these conditions in the vicinity of the Arabian Sea. Based on this finding, we conclude with a discussion of how this type of geopolitical scenario development can be integrated into social-physical simulations of geopolitically plausible climate intervention scenarios.

Introduction

Climate change impacts are accumulating around the planet, with global warming leading to increases in human mortality, expanded prevalence of agricultural pests, and widespread coral bleaching events (Masson-Delmotte et al., 2021). These impacts will worsen as global temperatures climb upward (Pörtner, 2022). Yet, there is no evidence humanity will halt the steady rise of temperature, given the existing failure to meet even modest policy commitments to slow the accumulation of greenhouse gasses in the atmosphere. Given this, some researchers are looking to temperature mitigation strategies, such as solar radiation management (SRM), which seek to reduce the amount of energy that is retained within the Earth system (Symons et al., n.d.). The most well-studied method of SRM is stratospheric aerosol injection, or SAI. This type of SRM requires the injection of reflective particles into the stratosphere, on a continuous basis, to reflect some of the direct, incoming solar radiation back to space. International science and policy groups have called for expanded research on this topic (UNEP, 2023b; WCRP, 2023), as have the White House Office of Science Technology and Policy (OSTP, 2023) and the US National Academies of Science, Engineering and Medicine (NASEM, 2021).

Existing modeling studies have simulated how the Earth system may respond to SAI. These studies range in complexity in terms of how the Earth system is represented—ranging from simple box models to fully-coupled physically parameterized process models (Keith, 2000)—and in terms of the type of aerosols that are simulated. Most existing simulations of SAI have been based on deployment scenarios that are geophysically idealized, such as deployment of aerosol at dynamically optimal locations on the planet, to precisely achieve certain global temperature targets (Richter et al., 2022; Tilmes et al., 2018). Such precisely-timed deployments within the model simulations occur across many degrees of latitude and national borders, often simultaneously in both the northern and southern hemisphere (e.g., 30 N, 15 N, 15 S, and 30 S; (Richter et al., 2022)). These types of simulated deployments imply (without explicitly stating), the presence of deployment infrastructure as well as reliable permissions for deployment operations, likely in numerous different sovereign jurisdictions.

These simulations are essential for establishing a baseline of how the Earth system may respond to aerosols under the most geophysically ideal circumstances. Likewise, these scenarios reflect an underlying scenario approach that treats SAI deployment as a geophysical temperature optimization problem, with key goals of optimizing deployment latitudes, altitudes, quantities of aerosols, all to achieve a dynamic globally averaged temperature target (MacMartin et al., 2022).

Yet, SAI is not an apolitical optimization problem, and whatever SAI program may emerge will reflect economic, political and legal realities. First, geopolitical negotiation — especially related to climate change topics — is characterized by historic and existing power dynamics (Falzon, 2021). More broadly, geopolitical power dynamics can include strategic military alliances, economic and trade agreements, and legacies of historic power relations (such as colonialism). The favorability of outcomes arising from geopolitical negotiation are skewed heavily toward those with more power. Second, geopolitical plausibility of coordinated SAI deployment is highly questionable given existing global coordination failures, such as the unsuccessful global efforts to thus far address ongoing climate change. For example, the global community continues to fail to comprehensively reduce greenhouse gas emissions (UNEP, 2023a), despite increasingly dire evidence of the consequence of climate change (Armstrong McKay et al., 2022; Pörtner, 2022). And while the Montreal Protocol is an example of a high-profile, global environmental policy that successfully reduced ozone-depleting substances, it was successful for a variety of specific reasons, including that the industries responsible for those ozone-depleting emissions manufactured the replacements, there was global agreement that action needed to be taken to reduce the ozone-depleting substances, and the group of states that were directly involved in the production of ozone-depleting substances was relatively small (DeSombre, 2000).

One driver of SAI being modeled as a multilateral global response to climate change has been the anticipation of very high economic costs for developing and sustaining a large-scale program. However, estimates of the costs for an effective program are declining to the point that climate science must give greater attention to the possibility of an uncoordinated and unilateral deployment at a local or regional scale. Costs for SAI deployment depend on the latitude, altitude, material being deployed, aircraft being used, and more (McClellan et al., 2012; Moriyama et al., 2017; Smith, 2020). Comprehensive estimates provided by Smith and Wagner (2018) suggest an average annual cost ranging $2.25 billion and $5.25 billion USD per year, to halve average projected increases in radiative forcing. Other estimates, which provide a detailed exploration of engineering possibilities, put the costs closer to $10 billion USD per year to halve projected increases in radiative forcing (Smith, 2020). As total estimated costs decline, the number of state and non-state actors that could plausibly act alone increases.

Consequently, uncoordinated SAI deployment may be just as realistic (if not more so) as a globally coordinated approach. Despite this, we have exceedingly few detailed scenarios of this type of deployment, let alone simulations that dynamically explore the Earth system implications of these scenarios. Simulations that do mimic the characteristics of a unilateral deployment, such as in particular regions of the planet including the tropics, the midlatitudes, or the Arctic (Krishnamohan and Bala 2022; Sun et al. 2020), illustrate the substantial consequences that could arise from unilateral deployment. A major theme in this work is the potential disruption of global bands of precipitation, specifically global monsoon systems in South Asia. In this way, existing scenario simulations provide critical insight into the way that the climate system might respond to SAI, but these neither reflect geopolitically realistic circumstances leading up to SAI, nor the geopolitically realistic interactions that may follow.

In this work, we aim to contribute to growing calls from governments and scientific organizations to better understand geopolitically plausible, realistic scenarios of climate intervention. The US White House Office of Science and Technology Policy has recently called for research that supports the understanding of geopolitical ramifications of SRM (OSTP, 2023). Likewise, the US National Academy of Sciences, Engineering, and Medicine has recently called for expanded research into a wide range of ‘solar geoengineering’ topics, including the exploration of unilateral deployment scenarios (NASEM, 2021).

Here we develop a method for designing a geopolitically plausible unilateral climate intervention (UCI) scenario. The goal of this method is to identify the characteristics of a geopolitical actor that would be among the most plausible initiators of SAI. We first define a series of conditions, based on evidence from international security research and deduced through game theory, and then identify a specific set of geopolitical actors, specifically focused on sovereign countries, that meet these criteria. We also provide a speculative scenario of unilateral initiation of SAI deployment over the Arabian Sea. This is followed by a discussion of research frontiers in this topic, namely suggestions for how to implement this in an Earth system modeling framework.

Four Conditions for Unilateral Climate Intervention

We use existing work about strategic decision-making to inform the scenario design procedure, including results from past work such as Bell and Keys (2023), and Keys et al. (2022). In this work, we focus on national governments because countries uniquely possess the stability, capability, long-term incentives, legal authorities and jurisdictions, and geography required to plausibly execute an SAI program.We consider the possibility for climate intervention being pursued by non-state actors in partnership with states and collections of states (e.g., wealthy individuals, corporate associations, etc.) in the discussion.

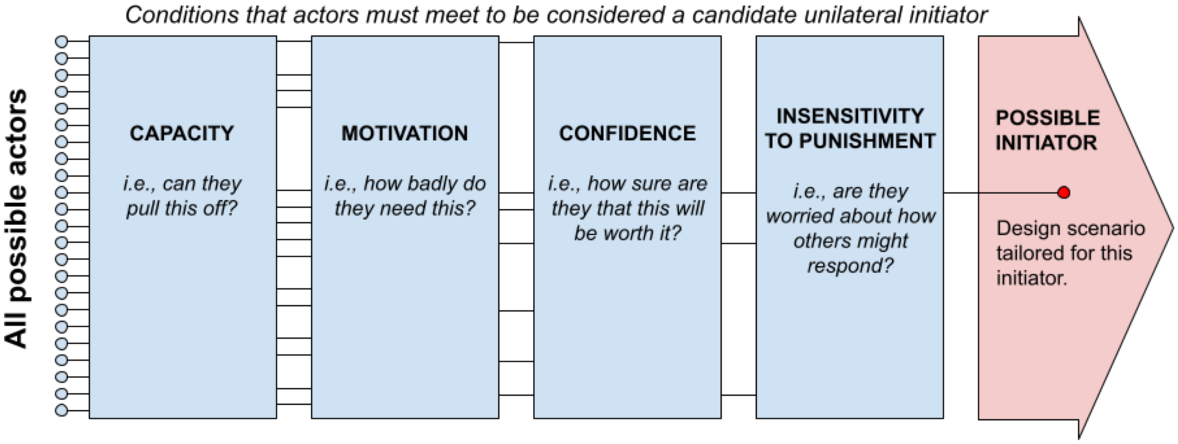


Figure 1. Conceptual illustration of the conditions that will be used to eliminate countries from consideration as unilateral deployers of SAI.

Capacity (i.e., can they pull this off?)

Willingness to modify the climate through SAI is not sufficient. States must first have the capacity to do so. We conceive of capacity as a function of both the long-term financial resources that a state must apply to SAI to support a multi-year program, as well as the feasibility of SAI implementation in each state's unique geography.

Research on the likelihood of SAI effectiveness finds that latitude, hemisphere, and the local composition of the atmosphere and stratosphere can drive significant differences in the costs—and therefore the plausibility—of SAI in different locations across the Earth's surface (Smith, 2024). We draw from SAI modeling done by Dai et al. (2018), who show that, all else being equal, aerosols are most effective when released at high altitudes near the equator. Closer to the poles, the net radiative forcing (RF) resulting from aerosol releases drops precipitously, and this is especially true in the southern hemisphere. Simulations run at different latitudes, altitudes, and seasons indicate that aerosols could be as much as two to four times more effective near the equator than they are when released more than thirty degrees to the north or south. It therefore stands to reason that states without access to release points near the tropics will face significantly higher costs to achieve an intended result.

Regardless of where they are located, states will be more likely to initiate an SAI program if they can absorb the considerable financial costs of doing so. The total costs associated with the development of technology, facilities, and ongoing deployment of SAI have been estimated to be as low as $5 billion per year (Smith, 2020; Smith & Wagner, 2018). The list of states that could afford this cost without substantial outside assistance is quite small, though further improvements to technology and our scientific understanding of SAI may reduce these cost estimates in the future.

As a starting point, countries with larger economies and sizable military budgets will have more discretionary income to use on an SAI program. According to 2023 military spending data from the Stockholm International Peace Research Institute (Tian et al., 2024), a $5 billion per year SAI program would exceed the entire defense expenditures of all but 44 countries. This distribution is highly skewed; only the United States ($916 billion), China ($296 billion), and Russia ($109 billion) spend more than $100 billion per year on defense. The countries for which $5 billion equates to less than 25% of the 2022 military budget consists of: these three superpowers, India ($84b), Saudi Arabia ($76b), the United Kingdom ($75b), Germany ($67b), Ukraine ($65b), France ($61b), Japan ($50b), South Korea ($48b), Italy ($36b), Australia ($32b), Poland ($32b), Israel ($27b), Canada ($27b), Spain ($24b), and Brazil ($23b).

Many of these countries are located far north of the equator, where simulations show the costs of effective SAI to be much higher than they would be in the tropics. About half of these countries—including the United States, China, India, Saudi Arabia, the United Kingdom, France, Australia, Spain and Brazil—have sovereign territory and overseas holdings in tropical latitudes. Others may need to rely on agreements to spray aerosols from—or perhaps even over—the sovereign territory of foreign partners.

The question of what costs a country might suffer to initiate SAI is as political as it is economic. Voters in democratic states can be reluctant to absorb extremely long and costly infrastructure programs without immediate benefits (Jacobs, 2011). Autocratic states, assuming political stability, have shown a greater willingness to invest in long-term "megaprojects" (Huda, 2022), including especially flashy and ambitious programs (Alderman & Eggeling, 2023). China's Belt and Road Initiative (Clarke, 2017) and Saudi Arabia's "NEOM" development (Garfield, 2018) are two of many examples of audacious and expensive long-term projects that would have been much harder to generate in a democratic society. We should therefore also consider the character of the government and the constraints on leaders to spend freely as factors in a state's "capacity" to initiate an SAI program.

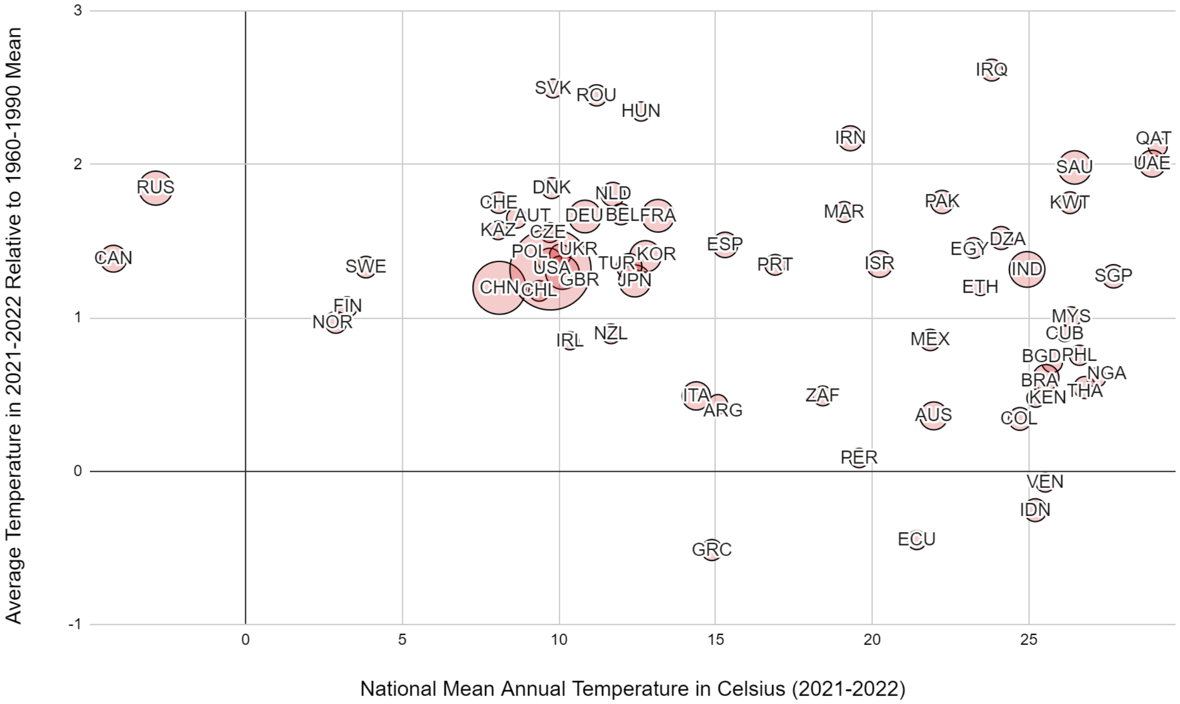
Motivation (i.e., how badly do they need this?)

There could be numerous motivations for intervening in the climate, but unacceptable local conditions may be the most likely trigger of unilateral SAI implementation. Any state could be motivated by altruistic reasons, such as serving a generic global good, or more specific outcome, such as trying to avoid key warming-related thresholds with global implications (e.g., the collapse of the West Antarctic Ice Sheet). However, the long history of international cooperation suggests states with these concerns would seek to generate multilateral initiatives that share the costs, rather than intervene on their own.

The more likely motivator for unilateral action would be acute self-interest, which would refer to a desire by a country to intervene to steer conditions toward something more tolerable for its own population. Some countries have less desirable weather than others in the present, and the rate of temperature change is also variable across the world. This means incentives to intervene in the climate are far from uniform. Two initial indicators of a country's motivation to unilaterally intervene in the global climate could therefore include a country's mean temperature, which reflects an objective motivation to cool one's climate, and the difference between temperatures experienced today and those observed in the recent past, as this may proxy more subjective feelings of urgency around halting further change.

Using data from the World Bank's Climate Knowledge Portal, we examine 2021-2022 mean surface air temperatures by country and the difference between this temperature and the 1960-1990 baseline for all the world's major economies (2022 GDP of greater than $100 billion, 63 countries). Temperatures range from nearly 30 C to around -5 C, with changes from 1960-1990 baselines of 0 to 3 degrees. Countries in the vicinity of the Persian Gulf and Arabian Sea stand out for being uniquely high on both of these metrics. Countries in many regions across the globe saw a mean annual temperature above 25 C in 2021-2022, including Bangladesh, Brazil, Cuba, Indonesia, Kenya, Kuwait, Malaysia, Nigeria, Philippines, Qatar, Saudi Arabia, Singapore, Thailand, United Arab Emirates, and Venezuela. However, many of these countries are located in regions where global temperatures are climbing relatively slowly. The only +$100b GDP countries where temperatures are over 25 C and the degree of change from the near past has been greater than 1.5 C are Saudi Arabia, Kuwait, Qatar, and UAE. Monthly data from Copernicus Climate Change Service shows that the summer of 2024 has been unprecedented, with mean June temperatures around four degrees Celsius warmer than the 1960-1990 historical baseline (Our World in Data 2024).

Figure 1: Mean Annual Temperatures and Change from 1960-1990 Baselines in the 63 Largest Economies



Note: Bubble size reflects 2022 Military Expenditures, with larger bubbles indicating larger military budgets.
Sources: World Bank, World Bank Climate Knowledge Portal

Confidence (i.e., how sure are they that this will be worth it?)

In order for a country to be confident in their unilateral deployment, they would need to believe that their efforts would be worth the cost. So, confidence can be expressed as a measure of the *a priori* expectation that a unilateral deployment of SAI would be effective. Part of this expectation would be informed by the understanding of local, regional, and global climate variability and change. Over the long-term, greenhouse gasses accumulating in the atmosphere will be the primary cause of our changing climate. However, on timescales of less than a decade, internal climate variability, such as the El Nino Southern Oscillation (ENSO), can lead to persistent multi-year warm or cool spells, including at the global scale. In other words, internal climate variability might over the short-term overwhelm the slower paced, forced changes of increasing greenhouse gas emissions. Thus, the climate conditions that a unilateral initiator experiences will always be a combination of internal climate variability and climate change. Given this, a potential unilateral initiator will very likely consider how internal climate variability might affect their confidence in the effectiveness of an SAI deployment..

By using earth system model data that included simulated SAI deployment, Keys et al. (2022) explored the combined effect of internal climate variability, greenhouse gas-forced climate change, and SAI deployment on local temperature changes. They introduced the concept of the probability of perceived failure of SAI, which is a metric of whether temperatures would go up (rather than down), following SAI deployment. A country with a relatively high potential for perceived failure (e.g., >50%) might be a country where they would be less confident in the desired outcomes of unilateral deployment of SAI.

The inverse of this metric, the potential for perceived success of SAI, is another way of expressing confidence that SAI deployment would be effective, considering the combined effects of internal climate variability, climate change, and SAI. Keys et al. (2022) show that large parts of the world may have a greater than 60% potential for perceived success, including much of South America, Africa, Southeast Asia, the Arabian Peninsula and Australia.

Insensitivity to Punishment (i.e., are they worried about how others might respond?)

A final consideration for would-be initiators is sensitivity to threats of penalty, backlash, sanction, or some similar form of international condemnation. A unilateral SAI initiator could easily become labeled a pariah and could be blamed for any disaster or weather anomaly, regardless of the scientific basis for any direct link between SAI in one place and a particular weather event in another (Nightingale & Cairns, 2014). Public perceptions about climate can have profound policy impacts, even if climate anomalies are not directly attributable to climate intervention (Keys et al. 2022). And even in the extremely implausible case in which an SAI program has universally positive effects, a unilateral initiator could face punishment and condemnation for breaking international norms without sufficient consensus-building and transparency within the relevant international laws and institutions.

For all of these reasons, potential SAI initiators would surely be influenced by their beliefs about how other countries might react after the fact (Bell and Keys, 2023). Fundamental differences between countries, in terms of relative power, economic structure, political system, and involvement in international institutions—may also influence a country's sensitivity to a negative international reaction. The specific determinants of sanctions sensitivity are still the subject of intense debate in the international relations literature (Bapat & Clifton Morgan, 2009; Drezner, 2024; Farrell & Newman, 2019; Pape, 1997; Walentek et al., 2021), but scholars generally agree that potential targets of sanctions are influenced by the severity of any punishment that sanctioning states could impose, the relative power of the states which are imposing sanctions, and the anticipated economic effects. The states that would be most likely to be deterred by anticipated negative international reactions include smaller states that are less expensive for others to sanction and states with very limited ability to retaliate, militarily, economically, or otherwise.

What kinds of states might have the lowest sensitivity to sanctions? It is likely that these would be states with economies that are either autarkic (low reliance on trade) or critical to the potential punishers who could enforce the costliest sanctions. For example, energy producers that export to the international market may be especially unlikely to be punished by larger importers. Russia's ability to overcome Western sanctions in its ongoing war against Ukraine illustrates this point well. Dependence on Russian oil has weakened the efficacy of sanctions against Russia and helped Russia secure new buyers for sanctioned goods (Glenn, 2023; Milov, 2024).

The Plausibility of Unilateral SAI Near the Arabian Sea

Thinking through these four conditions has allowed us to highlight an area of greatest risk in the vicinity of the Arabian Sea, which would be a most plausible location for SAI deployment for a number of reasons. First, the Arabian Sea is an expansive offshore area that can be directly accessed via the national airspace of coastal states across most of the Middle East and South Asia. India, Pakistan, Iran, Saudi Arabia, and the Gulf States are all proximate to the Arabian Sea, and this vast body of water stretches across the ideal latitudes for SAI deployment. Countries would not necessarily need to disperse aerosols over unpopulated international maritime spaces, though they may desire to do so given the understudied ecological and health impacts of sustained SAI dispersal over populated areas (Zarnetske et al., 2021).

Second, Arabian Sea countries have large economies with a history of significant defense expenditures and investment in ambitious long-term projects. India and Saudi Arabia have the fourth and fifth largest defense budgets on the planet, followed by Pakistan, Iran, and a number of Gulf states. Large-scale, multi-year infrastructure investments in the region include India's "Sagarmala" port and maritime logistics program (estimated cost of approximately $70 billion) and Saudi Arabia's "NEOM" futuristic city (up to $1.5 trillion). These projects demonstrate an appetite for transformational investment on the scale of a sustained SAI program, and they may portend a willingness to endure the costs of climate intervention programs.

Third, motivation may be higher here than anywhere on Earth. India is expected to lead the world in intolerable wet-bulb temperatures in excess of 35 C (Vecellio et al., 2023), and the Arabian peninsula is one of the hottest regions on the planet. In June 2024, Saudi Arabia's mean monthly temperature was 36.31 C - more than one degree higher than the previous record (35.24 C, 2019). Several major economic and military powers will soon see mean annual temperatures above 30 C, given the very rapid rate of warming experienced in this region.

Fourth, confidence could be high that unilateral deployment in this region could lead to a desired outcome. In a global deployment scenario, there are many regions that could have a high potential for perceived success (Keys et al., 2022). Such evidence may embolden states to have a high confidence in their ability to achieve a desired outcome. Yet, deployment of SAI in a single hemisphere has the potential to lead to large regional disruption, such as the failure of the South Asian monsoon (Krishnamohan & Bala, 2022). Thus, states reliant on these phenomena, such as India, may be less likely to intervene in the climate for fear of interference with the annual South Asian monsoon. However, other Arabian Sea states, such as those in the Arabian Peninsula, may be less concerned about such interference, and may prioritize their own well-being.

And finally, countries located around the Arabian Sea may be less concerned than most with international condemnation and economic sanctions. Some regional oil producers have proceeded with controversial nuclear weapons programs, chemical and biological weapons programs, wars, and campaigns of repression even under threat of coordinated international economic sanctions (Drezner, 2024). Even when sanctions impose lasting economic harm, nondemocratic governments tend to insulate regime insiders from the effects of sanctions and instead concentrate the consequences on the broader population (Allen & Lektzian, 2013; Ghomi, 2022).The region's complex international relations and rivalries will decrease the chances of a unified and coherent multilateral effort to sanction any SAI initiators.

The Arabian Sea is not the only area where unilateral SAI deployment could occur, but we believe it to be the most likely area based on a careful analysis of several conditions that would inhibit most states from doing so. As the world currently stands, Arabian Sea states would seem to have the clearest incentives and face the fewest disincentives for unilaterally initiating an SAI program. Saudi Arabia, due to its unusual resources, geography, and global influence, illustrates this argument particularly well.

The Illustrative Case of Saudi Arabia

Most Saudi Arabian cities experience sweltering temperatures that are among the hottest in the world. Riyadh's average high temperature exceeds 30 C seven months of the year and meets or exceeds 40 C in four of these months. The coastal city of Jeddah experiences average daily highs above 30 C in ten of twelve months, with six of those months at or above 35C. The holy city of Mecca averages daily highs above 40 C six months out of the year, including an average daily high of 45 C in the month of June. The northern part of the country near the head of the Arabian Gulf experiences more days above 50 C than any other place on Earth. The number of days above 50 C has doubled since 1980 (Almazroui, 2020; Dale & Stylianou, 2021).

More convincingly, Saudi Arabia has a history of short-term weather intervention, such as cloud seeding, suggesting a willingness to manipulate the atmosphere, as well as the scientific knowledge base needed to pursue these strategies (Krauss et al., 2010; Kucera et al., 2010). Saudi Arabia has also publicly stated its opposition to global governance of geoengineering, suggesting a tacit political interest in keeping the door open to unilateral decision-making (Biermann et al., 2022; Surprise, 2020). It has developed close international scientific ties, including techno-scientific cooperation with China (Alsudairi et al., 2023), the European Union (European Commission, 2022), and the United States (Doyle, 2024). As mentioned above, the Saudis are among the world's leaders in defense expenditures. A recent academic comparative study of global air power has ranked the Royal Saudi Air Force as one of the five most-capable air forces in the world since the early 2000s (Saunders & Souva, 2020). In 2022, Saudi defense officials announced that the country would also be merging the air force and its nascent space force into a single more robust organization (Helou, 2024).

Saudi Arabia may have additional economic motivations for pursuing SAI, including to delay the transition of the global economy away from fossil fuels. Saudi Arabia is second only to the United States in oil production, though while oil rents account for only 0.2% of the American economy, oil rents are nearly 20% of Saudi Arabia's (Mahmood & Saqib, 2022). Oil extraction supports the salaries of two-thirds of the Saudi Arabian workforce and oil generates more than 60% of the government's revenue. Saudi Arabia is the world's leader in oil exports by a wide margin, and in 2020 Saudi Arabia exported roughly double the amount of oil exported by Russia, the world's second-largest exporter (EIA, 2024). Roughly one in six barrels of oil traded around the globe this year was produced by Saudi Arabia. If SAI could stabilize global temperatures, it could reduce global incentives for decarbonization and preserve global demand for lucrative fossil fuels.

To date, Saudi Arabia has sought to balance these interests by pledging to counter the effects of continued carbon emissions, rather than reduce the oil production that drives those emissions. This was cemented into official climate policy in the 2021 Saudi climate strategy, which discusses afforestation, carbon capture, and adoption of renewables for some domestic energy production, but shies away from proposals to decrease oil exports. Saudi Arabia has also made this a key foreign policy objective. Riyadh hosted a Green Initiative Forum in October 2021 and it has also been a vocal opponent of calls to decarbonize coming from the United Nations and elsewhere (DeCoopman, 2022). In 2019 it joined the

United States to block the development of a global agreement to govern the deployment of "geoengineering" technologies (Biermann et al., 2022; Surprise, 2020).

Saudi Arabia's hot climate, reliance on continued global oil consumption, and demonstrated willingness to alter the climate in ways that might allow for continued carbon emissions make it a leading candidate for even more ambitious efforts to alter the global climate. As one of the more prominent opponents to global governance regimes that would control "geoengineering" technologies, Saudi Arabia is a viable initiator of a unilateral climate intervention. Coincidentally, it has the economy, technology, and geography to support that path.

Limitations

Saudi Arabia is not the *only* country that could meet all of the conditions necessary to start an SAI program. Any country could overcome the barriers to SAI implementation that we have identified above, including cost and location, by partnering with other states and private actors. For example, wealthy states without access to the ideal latitudes for effective SAI deployment could partner with better-positioned states with similar aspirations. Projects could even be initiated under the guise of foreign development assistance primarily for the benefit of warming tropical states with limited capacity to adapt to the changing climate.

Countries that are not presently motivated to modify the climate could see public opinion and political will change very rapidly following a major natural disaster or political realignment. The benefits of this methodological approach include not only its ability to highlight the presence of conditions that might spur unilateral climate intervention in the present, but also its identification of specific catalysts that might cause different kinds of states to consider SAI initiation in the future. Some countries may possess the capability, but hitherto would not be driven to do so by local climate concerns (e.g. Russia). Other states might be desperate for action, but would not have the capacity without regional or "minilateral" partnerships (e.g. southeast Asian nations and many smaller Arabian Gulf states).

This scenario development exercise also assumed that any initiators would be doing so out of their own self-interest based on the climate in their sovereign territory. However, future SAI programs could instead focus on specific goals with global implications, including the preservation of polar ice sheets and rain forests. Fear of climate tipping points could catalyze action driven by these concerns, rather than by local climate, and this would change the profile of would-be SAI initiators. This might lead major powers to implement SAI programs for global effect, far from their primary latitudes. For example, much of the US and EU lie far north of 30 N, but if they were optimizing for cooling the entire planet they could plausibly start a program from overseas holdings in the remote South Pacific. If developments in climate science increased the confidence with which an initiator might implement a program farther from the tropical latitudes, a very capable country like China could be motivated to initiate SAI over its vast and sparsely populated western provinces.

These scenarios are strictly *speculative* and they are not *predictive*. The climate is changing quickly, as are military technologies, economies, and norms around climate intervention. This paper has sought to highlight specific conditions that will make unilateral SAI initiation more or less likely, without conclusively identifying where, when, and by whom. The examples given above—including Saudi

Arabia, China, and a US/EU effort—illustrate possible futures, but this is not to say that other actors will not find ways to overcome the four primary conditions we have identified: capacity, motivation, confidence, and insensitivity to punishment.

Conclusion: Implications for Interdisciplinary SAI Simulations

That we can identify a potential initiator of SAI deployment means that the scientific community can be much more efficient in its choice(s) of simulations. This is particularly important given the expense in personnel and computation time for complex earth system simulations. In other words, all unilateral deployment scenarios are not equally plausible, so we can more efficiently target the simulation of the more plausible scenarios to investigate their geophysical implications for societies, ecosystems, and the broader Earth system.

The scenario described above could be translated into a deployment strategy following existing work (Smith & Wagner, 2018), providing the baseline information for implementing the strategy in an existing Earth system model, such as the Community Earth System Model (CESM) or the United Kingdom Earth System Model (UKESM). Both of these models have already been modified to include programmable scenarios of stratospheric aerosol deployment, and it may be relatively straightforward to represent a scenario depicting SAI deployment in the Arabian Sea.

An ensemble approach could be taken, similar to past SAI experiments (Richter et al., 2022; Tilmes et al., 2018), to identify the mean response of SAI for the world. Complementing the ensemble-based approach, it may be possible to explore a "storyline" approach, that aims to reveal the detailed physical changes of an individual or representative ensemble member (Shepherd et al., 2018). Such a storyline approach would further permit the identification of plausible respondents to an Arabian Sea deployment scenario.

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