

RESEARCH ARTICLE

Who Could Deploy Stratospheric Aerosol Injection? The United States, China, and Large-Scale, Rapid Planetary Cooling

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Received: 3 October 2024 | **Revised:** 21 February 2025 | **Accepted:** 11 March 2025

Funding: The authors received no specific funding for this work.

Keywords: climate change | geopolitics | solar geoengineering

ABSTRACT

Stratospheric aerosol injection, which would reflect a small fraction of sunlight away from the Earth to lower temperatures, involves many unanswered questions. One of these is, who could deploy it? We consider this with reference to a scenario in which global temperatures are reduced by 1°C by midcentury; we term this a ‘PLUS’ deployment—Planetary, Large-scale, Uninterrupted, and Speedy. The technical requirements of a PLUS deployment—a fleet of a hundred or more specialized aircraft—limit the number of capable actors to ten states. The geopolitical requirements—broad-spectrum capabilities sufficient to overcome external constraints—mean that only the US and China are capable of implementing unilaterally against strong opposition. As such, the US and China will be decisive in determining whether and how a PLUS-type deployment takes place. In particular, the degree of Sino-American alignment on this issue will strongly influence the likelihood of a PLUS deployment and its disruptive potential. We examine three cases in which activities with the potential to harm global commons were debated during the Cold War: scientific research in Antarctica, atmospheric testing of nuclear weapons, and experiments in outer space. Backed by evidence from these cases, we then consider several implications of our findings.

1 | Limits on Implementing a Big, Bold Deployment

Among several prospective climate technologies that could potentially manage the solar radiation entering the Earth system, the only one with a clear development path to deployment is the injection of sulfur gases to make sulfuric acid aerosols in the stratosphere. All other methods, including the use of solid aerosols in the stratosphere, entail larger scientific uncertainty and require successful research before the technology could be developed with confidence.¹ Stratospheric sulfate aerosol injection (SAI) would involve distributing large quantities of aerosols—typically sulfur species—in the upper atmosphere to reflect a small portion of incoming sunlight back to space to reduce global temperatures and associated impacts of climate change.

The annual direct cost of a large-scale SAI deployment is estimated to be in the tens of billions of dollars, well within the budgets of major economies and potentially even the largest corporations and wealthiest individuals (Smith 2020). SAI is controversial for many reasons and raises many ethical, political, and other questions (Preston 2013; Jamieson 1996; Scott 2012).

In this article, we consider one such question—who could deploy SAI? This question is deceptively simple in several ways.

First, when asking who could deploy SAI, ‘who’ may refer to the types of actors—states, corporations, individuals—or it may refer to specific actor identities. In this article, we are interested in both actor types and actor identities.

Policy implications

- Analyses of solar geoengineering must take account of the broader geopolitical context within which decisions about the technology will be made.
- Roughly ten states will be technically capable of deploying solar geoengineering on a planetary scale, but only the US and China will be powerful enough to do so unilaterally over the objections of others. The US and China will therefore be decisive in determining whether planetary cooling takes place and, if so, how.
- Policymakers should promote bilateral dialog between the US and China on solar geoengineering. Formal and informal dialog can be encouraged through ‘track II’ diplomacy and scientific collaboration.
- At the same time, decision-makers should also consider how to ensure the interests of other countries—especially in the Global South—are meaningfully represented in future governance of solar geoengineering.

Second, when asking who could deploy SAI, ‘could’ may be understood on two levels. On one level, ‘could’ may be taken to mean able to deploy in a purely technical sense—able to deliver aerosols at the right altitude at the right location. On another level, ‘could’ may be taken to mean able to overcome external constraints on deployment—constraints imposed by other actors or institutions. In this article, we are interested in both technical and geopolitical capabilities.

Third, assessing geopolitical capabilities means assessing power, and power is relative. Evaluating power in the international system involves focusing on structure, or the distribution of capabilities, normally viewed in terms of polarity. To assess geopolitical capabilities, therefore, we must consider the basic parameters of the international system and the ways in which those parameters will affect the opportunities available to different actors.

Fourth, when asking who could deploy SAI, ‘could’ implies *without substantial help from others*, on a unilateral basis and against substantial opposition. The question who could deploy SAI *with help from others* would produce a multitude of answers because any actor involved in successful cooperation would qualify. In this article, we are interested in unilateral deployment (Rabitz 2016). Even the restriction to unilateral action requires some qualification because, in a world with tightly interconnected supply chains, no nation is a true autarky.

Lastly, since SAI deployment could take a wide variety of forms, asking the question who could deploy SAI begs the further question, what kind of SAI? Many different types of deployment are conceivable: large or small, global or regional, short-term or long-term, etc. (Sugiyama et al. 2018). In this article, we focus on a large-scale, long-term SAI deployment designed to achieve peak additional cooling of 1°C by midcentury—that is, a cooling that reduces temperatures by 1°C compared to a world without SAI. In line with conventional thinking about global SAI, we assume that such a deployment would be carried out in the tropics or subtropics of both hemispheres.² For convenience, we refer to

this as a *PLUS* scenario: Planetary, Large-scale, Uninterrupted, and Speedy.

It is important to recognize what a PLUS deployment is *not*. It is not a regional deployment conducted, for example, over the poles. It is not a deployment that builds up gradually over multiple decades. In addition, it is not an experiment. Rather, a PLUS scenario is global, rapid, large-scale, and sustained.

We view achieving 1°C additional cooling by 2050 as an extreme scenario, since it would involve a cooling rate of approximately 0.5°C per decade, more than twice as fast as current warming rates and enough to create obvious risks. Given the risks inherent in such a rapid scale-up, we do not regard a PLUS deployment as sensible. However, some influential commentators are contemplating large, rapid deployments that closely resemble a PLUS scenario (e.g., Bodansky and Pomerance 2021). Insofar as this is shaping policy and political discourse about solar geoengineering, and to the extent that such a scenario represents an outer bound of political realism regarding how SAI might unfold, we regard a PLUS deployment as an appropriate starting point for considering the question of who could deploy.

Thus, considering the question who could deploy SAI leads us to consider several implicit and adjacent topics, including actor types, technical capabilities, the distribution of power, and deployment types. Preliminary analysis leads us to conclude that although roughly ten states will be technically capable of a PLUS deployment, only two of them—the United States (US) and China—will be powerful enough to implement one successfully. An important consequence of this duopoly is that the extent to which US and Chinese views regarding a PLUS deployment align—in the form of mutual support, mutual opposition, or opposing positions—will powerfully affect whether a large, planetary-scale deployment takes place, how one might unfold, and what impacts it might have on the international system.

Our conclusions are provisional. To probe their plausibility, we briefly examine three historical episodes in which the prospect of activities with potential to negatively affect global commons were debated during the Cold War: scientific research in Antarctica, aboveground nuclear tests, and experiments in outer space. We believe these cases provide prima facie evidence that our conclusions have merit. In our view, the significant implications our findings have for governance and policy—including a need to reorient governance discussions and proposals to account for the dominant positions of the US and China—warrant taking them seriously.

We proceed as follows. We begin by arguing that only a small group of states will be able to develop the specialized aircraft necessary to be regarded as technically capable of deploying SAI to achieve peak cooling of 1°C by 2050. We continue by arguing that the superpower status of the US and China makes them the only ones geopolitically capable of implementing a PLUS deployment against strong opposition, constraining the ability of other technically capable states to pursue a PLUS deployment unilaterally. This configuration means that Sino-American views will be decisive in determining the future of PLUS-type SAI and its consequences for international stability. We then briefly consider the Cold War-era controversies mentioned above, after

which we discuss some implications of these findings for international politics. We end with a short conclusion.

2 | Who Will be Technically Capable of a PLUS Deployment?

We define technical capability to implement a PLUS deployment as the ability of an actor to deliver the appropriate amounts of aerosols at the appropriate altitude and appropriate latitudes on a continuous basis without help from others. To explore technical capability, we first consider delivery mechanisms, then launch facilities.

To be effective, a deployment would need to inject well above the tropopause in the lower stratosphere, and to provide global coverage, such injections would need to occur in the tropics and subtropics, where the tropopause is at its apex. Commentators have speculated about a variety of possible mechanisms for delivering aerosols to the stratosphere, from balloons to tethered hoses to rockets. A rough consensus based on cost and technical considerations, however, is emerging that the most likely means of continuously delivering the requisite amounts of aerosols to the stratosphere is via a fleet of specially designed high-altitude aircraft (McClellan et al. 2012; Smith and Wagner 2018; Janssens et al. 2020; Bingaman et al. 2020). Researchers have considered several different aerosols for enhancing albedo, including sulfate, calcite, and diamond (Dykema et al. 2016). Nature has repeatedly demonstrated the efficacy of sulfate cooling via large volcanic eruptions, such as the eruption of Mount Pinatubo in 1991 (Ramachandran et al. 2000; Kirchner et al. 1999). Sulfate may be dispersed either directly as sulfuric acid or indirectly via the release of a precursor such as SO₂ or H₂S. Sulfur is widely available at low cost around the globe. Under a PLUS deployment scenario, implementation would involve injection of from one to ten teragrams of sulfur per year, implying an aircraft fleet numbering from less than a hundred to several hundred and an engine complement more than twice as large.

To implement a PLUS deployment, therefore, aircraft would require a combination of high payload capacity to carry large amounts of chemicals and engines capable of sustained combustion at high altitudes. Such aircraft do not exist today. The capacity to design and manufacture suitable aircraft is restricted to a small set of incumbent and major secondary aerospace companies.³ Leading airframe manufacturers include Boeing, Lockheed, Gulfstream, and Northrup (US); Airbus (France and Germany); Bombardier (Canada); Embraer (Brazil); Dassault (France); COMAC (China); United Aircraft Corporation (Russia); and Hindustan Aeronautics Ltd. (India). Leading engine manufacturers include General Electric and Pratt & Whitney (US); Rolls-Royce (UK); Safran (France); MTU (Germany); Ishikawajima-Harima Heavy Industries (Japan); United Engine Corporation (Russia); and Aviation Industry Corporation of China (Khaustovich 2022).

The aerospace industry is one of the most stable in the world, with many of its present features traceable to the aftermath of World War II. Indeed, this sector is a pillar of the defense industrial base, with home governments viewing aerospace companies as strategic assets (McGuire 2011; Hartley 2014). The

conditions under which these companies operate ensure that corporate strategies conform to government policies—these firms' overwhelming political, financial, and commercial reliance on their government customers effectively precludes their involvement in any activity opposed by the state (Gartzke 2010). This power imbalance means not only that aerospace companies would be extremely unlikely to develop aircraft capable of a PLUS deployment in the absence of at least tacit support from their respective national governments, but also that these companies would almost certainly follow the lead of their home governments if the latter wanted to pursue such development.⁴

Thus, only a few states—including the US, France, Germany, the UK, Japan, Canada, Russia, China, India, and Brazil—appear capable of developing the fleet of aircraft numbering in the hundreds that would be required to reduce global temperatures by 1°C by midcentury.

In addition to suitable aircraft, implementing a PLUS deployment would also require reliable access to airbases from which aircraft could launch and to which they could return. More specifically, to implement a PLUS deployment, a country would need secure access to air facilities in the tropics or subtropics of both northern and southern hemispheres. Six of the ten states identified above as capable of developing the necessary delivery vehicles—the US, France, the UK, Russia, China, and Brazil—possess such access today, either because they are physically located at those latitudes (the US and Brazil), control airbases within that space (France, the UK, and Russia as well as the US), or are involved in major infrastructure projects and investments within that space (China). Future Russian access to suitable launch facilities will depend on the fate of its airbase in Syria and the continuing presence of the Wagner Group in Africa. India's proximity to the equator may be sufficient to enable a PLUS deployment. Only Germany, Japan, and Canada definitively lack such access today, but their wealth and influence make it conceivable that any of the three might secure such access in the future. Hence, geographical considerations appear to constitute a minimal additional limitation on those countries capable of developing aircraft for a PLUS deployment.

3 | Who Will be Geopolitically Capable of a PLUS Deployment?

As noted earlier, implementing a PLUS deployment requires more than technical capability—it also requires enough power to overcome external constraints. To determine how much power is enough requires specifying the nature and severity of these constraints. 'Structure'—characterized in terms of the distribution of power across states—operates as the key constraint on state behavior in the international system (Waltz 1979; Walt 1987; Mearsheimer 2001). More precisely, the polarity exhibited by an international structure—whether it is multipolar, bipolar, or unipolar—determines the comparative flexibility of the system, while within the system—whatever its structure—the freedom of action enjoyed by any state is a function of its relative power (Schweller 1998; Wohlforth 1999).

Today, and for the foreseeable future, the US and China are far and away the most powerful states in the international system

(Allison 2017; De Graaf and van Apeldoorn 2018; Maher 2018; Medeiros 2019; Tunsjo 2019; Lind 2024). When the capabilities of the top two states far exceed those of the others, the system is bipolar, and the top two states are referred to as superpowers. In a bipolar system, the superpowers need not be equal, but a wide gap must separate them from the rest of the states in the system.

Recent analysis shows why the international system is bipolar. Using a set of conventional power metrics (military expenditure, military personnel, gross domestic product (GDP), and a 'composite metric' consisting of GDP times GDP per capita), Lind compares the current distribution of capabilities to that which characterized the Cold War and concludes, 'If the USSR was a superpower then, China is one today. The world is bipolar' (Lind 2024, 9).

Take GDP. In 2023, US GDP (purchasing power parity) was approximately \$27 trillion, while China's GDP was approximately \$33 trillion; the next largest GDP, India's, was approximately \$13 billion, less than half that of the leading state in the system (International Monetary Fund 2024). The GDP ratio (the ratio of a country's GDP to that of the leading state) for China was 130 (US = 100) in 2023, compared to a GDP ratio for the Soviet Union of 45 in 1970, during the height of the Cold War (Lind 2024).

Or take military expenditure. In 2023, US defense spending was approximately \$916 billion, China's defense spending was approximately \$269 billion, and Russia's defense spending, the next largest amount, was approximately \$109 billion (SIPRI Military Expenditure Database 2024). The military expenditure ratio for China was 32 in 2023, compared to a military expenditure ratio for the Soviet Union of 105 in 1970 (Lind 2024).

These figures underscore the significant difference in superpower strategies adopted by China, which has focused on building economic strength, and the Soviet Union, which focused on building military strength. More important for our purposes, they also underline the wide gap between the top two powers and the rest, and the aggregative nature of superpower capabilities across multiple domains. Metrics like GDP and defense spending may be relatively crude, but they also point toward other capabilities in science, technology, finance, diplomacy, etc. which a large and growing body of literature shows are increasingly dominated by the US and China (see, for example, Ikenberry and Lim 2017; Flint and Zhu 2019; Schindler et al. 2024). As Tunsjo concludes in another recent analysis, 'The combined effect of the narrowing power gap between China and the United States, the widening power gap between China and the third-ranking power, and the roughly similar bipolar distribution of capabilities between the current international system and the bipolar system in the twentieth century all indicate the return of bipolarity' (Tunsjo 2019, 2).

The international system is dynamic, and no one knows how long bipolarity will last. Some observers suggest, for example, that India will eventually close the gap between it and the two superpowers, which would shift the system from bipolarity to multipolarity (e.g., Ayres 2018). Of course, this is possible, as are many other eventualities. However, each depends on multiple contingencies, and we cannot predict the future. As Lind puts it, 'The world is bipolar, for now' (Lind 2024, 54). We assume,

on this conservative basis, that bipolarity will continue until at least midcentury.

Superpowers in bipolar systems are categorically distinct from lesser great powers. Buzan summarizes the differences: 'The criteria for superpower status are demanding in that they require broad spectrum capabilities exercised across the whole of the international system. Superpowers must possess first class military-political capabilities ... and the economies to support such capabilities. They must be capable of, and also exercise, global military and political reach' (Buzan 2018, 640). In contrast, Buzan writes, 'Achieving great power status is less demanding in terms of both capability and behavior. Great powers need not necessarily have big capabilities in all sectors, and they need not be actively present in the securitization or economic processes of all areas of the international system' (Buzan 2018, 640). In short, superpowers rule the world in a way that great powers do not—great powers influence behaviors and outcomes, but superpowers shape them at a more basic level.

The fact of bipolarity means that the US and China alone will be sufficiently powerful across multiple domains to both successfully implement a PLUS deployment on a unilateral basis and prevent other non-rival but technically capable states from doing so. Would the US and China be able to stop each other from implementing a PLUS deployment? We regard the answer to this question as unknowable in the abstract, but the consequences of a Sino-American dispute over a PLUS deployment could be very dangerous (see below).

Bipolarity therefore functions as the primary structural constraint on state behavior in the contemporary international system. The views of the US and China will be key determinants of whether a PLUS deployment occurs. Of course, not every behavior is likely to trigger superpower opposition. Rather, superpowers, like all states, are liable to oppose those behaviors they perceive as potentially threatening to their national interests (however they define those interests). Superpower interests, by definition, are global. This suggests that behaviors which might negatively affect global commons, or shared planetary resources such as the atmosphere and high seas, are likely to arouse the concerns of superpowers (Buck 2017). A PLUS deployment—planetary, large-scale, uninterrupted, and speedy—while expected to have large and widely distributed benefits, would clearly have the potential to negatively affect the atmosphere and climate system; as such, we assume that the prospect of such a deployment would arouse serious concerns on the part of both the US and China.

The precise way strategic competition between the US and China will constrain a PLUS deployment depends fundamentally on how the views of the superpowers compare. In theory and in simplified terms, regarding any prospective PLUS deployment, the US and China will be either mutually supportive or mutually opposed or have conflicting views. In the case of mutual support from the US and China, a PLUS deployment will likely occur. This would necessarily involve at least one technically capable state. In principle, neither the US nor China would need to participate directly, but in practice, it is hard to imagine at least one superpower not being directly involved in implementation. Regardless, both the US and China would approve

of any such deployment, even if tacitly. Others might object to it, but the overwhelming combined economic, diplomatic, and military power of the US and China relative to all other states would make any attempt to stop a PLUS deployment supported by both superpowers futile.

In the case of mutual opposition from the US and China, a PLUS deployment is unlikely to occur. Any technically capable state that considered implementation would in effect have to ‘go through’ the US and China, which in practice would be nearly impossible. Consider a hypothetical scenario in which India sought to carry out a PLUS deployment over the objections of the US and China. Both superpowers could employ a wide range of carrots and sticks to prevent it, either individually or in tandem. For example, India’s lucrative role as the ‘pharmacy of the world’ depends to an extraordinary degree on imports of active pharmaceutical ingredients from China, which the latter could bring to a halt at relatively little cost to itself (Lieberherr 2024). Alternatively, India’s military is highly dependent on equipment, spare parts, and maintenance provided by Russia, whose growing dependence on China resulting from the war in Ukraine makes India increasingly vulnerable to supply disruptions engineered by Beijing (Lieberherr 2024). Or consider India’s rapidly expanding digital infrastructure, which is highly vulnerable to cyberattack including by the world’s top cyber powers the US and China (Rajagopalan 2023). These examples are meant to illustrate that India, like all other non-superpowers in the present bipolar system, is constrained by multiple asymmetric dependencies and strategic and critical vulnerabilities vis-à-vis the US and China which significantly restrict its freedom of action and would almost certainly prevent it from implementing a PLUS deployment over joint Sino-American opposition.

The superpowers might choose to impose a formal or informal prohibition to help stop technically capable states from pursuing a PLUS deployment. Such a prohibition might be temporary (a moratorium) or permanent (a ban). Several actors have called for the adoption of different versions of a moratorium on solar geoengineering (e.g., Climate Overshoot Commission 2023). If the superpowers instituted a prohibition covering PLUS-type deployments, at least one of them would need to police it, at a minimum through monitoring.

In the case where the US and China—two roughly evenly matched superpowers—have conflicting views, whether a PLUS deployment takes place is more uncertain. Indeed, as noted above, we believe it is impossible to know a priori how a Sino-American dispute over a PLUS deployment would end. What is certain, however, is that the possibility of unilateral action by either superpower poses dangers, particularly if they see things differently. Disagreement regarding the desirability of a PLUS deployment would likely heighten tensions between the superpowers by exacerbating preexisting disputes and/or by adding a new stressor to their ongoing rivalry. Examples of the former might include government procurement of specialized aircraft from national champions opening a new front in the US–China trade war; development of advanced engines expanding the scope of technology competition; or the construction of remote airbases triggering concerns about power projection and security (Chivvis 2024). Examples of the latter might be broader objections related to perceived threats to state sovereignty or rights

to national self-determination. Heightened tensions could escalate into crises with the potential to precipitate conflict, raising the specter of systemic war between the US and China. Viewed in isolation, a Sino-American conflict solely over SAI may seem unlikely, but when viewed as part of a matrix of perceived threats, disagreement over a PLUS deployment might well trigger or otherwise catalyze a violent clash. Conflicting Sino-American views thus increase the risk of system instability.

As noted earlier, we assume that the US and China would have strong preferences regarding a PLUS deployment. However, if neither of them felt strongly about it, then other states, particularly the other technically capable states, would have greater scope to push for a PLUS deployment. Under these conditions, the course of events would be unpredictable, with more actors potentially working together to support and/or oppose a large-scale planetary deployment. We do not consider this possibility in detail here.

4 | Historical Analogs

Historical analogs help illustrate these dynamics. Specifically, the most recent bipolar period—the Cold War between the US and the Union of Soviet Socialist Republics (USSR)—featured multiple instances in which states grappled with activities with the potential to harm global commons. None of the episodes discussed below are perfect analogs for a Sino-American bipolar system in which a PLUS deployment is contemplated, yet they shed valuable light on the ways in which superpower preferences strongly influence whether and how actions that might negatively affect global commons take place.

4.1 | Scientific Research in the Antarctic

In 1957, twelve countries including the US and the USSR launched the International Geophysical Year (IGY), a cooperative effort to facilitate scientific research in Antarctica (for more on science, politics, and governance in Antarctica, see Berkman et al. 2011).⁵ Prior to the IGY, the Soviet Union had been minimally involved in Antarctic research, but as the profile of Antarctica rose internationally and the future of the continent emerged as an issue of global importance, the USSR decided to increase its involvement (Jacobsson 2011). Doing so meant joining an elite club of countries with proven capabilities to establish scientific stations and mount scientific expeditions in Antarctica (these subsequently came to be known as ‘activity criteria’ for participating in decision-making related to Antarctic matters) (Jacobsson 2011). Research under the IGY was coordinated by the Scientific Committee on Antarctic Research (SCAR), a non-governmental body. Following the successful conclusion of the IGY in 1958, participating countries decided to institutionalize cooperative arrangements to enable continued research.

Yet the unsettled legal status of Antarctica, portions of which were claimed by seven different countries (all of whom took part in the IGY), posed an obstacle to such institutionalization. The assertion of territorial claims created tensions among claimant states and between claimant and non-claimant states (the latter of which included the US and USSR) and threatened to

bring the Cold War to Antarctica, all of which impeded scientific research on the continent. At a conference organized by the US in Washington, D.C. in 1959, the twelve countries that participated in the IGY (all of whom met the activity criteria) agreed to ‘freeze’ the status quo by setting aside their disputes over territorial claims, neither renouncing nor pursuing nor contesting them but rather adopting a *modus vivendi* to allow other activities, most importantly scientific research, to proceed (Hannesian 1960). The basis for this solution was the so-called Escudero Declaration originally put forward by Chile. Three of the participating countries—Argentina, Chile, and Australia—had resisted accepting this formulation, fearing that it might cast doubt on their claims, but after the USSR tacitly agreed to it, the US pressed them publicly and all three fell into line (Hannesian 1960).⁶ This formulation—which came to be known as ‘sovereign neutrality’—was the key component of the Antarctic Treaty signed at the end of the meeting, which enshrined peace and science as core values (Triggs 2011). The Treaty prioritized freedom of scientific investigation and cooperation to that end, and parties agreed to support scientific research through information and data sharing and exchange of personnel. In addition, the Treaty demilitarized Antarctica and banned nuclear weapons testing on the continent. The twelve signatory states came to be referred to as the ‘Consultative Parties’; over the years, seventeen of the 46 additional countries that joined the Treaty were also recognized as Consultative Parties with rights to participate in decision-making by virtue of their conduct of substantial research in Antarctica.

In the decades that followed, SCAR continued to serve as the key coordinating mechanism for scientific research carried out in Antarctica. International cooperation enabled by the Antarctic Treaty facilitated multiple notable scientific achievements in geosciences, life sciences, and physical sciences (Walton et al. 2018). Work conducted under the auspices of the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) program, which was set up to investigate the functional processes of the Southern Ocean ecosystem, played a critical role in the creation of the Convention for the Conservation of Antarctic Marine Living Resources, signed in 1980. Similarly, the discovery of the ozone hole above Antarctica in 1985 led to the successful negotiation of the Montreal Protocol.

The case of scientific research in the Antarctic illustrates an instance in which mutual superpower support for an activity that might affect a global commons resulted in that activity taking place. Both the US and the USSR conducted research in the Antarctic, at times jointly (Boczek 1984). While some states initially objected to the diplomatic formulation that enabled continued scientific research under the Antarctic Treaty, they relented once the superpowers aligned.

4.2 | Atmospheric Testing of Nuclear Weapons

In 1963, in the aftermath of the Cuban Missile Crisis, the US and USSR (and UK) signed and ratified the Treaty Banning Nuclear Weapon Tests in the Atmosphere, Outer Space and Under Water (also known as the Partial Test Ban Treaty or PTBT—for an overview of the PTBT see Kimball and Boese 2003).⁷ Adoption of the PTBT was driven by global anxiety concerning

the environmental and health effects of radioactive fallout from atmospheric testing, which the Treaty banned. The Treaty did not ban underground testing, which was more technically challenging than aboveground testing. Yet only the US and the USSR (and the UK by virtue of the 1958 US–UK Mutual Defense Agreement) had developed capabilities for underground testing. Thus, an additional motivation for the three founding signatories was to prevent other states from joining the nuclear club (Hunt 2022). By the time the PTBT entered into force, nearly a hundred additional countries had signed it. This cemented a global norm against atmospheric testing of nuclear weapons.

None of the founding signatories conducted any more atmospheric tests—if they had, such tests would have been detected through technical means like air sampling that many countries possess. France and China declined to join the PTBT and thus were under no legal obligation to stop atmospheric testing, and yet eventually they did so anyway in response to negative global public opinion and political pressure. France announced a switch from atmospheric to underground testing in 1974 after years of Pacific regional and global protest culminated in suits brought by Australia and New Zealand before the International Court of Justice (ICJ) seeking to halt French aboveground tests (Franck 1975).⁸ The change in French policy was enabled by a secret US underground testing assistance program (National Security Council 1973). Likewise, China switched from atmospheric to underground testing in 1980 following years of pressure and prodding by the US and others; circumstantial evidence suggests that US technical assistance also facilitated the change in Chinese policy (Department of State 1980). All the other states that possessed nuclear weapons during the Cold War—India, Pakistan, and probably Israel—signed and ratified the PTBT, and none conducted atmospheric testing.

The case of atmospheric nuclear testing illustrates an instance in which mutual superpower opposition to an activity that negatively affects a global commons led to that activity being halted. France and China were holdouts, but over time, the global norm against such testing proved too powerful for either one to resist. This norm was effectively instituted by the US and the Soviet Union. Moreover, American assistance appears to have been critical to securing changes in both French and Chinese policies. In the end, mutual superpower support for prohibiting atmospheric testing of nuclear weapons resulted in no more testing.

4.3 | Project West Ford and Experiments in Outer Space

In 1959, the US Air Force contracted the Massachusetts Institute of Technology Lincoln Laboratory to lead what came to be known as Project West Ford. Project West Ford was intended to test a novel long-distance communications system for the military based on the creation of an orbiting belt of copper wires or ‘needles’ (for details see Morrow and Rogers 1964). In theory, an artificial ring of needles encircling the planet could be used to reflect radio wave transmissions sent from ground stations to receiving stations located around the world, to ensure reliable communications during times of conflict. Such a ring could be created by launching a dispenser into orbit that would release hundreds of millions of tiny needles (in total the

needles would only weigh in the tens of kilograms) to form a circular belt around the planet; this belt would disperse within a few years and the needles would burn up as they reentered the atmosphere. Project West Ford would conduct a space launch to create an orbital belt and assess the performance of such a communications system.

Project leaders scheduled the launch and experiment for 1961. As preparations were made, opposition arose from some US and foreign scientists, mostly optical and radio astronomers, who feared that an artificial ring would interfere with their work. In response, the US government pledged that no additional launches would take place until after results from the first experiment had been evaluated, including by independent US and foreign scientists (Findlay 1964). The launch took place in October, but the payload malfunctioned, and the needles failed to dispense as planned. Scientists who were critical of the launch were bolstered by an article appearing in *Pravda* (the official newspaper of the Central Committee of the Communist Party of the Soviet Union) titled ‘U.S.A. Dirties Space’ (Reuters 1961). Since it had not been possible to conduct the experiment as planned, however, the US government announced its intention to carry out a second launch to complete an experiment, prior to which it would consult more closely with scientists.

In 1962, a series of meetings of the Legal Subcommittee of the UN Committee on the Peaceful Uses of Outer Space (COPUOS) was convened to discuss establishing principles to govern space activities; this was undergirded by a mutual superpower interest in limiting the spread of the Cold War to outer space (Moltz 2019). At one of the early meetings, the Soviet representative articulated his government’s position by proposing that future space experiments pursued by one state be subject to a de facto veto by other states, because experiments like Project West Ford ‘might impede the use of outer space by other countries and be extremely dangerous’ (COPUOS 1962, 5). The US rejected this as overly restrictive. Inside and outside COPUOS, the USSR asserted that Project West Ford was part of a larger ‘space espionage’ effort that threatened to militarize outer space (CIA 1962). In July, the Soviets stated that if the US attempted a second launch, the USSR would destroy any experiment by orbiting needles in the opposite direction (CIA 1962). However, the US, evidently judging this threat to be non-credible, proceeded with a second launch in May 1963; this time the experiment was completed and regarded as a success. The Soviets responded with a letter to the UN Secretary-General titled ‘Dangerous United States Activities in Outer Space’ that criticized the follow-up effort (UN 1963). The US replied with its own letter to the UN Secretary-General stating that appropriate precautionary measures had been taken.

This dispute over the degree to which states should be restricted in their use of outer space to conduct scientific experiments was eventually resolved after both superpowers, in the interest of reaching an overall agreement, acceded to a compromise proposal originally put forward by France (Mineiro 2008). This proposal required states to accept two obligations: to prevent harmful contamination of outer space and to consult other states prior to carrying out an experiment or comparable activity in outer space; other states, however, would not have a veto over such activities. This formula was incorporated in a resolution

adopted by the UN General Assembly in 1963, which was the progenitor of the Outer Space Treaty signed in 1966. By that time, it was already becoming clear that advances in satellite communications had rendered the Project West Ford technology obsolete. The consultation provision of the Outer Space Treaty has never been formally invoked (Listner 2022).

The case of Project West Ford and outer space experiments demonstrates that when superpowers disagree about how to use a global commons, tensions between them may increase, and the outcome may be inconclusive. In the context of the space race, the US pursuit of Project West Ford aggravated relations with the Soviet Union, leading to a diplomatic row and the threat of countermeasures by the Soviets. The U-2 incident in 1960 illustrated the potential for relatively minor incidents to move superpowers up the escalation ladder. The US and the Soviet Union reached a legal compromise over the issue of outer space experiments; yet, simultaneous technical advances in the related but distinct field of satellite communications, combined with the absence of any formal consultation in subsequent years, suggest that effective resolution of the dispute was ultimately a product of contingent forces more than anything else.

The patterns exhibited in these cases generally accord with expectations derived from the analysis above. Where Cold War superpowers were mutually supportive of an activity with the potential to harm a global commons, as in the case of scientific research in the Antarctic, the activity took place. Where there was mutual opposition to such an activity, as in the case of atmospheric testing of nuclear weapons, the activity ceased. And where there were conflicting superpower views regarding the desirability of such an activity, as in the case of Project West Ford and experiments in outer space, the status of that activity was never fully settled. We take this as a *prima facie* argument for anticipating similar dynamics when it comes to a potential PLUS deployment under a bipolar system organized around the US and China.

5 | Discussion

The answer to the question who could implement a PLUS deployment thus appears to be the US and China, the two superpowers in today’s bipolar system. Only the US and China are capable of unilaterally deploying planetary, large-scale, rapid, and sustained SAI in the face of strong opposition. A small number of other states—France, Germany, the UK, Japan, Canada, Russia, India, and Brazil—are technically capable of a PLUS deployment, but only the US and China possess the broad-spectrum capabilities required to overcome additional economic, political, and military constraints on deployment. Indeed, this US–China duopoly stands as the principal constraint on other technically capable states’ ability to implement a PLUS deployment. More specifically, we have argued that the combination of Sino-American views regarding the desirability of a PLUS deployment—mutual support, mutual opposition, or opposing positions—is likely to function as the primary determinant of whether a PLUS deployment occurs. Under the scenario we have described, all other great, middle, and small powers, including climate vulnerable states, as well as corporations and individuals, will lack the suite of capabilities required to successfully

implement a large, rapid SAI deployment on their own (see, for example, Victor 2008; Millard-Ball 2012).

While the US and China are the only actors powerful enough to successfully implement a PLUS deployment unilaterally against opposition, they are also the only actors capable of preventing other technically capable states from doing so. The case of the PTBT offers some lessons that would be applicable to attempts to prohibit a PLUS deployment. The two superpowers (along with the UK) jointly devised and promoted the ban on aboveground nuclear tests. Not every nuclear-capable state agreed to it, but all eventually complied with it. They did so in response to public and private pressure rooted in a strong global norm against atmospheric tests grounded in the PTBT, combined with technical assistance provided by the US. A ban is not the same as the moratorium that has been called for in the case of solar geoengineering, but both are forms of prohibition.

If the US and China will be decisive in determining whether a PLUS deployment happens, then an obvious question is, what are their views about a planetary deployment likely to be? The answer is that we do not know. Neither the US nor China has an official position on SAI or solar geoengineering, and US and Chinese policymakers appear to possess limited awareness of the technology (Horton et al. 2023). We can say with greater confidence, however, that the degree to which their views align is likely to have consequences for international stability. In particular, Sino-American disagreement regarding the desirability of a PLUS deployment will increase discord between them—in a bilateral system, superpower discord nearly equates to global discord. In a previous section, we offered some examples of how such disagreement could sharpen the US–China rivalry. In the Project West Ford case, the Soviets did not act on their threat to destroy the space experiment, and technical advances reduced the salience of the issue, yet such an uneventful outcome should not be taken for granted in the case of SAI.

From a policy perspective, therefore, it is important to promote dialog between the US and China on SAI and solar geoengineering more broadly to cultivate shared understandings as well as to build trust, in order to reduce the likelihood that conflicting Sino-American views on this topic contribute to intensified superpower rivalry and heightened international systemic risk. In other words, to the extent possible, the US and China must ‘get on the same page’ when it comes to SAI and a possible PLUS deployment. One challenge will be to prevent discussions on SAI from being negatively affected by other issues important to the bilateral relationship. Recent US attempts to ‘compartmentalize’ Sino-American discussions on climate policy—to insulate them from more contentious trade, security, and technology issues—have had limited success (Hong 2023). Early dialog can be promoted through informal ‘track II’ diplomacy carried out by non-state actors (Jones 2015). Scientific collaboration can help establish a common understanding of the costs, risks, and possible benefits of SAI; in this regard, the recently renewed (and amended) US–China Science and Technology Agreement is important.

Although the other technically capable states—which largely correspond to the (non-superpower) great powers—will not be as decisive as the US and China, they will still likely be able to influence at least some aspects of decisions regarding

a PLUS deployment. In this, they are likely to resemble the non-superpower members of capabilities-based clubs like the Consultative Parties to the Antarctic Treaty and the nuclear club, who played supporting roles in the historical cases considered above. Technically capable states might, for example, participate directly in a PLUS deployment that was jointly backed by the US and China by developing technology, manufacturing equipment, or piloting aircraft. (Similarly, national champion aerospace companies might operate as vendors or contractors in a PLUS deployment, but not without political oversight—as noted earlier, these companies are heavily reliant on their home governments, from which they ultimately take their cues.) Or their expertise and experience might enable them to help broker diplomatic compromises to facilitate action, as Chile did with its Escudero Declaration in negotiations over the Antarctic Treaty. These states will not decide whether a PLUS deployment happens, but they could affect the precise form it might take as well as elements of the institutional context in which it is considered.

Other states that are not technically capable of a PLUS deployment may also influence events, though probably not as much as those that are technically capable, and in declining proportion to their geopolitical weight. Weaker states might use political and legal fora to express their views for or against deployment, seek to mobilize public opinion, press for action, or attempt to facilitate compromise. Examples from the cases above include Australia and New Zealand bringing suits against France before the ICJ to stop atmospheric nuclear testing, and France tabling a proposal at COPUOS to help reduce the scope of superpower disagreement over space experiments.

Clearly, decisions about a PLUS deployment will be taken and primarily influenced by more powerful countries. This will reinforce existing patterns of domination and control and continue to disempower those countries that have contributed least to climate change yet will suffer the most. In doing so, it will threaten a basic precept of most conceptions of procedural justice—that everyone deserves a meaningful voice in decision-making that affects them (Callies 2018). In theory, this situation could be improved by the adoption of governance arrangements that give less powerful countries a genuine say over PLUS-type SAI. This might occur, for example, if US–Chinese competition for global support created incentives for both countries to bind themselves to inclusive international institutions for governing SAI.

This points to a final consideration. Decisions about a PLUS deployment will not be taken in a geopolitical vacuum but will be made by the US and China in the context of their ongoing rivalry. Decisions about activities that threatened to impact global commons made by the US and the Soviet Union during the Cold War invariably reflected broader strategic concerns. Scientific research in the Antarctic proceeded in part because the Americans and Soviets both had a larger interest in keeping the continent demilitarized. Atmospheric testing of nuclear weapons was banned in part because the US and USSR (and the UK) saw it as a means to preserve their nuclear monopoly. Project West Ford was motivated first and foremost by security considerations, and the superpowers agreed to a compromise over space experiments due to their joint interest in establishing a general framework for governing outer space activities. The US and China will determine whether a PLUS deployment takes place because they

are now the most powerful actors in world politics. Superpowers view things through a global, strategic lens. Sino-American views regarding a PLUS deployment, and whether the US, China, or both choose to implement one, will thus ultimately hinge on how such a deployment figures in their grand strategies.

6 | Conclusion

In this article, we have argued that the US and China alone will be capable of implementing a PLUS deployment on a unilateral basis over the objections of others. A handful of other, less powerful states will also be technically capable, but they will be constrained in carrying out a deployment unilaterally by the bipolar structure of the international system. The broad-spectrum capabilities possessed by the superpowers—capabilities that extend far beyond the technical ability to conduct a PLUS deployment—mean that the combination of US and Chinese views about the desirability of such a deployment will ultimately determine whether planetary, large-scale, rapid, and continuous SAI takes place. This has important implications for policy, diplomacy, governance, and justice.

We have been careful to note that our analysis applies only to the case of a PLUS deployment, that is, 1°C cooling by 2050. A PLUS deployment is an aggressive scenario. We have focused on it not because we think it is a good idea—we do not—but because it is the type of scenario that informs some public discussions of solar geoengineering. As such, it is a useful point of departure for considering which actors could deploy SAI.

An outstanding question related to all this is, who could implement SAI under alternative deployment scenarios? For example, it is plausible that what matters most in the politics of SAI is the ability to start a deployment. Consider a subscale deployment that is large enough to significantly affect stratospheric aerosol distributions and radiative forcing on a global basis, yet small enough for states to argue that they are causing no significant transboundary harm (the threshold under international law). Once a subscale deployment is underway, perceptions and government positions are likely to change in ways that could make future deployments either easier or harder.

The ten countries we identify as technically capable of implementing a PLUS deployment certainly have the capacity to begin such a subscale deployment (Keith and Smith 2024). Subscale deployment may fail to arouse the concerns of the superpowers to the same degree as a PLUS deployment, in which case a broader set of countries might be able to initiate deployment, potentially altering global debates about SAI in the process. Under such a scenario, the future of SAI would depend on more than just Chinese and American views of the subject. These possibilities underscore the need to distinguish between different types of deployment when considering the politics of SAI and suggest directions for future research.

Acknowledgements

We thank the editors and reviewers for their helpful comments on the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Endnotes

- ¹For thorough reviews of scientific and governance aspects of SAI see National Academies of Sciences, Engineering, and Medicine (2021); United Nations Environment Programme (2023); Parson and Keith (2024).
- ²Note, however, that such a deployment could also be carried out at midlatitudes or higher but doing so would be significantly less efficient; see Keith and Smith (2024).
- ³The possibility of unforeseen technological innovations means that the capacity to field aircraft for a PLUS deployment may in principle extend beyond these companies. Where this is the case, our analysis may not apply.
- ⁴There is thus little scope for a rich individual “greenfinger” to implement a PLUS deployment independently, since a privately owned national champion aerospace company would still ultimately answer to its home government (Victor 2008).
- ⁵These twelve countries were Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, the UK, the US, and the USSR.
- ⁶Chile had backtracked on its own earlier proposal.
- ⁷The Comprehensive Nuclear-Test-Ban Treaty (CTBT), signed in 1996, would ban all nuclear testing including underground and thereby make the PTBT redundant for states party to the CTBT. The CTBT has not, however, entered into force, and neither the US, Russia, nor China has currently ratified it.
- ⁸France announced an end to atmospheric testing before the ICJ could reach a final decision, ultimately rendering the cases moot.

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