CLIMATE CONTROL

International Legal Mechanisms for Managing the Geopolitical Risks of Geoengineering

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Perspective
EXPERT INSIGHTS ON A TIMELY POLICY ISSUE

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In February 2009, a provincial weather bureau in northeastern China fired 313 sticks of silver iodide into the clouds over Beijing. Intended to alleviate the longest drought in almost 40 years, the effort led to massive snowfall and the closure of 12 highways.[1] Over the past decades, as weather modification technologies, such as cloud seeding, have matured and enlarged in terms of their scope to intervene with global climate change, the prospect of future man-made natural hazards has loomed larger. As climate change poses ever greater threats to human and natural systems, scientists and policymakers have explored novel ways to reduce greenhouse gas (GHG) concentrations in the atmosphere and to mitigate their effects on the climate.[2] *Geoengineering*—which we define as the intentional, large-scale manipulation of an environmental process on Earth to counteract the effects of climate change—represents a way to do both. But some forms of geoengineering have been extremely controversial in climate policy debates, because they involve diversion of resources away from emissions-reduction efforts, where there is clear scientific (if not political) consensus. This has limited the amount of research and policymaking on geoengineering.

As the impact of climate change on human and natural systems has increased in recent years,[3] many governments—including those of Canada, France, New Zealand, and Japan—have recently declared climate emergencies and begun considering more-extreme risk-management strategies. China's continued investment in weather-modification technologies[4] and Switzerland's leadership on a United Nations (UN) proposal for geoengineering governance suggest that geoengineering is being considered.[5] Although the scientific developments related to geoengineering have garnered attention, these technologies also require the development of effective and comprehensive governance mechanisms to address the new risks associated with them.

In this Perspective, we consider the geopolitical risks of geoengineering and the role of international legal mechanisms in managing these risks, bringing to bear insights from subject-matter experts on climate policy, international relations, and international law provided as part of a workshop,[a] as well as the relevant technical, international relations, and international law literature.

[a] Workshop participants included 24 academic research experts on solar radiation management, carbon dioxide removal (CDR), climate

What Is Geoengineering?

The term *geoengineering* covers a broad range of technologies that can be grouped into two categories: CDR and solar radiation management (SRM).[6] CDR technologies aim to take carbon dioxide out of the atmosphere, creating essentially "negative emissions," to lower atmospheric greenhouse gas concentrations and reduce warming. SRM technologies aim to reflect incoming sunlight away from the Earth with clouds or other reflective substances, thereby reducing the warming of the atmosphere. Both types of geoengineering are perceived by many climate scientists as a potential diversion of resources from emissions-reduction efforts.[7] There are important differences between the two categories, however, both in their likely effects and how they are viewed by researchers and policymakers. Crucially, most low-carbon climate scenarios assume significant use of CDR as a mitigation measure. The Intergovernmental Panel on Climate Change (IPCC) has already stated that it considers CDR to be a necessary element in reducing emissions. The anticipated role of CDR in mitigating the effects of climate change has important implications for its regulation.

There are many geoengineering technologies currently under investigation and development. Tables 1 and 2 list some of the more commonly investigated CDR and SRM technologies, respectively, although this list is not meant to be exhaustive.

policy, international relations, and international law. The workshop was conducted over two days and included focused discussions about future climate pathways, their associated geopolitical risks, and the role of international legal mechanisms in the resolution of those geopolitical consequences.

Abbreviations

CBD	Convention on Biological Diversity
CCAMLR	Conservation of Antarctic Marine Living Resources
CDR	carbon dioxide removal
CO_2	carbon dioxide
ENMOD	Environmental Modification Treaty
GHG	greenhouse gas
GtC	gigaton of carbon
IPCC	Intergovernmental Panel on Climate Change
LC/LP	London Convention and London Protocol
NOx	nitrogen oxide
SRM	solar radiation management
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
W/m^2	watt per square meter

The tables detail the following technical characteristics of each technology:

- **Technical readiness:** Measures the maturity of a specific technology. For example, "high" indicates a technology that has been proven successful in its mission operation, and "medium" indicates a component that has been validated in a relevant environment.
- **Cost magnitude:** Because rigorous cost estimates of geoengineering technologies are generally unavailable, our ratings indicate the cost order of magnitude with assumptions noted for the amount

Table 1. Select Carbon Dioxide Removal Technologies

Geoengineering Technology	Technical Readiness	Cost Magnitude (in U.S. dollars)	Time Scale	Secondary Effects
Large-scale reforestation or *afforestation* focuses on conserving forests and jungles, as well as large-scale planting of non-forested areas	High	$100 billion (for 1 gigaton of carbon [GtC[a]])	Decades	Increased fertilization and irrigation risk water pollution, nutrient runoff, and depletion of fresh water; microclimate alterations; unequal land-use burden on well-forested areas, likely developing countries
Bioenergy with carbon capture and storage captures CO_2 released from bioenergy applications (e.g., biofuels, biomass burning) and stores it in geological formations underground	Medium	Trillions (for 100 GtC)	About a decade	Emit CO_2 via bioenergy processes and CO_2 capture; land-rights conflict from higher demand for agricultural land and fertilization; microseismicity; disposal of captured CO_2 is a concern[8]
Direct air capture pulls CO_2 out of the air via chemical or electrochemical means	Medium	Trillions (for 100 GtC)	About a decade	Scaling up process requires large amounts of energy and water; threat of toxicity of chemicals; disposal of captured CO_2 is a concern
Ocean iron fertilization adds iron into the ocean to increase phytoplankton, which store CO_2 from the atmosphere	Low/medium	10 billion (for 100 GtC)	1–5 years	Surface cooling and/or sea surface temperature increase; ozone depletion; potentially produce other GHGs, such as nitrogen oxides (NOx); ecosystem disruption with ocean acidification, algal blooms, and ocean oxygen depletion, causing loss of ocean life.[9]

SOURCE: RAND analysis with cost orders of magnitude based on review publications.[10]

[a] The forestation cost magnitude is shown only for 1 GtC because there is less capacity for this technology to scale up because of limitations on how much land can be made into forest.

of CO_2 removed for CDR and the solar radiation in W/m^2 reflected for SRM. These estimates are based on assessments in the existing literature, including press releases, but given that many of these technologies have yet to be implemented or tested at scale, significant uncertainty remains.

- **Time scale:** This estimate, based on existing scientific studies to the extent possible, indicates the time from implementation to reaching an applicable climate goal. It refers to technical efficacy without additional time to account for political feasibility.
- **Secondary effects:** These are the potential climate, weather, and land use impacts of each technology, based on existing scientific studies to the extent possible.

CDR technologies represent a range of opportunities and costs. For example, forestation is readily deployable based on small-scale demonstrations. In contrast, scientists are still developing and testing in controlled research settings various approaches to pull CO_2 out of the atmosphere and store it—technology used by both bioenergy (with carbon capture and storage) and direct air capture. Significant investment would still be needed

Table 2. Solar Radiation Management Technologies

Geoengineering Technology	Technical Readiness	Cost Magnitude (in U.S. dollars) for Watt per Square Meter (W/m^2)	Time Scale	Secondary Effects
Stratospheric aerosol injection involves spraying inorganic particles (e.g., sulfur dioxide) into the stratosphere to reflect sunlight	Low/medium	Billions (for 2–5 W/m^2)	Years	Generally: higher latitude warming, changes in precipitation, ozone depletion, uncertain public health impacts from food/water contaminants, ocean acidification, high risk if SAI stops suddenly;[15] northern hemisphere deployment: severe drought in sub-Saharan Africa and India; southern hemisphere deployment: rain failure in northeast Brazil, more hurricanes in North Atlantic[16]
Marine cloud brightening involves spraying particles into marine clouds to make them more reflective	Medium	Billions (for 0.8–5.4 W/m^2)	Years	Decreased precipitation and lower temperatures, adversely affects crops. South America warmer and dryer; less rain over Amazon basin; more tropical rainfall;[17] risk to sudden stop, need to escalate over time[18]
Space mirrors are large mirrors put into space (e.g., orbit at Lagrange point 1) to block and reflect solar radiation	Medium	Trillions (for < 0.6 W/m^2)	Months	Weather changes, potential decrease in biosphere, precipitation may decrease with temperature, regional shading and sunlight increase impacts agriculture

SOURCE: RAND analysis with cost orders of magnitude based on review publications.[19]

to achieve the level of readiness required for large-scale implementation of these approaches.[11] Of the various CDR technologies, ocean iron fertilization would most readily affect the climate, in years compared with decades for the other geoengineering technologies, and would require the least investment.

Major Secondary Effects of Carbon Dioxide Removal

Although CDR is viewed more favorably than SRM in terms of its secondary effects, it is important to acknowledge the risks inherent in its deployment. Forestation of previously unforested areas likely requires fertilization and irrigation, which could cause water pollution, nutrient runoff, and depletion of fresh water supplies. Moreover, drastically changing the vegetation in a region through forestation will cause microclimate alterations and disrupt local ecological systems. These negative environmental effects and land-use demands are likely to be placed on the shoulders of developing countries because of the concept of conserving existing forests and planting in non-forested and less-developed areas.

Although bioenergy with carbon capture and storage processes is still being developed, there are concerns that bioenergy processes, as well as those used to capture CO_2, would themselves emit more CO_2. Like forestation, bioenergy with carbon capture and storage would create a higher demand for agricultural activity and fertilization to fuel the bioenergy component, which could lead to conflict stemming from land-rights disputes.[12] In addition, the issue of safe disposal or storage of captured CO_2 is a significant concern, given the danger associated with a sudden release of CO_2 into the atmosphere. Furthermore, storing CO_2 underground could lead to microseismicity.[13] Given these concerns, careful considerations need to be made about where storage sites are located.

Direct air capture has similar secondary effects and concerns as bioenergy with carbon capture and storage. As the technology stands today, it would take large amounts of energy and water to scale up direct air capture to a level that would impact the climate, and the technology also involves toxic chemicals that pull CO_2 out of the atmosphere. Like bioenergy with carbon capture and storage, once the CO_2 is removed, there are concerns about the storage or disposal of both CO_2 and the extracting chemicals.

Finally, ocean iron fertilization has the potential to generate surface cooling, however, some studies indicate that it could actually lead to an increase in sea surface temperatures because more energy is being harvested. In addition, ocean iron fertilization could counterproductively lead to the production of other greenhouse gases, such as NOx. The technology could also cause ozone depletion and ecosystem disruption through ocean acidification and algal blooms. If implemented on a global scale, modeling studies predict that the ocean would lose oxygen, killing fish and other ocean life.[14] Although ocean iron fertilization has a lower cost and faster time scale than other CDR technologies, these are serious risks to consider before proceeding with large-scale implementation.

With the exception of ocean iron fertilization, CDR technologies can be predominantly implemented locally within a country, where cross-boundary secondary effects might occur at borders on a regional scale. The intended climate effects would be global in reducing global GHG concentrations, similar to reducing GHG emissions. With ocean iron fertilization, it is more likely that issues of international waters' use will arise in implementation at scale.

Although SRM technologies would have a relatively faster impact on the climate than CDR approaches and include less expensive options (some by orders of magnitude), none of these technologies are at a high level of technical readiness. Characteristic of all SRM technologies, they would not reduce GHG concentrations, the cause of climate change, but rather counter the resulting warming. With respect to stratospheric aerosol injection, scientists have conducted conceptual tests on different types of aerosols and dispersion methods, therefore we assessed it to have a low to medium level of technical readiness. Stratospheric aerosol injection has yet to undergo formal testing in the actual stratospheric environment.[20] Marine cloud brightening is under development and has not been demonstrated at scale, with the exception of observations of particle emissions from ships causing bright streaks in clouds.[21] Space mirrors exist at a small scale, but they have a medium level of technical readiness because additional technological development would be needed to construct the mirrors at the necessary scale in space.[22]

Major Secondary Effects of Solar Radiation Management

Preliminary modeling studies have highlighted some potential secondary effects of SRM technologies. These effects have disincentivized consideration of the incorporation of these methods into future climate mitigation plans. Modeling of stratospheric aerosol injections, for example, has shown a likelihood of higher latitude warming, changes in precipitation, ozone depletion, ocean acidification, and food and water contamination.[23] Furthermore, if the implementation of aerosol injections suddenly stops, there would be an abrupt increase in solar radiation. In the months that follow, this would disrupt ecosystems and restart the climate change impacts that the aerosol injections were initially supposed to be mitigating because GHGs remain in the atmosphere for much longer than the aerosols that would be used.[24] In addition, modeling studies have shown that the location in which aerosol injections are implemented would influence the secondary effects. If aerosol injections are implemented in the northern hemisphere, it could cause severe droughts in sub-Saharan Africa and India.[25] If it is deployed in the southern hemisphere, however, it could cause rain failure in northeast Brazil and an increase in hurricanes in the North Atlantic.[26] Another modeling study has shown that different regions across the globe do not benefit equally in response to different levels of stratospheric aerosol injection, such as those that would be used for SRM.[27] These differential effects increase the chances for such decisions to appear malicious.

The secondary effects of marine cloud brightening include a decrease in precipitation and temperature, which would adversely affect agricultural crops. There are also many regional effects associated with marine cloud brightening, including warming and drying in South America, a decrease in rainfall over the Amazon basin, and an increase in tropical rainfall.[28] Like stratospheric aerosol injections, if marine cloud brightening is suddenly stopped, there may be negative effects: The so-called termination shock would include abrupt warming and ecosystem disruption in the following days.[29] It would also be necessary to escalate the implementation of marine cloud brightening to sustain its effect over time.

Finally, space mirrors could potentially cause weather changes and, as a result, a decrease in global biomass. As temperatures decrease, levels of precipitation may also decrease. Because space mirrors will serve as a physical shade from the sun, there will be regional shading, in addition to sunlight increase in different regions. This will likely affect agriculture and local ecosystems. And as with stratospheric aerosol injections, implementation choices that impact certain regions have the potential to be perceived as malicious.

The secondary effects of SRM approaches have disincentivized their incorporation into future climate mitigation plans. Stratospheric aerosol injections and marine cloud brightening could conceivably be implemented on a smaller scale to limit their effects to a specific region, but the interconnected nature of the climate system makes the boundary-crossing spread of secondary effects extremely difficult to avoid. To achieve effects on the scale of the global climate, all SRM technologies would need to be widely implemented across the global commons, although marine cloud brightening is more limited in its ability to scale up.

State of the Science

Currently, geoengineering research and early-stage deployment efforts are being conducted in many countries around the world. Geoengineering research has focused on studying the technical feasibility of various geoengineering technologies, conducting impact assessments, and considering the ethical, legal, and social implications of geoengineering technologies. The majority of this research has been carried out in academic and laboratory settings. In the United States, for example, Harvard researchers have launched the Stratospheric Controlled Perturbation Experiment (SCoPEx[30]), which seeks to clarify the risks and benefits of SRM, and researchers at the National Center for Atmospheric Research and the Pacific Northwest National Laboratory have modeled the effects of marine cloud brightening.[31] The Geoengineering Model Intercomparison Project and the Carbon Dioxide Remove Model Intercomparison Project are modeling the likely climate effects of geoengineering.[32] Academic research on geoengineering is ongoing in Canada, India, Japan, Australia, Germany, and the United Kingdom. Research programs in China are also modeling the climate effects of geoengineering and conducting impact assessments.[33] The Developing Country Impacts Modelling Analysis for SRM Fund effort provides grant funding to scientists in the southern hemisphere to research the impact of SRM. In addition to these research activities, early-stage deployment efforts focusing on forestation have been undertaken in Peru and Brazil.[34]

Geopolitical Risks of Geoengineering

Importantly, the development and implementation of geoengineering is not merely a matter of scientific and engineering advancement, but also a question of geopolitics. International geopolitical dynamics, and the internal political dynamics of states, have a significant influence on how countries respond to climate change, including how they view geoengineering.[35] Experts indicated that these responses could plausibly lead to international tensions, conflict, and even war.[36]

Geoengineering: Who Decides?

The primary concern is that some countries may decide to pursue geoengineering even as others condemn those efforts. As scholars have argued, this divergence results because "even optimal climate engineering would result in 'winners and losers': some states would gain relative to a world without climate engineering, some states would lose, and no state would be unaffected."[37]

It is worth noting that more powerful states might oppose geoengineering if they believe that they stand to lose more from the engineered climate than the status quo. For example, Russia could benefit from a warming climate in terms of its agriculture and polar activities. As it stands, many powerful countries, for example, the five permanent members of the UN Security Council, are ranked in the top one-third of countries least vulnerable to climate change and most ready to adapt.[38] By contrast, the countries that are most vulnerable to climate change and most likely to benefit from geoengineering tend to be low income and with little international political influence. Although especially vulnerable countries may be able to implement less-expensive SRM technologies on their own,[39] depending on the likely impacts of these efforts, they may be opposed by more powerful states. Moreover, because certain SRM technologies are less expensive a range of non-state actors could unilaterally decide to implement them, which would require states to respond.

Tensions may also arise between high carbon-emitting countries (most notably China and the United States) and low carbon-emitting countries because of their different levels of responsibility for the effects of climate change. High carbon-emitting countries may support geoengineering to remove the need to reduce emissions, but low carbon-emitting countries may oppose such geoengineering efforts for a number of reasons. For example, a country that employs SRM instead of reducing its emissions is postponing or geographically displacing the consequences of climate change while failing to contribute to a long-term global solution. In contrast, a country that uses CDR instead of traditional emission-reduction measures is reducing the amount of greenhouse gases it contributes, but it will need to scale up its CDR efforts without parallel efforts to reduce emissions. In either case, low carbon-emitting countries may argue that high carbon-emitting countries have failed to meet their legal obligations under the UN Framework Convention on Climate Change and are trying to use geoengineering to compensate for their failures. Alternatively, industrialized countries in the West may grow increasingly frustrated at the slow pace of emissions reductions in fast-growing nations in Asia, leading to tensions between the two blocs.

Even if states agree that geoengineering can or should be used, potentially contentious issues could still arise.[40] First, what is the optimal climate that geoengineering activities should seek to achieve? If countries have a difficult time reaching agreement, conflicts could emerge over global consensus regarding control of the thermostat.[41] Second, states could fight over the territory and resources needed to implement geoengineering. SRM, for instance, could create a future in which "land grabs will turn into sky grabs and territorial disputes will extend to the stratosphere."[42] Third, states could try to compel geoengineering laggards or free-riders to contribute to international CDR efforts through parallel geoengineering efforts, much like states try to compel emissions reductions today.[43] And fourth, tensions could rise if states blame geoengineering by others, including both SRM and CDR, for their own environmental misfortunes, including disruptions to ecosystems and land-use patterns and water contamination. Geoengineering activities abroad may provide world leaders with a convenient scapegoat when their citizens suffer from negative climate impacts, such as flooding or crop failure, even if the geoengineering intervention is not the true cause of their suffering.[44]

Potential for Positive Geopolitical Outcomes

Although geoengineering may inflame geopolitical tensions, it could also serve as a tool for mitigation or resolution of those tensions. For one thing, climate change itself poses significant risks for international politics, including an increased risk of conflict and war resulting from natural disasters and resource scarcity.[45] Countries could try to reach agreements to cooperate on the use of geoengineering, which could ease tensions that have emerged because of disparate climate impacts. The process of trying to achieve consensus on geoengineering may itself lead to greater cooperation among states on unrelated issues of global importance.

Mechanisms for Managing International Governance Challenges

Existing International Legal Mechanisms

International environmental law, the body of law most relevant to geoengineering, is a set of rules, treaties, and conventions that set global standards and obligations concerning the environment for state parties, such as enhanced regulation of carbon emissions, restrictions on environmental modification, and the protection of biodiversity, among others. As concern grows about climate change and the environment, the UN and other international bodies have established new legal mechanisms to address related issues. However, these mechanisms have varying and limited binding capacity on member states and lack effective enforcement apparatuses and implementation. Although some international legal agreements, such as the Paris Agreement, an agreement within the UN Framework Convention on Climate Change (UNFCCC), may ultimately be more successful in promoting effective implementation, many instruments do have not enforcement mechanisms or effective dispute settlement bodies. Within the United States, the Environmental Protection Agency is responsible for enforcing environmental obligations under the international agreements to which the United States is a signatory, including the Vienna Convention, the Montreal Protocol, and the UNFCCC, among others.

Among experts on international law and international relations, there is ongoing debate about whether existing international legal mechanisms can be used to manage potential international conflicts arising from geoengineering.[46] Currently, there is no overarching multilateral international agreement that regulates the full spectrum of geoengineering activities.[47] Nonetheless, a number of existing international legal agreements address discrete aspects of geoengineering governance, albeit with some respective shortcomings. For example, most existing legal mechanisms address only a subset of, rather than all, geoengineering technologies. We identify these agreements:

- **Environmental Modification Treaty (ENMOD):** Adopted through a UN General Assembly Resolution in 1976, ENMOD prohibits the deployment of weather modification techniques as a weapon. Under Article I, parties to ENMOD have "undertake[n] not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury" to any other party.[48] Although ENMOD has been described as the "most relevant treaty to geoengineering," it permits most peaceful environmental modification techniques so long as they are undertaken "with due consideration for the needs of the developing areas of the world."[49] However, the extent to which ENMOD prohibits unintentionally hostile effects of environmental modification techniques has been the subject of debate, as has the applicability of the

ENMOD to non-international armed conflicts.[50] ENMOD does provide for the establishment of a Consultative Committee of Experts to be chaired by the Secretary-General of the UN to address any problems arising in relation to its objectives, however, none of the 78 state parties to ENMOD have ever used this mechanism.[51]

- **UNFCCC:** The UNFCCC calls for the stabilization of greenhouse gas concentrations in the atmosphere at a level that may require some geoengineering activities.[52] The UNFCCC could serve as a one-stop shop for the regulation of geoengineering at the international level, given that 197 countries have ratified the Convention. However, the agreement does not explicitly reference geoengineering nor are its provisions binding.[53] Moreover, because the UNFCCC relies on consensus, the controversial nature of geoengineering makes it less likely to be an effective decisionmaking forum. However, through annual conferences of parties, it could serve as a forum for countries to raise geoengineering-related issues for discussion, which may facilitate greater international cooperation on these issues. Two such international agreements that operationalize the UNFCCC are the Kyoto Protocol and its successor, the Paris Agreement.
- **Montreal Protocol on Substances That Deplete the Ozone Layer:** The Montreal Protocol, signed by every UN member state, which has been called the "most successful case of international environmental implementation,"[54] regulates specified ozone-depleting substances, but it does not explicitly reference either aerosol injections or ocean iron fertilization. As a result, its applicability to these activities remains unclear.[55] However, one expert suggested that if "sulfate aerosol injections . . . [adversely] impact the stratospheric ozone layer," then the Montreal Protocol may be implicated.
- **Convention on Biological Diversity (CBD):** The CBD is a legally binding treaty, with 196 member states, that aims to conserve and protect biodiversity. In 2010, the CBD imposed a moratorium on geoengineering activities until there is an adequate scientific basis for their deployment. The moratorium aimed to provide an opportunity to assess the positive and negative impacts of CDR and SRM on biodiversity based on the effectiveness and feasibility of geoengineering technologies.[56] However, the CBD does not provide criteria for determining whether an "adequate scientific basis" has been achieved, thereby making it difficult to identify when the moratorium can be lifted.[57] It does permit small-scale scientific research studies conducted in a controlled setting.[58] Moreover, despite the moratorium, the CBD lacks an enforcement mechanism.
- **London Convention and London Protocol (LC/LP):** Since 2013, amendments to the LC/LP have prohibited the "placement of matter into the sea from vessels, aircraft, platforms, or other manmade structures at sea for marine geoengineering activities," but this prohibition is nonbinding and only applies to marine geoengineering activities.[59] Even so, according to one expert, the LC/LP could serve as a "very early stage governance framework" for geoengineering,

despite the LP currently having only 53 state parties. Another expert noted that marine cloud brightening would "certainly be implicated."[b]

Table 3 provides additional details regarding enforcement, review, and implementation mechanisms and the signatories of these agreements.

In addition to these international agreements, several international organizations, including the IPCC and the UN Environmental Program, have begun to consider the implications of geoengineering. As the deployment of geoengineering becomes a reality, these organizations may serve as a starting point for the management of any resulting tensions.

Proposed New International Governance Frameworks

Currently, there is no single international institution or treaty that can provide effective governance of the full range of geoengineering activities. Some legal experts have called for the development of a new international agreement dedicated to geoengineering, with one legal scholar noting that international law must "catch up" with the maturing capabilities of geoengineering technologies before a "geoengineered catastrophe" occurs.[60]

Existing international agreements and bodies of law may provide a useful model for the development of new governance frameworks for geoengineering. Several existing bodies of law, such as outer space law and the law of the sea, provide templates for delineating international responsibility in the global commons. The Convention on International Liability for Damage Caused by Space Objects, for example, governs international responsibility for damages arising from the launch of space objects.[61] The Space Liability Convention, as it is commonly known, permits claims to be brought by states against other states, and its signatories include a majority of countries.[62] Although issues of causation, and the subsequent apportionment of liability, may be less clear for damage arising out of geoengineering, the Space Liability Convention may provide policymakers with a jumping-off point for future geoengineering governance. The law of the sea may provide another template for geoengineering governance. The UN Convention on the Law of the Sea (UNCLOS), whose signatories include a significant majority of countries, provides a comprehensive governance mechanism for marine and maritime issues.[63] UNCLOS also mandated the creation of the International Tribunal for the Law of the Sea, an independent judicial body that adjudicates disputes related to the use of the world's oceans.[69] The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), part of the Antarctic Treaty System, provides another model for geoengineering governance. Although CCAMLR has relatively few members, it has been successful in establishing protected marine areas and monitoring the effect of fishing and other marine activities in and near Antarctica.[70]

Although these existing mechanisms for regulating the global commons can serve as a starting point, the ultimate success of geoengineering governance will depend

[b] At the same time, if, for example, Australia conducts marine cloud brightening to save the Great Barrier Reef, there may be regional effects instead of global ones. As a result, regional governance mechanisms may be implicated.

Table 3. International Legal Mechanisms

Instrument	Relevant Features	United States	India	Russia	China
ENMOD[64]	Consultative Committee of Experts, chaired by UN Secretary General; Period Conference of State Parties Review conferences	Ratified January 17, 1980	Ratified December 15, 1978	Ratified (as Soviet Union) May 30, 1978	Accessed June 8, 2005
Montreal Protocol[65]	Meeting of the Parties, a governance body with a working group for technical support, meet annually; Multilateral Fund provides financial and technical assistance	Ratified April 21, 1988	Accepted November 10, 1988	Accessed June 19, 1992	Accessed March 26, 1990
UNFCCC[66]	Conference of the State Parties meets annually to assess progress; UNFCCC Secretariat established to support the Convention's work	Ratified October 15, 1992	Ratified November 1, 1993	Ratified December 28, 1994	Ratified January 5, 1993
CBD[67]	Conference of the Parties reviews progress, supported by CBD Secretariat, which has two subsidiaries that provide advice on technical matters and implementation	Signed June 4, 1993 but has not ratified	Ratified February 18, 1994	Ratified April 5, 1995	Ratified January 5, 1993
LC/LP[68]	Convention work is supported by Permanent Secretariat, which is hosted by the International Maritime Organization; member parties meet periodically for consultative meetings; Joint Group of Experts on Scientific Aspects of Marine Environmental Protection support consultative meetings	Ratified August 30, 1975	Has not signed or ratified	Excluded February 20, 1994	Applied July 1, 1997

NOTE: *Ratification* refers to consent to be bound as state party, giving domestic legal effect to the treaty. *Accession* means that ratification occurred after the treaty entered into force. *Acceptance* has the same legal effect as ratification but indicates that the country's domestic law does not require that the treaty be ratified by the head of state. *Signed* means that a country has indicated their willingness to be bound to the treaty but is not a state party. *Application* refers to a provisional application that shows a state's intent to be bound once domestic ratification procedures are complete. *Exclusion* indicates nonacceptance of certain convention provisions or amendments.

in large part on the willingness of powerful states to work together toward a common goal. The existing balance of power in the international system—and, in particular, the composition of the UN Security Council—will make it difficult for less powerful states and the very groups that are most vulnerable to the effects of climate change to influence the trajectory of future geoengineering governance. One policy option available to the United States and other powerful states is to exercise moral leadership and advocate on behalf of those states and groups that have less sway in the international system.

Other Geoengineering Governance Options

Short of a comprehensive geoengineering governance mechanism, as geoengineering technologies mature and the prospect of deployment becomes a reality, the international community can begin to develop tools to collectively address the environmental and geopolitical consequences of geoengineering activities. There are several potential tools for regulating and managing the secondary effects of geoengineering.[71] We note, however, that these governance tools may be more effective if they are individualized to address the unique risks posed by each type of geoengineering technology.

- **International governance of geoengineering research:** The establishment of a mechanism for international governance of geoengineering research activities may represent a stepping-stone toward broader international cooperation on geoengineering governance. Because geoengineering research carries less risk of negative secondary effects, it may be easier for the international community to develop guidelines for research, testing, and small-scale deployment of geoengineering technologies. As geoengineering technologies mature, these agreed-upon guidelines could provide a starting point for the negotiation of broader geoengineering governance mechanisms.
- **International consensus on procedural norms:** The development of agreed-upon procedures related to notification, transparency, and verification of geoengineering activities represents another potential stepping-stone toward broader geoengineering governance. Experts regard achieving an international consensus on procedural issues as more feasible in the short term. Although international consensus on procedural matters will not fully address the range of potential geopolitical consequences of geoengineering, the process of developing workable procedures related to geoengineering activities can kickstart the conversation.
- **Domestic geoengineering legislation:** Until consensus on the development of a comprehensive international governance mechanism is reached, domestic legislation may effectively manage at least some of the consequences of geoengineering activities. The international community can take steps to encourage the enactment of domestic geoengineering legislation.

Policy Implications

Policymakers and researchers should take preparatory steps to bridge the gap between maturing geoengineering technologies and available governance mechanisms before a geoengineering crisis occurs. Our analyses reveal fundamental differences in the alternative geoengineering technologies, their role in managing potential risks, and their readiness for deployment at a scale that would require additional research and study. In addition, gaps remain in the governance of geoengineering technologies and policies. Accordingly, we recommend the following courses of action.

Enhance understanding among researchers and decisionmakers regarding the actual rate of innovation, investment, and deployment of different geoengineering technologies by working with researchers and commercial industries to elucidate technology pathways. Characterizing technology pathways for specific geoengineering technologies; the key barriers to their deployment, including cost, impact and effectiveness; and their readiness for deployment will enable decisionmakers to better anticipate the potential risks associated with each technology. This requires analyzing both supply-side and demand-side considerations for various geoengineering technologies through research and geoengineering field tests and private enterprise.[72] Opposition to technology deployment could stifle innovation and impede the realization of both the benefits and the externalities of various geoengineering technologies.

Enhance understanding of the costs and benefits of different geoengineering technologies by assessing their potential biophysical consequences—and benefits—individually and then in technology portfolios. Enhancing understanding of the environmental impact, risks, and positive externalities of deploying different geoengineering technologies could assist in prioritizing future investments and establishing appropriate rules and norms for technology deployment.

Enhance understanding among policymakers and researchers regarding the geopolitical risks associated with different biophysical consequences of geoengineering by investing in integrated, future studies of technology outcomes. This could include identifying which nations or regions have the most to gain or lose from large-scale deployment of geoengineering; which nations and states pose the greatest risk of deploying harmful geoengineering technologies, such as rogue nations or countries that strategically compete with the United States; and how such technologies may ameliorate or exacerbate existing tensions regionally and globally. This evaluation could also encompass identifying environmental, social, and political management challenges.

Determine the extent to which existing international governance mechanisms are applicable to different geoengineering activities, as well as the appropriate scope and contents of a comprehensive international governance framework for geoengineering through a more rigorous and comprehensive gap analysis. Further research and analysis on the effective implementation of geoengineering governance framework is needed once model frameworks are drafted, including recommendations on enforcement, review, and compliance mechanisms and the cost-benefit analysis of robust international cooperation on the development and deployment of geoengineering technologies. It may be useful to consider whether a single governance framework can accommodate the full range of geoengineering activities or whether, as we anticipate, separate governance mechanisms will be needed for CDR and SRM.

Exploit different systems-based and decision analytic processes to gain insights into the complexities of geoengineering technologies. Given the complexities of rapidly changing technology and geopolitical landscapes, enhancing the toolkit of methods that decisionmakers and researchers could use to gain insights can accelerate risk management and governance. For example, developing and exploring a range of climate, technology, and geopolitical scenarios can help identify key opportunities, vulnerabilities, and contingencies in the governance of geoengineering. In addition, such tools as simulation and tabletop exercises could help model the likely geopolitical consequences of geoengineering, as well as the decisionmaking processes of individual states in the international system in the event of a geoengineering crisis. This approach would shed light on the intricate geopolitical dynamics associated with more widespread deployment of geoengineering technologies and highlight potential pitfalls to be avoided in the development of geoengineering governance mechanisms.

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About This Perspective

The prospect of using geogengineering to address the accelerating effects of climate change is becoming more and more likely, and many of the potential technologies have negative externalities on the global to regional scale. In this Perspective, we review the state of different geoengineering technologies, highlighting differences in technological development stage, price, time scales, and potential secondary effects. We then discuss the geopolitical risks that may be introduced by geoengineering implementation. Given the many serious risks that geoengineering poses, we conclude by examining whether existing international governance mechanisms manage the geopolitical risks associated with geoengineering.

This Perspective draws on a review of the relevant technical, international relations, and international law literature, as well as a scenario-development workshop in which 24 academic research experts on climate policy, international relations, and international law considered the geopolitical risks of geoengineering and the role of international legal mechanisms in the management of these geopolitical risks. The workshop was conducted virtually in two three-hour sessions over two days. This Perspective and the recommendations contained herein should be of interest to decisionmakers and policymakers in the area of climate risk management.

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