Title
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Publication Date
2012-10-05

Peer reviewed

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Continued failure to limit emissions of carbon dioxide and other greenhouse gases that are causing global climate change has brought increased attention to climate engineering (CE) technologies, which actively modify the global environment to counteract heating and climate disruptions caused by elevated greenhouse gases. Some proposed forms of CE, particularly spraying reflective particles in the upper atmosphere to reduce incoming sunlight, can cool the average temperature of the Earth rapidly and cheaply, thereby substantially reducing climate-related risks. Yet CE interventions provide only imperfect corrections for the climatic and other environmental effects of elevated greenhouse gases, and carry their own environmental risks. Moreover, they may also increase risks, by weakening political support for essential emission reductions or providing new triggers for international conflict. These technologies thus require international governance, but also pose novel and severe challenges to current international laws and institutions. Effective governance of CE will require a capacity to make decisions regarding the conditions, if any, under which specific interventions are authorized, plus real-time operational oversight of any interventions that are conducted. Decision processes must be effectively linked with scientific research and assessment, and with institutions to manage and respond to threats of CE-related conflict. We advance preliminary suggestions to address two priority areas for early investigation: how international cooperation on early CE research can help develop shared norms that can grow robust enough to support future decision needs; and how early research and development on CE can be made to complement and encourage, rather than undermining, parallel efforts to reduce climate risks by cutting emissions.

I. INTRODUCTION: THE OPPORTUNITY AND CHALLENGE OF CLIMATE ENGINEERING

There is a large and growing gulf between the gravity of threats posed by climate change and the seriousness with which the issue is being addressed. Politically motivated attacks on climate science and scientists notwithstanding,[1] evidence continues to mount of rapid climate changes underway, their predominant cause in human emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs), the likelihood of more extreme changes over coming decades, and the potential of serious and disruptive impacts — many already observable.[2] Yet as the Kyoto Protocol's

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[1] *See, e.g.*, NAOMI ORESKES & ERIC M. CONWAY, MERCHANTS OF DOUBT 169-215 (2010) (criticizing pseudo-scientific attempts to deny global warming).

[2] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), CLIMATE CHANGE 2007: IMPACTS, ADAPTATION AND VULNERABILITY (M.L. Perry et al. eds., 2007) [hereinafter IPCC, IMPACTS]; INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS (S.D. Solomon et al. eds., 2007) [hereinafter IPCC, SCIENCE]; INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), CLIMATE CHANGE 2007: SYNTHESIS REPORT (2007); U.S. NAT'L RESEARCH COUNCIL (NRC), AMERICA'S CLIMATE CHOICES: PANEL ON ADAPTING TO THE IMPACTS OF

"first commitment period" concludes in 2012,[3] industrialized nations have failed to achieve even the modest emission targets in this treaty, while continuing negotiations have achieved no progress on longer-term emission cuts. At the domestic level, proposed emission controls have been delayed or weakened in every national jurisdiction, while global emissions — far from turning the corner to steep declines as required — continue to rise faster than projected.[4]

The slow dynamics of the climate system, whereby even large changes in current emissions would take decades to significantly slow climate change, both magnify the long-term risks of current inaction and exacerbate the political obstacles to serious efforts because such efforts mainly impose near-term costs for future benefits.[5] At the same time, uncertainties in the quantitative sensitivity of climate to GHGs, and in the response of key climate impacts, provide rhetorical tools to support inaction or delay and imply that even rapid adoption of steep emissions cuts would not eliminate (although it would of course reduce) risks of severe climate-change impacts.[6] Human society thus faces serious climate-change risks of two distinct origins — continued failure to act on global emissions or bad luck in how key uncertainties resolve — or any combination of the two.[7]

In this context, the past five years have seen a sharp increase in attention to climate engineering (CE) technologies. These are engineered interventions to modify global-scale properties of the Earth's environment, with the aim of counteracting the

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CLIMATE CHANGE (2010); U.S. NAT'L RESEARCH COUNCIL (NRC), AMERICA'S CLIMATE CHOICES: PANEL ON ADVANCING THE SCIENCE OF CLIMATE CHANGE (2010) [hereinafter NRC, SCIENCE].

[3] Kyoto Protocol to the United Nations Framework Convention on Climate Change, Dec. 11, 1997, 2303 U.N.T.S. 162, *available at* http://unfccc.int/resource/docs/convkp/kpeng.pdf.

[4] ANDREW E. DESSLER & EDWARD A. PARSON, THE SCIENCE AND POLITICS OF CLIMATE CHANGE 28-29 (2d ed. 2010); DAVID G. VICTOR, GLOBAL WARMING GRIDLOCK (2011); Corinne Le Quéré et al., *Trends in the Sources and Sinks of Carbon Dioxide*, 2 NATURE GEOSCIENCE 831 (2009). Note that there are a few more promising signs of action at the sub-national level, most notably in California's comprehensive greenhouse-gas regulations enacted in October 2011. CAL. CODE REGS. tit. 17, §§ 95800-96023 (2011).

[5] The significance of long lags in the physical climate system is discussed by T.M.L. Wigley, *The Climate Change Commitment*, 307 SCI. 1766, 1766 (2005), and William Daniel Davis, Note, *What Does "Green" Mean? Anthropogenic Climate Change, Geoengineering, and International Environmental Law*, 43 GA. L. REV. 901, 901 (2009). For discussions of the resultant challenges to decision-making, see, for example, Eric Biber, *Climate Change and Backlash*, 17 N.Y.U. L. REV. 1295 (2009); Mark Squillace, *Climate Change and Institutional Competence*, 41 U. TOL. L. REV. 889, 889-91 (2010); and Arild Underdal, *Complexity and Challenges of Long-Term Environmental Governance*, 20 GLOBAL ENVTL. CHANGE 386, 387-88 (2010).

[6] *See, e.g.*, IPCC, IMPACTS, *supra* note 2; IPCC, SCIENCE, *supra* note 2; NRC, SCIENCE, *supra* note 2.

[7] David W. Keith, Edward A. Parson & M. Granger Morgan, *Research on Global Sun Block Needed Now*, 463 NATURE 426 (2010).

heating and climate disruptions caused by elevated GHGs.[8] These are not new ideas. They were discussed as potential responses to human-caused climate change in the 1960s and 1970s,[9] but faded from prominence as the climate issue came onto policy agendas in the late 1980s.[10] CE began to gather renewed attention after 2000,[11] and has seen sustained high interest over the past five years.

With this surge of attention has come a surge of controversy. CE elicits strong reactions, and the resurgence of interest in it has seen extreme assessments, both positive and negative.[12] These wide-ranging reactions reflect the widely varying effects CE can have on climate-change risk. If used appropriately, it can substantially reduce climate-related risks, whether these come from continued high emissions or

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[8] *See, e.g.*, ASILOMAR SCIENTIFIC ORGANIZING COMM., ASILOMAR CONFERENCE RECOMMENDATIONS ON PRINCIPLES FOR RESEARCH INTO CLIMATE ENGINEERING TECHNIQUES (2010) [hereinafter ASILOMAR, RECOMMENDATIONS]; *Solar Radiation Management*, *in* NRC, SCIENCE, *supra* note 2, at 377-88; ROYAL SOC'Y, GEOENGINEERING THE CLIMATE: SCIENCE, GOVERNANCE, AND UNCERTAINTY (2009); TASK FORCE ON CLIMATE REMEDIATION RESEARCH, BIPARTISAN POL'Y CTR., GEOENGINEERING: A NATIONAL STRATEGIC PLAN FOR RESEARCH ON THE POTENTIAL EFFECTIVENESS, FEASIBILITY, AND CONSEQUENCES OF CLIMATE REMEDIATION TECHNOLOGIES (2011).

[9] See, for example, the discussions of engineered responses to anthropogenic climate change in ENVTL. POLLUTION PANEL, PRESIDENT'S SCI. ADVISORY COUNCIL, RESTORING THE QUALITY OF OUR ENVIRONMENT (1965); and MIKHAIL I. BUDYKO, CLIMATE AND LIFE (David H. Miller ed., Academic Press 1974). For an excellent historical account of early discussions of these technologies in the context of parallel efforts in small-scale weather modification, see JAMES RODGER FLEMING, FIXING THE SKY (2012).

[10] *See, e.g.*, U.S. NAT'L RESEARCH COUNCIL, POLICY IMPLICATIONS OF GREENHOUSE WARMING: MITIGATION, ADAPTATION, AND THE SCIENCE BASE (1992); David W. Keith, *Geoengineering the Climate: History and Prospect*, 25 ANN. REV. ENERGY & ENV'T 245 (2000); Thomas C. Schelling, *Climatic Change: Implications for Welfare and Policy*, *in* U.S. NAT'L RESEARCH COUNCIL, CHANGING CLIMATE 449 (1983).

[11] Although many scientists expressed reluctance even to discuss the approach, a 2006 essay by the distinguished atmospheric scientist Paul Crutzen is widely credited with re-establishing the respectability of doing so. Paul J. Crutzen, *Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?*, 77 CLIMATIC CHANGE 211 (2006). See also the commentary in the same journal issue, including Ralph J. Cicerone, *Geoengineering: Encouraging Research and Overseeing Implementation*, 77 CLIMATIC CHANGE 221, 221 (2006); Jeffrey T. Kiehl, *Geoengineering Climate Change: Treating the Symptom over the Cause?*, 77 CLIMATIC CHANGE 227, 228 (2006); and Mark G. Lawrence, *The Geoengineering Dilemma: To Speak or Not to Speak*, 77 CLIMATIC CHANGE 245, 245-47 (2006). For earlier discussions of the same dilemma, see Daniel Bodansky, *May We Engineer the Climate*, 33 CLIMATIC CHANGE 309 (1996); and Stephen H. Schneider, *Geoengineering: Could — Or Should — We Do It?*, 33 CLIMATIC CHANGE 291, 291 (1996).

[12] For examples of favorable extremes, see EDWARD TELLER, RODERICK HYDE & LOWELL WOOD, UNIV. OF CAL. LAWRENCE LIVERMORE NAT'L LAB., ACTIVE CLIMATE STABILIZATION: PRACTICAL PHYSICS-BASED APPROACHES TO PREVENTION OF CLIMATE CHANGE (2002); and STEVEN D. LEVITT & STEPHEN J. DUBNER, SUPERFREAKONOMICS 235-300 (HarperLuxe 2011) (2009). For examples of unfavorable extremes, see ETC GRP., The EMPEROR'S NEW CLIMATE: GEOENGINEERING AS 21ST CENTURY FAIRYTALE 6 (2009), *available at* http://www.etcgroup.org/upload/publication/pdf_file/etcspecialreport_rsgeoeng28aug09.pdf; and Clive Hamilton, *The Clique that Is Trying to Frame the Global Geoengineering Debate*, GUARDIAN, Dec. 5, 2011, http://www.guardian.co.uk/environment/2011/dec/05/clique-geoengineering-debate. More measured assessments are in ASILOMAR, RECOMMENDATIONS, *supra* note 8; ROYAL SOC'Y, *supra* note 8; Jason Blackstock & Jane Long, *The Politics of Geoengineering*, 327 SCI. 527, 527 (2010); and Keith, Parson & Morgan, *supra* note 7.

high sensitivity in climate or impacts. But they also pose their own serious risks — from direct environmental harms, improper use, or destructive interactions with other aspects of climate-change management or international relations — which have led some observers to deem it dangerous hubris to consider ever using them, to develop them, or even to do research on them.

This acute tension between CE's potential to either reduce or exacerbate climate-related risks depending on how it is used leads directly to questions of law and governance: How can these interventions be studied, assessed, developed, and — if necessary — used, to achieve the benefits and avoid the harms? The clear importance of this question has generated a surge of interest and a recent literature on the implications of CE for law and governance. Although some of this literature has considered domestic law and governance,[13] the main focus of interest and concern is at the international level, due to the global scale of effects of both climate change and potential CE interventions.

The aims of this Article are to (1) review the main points in this new literature on international law and governance of CE and highlight key areas where it has thus far failed to address the key legal, institutional, and political challenges posed by these technologies; (2) provide a more specific characterization of attributes of CE interventions of likely legal and governance significance; and (3) identify key questions and challenges that must be addressed in the near term to limit risks posed by CE technologies. Part II introduces the major CE technologies being considered and identifies the prominent characteristics that shape their governance challenges. Part III summarizes the current literature on CE governance and identifies its major gaps and limitations. Part IV characterizes the nature of the governance needs posed by CE, arguing that they include three distinct functions — related to regulatory and operational decision-making, scientific research and assessment, and management of security threats — that must be addressed and effectively integrated. Part V characterizes the nature and severity of the challenges these functional needs imply for international law and governance. Part VI concludes by outlining two areas for high-priority near-term research and analysis.

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[13] *See, e.g.*, KELSI BRACMORT, RICHARD K. LATTANZIO & EMILY C. BARBOUR, CONG. RESEARCH SERV., GEOENGINEERING: GOVERNANCE AND TECHNOLOGY POLICY (2011).

II. CLIMATE ENGINEERING TECHNOLOGIES

Proposed climate engineering interventions fall into two classes. The distinctions between these, which arise from their primary modes of operation, have far-reaching consequences both for their potential contributions to reducing climate-change risks and for the challenges they pose to international law and governance.[14] In this Part, we briefly describe and distinguish the two classes, and then turn our focus to those interventions that offer the greatest potential impacts – both positive and negative – at the lowest relative cost, and thus create the most acute governance needs.

A. — Managing Carbon vs. Managing Sunlight: the Importance of High Leverage

The first class of CE technologies intervenes in the global carbon cycle to remove CO_2 from the atmosphere, offsetting the elevated concentrations from burning carbon-based fuels. The second intervenes in the radiation balance of the Earth to reduce absorption of sunlight at the Earth's surface, offsetting the heating caused by atmospheric GHGs when they absorb outgoing infrared radiation and thus impede the Earth's ability to cool by radiating energy to space.

Many specific proposals have been advanced within each class, ranging from the small-scale and familiar to the exotic and high-tech. Proposals to increase CO_2 removal include increasing ocean carbon uptake by fertilizing plankton, increasing land carbon uptake by planting forests, changing land management, introducing modified species that retain more carbon, or removing CO_2 chemically from the air in engineered structures resembling large screens or power-plant cooling towers.[15] Proposals to reduce absorption of sunlight include placing reflective screens in space to shade a little of the Sun's disc; making the Earth's surface whiter through modified building materials or crops, or spreading light-colored material over the land or ocean surface; making more or whiter marine clouds by spraying sea water or other

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[14] Early discussions of these technologies have been marked by substantial confusion and unnecessary conflict over terminology. While most contributions have denoted the technologies at issue by the historical term "geoengineering," we adopt the alternative "climate engineering," because it clarifies that the objective is management of climate. While several contributions have argued over which specific interventions should be called geoengineering (or climate engineering in our usage), we find these debates unfruitful and prefer to be explicit regarding the specific characteristics or criteria on the basis of which we include or exclude specific technologies from our scope.

[15] Similar chemical processes can be used to remove CO_2 from combustion gases in smokestacks. Carbon dioxide removed by any such chemical process, whether from smokestacks or the free atmosphere, must be put somewhere. The leading candidates are to store the CO_2 underground, e.g., in deep salty aquifers or depleted oil and gas reservoirs, or to react it with sedimentary rock in a process that accelerates natural weathering. *See, e.g.*, Klaus S. Lackner, *Carbonate Chemistry for Sequestering Fossil Carbon*, 27 ANN. REV. ENERGY & ENV'T 193 (2002); E.A. Parson & D.W. Keith, *Fossil Fuels Without CO_2 Emissions*, 282 SCI. 1053 (1998); Jennie C. Stephens & David W. Keith, *Assessing Geochemical Carbon Management*, 90 CLIMATIC CHANGE 217 (2008).

condensation nuclei into the lower atmosphere; or increasing the reflectivity of the atmosphere by spraying fine, light-colored particles into the stratosphere.

Although these proposed interventions differ on multiple dimensions, the characteristic of greatest importance in determining their potential contributions to managing climate change and their associated risks is their leverage: the ability to exert large influence over global climate from relatively small inputs. Leverage varies widely among the approaches identified above, broadly distinguishing carbon-cycle approaches from solar-radiation approaches. All presently-identified carbon-cycle interventions have low leverage: i.e., using them to achieve a discernible impact on global climate would require intense efforts, processing large volumes of material, over large spatial areas and sustained for decades.[16] Consequently, while these approaches may offer valuable contributions to managing climate change, they do so in a way that resembles known approaches to reducing emissions and poses similar governance challenges: motivating costly efforts toward a globally shared risk-management goal, coordinating efforts to limit aggregate costs, monitoring performance and results to learn how to do it well, and building confidence that costly efforts are being reciprocated. These are the challenges of climate and other global environmental problems that scholars and practitioners have recognized for decades, which current policies and institutions seek to address, however ineffectively.

In contrast, some radiation-based methods offer extremely high leverage. The approach now receiving most attention, stratospheric injection of sulfur, illustrates the extreme leverage involved. Under suitable conditions, sulfur particles sprayed in the stratosphere can form a fine mist of aerosols that reflect incoming sunlight, thereby reducing the solar energy absorbed at the Earth's surface. In practical terms, these aerosols would make the sky whiter and the Earth a little brighter when viewed from space. Because particles' average residence time in the stratosphere ranges from a few months to a few years, a small injection rate can maintain a large stock and thus a large reflective effect. Preliminary calculations suggest the reflective effect of these

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[16] J. ERIC BICKEL & LEE LANE, COPENHAGEN CONSENSUS CTR., AN ANALYSIS OF CLIMATE ENGINEERING AS A RESPONSE TO CLIMATE CHANGE (2009); M. GRANGER MORGAN & KATHARINE RICKE, INT'L RISK GOVERNANCE COUNCIL, COOLING THE EARTH THROUGH SOLAR RADIATION MANAGEMENT (2010).

particles is so strong that five to ten grams of sulfur, suitably dispersed in very fine particles, can offset the heating effect of a ton of CO_2 in the atmosphere.[17]

Other stratospheric approaches using advanced materials or distribution methods — perhaps with engineered particles that stay aloft longer, reflect more strongly, or are controllable — may give even higher leverage.[18] But sulfur provides a demonstration that these approaches can work, even with present knowledge and methods. Sulfur injection also raises clearly the governance challenges that will be posed by any high-leverage, radiation-based CE method, even if more advanced future methods may pose these challenges even more sharply. We thus take it as the exemplar of high-leverage CE technologies throughout our discussion of law and governance needs.

B. High-Leverage CE Technologies: Fast, Cheap, and Imperfect

High-leverage CE approaches such as stratospheric sulfur injection have three prominent characteristics, all related to their high leverage. These characteristics powerfully shape the contributions CE technologies can make to managing climate change, the risks they pose, and thus the nature of the governance challenges they present. These technologies are fast, cheap, and imperfect.[19]

These approaches can cool the global climate rapidly. The occasional volcanic eruptions that inject large plumes of material into the stratosphere provide a natural illustration of the speed of effect. The 1991 eruption of Mt. Pinatubo in the Philippines emitted 20,000,000 tons of Sulfur dioxide, which caused a global cooling of about half a degree Celsius that appeared within six months and lasted about two years.[20] Readily manageable levels of effort to replicate this effect could achieve significant global cooling, of similar or larger magnitude, within a few months to a year or two.

These interventions are also cheap, again a result of high leverage. Initial analyses suggest the cost of fully offsetting projected heating this century might range

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[17] ROYAL SOCIETY, *supra* note 8, at 31; Phillip J. Rasch et al., *An Overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols*, 366 PHIL. TRANSACTIONS ROYAL SOC'Y A 4007 (2008).
[18] David W. Keith, *Photophoretic Levitation of Engineered Aerosols for Geoengineering*, 107 PROC. NAT'L ACAD. SCI. 16428 (2010).
[19] *See* Keith, Parson & Morgan, *supra* note 7, at 426; *see also* ROBERT J. LEMPERT & DON PROSNITZ, RAND CORP., GOVERNING GEOENGINEERING RESEARCH: A POLITICAL AND TECHNICAL VULNERABILITY ANALYSIS OF POTENTIAL NEAR-TERM OPTIONS 3 (2011).
[20] Brian J. Soden et al., *Global Cooling After the Eruption of Mt. Pinatubo: A Test of Climate Feedback by Water Vapor*, 296 SCI. 727 (2002).

from order $100,000,000 to $1,000,000,000 per year — i.e., from about two one-millionths (0.0002%) to two one-thousandths (0.2%) of the global economy, or roughly one thousand times less than the estimated cost of achieving the same result by cutting emissions.[21] Indeed, some writers have suggested that to understand the strategic implications of CE technologies, it is a useful approximation to think of their direct cost as zero.[22]

But there is a catch, and it is a big one. These interventions are highly imperfect correctives to the climatic and other environmental effects of elevated GHGs. This is not just a matter of their direct environmental risks, although these are real and cannot be ignored. Early assessments suggest that the identified risks from stratospheric sulfur injection — mainly increases in stratospheric ozone loss and acid deposition[23] — are moderate in magnitude and potentially ameliorable by fine-tuning approaches. These results are not yet confidently established, and require careful further investigation and risk assessment — but on present knowledge, they suggest that direct environmental effects will likely be the least serious of the CE's imperfections.

The more prominent imperfections of CE approaches are the multiple ways they fail to precisely undo the environmental disruptions caused by elevated GHGs. In part, these limitations arise from offsetting a heating that occurs in the atmosphere, where GHGs impede the Earth's ability to cool by emitting infrared radiation, with a cooling at the surface, where the sunlight reflected by CE would otherwise have been

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[21] *See, e.g.*, AURORA FLIGHT SCIENCES, GEOENGINEERING COST ANALYSIS: FINAL REPORT (2011); MORGAN & RICKE, *supra* note 16; Alan Robock et al., *Benefits, Risks, and Costs of Stratospheric Geoengineering*, 36 GEOPHYSICAL RES. LETTERS L19703 (2009).

[22] *See, e.g.*, Scott Barrett, *The Incredible Economics of Geoengineering*, 39 ENVTL. & RESOURCE ECON. 45 (2008); Keith, *supra* note 10, at 272; David W. Keith & Hati Dowlatabadi, *A Serious Look at Geoengineering*, 73 EOS 289 (1992). Note that while some writers have disputed this claim, they all — with one exception — mean the direct costs of CE are not all that matter, and that a complete cost accounting must include the societal costs of its external harms, risks, and imperfections, which may be large. *See, e.g.*, ETC GROUP, *supra* note 12; Bidisha Banerjee, *The Limitations of Geoengineering Governance in a World of Uncertainty*, 4 STAN. J.L. SCI. & POL'Y 15, 27 (2011); Marla Goes, Nancy Tuana & Klaus Keller, *The Economics (Or Lack Thereof) of Aerosol Geoengineering*, 109 CLIMATIC CHANGE 791 (2011). We agree with these commentators on the importance of considering all external costs, but regard it as important to consider the low direct, internal cost separately, precisely because the ease and low cost of CE to the implementer is a primary determinant of the associated governance challenges. The one exception is David G. Victor, *On the Regulation of Geoengineering*, 24 OXFORD REV. OF ECON. POL'Y 322, 327 (2008), who speculates that a likely response to the imperfections of simple CE interventions will be to develop multi-intervention "cocktails" that aim to correct or mitigate these imperfections, analogous to the multi-drug cocktails developed to treat HIV infection. Such a multi-faceted approach would, presumably, carry significantly higher direct costs.

[23] *See, e.g.*, Crutzen, *supra* note 11; S. Tilmes et al., *Impact of Geoengineered Aerosols on the Troposphere and Stratosphere*, 114 J. GEOPHYSICAL RES. D12305 (2009).

absorbed. Because the CE intervention makes a change to global climate that is not precisely the reverse of the one it seeks to offset, it does not restore the original climate. Even considering only global averages, CE controls precipitation more strongly, relative to its effect on temperature, than GHGs do.[24] Using CE to precisely reverse the global-average heating caused by elevated GHGs would thus produce a global climate drier than the starting point. Consequently, even when only two dimensions of climate are considered, global-average temperature and precipitation, CE's ability to restore these is constrained. With this basic constraint on controllability even in global averages, there will be many additional divergences in regional and seasonal effects, but assessing these in detail requires climate model studies of the joint effects of elevated GHGs and specific CE interventions. These studies are at a preliminary stage, but some early investigations have suggested the possibility of many such divergences, including potential disruption of important processes such as the South Asian Monsoon.[25]

Additional limitations arise from the fact that CE does nothing to reduce CO_2 levels. Elevated atmospheric CO_2 does not just change radiation and climate, but has other environmental effects as well. CO_2 is taken up in the surface oceans, where it forms carbonic acid and makes oceans more acidic. Ocean acidity obstructs the formation of carbonates, which are crucial components of coral reefs and the shells of many marine organisms.[26] Elevated CO_2 also has direct effects on ecosystems, mainly through altering competitive relationships among plants using different photosynthetic processes, which differ in their ability to take up and use CO_2. Because CE measures target only the radiative and climate effects of GHGs, they would do nothing to offset any of these chemical or biological effects, which would continue unabated as long as atmospheric CO_2 continued to rise.

These three characteristics — rapidity, low cost, and imperfection — are of course simplifications, and uncertain in their specifics. Further research will expand knowledge of specific approaches' costs, effects, and risks, in global and regional climate and other dimensions. Further research may also identify ways to tune or combine currently known methods or new ones to limit their imperfections and

[24] G. Bala, P.B. Duffy & K.E. Taylor, *Impact of Geoengineering Schemes on the Global Hydrological Cycle*, 105 PROC. NAT'L ACAD. SCI. 7664 (2009).

[25] Alan Robock, Luke Oman & Georgiy L. Stenchikov, *Regional Climate Responses to Geoengineering with Tropical and Arctic SO_2 Injections*, 113 J. GEOPHYSICAL RES. D16101 (2008).

[26] Scott C. Doney et al., *Ocean Acidification: The Other CO_2 Problem*, 1 ANN. REV. MARINE SCI. 169 (2009).

harms,[27] or may identify more severe harms than are currently recognized. But the broad characterization of these approaches as fast, cheap, and imperfect is likely to be robust to further scientific and technological progress, because it is rooted in basic atmospheric processes and the foundations of how the approaches gain their high leverage. For the next several decades, the relevant time-scale to resolve the looming crisis of climate change, it is thus highly likely that any available CE approaches will remain fast-acting, low in direct cost, and imperfect in their correction for the environmental effects of GHGs, and thus that any legal or governance response to these technologies must address these characteristics.

C. Implications for Governance: The Climate Engineering Dilemma

These three characteristics both create the need for CE governance and define the broad outlines of that need. Most fundamentally, these characteristics create an acute tension between reasons to pursue, and reasons to avoid, development of CE capability. On the one hand, the availability and appropriate use of CE can bring large reductions in climate-related risks. The most widely proposed way they can achieve this, as suggested above, arises from their ability to cool the Earth rapidly, and thus to ameliorate some severe climate changes even once they are underway or imminent. This capability for rapid, albeit imperfect, action is unique to high-leverage CE interventions, and represents a large potential to reduce climate-change risks. Thus, to limit or prohibit research, assessment, and development of CE capability based on fear of its potential negative impacts would mean that in some future panic over severe climate impacts underway — a possibility even under extreme emission cuts — the only response available would be a crash deployment of unrefined and untested CE approaches, with little knowledge of their effects and risks and little foundation for effective, legitimate, and efficient decision-making.

While such emergency response is the most widely proposed model for beneficial use of CE, others have also been proposed. Even absent any climate emergency, CE can be used as part of a low-cost inter-temporal climate response by deploying it incrementally to shave the near-term peak of global heating that would occur this century even with aggressive emission cuts. Such an incremental deployment, phased in then out over a century or so, could reduce near-term climate disruption and associated risks, thereby buying time and allowing emissions cuts and

[27] Victor, *supra* note 22; *see also* Davis, *supra* note 5, at 943.

adaptation measures to be made in an orderly program of technology deployment and capital turnover, at much lower cost and disruption than under more rapid deployment.[28] Still other models for beneficial use of CE have proposed regional-scale deployments where precisely targeted interventions could reduce specific identified risks — for example, by injecting reflective aerosols only at high latitudes in summer, where interactions between melting of ice and snow and increasing absorption of sunlight are already driving rapid heating; or by targeting sunlight reduction over tropical ocean regions where elevated sea-surface temperatures pose risks from increasing intensity of tropical storms.[29]

On the other hand, there are multiple ways that the availability, development, or potential deployment of CE interventions can make climate-related risks worse. We have already noted CE's potential for direct environmental harms and its imperfect compensation for the environmental disruptions caused by elevated GHGs. CE also has the potential to cause harm by mechanisms that are mediated by human decisions. Two such mechanisms have been identified: inducing excessive reliance and creating new grounds for conflict. Naïve reliance on the prospect of CE providing cheap and easy control of climate change could further undermine the already weak political will for other essential elements of climate response, particularly emission cuts.[30] The longer such excessive reliance on CE and neglect of mitigation continued, the more the opportunity to limit climate risks by emission cuts would be foreclosed, thereby increasing climate risks and the extent to which, if bad risks were realized, CE would be the only available response.[31]

If such a course continued — to the point where large-scale CE deployment was masking several degrees of global heating while emissions grew unabated — additional severe risks could arise related to CE's rapidity of both action and reversal.

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[28] *See, e.g.*, ROYAL SOC'Y, *supra* note 8; T.M.L. Wigley, *A Combined Mitigation/Geoengineering Approach to Climate Stabilization*, 314 SCI. 452 (2006). On the large cost advantages of phasing mitigation in gradually, see WILLIAM D. NORDHAUS, A QUESTION OF BALANCE (2008); and T.M.L. Wigley R. Richels & J.A. Edmonds, *Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations*, 379 NATURE 240 (1996).

[29] Michael C. MacCracken, *On the Possible Use of Geoengineering to Moderate Specific Climate Change Impacts*, 4 ENVTL. RES. LETTERS 045107 (2009).

[30] *See, e.g.*, Keith, *supra* note 10; Keith, Parson & Morgan, *supra* note 7. For examples of advocacy that the prospect of CE makes it unnecessary to do mitigation, see LEVITT & DUBNER, *supra* note 12; and TELLER, HYDE & WOOD, *supra* note 12.

[31] Even in this case severe impacts are not certain, of course: Just as unfavorable resolution of scientific uncertainties can bring severe climate impacts even with steep emission cuts, extremely favorable resolution of uncertainties could bring climate impacts of manageable severity, even with decades more unrestrained emissions growth.

If CE is used to suppress large global heating, then stopping the CE intervention, whether inadvertently or by choice, would re-impose all the suppressed heating within a few years. Because the severity of impacts depends on both the magnitude and rate of heating, and because many social and ecological adaptation processes are rate-limited, such rapid heating would be far more harmful than if CE had not been used and the same total heating had occurred more slowly as emissions rose. The time structure of this risk, by which a series of incremental choices yield a state from which reversal is perilous, has been likened by many observers to addiction.[32]

CE also has the potential to be a new and severe source of international conflict. Conflict related to CE could arise from disagreement among nations over whether, when, and how to use it; from unilateral deployment and other nations' responses to it; or from allegations that CE interventions, whether intended for research or operational deployment and whether undertaken with broad international consultation or unilaterally, have caused harms. In perhaps the most explosive scenario, nations or other actors might allege not just that CE interventions have harmed them, but that the interventions were undertaken with reckless disregard for their interests or even with hostile intent.

CE thus offers the prospect of either risk-reducing benefits or exacerbated or newly-created harms. Which of these dominates depends on the decisions made about its development and use. This paired possibility is not unique to CE; indeed, it characterizes many technological expansions of human capabilities. CE may be unusual, however, in how much it broadens the range of possibilities. Under extreme assumptions of a century of prudent and responsible global decision-making, CE can bring large reductions in climate-related risks. Under extreme assumptions of sustained destructive use (whether due to error, negligence, or destructive intent), CE could bring catastrophic outcomes far worse than appear plausible under any scenario of GHG-driven climate change alone, including (in theory) the possibility of re-creating the "Snowball Earth" conditions under which the early Earth froze from pole to pole.[33] This vast range of possibilities accounts for the extreme range of reactions to CE in early commentary, and illustrates the crucial role for effective governance of CE to help gain the risk-reduction benefits it offers while limiting the associated risks.

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[32] Goes, Tuana & Keller, *supra* note 22.
[33] P.F. Hoffman et al., *A Neoproterozoic Snowball Earth*, 281 SCI. 1342 (1998).

III. CE GOVERNANCE: THE EMERGING LITERATURE AND ITS LIMITATIONS

The need for international law and governance to address challenges posed by the prospect of CE has been recognized since the return of attention to these technologies several years ago, and there is a small but rapidly growing literature on the shape of these governance challenges. Although this is a new and undeveloped field, this early literature shows several points of strong consensus. Four of these are especially prominent.

First, the early literature on CE governance has established that no current international law constrains or regulates the specific activities that might be contemplated in CE field research or potential future deployment.[34] The reasons that current instruments do not control CE are variable across treaties. The three environmental treaties of greatest relevance to CE — on climate change,[35] stratospheric ozone depletion,[36] and long-range air pollution[37] — impose obligations to reduce national emissions of relevant pollutants or related production, which currently proposed CE interventions would not violate. The Convention on Environmental Modification prohibits large-scale environmental modification, but only when undertaken for military or other hostile purposes.[38] By virtue of its purpose to reduce risks related to climate change, CE would fall under the Convention's explicit exemption for activities undertaken for peaceful purposes.

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[34] *See, e.g.*, Royal Soc'y, *supra* note 8, at 60; SOLAR RADIATION MANAGEMENT GOVERNANCE INITIATIVE (SRMGI), SOLAR RADIATION MANAGEMENT: THE GOVERNANCE OF RESEARCH (2011); Jason J. Blackstock & Arunabha Ghosh, Does Geoengineering Need a Global Response — And What Kind? International Aspects of SRM Research Governance (Mar. 21, 2011) (unpublished manuscript), *available at* http://www.srmgi.org/files/2011/09/SRMGI-International-background-paper.pdf (background paper for the Solar Radiation Management Governance Initiative conference); Daniel Bodansky, *Governing Climate Engineering: Scenarios for Analysis* (Harvard Project on Climate Agreements, Discussion Paper No. 2011-47, 2011); Edward Parson et al., "Mechanics" of SRM Research Governance (Mar. 31, 2011) (unpublished manuscript), *available at* http://www.srmgi.org/files/2011/09/SRMGI-Mechanics-background-paper.pdf (background paper for the Solar Radiation Management Governance Initiative conference).

[35] United Nations Framework Convention on Climate Change, May 9, 1992, S. TREATY DOC. No. 102-38, 1771 U.N.T.S. 107, *available at* http://unfccc.int/resource/docs/convkp/conveng.pdf [hereinafter UNFCCC]; John Virgoe, *International Governance of a Possible Geoengineering Intervention to Combat Climate Change*, 95 CLIMATIC CHANGE 103, 109 (2009) ("[The UNFCCC] does not address the possibility of *intentional* attempts to change the climate, except for the 'enhancement of sinks and reservoirs.'" (quoting UNFCCC Arts. 4.1(d) and 4.2(a))).

[36] Montreal Protocol on Substances that Deplete the Ozone Layer, Sept. 16, 1987, 1522 U.N.T.S. 3; EDWARD A. PARSON, PROTECTING THE OZONE LAYER: SCIENCE AND STRATEGY (2003).

[37] Convention on Long-Range Transboundary Air Pollution, Nov. 13, 1975, 1302 U.N.T.S. 217 [hereinafter CLRTAP]; Protocol to the CLRTAP on Further Reduction of Sulfur Emissions, June 14, 1994, 33 I.L.M. 1542. Note that the applicability of this regime is further limited by the fact that its membership and scope are merely regional.

[38] Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, May 18, 1977, 1108 U.N.T.S. 151.

Parties to the Convention on Biological Diversity adopted a decision discouraging CE in 2010, but in view of the explicitly advisory language used[39] and the non-binding character of all decisions under this Convention,[40] the decision lacks legal force.

Finally, the broad obligation for environmental protection established under the Law of the Sea Convention,[41] plus various customary international law principles such as the duty to avoid trans-boundary harm,[42] could be interpreted to impose obligations related to CE, but these are so broad and vague that they provide at most a normative background to inform states' negotiation of specific obligations or constraints rather than representing existing obligations. In view of this lack of current law, any nation would be within its rights to conduct CE field research, even large-scale field trials leading to deployment, so long as it avoids territorial intrusion on non-consenting states or demonstrable hostile intent. As a political matter, many other states would likely exert pressure to stop such activity, and could invoke various broad legal principles to support this pressure, but no current international legal obligation would prohibit it.

The second strong point of consensus in the literature on CE governance is that research is needed into the feasibility, effects, and potential risks of CE

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[39] Decision X/33 on Biodiversity and Climate Change, *in* UNEP, Report of the Conference of the Parties to the Convention on Biological Diversity at Its Tenth Meeting ¶ 8(w), U.N. Doc. UNEP/CBD/COP/10/27 (Oct. 29, 2010), *available at* http://www.cbd.int/doc/decisions/cop-10/cop-10-dec-33-en.pdf. (inviting parties and governments to consider "[e]nsur[ing] . . . , in the absence of science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach and Article 14 of the Convention, that no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts . . . .").

[40] Brooke Glass-O'Shea, *Watery Grave: Why International and Domestic Lawmakers Need to Do More to Protect Oceanic Species from Extinction*, 17 HASTINGS W.-NW. J. ENVTL. L. & POL'Y 191, (describing the CDB as "a treaty that leaves adherence and implementation entirely up to the discretion of the signatories and provides no consequences for inaction - in essence, a toothless treaty" (citation and internal quotation marks omitted)).

[41] United Nations Convention on the Law of the Sea, Dec. 10, 1982, 1833 U.N.T.S. 397. Similarly broad duties are stated in the Antarctic Treaty System, including the Protocol on Environmental Protection to the Antarctic Treaty, Oct. 4, 1991, 30 I.L.M. 1455, and the Outer Space Treaty, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, Jan. 27, 1967, 18 U.S.T. 205, 610 U.N.T.S. 205. *See also* SRMGI, *supra* note 34, app. 3 at 10-11; Bodansky, *supra* note 11, at 314-15.

[42] The initial statement of extension of *sic utere* principle to include environmental harms is in Trail Smelter (U.S. v. Can.), 3 R.I.A.A. 1905 (Perm. Ct. Arb. 1941), and was subsequently articulated, with modifications, in the Stockholm and Rio Declarations, United Nations Conference on the Human Environment, Stockholm, Swed., June 5-16, 1972, *Stockholm Declaration*, U.N. Doc. A/CONF. 48/14/Rev. 1, Ch. 1, Principle 21 (June 16, 1972); and United Nations Conference on Environment and Development, Rio de Janiero, Braz., June 3-14, 1992, *Rio Declaration on Environment and Development*, U.N. Doc. A/CONF. 151/5/Rev. 1 (Vol. 1), Annex 2, Principle 2 (Aug. 12, 1992).

technologies — and that this should begin immediately. At present, it is not known how well specific interventions and delivery methods would work; their effects and risks, and the distribution thereof across world regions; or how confidently these matters can be known. Research into these matters is needed to inform decisions of what interventions, if any, will be warranted, under what conditions; to identify what risks these may pose, to whom, and how these can be mitigated; and thus to determine what specific forms of laws and institutions are likely to be needed to govern development and use of CE technologies.[43]

Some of this needed research, including laboratory and climate-model studies, is already underway and carries no environmental risk. Understanding capabilities of specific reflective materials and delivery methods will also require field studies in the atmosphere. Much can be learned from such field studies at tiny scale, comparable to the environmental impact of a single airplane. Although such studies, like indoor lab-bench and modeling studies, pose virtually no environmental risk, and are moreover already underway in several countries, there are already indications that these raise more controversy.[44] Moreover, if operational-scale CE interventions are ever seriously contemplated, predicting their large-scale climate and environmental effects based only on model or small-scale experiments will inevitably leave substantial outstanding uncertainties, which can only be reduced through larger-scale experimental interventions. There are lively debates underway on how to design specific large-scale interventions to provide maximal information about the response to real operational deployments while minimizing the scale, duration, and risk of the exploratory intervention, and indeed on the extent to which this balancing of information-gathering and risk-limiting objectives can be achieved.[45] Although these inquiries have not yet yielded specific quantitative estimates of the tradeoffs between knowledge and risk, it appears likely both that learning about the performance and risk of full-scale operational interventions will require experimental perturbations of

[43] The importance of early research into CE has been affirmed by all assessments thus far. *See, e.g.*, ASILOMAR, RECOMMENDATIONS, *supra* note 8; BIPARTISAN POL'Y CTR., *supra* note 8; BRACMORT, LATTANZIO & BARBOUR, *supra* note 13; ROYAL SOC'Y, *supra* note 8; SRMGI, *supra* note 34; Keith, *supra* note 10; Keith, Parson & Morgan, *supra* note 7.

[44] *See, e.g.*, Hamilton, *supra* note 12; John Shepherd & Granger Morgan with Jane Long et al., Thresholds and Categories (Mar. 21, 2011) (unpublished manuscript), *available at* http://www.srmgi.org/files/2011/09/SRMGI-background-paper-Thresholds.pdf (background paper for the Solar Radiation Management Governance Initiative conference).

[45] See, for example, the debate mapped out in Douglas G. MacMynowski et al., *Can We Test Geoengineering?*, 4 ENERGY & ENVTL. SCI. 5044 (2011); and Alan Robock et al., *A Test for Geoengineering*, 327 SCI. 530 (2010).

sufficiently large scale that they qualitatively resemble deployment and raise similarly intense controversies; and that even if such large-scale experiments are performed, any actual move to operational deployment will still carry substantial uncertainties until it is actually undertaken and the consequences observed.

Third, research itself needs governance, and informal international consultation and collaboration on this should begin soon. While the smallest-scale and least controversial forms of CE research can be funded and controlled by national governments, the potential for international interest and controversy increases as field studies of increasing spatial scale are proposed or undertaken, most clearly if these are conducted in a location or at a scale such that their effects extend beyond national territory. Early investigations of CE governance have argued that there is value in informal international cooperation in CE research, involving open exchange of information about proposed studies, results, and any early indications of risks, and possibly including jointly supported and managed international research programs. The literature has also suggested that early international cooperation not be limited to scientific programs, but also include collaborative risk assessment and consultative processes involving broad groups of stakeholders.[46]

Finally, the early CE governance literature suggests that it is not advisable to attempt to negotiate any formal international agreement on CE at present, either by making a treaty or establishing an international organization. Given current limited knowledge about the feasibility, risks, and benefits of specific approaches, such negotiations would risk locking in governance arrangements that may later turn out to be ill-advised, including the possibility that early negotiations may be captured by advocates of broad prohibitions on development or testing of these technologies. Rather, early informal cooperation on scientific research and risk assessment should seek to develop relevant norms from the ground up, by a decentralized process, in the hope that these will grow sufficiently robust to support future decision-making on proposals for large-scale CE interventions, whether for research or for operational deployment.[47]

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[46] *See, e.g.*, ASILOMAR, RECOMMENDATIONS, *supra* note 8; SRMGI, *supra* note 34; Keith, Parson & Morgan, *supra* note 7; David Victor et al., *The Geoengineering Option: A Last Resort Against Global Warming?*, 88 FOREIGN AFF. 64 (2009).

[47] SRMGI, *supra* note 34; Keith, Parson & Morgan, *supra* note 7; Victor, *supra* note 22; Victor et al., *supra* note 46.

The current literature on CE governance has several major gaps, however, that limit its usefulness in characterizing governance needs or informing near-term decisions. First, the strongest points of concrete consensus provide only negative guidance. For example, the advice not to pursue formal international action until research has brought advances in relevant knowledge is important, but offers no insights into potential future actions or conditions under which they would be warranted. Moreover, to the extent current work has addressed specific questions of law and governance, its scope has been rigorously limited to governance of CE research, avoiding any consideration of future controversies over operational deployment and the many ways early decisions on research may influence – for good or ill – the norms, framings, precedents, and institutions available to guide these future decisions. Current work has tended to favor elaboration of normative principles that ought to guide decisions on CE, with little consideration of potential configurations of states' interests and capabilities that may influence or constrain likely decisions and associated political risks. Finally, key points of consensus in the literature are frustratingly obscure regarding any potential linkage to operational implementation or a route toward it. The call to make CE governance adaptive is clearly attractive, but no specific ways have been proposed to put this into practice, nor advice offered on how to overcome the bureaucratic and political obstacles that have disabled many prior attempts to build adaptive governance institutions. Similarly, the call to avoid top-down decisions but instead build governance norms from the ground up sounds right, but gives no guidance on how to nudge such a bottom-up norm-building process along. In the final two Parts, we take initial steps toward filling those gaps.

IV. Functional Requirements for International CE Law and Governance

What would effective governance of CE technologies achieve? Broadly speaking, it would promote their development and use in ways that their risk-reduction benefits were dominant, while limiting or preventing their use in ways that their risks were dominant, particularly the extreme ones. To achieve this salutory outcome, the governance system must be able to discharge three distinct functions: decision-making of a regulatory or operational nature, scientific research and assessment, and management and response to security threats. We elaborate on each of these in turn.

A. Regulatory and Operational Decision-making

Gaining the benefits of CE capacity while limiting the associated risks will require, in the first place, a capacity to make decisions. This capacity must exist at the international level because of the high-stakes interests states are likely to perceive to be at play in CE interventions, and the inability of even powerful states to advance and protect these interests unilaterally. Some uncertain number of states will be capable of unilateral action, and others are likely to perceive such unilateral action, at sufficient scale, as a serious threat to their interests. Whether proposed action is unilateral or multilateral, no state is likely to willingly let others conduct CE at a scale able to influence global climate without demanding participation in the decision-making, within the limits of their ability to press such demands. Moreover, the conduct of separate, uncoordinated CE programs, whether by individual states or groups of states, is likely to impair the aims of each and bring additional risks. Under these circumstances, states are likely to support — indeed demand — establishment of some form of capacity for joint decisions at the international level.

Because of the nature of CE and the need for large-scale field research, there will be no clear dividing line between research and deployment. Moreover, even relatively small-scale CE research will require international decisions to authorize and oversee field interventions above whatever threshold of spatial scale, duration, intensity of perturbation, or anticipated risk has been judged to exceed the scope of purely national scrutiny and control. The need for decisions to be made internationally increases as the scale of proposed intervention grows toward that of operational deployments. Whether the aim of an intervention is to advance knowledge or to gain operational benefits, the required decisions will take the same form: Who, may put what material, where, when, under what conditions, and with what restrictions or oversight? The restrictions or conditions may take various forms. For example, the initial decision to authorize an intervention might include a statement of anticipated consequences, and of degrees of departure from these that would trigger a requirement to modify, reduce, or cease the intervention. To state the need for a decision capacity, however, does not presume the decision outcome either for or against authorizing CE, merely an expectation that at some time, under some conditions, there may be interest in doing so. Negative decisions — whether a general prohibition, a conditional or limited moratorium, or a one-time decision not to authorize a particular proposed intervention — also require the capacity to make decisions.

The character of these decisions will partly be regulatory, in that they dispense permissions, restrictions, and prohibitions. But to the extent that their outcome ever allows proposed interventions to proceed, their character will also be operational. Whether the decision body conducts approved interventions itself, or (more likely) authorizes some other body to do them — e.g., a government, a not-for-profit organization, or a firm — it must exercise oversight to ensure the intervention is done as approved, monitor performance and consequences, and be prepared to require stopping or modifying the intervention in near-real time, depending on these observations. Decisions will also be required to respond to failed interventions or to harms caused by (or alleged to be caused by) interventions.

In contrast to the myriad decentralized decisions and non-decisions that are driving climate change, the explicit and intentional nature of CE decisions will confer a heightened obligation to respond to realized harms, whether anticipated or not. This will probably mean some form of liability and compensation system, although the challenges of identifying what type and size of harms are compensable, and how strongly the causal role of the intervention must be demonstrated, will be formidable. Depending on the details, such a compensation program could represent a large share of the cost of a CE program.

To operate effectively, the decision process will have to satisfy multiple conditions. Its participation, procedures, and transparency must be widely perceived as legitimate.[48] In addition, its substantive decisions must be competent and prudent, so that it succeeds at reducing, not increasing, aggregate climate-change risks. This condition will imply different requirements for decisions about whether and when to authorize interventions versus the operational oversight and control decisions once an authorized intervention is underway. Authorization decisions will have to fairly and competently integrate both relevant scientific information and diverse views and preferences about consequences and risks. But in subsequent operational decisions, priority will shift to accurate, rapid assimilation and interpretation of real-time observations and to competent, clear, timely decisions to identify and respond

[48] *See, e.g.*, HOUSE OF COMMONS, SCI. & TECH. COMM., THE REGULATION OF GEOENGINEERING, H.C. 221 (2010) (U.K.), *available at* http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/221.pdf; Jane Long & David Winickoff, *Governing Geoengineering: Principles and Process*, 1 SOLUTIONS 60 (2010).

appropriately to unanticipated or harmful consequences as they materialize. These operational decision requirements would appear to preclude negotiated political decisions.

Yet however difficult it may be for states to give up control over such operational decisions, it is even less likely that they will let prior authorization decisions be removed from their collective political authority. These divergent criteria suggest some form of two-level decision process. Interventions would be authorized by a political body, perhaps with explicit statements of an expected range of consequences. These decisions might be made by negotiation with no codified decision process, or might follow some specified decision rule, such as some level of super-majority, perhaps with additional approval requirements by nations identified as likely to be most strongly affected by a particular proposal. Some executive or technical body would then be responsible for monitoring interventions and results, and responding rapidly to indications of unanticipated outcomes or heightened risks, operating with clear delineation of authorities and chain of command.

B. Scientific Research, Assessment, and Decision Inputs

As we note above, uncertainty is prominent on CE and research is needed on the feasibility and optimization of specific interventions; on the regional and seasonal effects and risks of specific interventions; on how these interact with continued greenhouse-driven climate change and natural variability; on the controllability of regional effects of interventions and how this might advance; on the requirements for monitoring interventions underway, including identification of early warning signs and attribution of harms; and on how to identify unannounced or clandestine interventions. Although much can be learned from laboratory and model studies, and small field experiments with minimal environmental risk, understanding and quantifying atmospheric responses at regional or larger scales will require experimental perturbations at similarly large scales.

Such research will itself require international governance as the scale of interventions grows beyond a single nation's territory — or as other nations assert claims to participate due to the international significance of the research, even if physical trans-boundary effects are small.[49] But this governance will differ from

[49] Shepherd & Morgan with Long et al., *supra* note 44.

purely political decision-making, in that it must have a substantially scientific character. Decisions whether to authorize proposed research interventions will need to be informed by judgments of their scientific promise and the balance between the knowledge they offer and the scale of environmental disruption they impose. These judgments must be made, in part, based on what has been learned from prior research. Interpreting the results of interventions, their implications for judgments of effectiveness and risk, and for the potential value of further research all require scientifically sophisticated judgments.[50]

A well designed research program will advance knowledge of the effects and risks of CE interventions and reduce uncertainties, but will not fully resolve them. If and when large-scale interventions are proposed, whether for research or operational climate modification, their effects cannot be fully known without actually doing them and observing what happens. Uncertainty will persist in part because of natural weather and climate variability, which obscures attempts to observe and attribute effects to interventions. Continuing uncertainty will also be compounded by ongoing greenhouse heating and by continued advances in the set of technological interventions to be considered. Consequently, even in an ideally designed and executed research program, each expansion of the scale of intervention will carry some risk.

In view of these continuing uncertainties, there will not be a clean boundary between an early period of "scientific" CE governance and some later period of "operational" governance. Rather, future decisions about CE interventions will continue to depend on uncertain scientific judgments synthesized from prior research — judgments about projected effectiveness and risks of proposed interventions, about attribution of consequences to interventions underway, and about appropriate monitoring and adaptation strategies — even as they also seek to advance operational risk-management objectives. Moreover, as the severity of climate impacts and the scale of proposed interventions increase, these scientific judgments will be linked increasingly tightly with national and regional interests. Decision-makers are likely to be acutely sensitive to any unusual conditions their region experiences during or after an intervention, and quick to attribute them to the intervention, particularly if they are harmful. Advances in scientific knowledge and technological capabilities will not

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[50] BIPARTISAN POL'Y CTR., *supra* note 8; ROYAL SOC'Y, *supra* note 8; SRMGI, *supra* note 34.

necessarily make regional interests more convergent, particularly if they increase the regional controllability of effects and thus create or clarify tradeoffs between costs and benefits to different regions. Coherent decision-making in such a setting will pose hard challenges of keeping decision-making linked to scientific understanding, however imperfect, and protecting scientific deliberations and judgments from political pressures.

C. Management and Response to Security Threats

If and when decisions about CE deployment are considered, their stakes to states will be high — even higher than those already presented by climate change and its impacts. If and when such decisions are being considered, that fact alone will probably mean that at least some decision-makers perceive the situation as a crisis. CE's high leverage implies the possibility of extreme effects. Uncertainty about regional effects will provide ample room for partisan bias in debates about both proposed interventions and attribution of effects. Choices between alternative interventions may present inter-regional tradeoffs. In view of all these factors, state decision-makers could readily perceive decisions about CE as implicating such core interests — e.g., large economic and environmental gains or losses, large shifts in capabilities of governing institutions, and hardship or loss of life on a substantial scale — that they justify resort to violence to protect these interests.

CE governance thus raises risks of violent conflict through multiple causal routes. Unilateral initiation of a CE intervention by one state could pose such a risk, as could disagreement among other states over how to respond to it. Even if, as we argue below, the capability for unilateral CE action is more limited than has been suggested, it is still sufficiently widespread to be destabilizing. Conflict could also arise from states disagreeing whether, when, and how to undertake CE, and how to identify and respond to its consequences. Even if states agreed in principle to deploy CE in an emergency, they could readily disagree on what conditions count as an emergency, particularly if changes underway are bringing disparate regional effects. Even if they agree that observed conditions warrant some intervention, they could disagree over how to intervene, especially if the available responses appear to have strong regional distributive effects. They could disagree over how these decisions are made, and by whom. And they could disagree over allegations that interventions have caused harm, either inadvertently or intentionally.

With so many ways for CE to generate conflict, effective CE governance must include the capability to manage risks of conflict. Preventing conflict would require this capability to be in place before serious proposals to deploy CE are considered. Managing these risks will mean, on the one hand, anticipating and averting potential conflicts before they escalate to violence, through decision processes that consider and integrate states' interests broadly enough, and that keep harms small enough and well enough compensated, that they are broadly perceived as legitimate. But the success of such advance avoidance of conflict cannot always be assured. CE governance must thus also be able to deter and avoid violent conflict when it is imminently threatened; and in extremis, be able to credibly threaten, authorize, and deploy deadly force in situations of realized or imminent violence, as needed to stop or end violent conflicts and restore order.

V. THE INTERNATIONAL GOVERNANCE CHALLENGE OF CE

The current state of affairs on CE can be summarized as follows. CE technologies raise high stakes that pose acute and novel challenges to international governance, which are not addressed by current international laws and institutions. To avoid substantial risks related to CE, governance structures will be needed at or before the point when serious proposals for large-scale CE deployment are first advanced.

The major reason CE poses such acute and novel challenges to the international legal order is its requirement for three distinct kinds of governance functions: regulatory and operational decision-making, scientific research and assessment, and management of security threats. Not only is it the case that no current international law controls CE; no current multilateral regime has demonstrated capability to discharge all three functions. Even the first required function — competent and legitimate decision-making, including timely operational decisions, on matters that distribute significant material stakes among nations and regions — represents a challenge to international governance with few historical precedents. The novelty and magnitude of CE governance challenges are increased further by the need for decisions to be effectively integrated with scientific assessment processes, and with processes to anticipate, avoid, and respond to threats of violent conflict.

Successfully integrating these three functions is often challenging even to national governments, which clearly have the legitimate authority to do so.

The large disparity between governance needs implied by the characteristics of CE technologies, on the one hand, and the capabilities of international law and institutions, on the other, might initially suggest the stark conclusion that these technologies will compel or require development of the functional equivalent of a global state. This extreme conclusion can be mitigated in at least three ways, however. First, not all three governance functions are likely to be required all the time, with equal priority, or immediately. In view of current uncertainties about CE effects and implications for state interests and capabilities, the near-term tasks of research, technology development, and risk assessment may remain the principal governance needs for a decade or more. It may thus be possible to defer most high-stakes and potentially divisive questions of regulatory and security governance. It is of course important to plan for these while taking early steps in research and research governance. But these high-stakes questions may be deferrable for long enough that advances in scientific understanding, or in perceived risks and interests in climate change, may make them less fraught than the starkest current speculation suggests.

Second, the requirement that the three functions be integrated can readily be over-stated. Granted that to effectively manage risks, regulatory and operational decisions must take reasonable account of scientific evidence, but this integration need not, indeed cannot, be either authoritatively compelled or precisely codified. CE technologies evoke in a new context the metaphor of "Spaceship Earth" – the vivid image of a finite planet requiring rational and skilled operation to provide for its inhabitants, which gained prominence during the growth of modern environmentalism in the 1960s.[51] But the metaphor may exaggerate the rigor of managerial requirements, in that there are unlikely to be precise, narrow conditions within which the "spaceship" must be flown to avoid crashing. Rather, muddling through with a view both to parties' key interests and to the implications of advancing scientific knowledge may well — as on many global environmental challenges prior to climate change — be sufficient. Similarly, regulatory and operational decisions will have to accommodate the most acute state interests at stake and thereby anticipate and

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[51] BARBARA WARD & ILIE CEAUSESCU, SPACESHIP EARTH (1968); KENNETH E. BOULDING, The Economics of the Coming Spaceship Earth, in H. Jarrett (ed.) Environmental Quality in a Growing Economy, pp. 3-14. Resources for the Future/Johns Hopkins U Press, Baltimore MD, 1966.

manage potential conflict threats, but this will not necessarily require formal procedural linkages to security decision-making processes.

Third, the threat of unilateral action — the most alarming scenario advanced in the CE governance debate thus far — may be less acute than many observers have suggested. Transfixed by low direct cost estimates, some commentators have suggested that unilateral manipulation of the global climate is within the reach of virtually all states, plus many non-state actors. Colorful scenarios have been proposed in which large-scale CE is undertaken by terrorist groups, apocalyptic cults, or wealthy individuals.[52] But more detailed consideration of the physical requirements to achieve a sustained, non-trivial change in global climate — as would be needed for unilateral action to represent a serious threat — suggests the presence of stringent additional, non-financial constraints that call expansive claims of unilateral capabilities into question.

These constraints largely flow from the fact that the most promising high-leverage interventions are both fast to act *and* fast to decay. Making a sustained influence on global climate thus requires ongoing inputs of order millions of tons of material per year — a scale that is small relative to global processes, but fairly large relative to human enterprises. This input would require delivery equipment (e.g., aircraft, balloons, ships, or tethered pipes) that are large enough to be easily observable (including remotely) and are either themselves fixed in location or dependent on fixed infrastructure (e.g., airports, ports, or materials processing facilities). Regardless of cost, any non-state actor seeking to run such an operation would need support of a host state to provide operating bases and registration for vessels and aircraft. Distribution equipment and associated infrastructure will be hard to conceal and potentially vulnerable to military attack. Consequently, any state seeking to conduct or sponsor sustained CE unilaterally, against strong opposition from other powerful states, would need not just the requisite financial, infrastructural, technological, and aerospace capabilities, but also — in the case of strong opposition — the global stature and military capability to defend the operation and associated facilities from targeted military attack.[53]

[52] *See*, *e.g.*, Victor, *supra* note 22, at 324; *see also* ROYAL SOC'Y, *supra* note 8, at 50; Davis, *supra* note 5, at 926; Squillace, *supra* note 5, at 899.
[53] Note that in contrast to Joshua B. Horton, *Geoengineering and the Myth of Unilateralism: Pressures and Prospects for International Collaboration*, 4 STAN. J.L. SCI. & POL'Y 56 (2011), our argument

These conjectures are based on presently identified CE approaches, and are thus provisional. But subject to this qualification, these considerations greatly reduce the number of actors likely able to conduct CE in defiance of world opinion at a scale and duration big enough to matter. No eccentric billionaire, doomsday cult, or other non-state actor is likely to have this capability, and the states possessing the required assets — in particular the global stature and military strength to make it costly for others to compel them to stop — are likely to number only a dozen or so. This number is approximate, not just because of uncertainty but because it depends on the intensity of opposition: As other states' opposition and willingness to exert pressure grows, the number of states able to act unilaterally in defiance of that pressure decreases. The number is still large enough for conflict over CE to be destabilizing, but substantially smaller and less destabilizing than has been suggested.

The same nations also roughly match the set of major economies and greenhouse-gas emitters often proposed as the most promising groups to negotiate effective global action on emission cuts and other elements of managing climate change. Existing forums with approximately the appropriate membership range from the G-8 plus 5, to the Major Economies Forum (MEF), through the G-20.[54] While issues of legitimacy would favor broader participation in CE governance,[55] negotiation complexity and challenges to decision-making, particularly operational decisions, would tend to increase in larger groups, and smaller groups such as these define roughly the minimum level of participation needed to effectively control CE decisions, given the need to limit unilateral action and respond to CE-associated security threats.

These three considerations provide some comfort about the severity of governance challenges posed by CE, but little concrete guidance on near-term steps to increase the likelihood of successfully resolving these challenges. In closing, we take initial steps toward providing that guidance.

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limits the threat of unilateralism based on constraints on capabilities, not on the claim that the prospect of retaliation would make unilateral action irrational.

[54] The "G-8 plus 5" nations include United States, Russia, Japan, Germany, United Kingdom, France, Italy, and Canada, plus China, India, Brazil, Mexico, and South Africa. To this group of thirteen, the Major Economies Forum adds Australia, South Korea, and Indonesia, plus the European Union, seventeen in total. To these seventeen, the G-20 adds Turkey, Saudi Arabia, and Argentina. *See* Parson et al., *supra* note 34; L-20 LEADERS FORUM, KEY ELEMENTS IN BREAKING THE GLOBAL CLIMATE CHANGE DEADLOCK (2008), *available at* http://www.l20.org/publications/38_qF_Paris-Meeting-Report-Final.pdf (report of meeting on March 31 and April 1, 2008).

[55] *See, e.g.*, Barrett, *supra* note 22; Albert C. Lin, *Geoengineering Governance*, 8 ISSUES LEGAL SCHOLARSHIP 1 (2009).

VI. CONCLUSION: NEAR-TERM ISSUES FOR CE GOVERNANCE

In this final Part, we address in a preliminary way the question of what this future need implies for near-term choices. We do not present a complete governance proposal, because the nature of future needs will depend on things still to be learned, and governance decisions thus must be adapted over time in response to experience, research results, and the evolution of the climate-change issue. Rather, we suggest two key questions that should be the focus of inquiry regarding these near-term choices.

First, if we accept the current consensus that research and informal international research collaboration are the most immediate needs, how can these early steps best encourage the development of shared norms that will grow robust enough to support future decision-making on CE if and when the stakes mount? The aspiration for such decentralized, bottom-up norm development has been widely expressed, with little specificity about how it would happen or what early choices might promote it.[56] Such development could be encouraged by promoting inclusiveness and transparency in early scientific work — including wide sharing of proposals, data, analyses, results, and risk assessments. Bodies established to promote scientific exchange and cooperation should not, however, be expected to develop policies beyond those minimally required to coordinate research, lest the intense political views and interests likely to attend debates over policy impair their ability to promote open and critical scientific exchange.

At some point in the future, development of CE governance will come under the authority of negotiations among governments. The key question in adaptive norm development is what comes between early steps in research and scientific cooperation, and such future state negotiations. What consultations, assessments, or other processes can smooth the transition or integration of these processes to advance decision-relevant knowledge, promote effective scientific input into decisions, and responsibly manage both environmental and political risks? In what kind of forums should such consultations take place, and what tasks or questions should be posed to them?

Clearly these bodies must be thoroughly informed by ongoing research and technology development, but they cannot be exclusively scientific in their

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[56] *See, e.g.*, Keith, Parson & Morgan, *supra* note 7; Victor, *supra* note 22; Victor et al., *supra* note 46.

participation, mandate, or operations, as they must integrate additional societal and political factors in their deliberations. One plausible model would be a senior consultative body of people with deep and diverse experience in government, diplomacy, science and other fields — a "World Commission on Climate Engineering."[57] Such a body might operate in various ways: e.g., as an elite advisory panel issuing reports and advice to governments and international organizations; as an educational body disseminating information on CE; as a forum eliciting broad stakeholder and citizen input through invited submissions, public hearings, and testimony; or as a convener of more exploratory investigations of potential CE uses, outcomes, and risks, using such processes as simulation-gaming or scenario exercises. In the absence of any clear basis to favor one particular model or process, early establishment of a few such bodies exploring alternative processes, models, and outputs is likely to be valuable.

The second key question to inform near-term decisions is how to make the potential availability and investigation of CE technologies serve to enhance and complement other necessary elements of climate response, particularly emission cuts, rather than competing with or undermining them. As on the prior question, a few early conjectures on this appear plausible, but many questions remain. One plausible conjecture is that for CE to constructively influence mitigation decisions, negotiations and decisions on the two responses should be linked through discussions in a single forum that has the membership, capacity, and decision authority to act on both. For example, if the leading forum for mitigation decisions shifts from the current U.N. process to some smaller group of major economies, this same group should be the leading site for decisions on CE and its governance. Putting the issues in the same forum would facilitate integrated decisions that could increase benefits or ease political difficulties. For example, CE's speed of effect suggests the potential to couple aggressive mitigation and CE initiatives in parallel, so CE's near-term climate-control benefits could help make the entire effort, including the costs of mitigation, more politically palatable.[58]

Locating the issues together would also facilitate linking negotiations to strengthen incentives for mitigation. Several forms of linkage appear to have some promise, although these are based on uncertain assumptions about the distribution of

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[57] *See, e.g.*, Blackstock & Ghosh, *supra* note 34.
[58] *See, e.g.*, Biber, *supra* note 5.

states' interests and pose their own risks, and would therefore need further exploration. Given the intensity of views about CE, such negotiations may need to begin within clear boundaries that aim to limit political risks. One useful approach might be for governments to announce, before starting negotiations, that they are provisionally suspending any claims of legal rights to conduct CE interventions above some specified scale, to promote constructive multilateral agreement on comprehensive management of climate change.

Such statements, particularly if informally coordinated among a few major CE-capable nations, would provide two benefits. On the one hand, they would sooth alarm about rapid, unilateral, or reckless pursuit of CE. On the other hand, by implying a potential future threat to proceed with CE under certain conditions — i.e., if negotiations fail and severe climate impacts are mounting — they would create stronger incentives to negotiate serious measures on emissions.[59]

This proposal relies on the contestable assumption that some nations are so hostile to CE that a threat of others potentially pursuing it could motivate them to increase efforts to cut emissions. This assumption could fail if, for example, the states most hostile to CE are those already most committed to mitigation, in which case increasing their mitigation incentives would bring only small benefit. Even if this assumption is not valid, however, a governance structure in which a relatively small group of major world powers exercises effective control over CE decisions could allow them to deploy effective mitigation incentives, both collectively on themselves and on other states. For example, these states could collectively commit not to allow large-scale CE unless some targeted level of global emission cuts is achieved. This would reverse the implied threat in the previous proposal: instead of saying "unless we all mitigate enough, we will do CE," it says "unless we all mitigate enough, we will not allow CE to be done." In this case, the concern that key states' incentives might go the wrong way appears less problematic, but other problems could arise. For example, nations might attempt to free-ride, declining to make the called-for mitigation and daring the group to act on its threat. Alternatively, the threat to block CE might not be credible, particularly in the case of a clear and widely agreed climate

[59] This proposal draws on the analogy of the provisional suspension of sovereign claims in Antarctica that played a key role in negotiation of the Antarctic Treaty System. *See, e.g.*, Rip Bulkeley, *The Political Origins of the Antarctic Treaty*, 46 POLAR REC. 9 (2009); Gillian Triggs, *The Antarctic Treaty System: A Model of Legal Creativity and Cooperation*, *in* SCIENCE DIPLOMACY: ANTARCTICA, SCIENCE, AND THE GOVERNANCE OF INTERNATIONAL SPACES 39 (Paul Arthur Berkman et al. eds., 2009).

emergency — although the difficulty of achieving such wide agreement on the presence of an emergency or how to respond would bolster the credibility of the threat.

In an even sharper use of group power, such a group of states controlling world CE decisions could threaten to exclude states that have not met joint mitigation goals from CE governance decisions about precisely what is done, when, and with what conditions. Such aggressive bargaining would avoid the credibility and free-riding problems of the prior approaches, but at the cost of substantial elevation of potential conflict over CE and its control.

These reflections on the two key near-term governance questions are speculative, but provide starting points for more extended inquiry and perhaps experimentation. Whatever near-term steps are taken, as climate change continues, CE governance decisions cannot be avoided, and will have high stakes — even if recognition of these stakes may develop slowly. Moreover, it is hard to escape the conclusion that any way of meeting the core governance requirements of CE will represent an expansion of international governance capability both large in scale and novel in character. It is thus possible these technologies may be the catalyst for growth of governance capability that has far-reaching implications for other global challenges, for the capabilities and legitimacy of international institutions in general, and for the operation of the international system.