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An Economic Analysis of Liability and Compensation for Harm from Large-Scale Field Research in Solar Climate Engineering

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Abstract

Solar climate engineering is under increasing consideration as a potential means to reduce climate change risks. Its field research may generate knowledge to reduce climate risks to humans and the environment and will, at a large-enough scale, pose its own risks, some of which will be of the transboundary kind. Liability or compensation for harm is frequently referenced as a possible component of international regulation of solar climate engineering but has been insufficiently developed. This article offers an economic analysis of the possible interrelated roles of rules, liability, and compensation in the future international regulation of large-scale field research in solar climate engineering. Notably, the benefits, risks, and incentives of climate-engineering research are unlike typical high-risk activities. The analysis proposes a hypothetical international agreement that links general and procedural rules for research, an international compensation fund, and limited, indirect state liability with a duty-of-care defence.

Keywords

climate engineering – geoengineering – solar-radiation management – liability – compensation – economic analysis of law

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1 Introduction: Solar Climate Engineering

Thus far, internationally coordinated efforts to reduce climate change risks by cutting greenhouse gas emissions and by adapting society and ecosystems to a changed climate appear insufficient to prevent dangerous climate change and resultant impacts. Many observers remain pessimistic about future efforts.

As a response, some scientists and other experts believe that we should consider intervening in natural systems at large scales in order to counteract climate change. Solar climate engineering (often called solar geoengineering or solar radiation management—SRM), would strive to make the planet more reflective in order to compensate for the warming aspect of climate change. Possible techniques include marine-cloud brightening and stratospheric aerosol injection. In general, the implementation of solar climate engineering is expected to be relatively fast and inexpensive, and would not require global collective action. The IPCC concluded in its most recent assessment report that 'Models consistently suggest that SRM would generally reduce climate differences compared to a world with elevated greenhouse gas concentrations and no SRM'.[1] In fact, recent modeling suggests that optimized solar climate engineering could prevent the large majority of climatic anomalies.[2] However, risks are large and include spatially and temporally uneven compensation of temperature and precipitation anomalies, altered sunlight characteristics, and damage to stratospheric ozone. Gaps in domestic and international regulation of solar climate engineering remain.[3]

Some researchers are interested in solar climate engineering field trials, which would in some ways be novel. Although current proposals for these would present low-to-negligible environmental risks, if that early work is promising, later trials would increase in space, duration, and perturbation.[4]

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1 Olivier Boucher et al., 'Clouds and Aerosols', in *Climate Change 2013: The Physical Science Basis*, edited by Thomas F. Stocker et al. (Cambridge: Cambridge University Press, 2013), at 575.

2 This would be a Pareto improvement with respect to annual mean temperature and precipitation at the regional scale. Ben Kravitz et al., 'A Multi-Model Assessment of Regional Climate Disparities Caused by Solar Geoengineering', 9(7) *Environmental Research Letters* 074013 (2014).

3 For existing international law, see Jesse Reynolds, 'Climate Engineering Field Research: The Favorable Setting of International Environmental Law', 5(2) *Washington and Lee Journal of Energy, Climate, and the Environment* 417 (2014).

4 John A. Dykema, David W. Keith, James G. Anderson, and Debra Weisenstein, 'Stratospheric Controlled Perturbation Experiment: A Small-Scale Experiment to Improve Understanding of the Risks of Solar Geoengineering', 372(2031) *Philosophical Transactions of the Royal Society*

Large-scale and climate-response tests would pose genuine environmental risks, some of which would be transboundary.

Because large-scale field research in solar climate engineering will generate transboundary risks, there has been extensive consideration of existing and potentially new international regulatory instruments. Proposals have mostly emphasized rules, broadly defined, ranging from command-and-control to nonbinding norms. However, there are other regulatory means—such as liability—that would seek to guide behaviour in order to reduce risks. Liability provides, moreover, a basis to compensate victims for harm. Although liability including compensation for harm from climate engineering is frequently mentioned in passing, there are few scholarly works that explore this potential mechanism in depth.[5] Furthermore, the publications to date focus on the distant and uncertain implementation scenarios, whereas field research is more urgent and more probable, as well as a problem in its own right. In particular, field research in solar climate engineering is fairly likely to occur in the near future; it would probably be carried out by state, quasi-state, or non-state scientific groups operating with some form of state sanction; it would not necessarily be performed in consultation (or after having reached consensus) with many states; it would occur under conditions of relatively poor knowledge about outcomes; and it would presumably be intended to generate shared

A: Mathematical, Physical and Engineering Sciences, art. 20140059 (2014); David W. Keith, Riley Duren, and Douglas G. MacMartin, 'Field Experiments on Solar Geoengineering: Report of a Workshop Exploring a Representative Research Portfolio', 372(2031) *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, art. 20140175 (2014).

5 Bidisha Banerjee, 'The Limitations of Geoengineering Governance in a World of Uncertainty', 4(1) *Stanford Journal of Law, Science, and Policy* 15 (2011); Martin Bunzl, 'Geoengineering Harms and Compensation', 4(1) *Stanford Journal of Law, Science and Policy* 70 (2011); Gareth T. Davies, 'Law and Policy Issues of Unilateral Geoengineering: Moving to a Managed World', in *Select Proceedings of the European Society of International Law*, edited by Hélène Ruiz Fabri, Rüdiger Wolfrum, and Jana Gogolin (Oxford: Hart, 2008); Clare Heyward, 'Benefiting from Climate Geoengineering and Corresponding Remedial Duties: The Case of Unforeseeable Harms', 31(4) *Journal of Applied Philosophy* 405 (2014); Joshua B. Horton, Andrew Parker, and David Keith, 'Liability for Solar Geoengineering: Historical Precedents, Contemporary Innovations, and Governance Possibilities', 22(3) *New York University Environmental Law Journal* 225 (2015); Toby Svoboda and Peter J. Irvine, 'Ethical and Technical Challenges in Compensating for Harm Due to Solar Radiation Management Geoengineering', 17(2) *Ethics, Policy and Environment* 157 (2014); Jesse Reynolds, 'Response to Svoboda and Irvine', 17(2) *Ethics, Policy and Environment* 183 (2014); Barbara Saxler, Jule Siegfried, and Alexander Proelss, 'International Liability for Transboundary Damage Arising from Stratospheric Aerosol Injections', 7(1) *Law, Innovation and Technology* 112 (2015).

knowledge. By contrast, implementation of solar climate engineering is less certain to occur; it would be done (if at all) at a later date; it would probably be performed by a state, group of states, or an intergovernmental organization; it would likely be preceded by international negotiations and perhaps agreement among many states; it would occur under conditions of relatively good knowledge about outcomes; and it would be intended to alter the world's climate and to reduce climate risks. Furthermore, in the implementation scenario, legal rules for liability and compensation would be shaped in part by the decision-making process on implementation, which could take a wide range of forms. Therefore, research and implementation may be different enough to warrant distinct international regulatory approaches. The latter need not be resolved in order for the former to be addressed.

This article considers the potential roles of liability and compensation for harm in the international regulation of large-scale field research in solar climate engineering. It considers a generic technique of solar climate engineering that would have the potential to reduce climate change risks, but would first be tested outdoors at a large scale with significant climatic impacts. This technique could be stratospheric aerosol injection, marine cloud brightening, or another proposed method, currently known or unknown. A regulatory regime would have two purposes: first, to incentivize the socially optimal levels of activity and care in a manner that balances the benefits and harm of the activity with the costs of preventing harm, and, second, to compensate victims. These two purposes may operate congruently, or they may, at times, conflict. The regulatory regime that is ultimately proposed here also aims to be politically feasible.

The method used here is an economic analysis of law, which assesses the incentives of existing and proposed laws on present and future actors. A strand within this discipline is the study of various means of regulating the risks of accidents.[6] It systematically weighs the expected welfare gains and losses for all parties from the activity in question and from the precautions taken to reduce risk. Precautions can include greater care and reduced activity, by potential injurers as well as potential victims. Such an analysis then considers the likely changes in incentives and welfare resulting from various regulatory means, including rules-based regulation, liability, injunctions, corrective taxes, and fines, all of which can be used singly or in combination.

The following section briefly sketches some relevant characteristics of solar climate engineering and its research. The third section systematically examines how the characteristics of this research may justify particular regulatory

6 See, e.g., Steven Shavell, 'Liability for Accidents', in *Handbook of Law and Economics*, edited by A. Mitchell Polinsky and Steven Shavell (Amsterdam: North-Holland, 2007).

mechanisms. The penultimate section considers some further aspects of liability and compensation. The final section proposes an international agreement that would regulate large-scale field research in solar climate engineering by linking general and procedural rules, an international compensation fund, and limited, indirect, state liability with a duty-of-care defence.

Some notes on terminology are in order. 'Climate engineering' herein refers to highly leveraged methods of solar climate engineering, such as stratospheric aerosol injection or marine cloud brightening, although some aspects of this article could be applied to other climate-engineering techniques. 'Research' indicates only large-scale field tests of climate engineering that would generate significant transboundary risks to humans and the environment. For convenience, I omit the word 'potential' before 'injurer', 'victims', and 'harm.' That last term refers to what the victim suffers, whereas 'damages' refers to what the victim should receive as compensation. Harm is significant undesired impacts to people, property, and the environment due to the accidental or expected consequences of research. These impacts could include changes in precipitation, loss of stratospheric ozone, changes in the quantity and quality of incoming sunlight, extreme weather events, and human and environmental health impacts from the materials and machinery used. A victim is a person, group of people, or state that suffers harm. Note that harm is not limited to net harm; a victim may also experience benefits or even net benefits from research. 'Government' includes all authorities that can legitimately pass regulation, such as intergovernmental organizations that are widely perceived as legitimate. When comparing regulatory means, 'rules' is shorthand for 'rules-based regulation', even though all law consists of rules. Male pronouns are intended to include all persons.

2 Characteristics of Climate-Engineering Research

An economic analysis of the potential role of liability and compensation in the international regulation of field research in climate engineering requires the description of some key characteristics of climate engineering and its research.

The most important characteristic is the incentive structures that actors face. Greenhouse gas emissions, emission abatement, and negative-emission technologies are public goods. These are 'goods' in the general economic sense of something that satisfies a want and provides utility, not in any normative sense. A public good is such that one actor's use of it does not reduce other actors' ability to use it ('non-rivalrous') and is also such that no actor can be prevented from using it ('non-excludable'). As implied, public goods are not necessarily beneficial. In fact, most public goods are neither universally beneficial nor universally harmful, as both a public good's impact on actors and actors' preferences for goods vary. Nevertheless, some public goods generate mostly positive effects. We can thus recognize abatement, for example, as a beneficial public good because most countries will be harmed by climate change, especially at its greater magnitudes.

Unlike traditional rivalrous and excludable 'private' goods, public goods are usually supplied at levels far from their social optima. The provider of a beneficial public good that is costly for him to produce cannot exclude those who would enjoy the benefits while refusing to pay for them—a group known as free riders. Unable to charge fees, the provider has a low incentive to supply the beneficial public good and will undersupply it. In fact, many of the core functions of government involve the direct provision of beneficial public goods or the incentivization thereof. By extension, these functions are difficult to reproduce at the global scale due to a lack of centralized law-making and enforcement.

Climate engineering would be a public good, and possibly a beneficial one. It would be a public good in that its climatic effects would be non-rivalrous and non-excludable. It presently appears that it would be a generally beneficial one because modelling suggests that optimized climate engineering could greatly reduce the temperature and precipitation anomalies of climate change.[7] If it could indeed provide a low-cost backstop, its expected present net economic value might be on the order of tens of trillions of dollars.[8] Current evidence indicates that climate engineering could offer such great benefits to a single state at such low direct cost that unilateral implementation would yield net benefits to that state. Therefore, although both abatement and climate engineering are, or presently appear to be, beneficial global public goods, the incentives for their provision are distinct. Whereas the former will be greatly undersupplied in a manner typical of most beneficial public goods, the latter might be oversupplied. However, the oversupplying of a beneficial public good such as climate engineering would be an easier problem to resolve.[9] Regardless,

7 Kravitz et al., supra note 2.

8 Nordhaus estimated this value at approximately $17 trillion: William D. Nordhaus, *A Question of Balance: Weighing the Options on Global Warming Policies* (New Haven: Yale University Press, 2008), at 19, 77–79. Bickel concurs: 'adding SRM to a policy of emissions controls, even a strict one, holds the potential of avoiding significant climate damages, with potential economic benefits in the tens of trillions of dollars, even if SRM itself causes damage.' J. Eric Bickel, 'Climate Engineering and Climate Tipping-Point Scenarios', 33(1) *Environment Systems and Decisions* 152 (2013), at 166.

9 *See* Scott Barrett, *Why Cooperate? The Incentive to Supply Global Public Goods* (Oxford: Oxford University Press, 2007), at 37–41; Daniel Bodansky, 'What's in a Concept? Global Public Goods, International Law, and Legitimacy', 23(3) *European Journal of International Law* 651 (2012), at 665.

climate engineering might turn out to be a generally beneficial, mixed, or generally harmful public good.

Moreover, if research indicates that climate engineering would be effective, the knowledge of climate engineering and the capacity for implementation would have a value greater than the simple expected net reduction of climate harm. This is because this knowledge and capacity could act as something akin to a climate insurance policy.[10] This is due to three factors. First, the probability distribution of harm from climate change has a long tail, with low probabilities of very great harm.[11] Second, people are generally risk-averse, and are willing to pay a premium in order to reduce risks of great harm.[12] In the case of climate change, this risk aversion would extend to society collectively. Third, climate change is delayed relative to the emissions that cause it. At any given time, we are committed to an unknown minimum amount of climate change, independent of subsequent abatement. Further, if we were to learn that the resulting harm from climate change were much greater than expected, it would then be too late for adaptation and abatement to be effective. In contrast, climate engineering appears to be able to be rapidly implemented and optimized.

An accurate assessment of net benefit or harm from climate engineering is not necessary for the purposes of this article; only that it presently appears that implementation and the capacity to carry it out could be very beneficial.

Likewise, climate-engineering research is a public good, and probably a beneficial one. The generation of useful knowledge through research is generally a public good because the produced knowledge is non-rivalrous and non-exclusive.[13] This requires that the knowledge be shared widely and not be subject to restrictions, such as intellectual-property claims. In fact, there are emerging norms toward transparency and limitations on, or full rejection of,

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10 Gernot Klepper and Wilfried Rickels, 'Climate Engineering: Economic Considerations and Research Challenges', 8(2) *Review of Environmental Economics and Policy* 270 (2014), at 280–282.

11 This is because of the chances of a higher-than-expected climate sensitivity, higher-than-expected marginal climate harm, unexpectedly rapid climate change, positive feedback cycles in natural systems, and lesser-than-expected abatement or adaptation. Some of these are discussed in Martin L. Weitzman, 'Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change', 5(2) *Review of Environmental Economics and Policy* 275 (2011).

12 As noted, climate engineering also has probability distributions of benefits and risks. How these, and those of climate change, as well as risk-aversion, interact under conditions of uncertainty is complex.

13 Dominique Foray, *The Economics of Knowledge* (Cambridge: MIT Press, 2004) at 113–29.

patents for solar climate engineering.[14] That research would be a beneficial public good if it produces knowledge that clarifies humanity's options to respond to climate change, and does so with relatively low risk to present and future generations. If that research were to indicate that climate engineering could indeed greatly reduce climate risks, then the value of such knowledge would be large, perhaps on the same order as that of beneficial climate engineering implementation. Note that, as stated above, the value of the capacity to implement climate engineering can be greater than its mere ability to reduce climate change harm. Alternatively, if the research were to indicate that climate engineering holds little potential, or would be too risky to pursue, then this too would have value, as it could prevent uninformed implementation of, or unwarranted reliance upon, climate engineering.[15]

Two caveats in characterizing climate-engineering research as beneficial are in order. First, the knowledge itself could turn out to have low or even negative value. At the very least, research could produce ambiguous results. More worrying, the generated knowledge could lead to a misuse of climate engineering, technological 'lock-in', normatively undesirable international politics, international conflict, an intergenerational transfer of a requirement to maintain a perilous system, or an undue reduction in emission abatement. Second, the process of acquiring the knowledge through research could itself have negative impacts. This depends on several developments that remain unclear. For example, there is a feasible scenario in which modelling, laboratory work, and outdoor experiments gradually indicate large potential benefits and low risks for the subsequent steps in research. Research could thus proceed in small, justified steps in terms of scale, perturbation, and risk. There is also a feasible

14 Margaret S. Leinen, 'The Asilomar International Conference on Climate Intervention Technologies: Background and Overview', 4(1) *Stanford Journal of Law, Science, and Policy* 1 (2011); Solar Radiation Management Governance Initiative, *Solar Radiation Management: The Governance of Research* (2011), <www.srmgi.org/report/>; Anne C. Mulkern, 'Researcher: Ban Patents on Geoengineering Technology', *ClimateWire* <www.scientificamerican.com/article.cfm?id=researcher-ban-patents-on-geoengineering-technology>; Bipartisan Policy Center's Task Force on Climate Remediation, *Geoengineering: A National Strategic Plan for Research on the Potential Effectiveness, Feasibility, and Consequences of Climate Remediation Technologies* (2011), <http://bipartisanpolicy.org/library/report/task-force-climate-remediation-research>; Steve Rayner et al., 'The Oxford Principles', 121(3) *Climatic Change* 499 (2013).

15 For example, reliance upon the prospect of future climate engineering in the absence of knowledge could lead to undue reductions in abatement. See Jesse Reynolds, 'A Critical Examination of the Climate Engineering Moral Hazard and Risk Compensation Concern', 2(2) *The Anthropocene Review* 174 (2014/2015).

scenario in which low-risk research reveals little, and the only means to resolve lingering uncertainties is to escalate to risky climate-response tests. Likewise, climate-engineering field research could be conducted in a responsible manner that minimizes risk, is consistent with social and legal norms, and avoids pitfalls, such as misuse or large reductions in abatement. Alternatively, it could be done in a manner that poses unnecessary risks and is contrary to these norms. Finally, even responsibly conducted field tests with justified expected risks may, in fact, harm some people and the environment. This final aspect is the subject of this article.

For purposes of this article I will assume that climate-engineering field research would be beneficial, which is consistent with current models of the climatic effects of optimized climate engineering,[16] models of the capabilities and feasibility of climate-response tests,[17] cost estimates of research programs,[18] and emerging norms for research and its governance.[19] This is not an assertion that this is how the future will necessarily unfold, but instead an assumption of a reasonably likely scenario for which policymakers and others should prepare. Moreover, the incentive structure generated by a high-value beneficial global public good is distinct. In contrast, less optimistic scenarios would yield incentive structures more akin to typical risky activities, particularly to new 'development' risks.

Besides understanding incentive structure and gross benefits, it is useful to have a rough estimate of the possible harm from climate-engineering field tests. A large-scale climate-response field test would face trade-offs among its intensity, duration, and the confidence of its results in detecting a signal amid the noise of weather. Modelling has suggested that the transient climate response to climate engineering could be bound to within 1.5°C of the actual value, with 90 per cent confidence, through a global test of ten years at an intensity of 0.4W/m^2, equal to one-tenth of that required to compensate the warming effect from a doubling of the atmospheric CO_2 concentration.[20] According to this model, such a test might reduce precipitation in southern Asia, an area of particular concern, by a few percentage points. The severe 2012 drought in

16 Kravitz et al., supra note 2.

17 Douglas G. MacMynowski, David W. Keith, Ken Caldeira, and Ho-Jeong Shin, 'Can We Test Geoengineering?', 4(12) *Energy and Environmental Science* 5044 (2011).

18 Caldeira and Keith called for a research program ramping up to $100 million annually. Ken Caldeira and David W. Keith, 'The Need for Climate Engineering Research', 27(1) *Issues in Science and Technology* 57 (2010). See also Keith et al., supra note 4.

19 See supra note 14. See also Edward A. Parson and David W. Keith, 'End the Deadlock on Governance of Geoengineering Research', 339 (6125) *Science* 1278 (2013).

20 Douglas G. MacMynowski et al., supra note 17.

southern Asia, when rainfall was twelve per cent below average, is estimated to have caused a loss of one-half of one percent of the region's annual economic activity, or about $12 billion.[21] Assuming, to be cautious, that the field test might have the same impact as the 2012 drought, a ten-year field test might cause harm on the order of $100 billion in discounted present value. This does not necessarily imply that southern Asia or other harmed regions would experience net harm. The benefits of climate-engineering research may outweigh the harm. For example, because southern Asia faces large climate change risks, the development of climate engineering might confer large net benefits.

Another relevant characteristic is the nature of the injurer. In particular, economic analyses of risk-reduction policies typically assume that the injurer is a profit-maximizing firm. This is not so with climate-engineering researchers, who differ from profit-maximizers in two important ways. First, typical of producers of beneficial public goods, the researchers will capture little of the benefits that they may produce. Instead, the researchers pursue a mix of satisfaction from generating knowledge, career advancement (with its concomitant income increases), and public acclaim. It is difficult to imagine these privately captured values approaching trillions of dollars. As stated above, this assumes open publication of results and minimal intellectual property claims, which are consistent with emerging norms of research. Because beneficial public goods, such as climate-engineering research, are usually sub-optimally produced, policymakers should be cautious about imposing excessive regulatory burdens. This is particularly important given that the states that are likely to conduct climate-engineering field research (i.e. the industrialized countries) are relatively less vulnerable to climate change. The second important difference is that, whereas profit-maximizing firms typically prefer that their negative impacts remain external and unpublicized, climate-engineering researchers will presumably strive for a better understanding of all benefits and costs of climate engineering, at least to the extent that they are motivated by the generation of useful knowledge. The researchers will therefore prefer to learn of any possible harm, and will likely publicize it.

21 This is intended to be a very high-end estimate. The half-per-cent figure is from the World Bank, which estimated that impact and later said, prospectively, that 'A second poor monsoon … could reduce overall GDP growth by 0.5 percentage points or more.' World Bank, *Global Economic Prospects*, vol. 6, January 2013 (Washington: World Bank, 2013) at 154; World Bank, *Global Economic Prospects*, vol. 7, June 2013 (Washington: World Bank, 2013) at 194.

A further, related, characteristic of climate engineering is that it is politically controversial and is already under great scrutiny. Any field tests will be watched closely by governments, other natural scientists, social scientists, and environmental organizations, increasing the likelihood that secondary effects will be observed and publicized.

Finally, research will likely be carried out with state approval and funding. The threat that this approval and financial support could be revoked may make other, ex-ante regulatory means relatively more effective.

3 Comparing Regulatory Means

An economic analysis of the law can compare under what circumstances rules and liability, both strict and negligence-based, would each be more efficient means to reduce the total costs from accidents and their prevention. Other regulatory means include corrective taxes, fines for inflicted harm, and injunctions. In many cases, multiple regulatory means can be combined for complementarity. Here, I examine the relevant factors in the case of large-scale climate-engineering research.

3.1 *Information Regarding Risk Reduction*

If the injurer has superior information relative to the government regarding the risk and the cost required to reduce it, and especially if these costs vary widely among injurers, then liability or fines for harm done would be favoured. In this way, the injurer could adjust his levels of activity and care as he sees fit, in balance with maximizing output. However, if the government has superior information, and especially if the costs of taking care are relatively consistent across injurers, then it would be better positioned to incentivize optimal behaviour through rules, taxes, or injunctions.

For the foreseeable future, climate-engineering researchers will have superior information relative to government regulators. Furthermore, a new domain of research, such as climate engineering, will be very dynamic, with many experiments being entirely novel. Indeed, it is presently difficult to imagine how detailed rules for research could remain optimal, and even relevant, several years after their creation. Note that this may not always be the case. Imagine that, in a few decades from now, after numerous field experiments of increasing scale whose methods and results have been made publicly accessible, climate-engineering research has matured and stabilized, and its regulators are as familiar with its methods and risks as the scientists themselves. Research may need to be continued, and full implementation may need to be deferred, in order to further verify previous results. In this possible, but somewhat distant, case, the scientists would no longer possess superior information as to how to reduce risk.

3.2 *Injurer's (In)ability to Pay*

If an injurer has inadequate assets to pay damages, he may not be able to fully pay liability and fines for harm done. He could simply go bankrupt, and be unable to pay further. This possibility reduces the incentives for optimal levels of activity and care under ex-post regulatory means, such as liability and fines for harm done. This is the so-called 'judgment-proof problem'. In some cases, mandatory insurance can make liability and fines more feasible, depending on the insurer's assessment of likely damages or fines (plus administrative costs) and the subsequent insurance premiums.[22] Yet, very large damages may not be insurable. By contrast, an injurer's inability to pay will not hinder ex-ante means such as rules, taxes, or injunctions. He must abide by them or not proceed with his activity.

The budget of a climate-engineering research group might be on the order of tens of millions of dollars, whereas harm may be on the order of tens of billions or more. This factor appears to support the ex-ante means of regulation, taxes, and injunctions. Liability with mandatory insurance is another potential option, although premiums could be prohibitive and a sufficiently robust insurance market may be unable to develop. A further possibility would be for the liability or fines to be absorbed by collective entities such as governments or international organizations, because, as stated above, climate-engineering research presently appears to be a beneficial public good of great value, and its social benefits would be not be fully captured by the researchers.

3.3 *Injurer's Levels of Activity and Care*

In all cases, the injurer's level of activity will influence the victim's risk, whereas only in a subset of cases could the injurer take effective precautions to reduce risk. If the latter is indeed the case, then regulation and liability may be preferable. If not, and the activity is simply dangerous, then other means may be closer to optimal.

It remains unclear how relatively important the level of care in climate-engineering research would be. To some degree, risks such as changes in precipitation might be inherent to the activity. However, researchers can alter the spatial scale, duration, and intensity of field experiments, as well as abide by procedural duties, such as environmental assessment, which may manage risk further.

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22 See text to n 26–32 infra.

3.4 *Victim's Level of Care*

Some accidents are unilateral, in that only the injurer's levels of activity and care influence expected harm. Here, ex-ante regulatory means are generally more efficient. Others are bilateral, in that the victim's levels of activity and care are also influential. If so, then ex-post regulation, such as that found with liability and injunctions, may be preferred, as the judge can take into account the victim's behaviour. In particular, liability offers the possibility of contributory negligence on the part of the victim, or comparative negligence.

Risky, large-scale climate-engineering field research initially appears to be an example of a unilateral risk. However, bilateral accidents should not be ruled out. A potential victim can take precautions to reduce his exposure to extreme weather events and climate change. From an economic perspective, the fact that he does not contribute to the risk from climate engineering is not relevant, just as a pedestrian should look for cars—including those with reckless drivers—when crossing the street.

Imagine that a large-scale climate-engineering field trial induces a change in precipitation, which causes harm to two countries. The first had undertaken all reasonable steps to prepare for extreme weather events and climate change. This country should arguably be compensated. The second had failed to devote adequate resources to protective infrastructure and disaster preparedness, even though it possessed such resources. This one should be held to be contributorily negligent. It would be inefficient to compensate that country, because doing so would provide an incentive for future negligent governance. However, a contributory-negligence standard would require that policymakers establish a level of care for the victims, and a judge would need to assess whether such a standard had been followed.

3.5 *Information Regarding Harm*

Often, victims themselves possess detailed information regarding the frequency and magnitude of the harms that they have suffered. This causes liability and injunctions to often be closer to optimal, as the victims can instigate action. At other times, the victims remain ignorant, while governments have superior information due to their investigative abilities. This could be the situation when the harm is minor (but perhaps frequent and widespread), when it is delayed relative to the injurer's action, or when its cause is not commonly known. These situations would favour government-instigated regulation: rules, fines, and taxes.

At first glance, climate engineering appears to be a case of the latter, as a large number of people may experience, for example, altered precipitation, yet remain unaware as to the possible cause. However, states can also serve as victims, and, if aware of the harm, could begin proceedings leading to liability or an injunction. Furthermore, as described above, researchers may actively seek and likely publicize information about harm. It thus appears that a state could be aware of possible harm from large-scale research.

3.6 *Concentration of Harm*

Sometimes harm from accidents is highly concentrated, in that a few victims suffer to a great degree. They would have sufficient incentive to take action, such as requesting damages or an injunction. At other times, harm is diffuse, in that a large number of victims suffer only slightly. Even if they were aware of the harm, individually they would not have sufficient incentive to take action against the injurer, and they may find it difficult to collectively organize themselves. In this case, government-initiated means, such as rules, fines, and taxes, would be more efficient. An alternative is the class-action suit, in which one party files a suit on behalf of all victims, who can then choose to join the class.

As with the quality of information regarding harm, this characteristic may cause the centralized means of rules, fines, and taxes to be closer to optimal. However, we can again conceive of a state being the victim. If harm were great enough, and the state's leadership were aware of it, then it may have domestic political incentives to request compensation.

3.7 *Ability to Assign Responsibility*

If the harm cannot be attributed to the activity of a particular party due to multiple potential injurers or due to uncertain causal linkage, the injurer(s) will have reduced incentives to adjust their levels of activity and care when facing ex-post regulation, such as fines and liability. This difficulty can sometimes be remedied, albeit imperfectly. In the case of multiple injurers, liability can be joint and/or several, or possibly vicarious. In the case of uncertain causation, fines or damages from liability can be increased in proportion to how often the government or judge believes that injurers are actually required to pay, or reduced in proportion to the assessed probability of causation.

Climate-engineering field research is unlikely to pose the problem of multiple possible injurers because it will be in the researchers' interest to coordinate research activities in order to minimize overlapping effects. Without such coordination, their results would be less robust and of less value to the researchers themselves. However, attributing causation will be very challenging, and it is the greatest impediment to fines or liability.[23] Suppose that a

23 'Given the chaotic and highly variable nature of the climate system, it could be very difficult to determine what harmful impacts are due to SRM rather than natural occurrences

country, after a nearby climate-engineering field test, suffered a severe weather event, perhaps an event that was consistent with modelled predictions of the experiment. Judges and others would wish to know how probable it was that the event could be attributed to the research. If it could be, they should further ask whether the research was merely a contribution that made an already occurring event more extreme, or whether it was fully responsible for the event. Recent advances in modelling permit increasing confidence in the generation of probability distributions that particular weather events are attributable to a factor such as climate change or—perhaps—climate engineering. Joshua Horton and colleagues point to probabilistic event attribution for the impacts of climate engineering, noting that 'Using [Fraction Attributable Risk] or similar methods, scientists have demonstrated probabilistic causal attribution for a growing number of discrete weather events'.[24] Such attribution should improve in the future. I do not wish to imply that this will be simple or clearly decisive, only that it may be feasible. If values can reasonably be estimated, a rule of proportional liability instead of a simple all-or-nothing threshold could offer an efficient outcome.

3.8 *Administrative Costs*

All regulation has administrative costs. Those costs of the ex-ante regulatory means, such as rules and taxes, are borne independently of whether the harm actually occurs, whereas those of the ex-post means of liability and fines for harm done are incurred only in the case of actual harm of which the victim (or his government agent) is aware and upon which he acts. However, those latter means require an assessment of whether harm was done, whether it can be attributed to the purported injurer, how much damages (in the case of liability) should be awarded, whether the injurer (in the case of a negligence rule) was negligent, and (in the case of contributory negligence) whether the victim was negligent. How these administrative costs would balance out in climate-engineering research is unclear.

in the climate system.' Svoboda and Irvine, supra note 5, at 158. See also Davies, supra note 5. This has also been a major difficulty in developing liability for climate change. See Miles Allen, 'The Scientific Basis for Climate Change Liability', in *Climate Change Liability: Transnational Law and Practice*, edited by Richard Lord, Silke Goldberg, Lavanya Rajamani, and Jutta Brunnée (Cambridge: Cambridge University Press, 2011).

24 Horton et al., supra note 5, at 262. See Peter A. Stott et al., 'Attribution of Weather and Climate-Related Extreme Events', in *Climate Science for Serving Society: Research, Modeling and Prediction Priorities*, edited by Ghassem R. Asrar and James W. Hurrell (Dordrecht: Springer, 2013). But see Svoboda and Irvine, supra note 5.

4 Additional Aspects of Liability and Compensation

4.1 *Importance of Compensation*

Although the regulatory means considered here could theoretically incentivize the injurer to adjust his activity and care closer to the optimal levels, they do not all have equivalent distributional effects. Specifically, compensation of victims is an important goal of risk regulation, for normative reasons and often for political reasons. This necessarily occurs only under a liability regime. Some other means, such as fines and taxes, involve a wealth transfer from the injurer to the government. This may be preferable if, for example, a large majority of an area's residents were harmed, but only slightly. Consequently, it can be more efficient for the state to stand as the victim and use the awarded damages for public purposes, rather than distribute small amounts of compensation to many people. Of course, under these regulatory means, or even under rules and injunction, the government may choose to compensate victims, which would require some determination of the magnitude of the harm.

Large-scale climate-engineering research will pose transboundary risks, which are often politically contentious. It is likely to be particularly controversial because of its relationship to climate change, divergent historical contributions to greenhouse gas emissions, relations between industrialized and developing countries, and a possible perception of the abdication of responsibility. The residents of the harmed countries may feel unjustly victimized in the absence of compensation, and their political leaders may come under domestic pressure to seek compensation.

4.2 *Insurance, Pools, and Public Risk-Sharing*

When harm may be great but has a low probability of occurring, it is generally advantageous for multiple injurers—and sometimes for society as a whole—to share the risk. One such means is insurance. With insurance, an injurer may be willing to pay the insurance premium even if this is greater than the expected damages due to his aversion to risk. Mandatory insurance has the additional benefits of addressing the judgment-proof problem (i.e. potential bankruptcy of the injurer) and avoiding adverse selection.[25] Insurance can approach optimality when insurance markets are well developed, when there

25 Adverse selection is a manifestation of information asymmetry in which those potentially insured actors (whether injurers or victims) self-select whether to get insurance, as well as which policy to get, based upon their ex-ante knowledge regarding their personal profile of risk exposure. This leads to their segregation, reducing insurance's ability to efficiently pool risk.

is a sufficiently large insurance market to pool risk, when the activity is familiar enough that insurers can estimate risk through actuarial data, when mechanisms can minimize moral hazard and adverse selection, and when damages are neither large enough nor linked enough to exceed the insurer's assets and threaten insolvency.[26] Insurance for new, uncertain, or potentially great risks is uncommon.[27] In the case here, there is no market for insurance for liability from climate-engineering research, and it is difficult to imagine one forming soon. Insurers may be reluctant or unable to estimate potential damages of this novel activity, and the damages could be great enough and linked enough to potentially bankrupt them.

Other means of spreading risk besides insurance may have potential. For example, a group of similar injurers can form a risk-sharing pool in which they agree to mutually pay for the damages levied on any of them.[28] Advance payments, analogous to insurance premiums, are not always necessary. Conditions tend to be favourable for an injurers' pool when the injurers have similar risk profiles, have long-term relations, are mutually trusting, and have common interests in improving the sharing of information regarding risks and the costs to reduce them.[29] Climate-engineering researchers seem to meet some of these characteristics. However, even the collective assets of all climate-engineering researchers are probably not sufficient to pay tens of billions of dollars in damages. Further, the researchers will likely create rather different types and magnitudes of risks among themselves.

A third means to share risk is through public institutions. This would have the advantages of the availability of large assets, the reduction of moral hazard by monitoring injurers through mandatory inspection and regulation, and the reduction of adverse selection and free-riding through coercion.[30] Because

26 Note that 'moral hazard' here refers to its dominant meaning with respect to insurance, in which actors who obtain or increase insurance begin thereafter to take greater risks or to file greater claims. In the climate-engineering literature, the phrase is sometimes (but inaccurately) used to refer to a concern that the consideration of climate engineering would undermine abatement efforts.

27 Göran Skogh, 'Development Risks, Strict Liability, and the Insurability of Industrial Hazards', 23(87) *Geneva Papers on Risk and Insurance. Issues and Practice* 247 (1998).

28 Michael Faure and Göran Skogh, *The Economic Analysis of Environmental Policy and Law: An Introduction* (Cheltenham, UK: Edward Elgar, 2003), at 273–6.

29 See Göran Skogh, 'Risk-Sharing Institutions for Unpredictable Losses', 155(3) *Journal of Institutional and Theoretical Economics/Zeitschrift für die gesamte Staatswissenschaft* 505 (1999).

30 As described supra, in section 2, free-riding is to benefit from a public good without paying for it. In the context of risk and insurance, this is when potentially insured actors

climate-engineering research presently appears to offer a beneficial public good of large value, and because private insurance and risk-sharing pools may each be unfeasible, risk-bearing by public institutions may be warranted. The absorption by public institutions of liability for transnational harm amounts to state liability.

A final, non-exclusive possibility is that victims could carry first-party accident insurance, which could also theoretically lead to an efficient outcome. At the individual level, such insurance could resemble that for climate change, which will likely manifest as premium increases in already existing forms of insurance, rather than as new, specific insurance.[31] Most important here is that insurance is not widespread in some developing countries that may suffer harm from climate-engineering field research.[32]

4.3 *Vicarious Liability*

Seeking damages from multiple injurers can present a barrier for victims. Pursuing all potential injurers and determining which one(s) is/are actually liable consumes scarce resources. In these situations, it can be advantageous to hold a single injurer vicariously liable for harm, even if he may not have performed the harmful act but had some control over those who did. A typical example is that of a firm whose employees create risk. If held liable, the firm will have incentives to regulate its employees and contractors in whatever manner it deems best, and can try to pass on the cost of damages to the actual injurers. This can be particularly efficient if the vicariously liable party has greater information than the actual injurer concerning the costs of taking care to reduce risks. Furthermore, this can sometimes address the judgment-proof problem, in which the actual injurer may lack the financial resources to pay damages. On the other hand, vicarious liability can increase administrative costs, as there could be legal suits between the victim and the liable party, as well as between the liable party and the injurer. Similarly, in international environmental law, the state is liable for transboundary harm due to its acts that were contrary to international law and to space activities.[33] If these were

(whether injurers or victims) choose not to purchase insurance under the assumption that, in the event of harm, the insurer or the government will pay for the harm.

31 Evan Mills, 'The Greening of Insurance', 338(6113) *Science* 1424 (2012).

32 Joanne Linnerooth-Bayer et al., 'Insurance, Developing Countries and Climate Change', 34(3) *The Geneva Papers on Risk and Insurance* 381 (2009).

33 International Law Commission, 'Draft Articles on Responsibility of States for Internationally Wrongful Acts', in *Report of the International Law Commission, 53rd session, Official Records of the General Assembly* UN A/56/10 (2001), art. 31; Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including

actually performed by domestic private actors, the state can then choose to pursue reimbursement from the actual injurer in a manner roughly analogous to vicarious liability.[34] In the case of accident from nuclear power or the maritime transport of oil, a particular party is deemed the operator and is held liable.[35] Again, it may choose to pursue the other parties who may actually be responsible.

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the Moon and Other Celestial Bodies (open for signature 19 December 1966, entered into force 10 October 1967) 610 UNTS 205, article VII; Convention on International Liability for Damage Caused by Space Objects (adopted 29 November 1971, entered into force 1 September 1972) 961 UNTS 187 (hereinafter Space Liability Convention).

34 See Eric A. Posner and Alan O. Sykes, 'An Economic Analysis of State and Individual Responsibility under International Law', 9(1) *American Law and Economics Review* 72 (2007).

35 The cornerstones are the Paris Convention on Third Party Liability in the Field of Nuclear Energy (opened for signature 29 July 1960, entered into force 1 April 1968) 956 UNTS 251; Vienna Convention on Civil Liability for Nuclear Damage (opened for signature 21 May 1963, entered into force 12 November 1977) 1063 UNTS 265. The Paris Convention is furthered by the Supplementary Convention to the Paris Convention of 29th July 1960 on Third Party Liability in the Field of Nuclear Energy (opened for signature 31 January 1963, entered into force 4 December 1974) 1041 UNTS 358, and by the Protocols of 28 January 1964 (entered into force 1 April 1968, 956 UNTS 335), 16 November 1982 (entered into force 7 October 1988, 1519 UNTS 329), and 12 February 2004, the last of which is not yet in force. The Vienna Convention was amended by a Protocol of 12 September 1997 (entered into force 4 October 2003, 2241 UNTS 270). It may someday be furthered by the Convention on Supplementary Compensation for Nuclear Damage (opened for signature 29 September 1997) (hereinafter Convention on Supplementary Compensation). The two systems are partially linked by the Joint Protocol Relating to the Application of the Vienna Convention on Civil Liability for Nuclear Damage and the Paris Convention on Third Party Liability in the Field of Nuclear Energy (opened for signature 21 September 1988, entered into force on 27 April 1992) 1672 UNTS 301. Protocol of 1992 to Amend the International Convention on Civil Liability for Oil Pollution Damage, 1969 (adopted 27 November 1992, entered into force 30 May 1996) 1956 UNTS 255 (hereinafter Civil Liability Convention); Protocol of 1992 to Amend the International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage, 1971 (adopted 27 November 1992, entered into force 30 May 1996) 1953 UNTS 330; Adoption of Amendments of the Limitation Amounts in the Protocol of 1992 to Amend the International Convention on Civil Liability for Oil Pollution Damage, 1969 (adopted 18 October 2000, entered into force 1 November 2003) IMO Res. LEG.1 (82); Adoption of Amendments of the Limits of Compensation in the Protocol of 1992 to Amend the International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage, 1971 (adopted 18 October 2000, entered into force 1 November 2003) IMO Res. LEG.2 (82); Protocol of 2003 to the International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage, 1992 (adopted 16 May 2003, entered

Such an arrangement could be useful in the case of climate-engineering research. Just as it may be more efficient for the victims' government to stand in their place, so too could the injurer's government be held vicariously liable. After all, it has greater financial resources than the researchers, may be easier for victims to identify, and would be in a position to influence the researchers' levels of activity and care through funding conditions and domestic regulation.

4.4 *Strict Versus Negligence-Based Liability*

Awards of liability require demonstration of harm, causation, and (usually) fault. The standards for the latter criterion lie on a spectrum. For many purposes, including here, only two standards need to be considered: strict liability, in which the victim need not demonstrate fault, although the injurer may claim particular defences; and negligence, in which the injurer can avoid liability by abiding by a determined level of care. In the case of many environmental risks, this level of care can be demonstrated by obtaining appropriate permits. If this standard of care is equal to the socially optimal level, and if there is negligible uncertainty regarding the determination of care in each case, then both strict and negligence-based liability will lead to efficient injurer behaviour. However, this standard of care must be established by policymakers, and whether a particular injurer abided by it must be determined by a judge or a permit-issuing regulator. Furthermore, under negligence-based liability, the injurer does not have incentives to adjust his level of activity. Either form of liability can lead to greater administrative costs, depending on how challenging it is do determine whether the standard of care was followed, compared with the potentially larger number of cases under strict liability. When the injurer has superior information relative to policymakers regarding how to exercise care, or when the level of activity is much more important than the level of care, strict liability is preferred. Indeed, there is a tradition of strict liability with ultra-hazardous activities, both domestically and internationally.[36]

If climate-engineering field research were to be subject to civil liability—setting aside the various difficulties and drawbacks with this, already discussed—then it could be characterized as an ultra-hazardous activity, in that, regardless of how much care the injurer takes, it would remain very risky. Furthermore, a government would face difficulty in setting the standard of care and in determining whether it was followed in a given case. On the other

into force 5 March 2005) IMO Doc. LEG/CONF.14/20. See also International Convention on Civil Liability for Bunker Oil Pollution Damage (adopted 23 March 2001, entered into force 21 November 2008).

36 See Joni S. Charme, 'Transnational Injury and Ultra-Hazardous Activity: An Emerging Norm of International Strict Liability', 4 *Journal of Law and Technology* 75 (1989).

hand, if the state were to stand as the injurer, then its duty of care could simply be the fulfilment of its obligations under international law.

4.5 *Determining Damages*

Defining and calculating damages from environmental harm in general can be challenging. The harm can be very widespread, can include many victims, and can impact public resources and non-use values. This will be even more so in the cases of climate change and climate engineering. Yet, there are definitions of environmental harm in existing regimes of international environmental liability. Damage, according to the Draft Principles of the International Law Commission, includes 'loss of life or personal injury; … property, including property which forms part of the cultural heritage; … impairment of the environment; … costs of reasonable measures of reinstatement of the property, or environment … [and] of reasonable response measures'.[37] In the case of harm from nuclear accidents, damage is similarly defined, but the international agreements add the costs of preventative measures and economic losses, and they limit environmental damage to the economic losses arising from environmental impairment and reinstatement measures that are actually undertaken.[38] Therefore, although defining damage for liability from large-scale climate-engineering field research may be daunting, it is not unprecedented.

5 Proposing an Effective and Feasible Regime

Based upon the above analysis, I propose a system of international regulation of large-scale climate-engineering field research. The goals of this are, first, to

37 International Law Commission, 'Draft Principles on the Allocation of Loss in the Case of Transboundary Harm Arising Out of Hazardous Activities', in *Report of the International Law Commission, 58th Session, Official Records of the General Assembly*, A/61/10 (2006), principle. 2(a).

38 Convention on Supplementary Compensation, supra note 35, article. I.6; Protocol to Amend the Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, as Amended by the Additional Protocol of 28 January 1964 and by the Protocol of 16 November 1982 (opened for signature 12 February 2004), Article I.B. Note that the latter is not yet in force, and thus a narrower definition of damage is currently in effect for parties to the Paris Convention. See also Space Liability Convention, supra note 33, Article I(a); Civil Liability Convention, supra note 35, article. I.6; Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on Environmental Liability with Regard to the Prevention and Remedying of Environmental Damage, Article 2.1 (hereinafter European Environmental Liability Directive).

maximize social welfare by balancing the development of climate-engineering's potential through research, the prevention of harm from any negative side-effects, and the cost of such harm prevention, and, second, to provide compensation for victims. It also strives to be politically feasible, in the sense of offering net gains to all countries that should participate as parties. This proposal links procedural and general rules, an international compensation fund, and indirect state liability. This combination could be viewed from one perspective as limited, possibly vicarious, state liability with a duty-of-care defence and with residual damages covered by a compensation fund. However, it is perhaps better viewed as a compensation fund with limited, indirect, and possibly vicarious, state liability in the case of negligence. Although this strives to be a feasible policy proposal, I acknowledge the present low appetite for new multilateral environmental agreements. Therefore, the proposal can be considered as a hypothetical, ideal, starting point for future discussions.

This proposed combination is warranted because the characteristics described above variously point both toward, and away, from both liability and rules. The most important five factors are reiterated here. First, climate-engineering research currently appears to present a beneficial public good with a large value, despite posing transboundary risks. Holding the researcher (who, in any case, will lack sufficient assets) or the state fully liable would discourage the provision of this beneficial public good.[39] Second, climate-engineering research is a complex, technical subject that will continue to change rapidly. Regulators will find it difficult to craft detailed rules regarding what is required, permitted, and prohibited. Furthermore, if they were to attempt to do so, their rules would quickly become obsolete, as new methods were proposed. Importantly, it will be the researchers themselves—at least for the foreseeable

39 As an analogy, consider liability for harm from vaccines. A small percentage of those immunized will experience negative effects, sometimes quite severe. Yet immunization is not merely a matter of balancing the benefits and risks to oneself or one's family, but is also a beneficial public good, in that if a certain critical mass of a population remains unvaccinated, an outbreak may occur, particularly among those who cannot be vaccinated for particular health reasons. Holding researchers or manufactures strictly liable, assuming that they complied with a duty of care and were not negligent, would inhibit this public good. In response to the concern that civil suits were threatening the development and sale of vaccines, the US federal government established a public compensation fund supported by a tax on vaccines, providing compensation for those who suffer negative reactions, with no need to demonstrate fault. See Lainie Rutkow et al., 'Balancing Consumer and Industry Interests in Public Health: The National Vaccine Injury Compensation Program and its Influence During the Last Two Decades', 111(3) *Penn State Law Review* 681 (2006).

future—who will have the requisite knowledge regarding the risks posed by research in general and by a specific proposed project, and how to minimize these risks.[40] Third, a private insurance market appears to be almost impossible to develop, and a private risk-sharing pool among researchers would be insufficient and difficult to maintain. Fourth, given the history of international climate change negotiations and of disputes over transboundary harm, states that believe that they had been harmed by climate-engineering research would likely demand compensation. Even if such projects were widely understood as steps toward reducing climate change risks, the leaders and the residents of a harmed state would likely express deep dissatisfaction about remaining uncompensated. Finally, several conditions point to the advantages of states serving as both injurers and victims: the continuing primacy of states in international law; the greater assets of states; states' abilities to better control moral hazard, adverse selection, and free-riding among researchers; the non-commercial character of research (at least to date); the fact that projects would be state-sanctioned in some way; and the ease for victim states (relative to individuals) to perceive harm, to be aware of its possible cause, and to have sufficient incentive to take action.

Based upon the above analysis, I propose the following components of a multilateral agreement. It would establish general rules for research. These could include both the typical procedural obligations found under international environmental law—such as prior impact assessment, notification, consultation with potentially affected states, and cooperation in the event of harm—as well as the codification of some presently emerging norms for climate-engineering research—such as open publication of results, a prohibition on private patents on inventions that are essential for climate-engineering implementation (or perhaps, instead, the pooling or compulsory licensing thereof), public input in decision-making, and international coordination.[41] A standing committee would develop and regularly update recommendations as to how these general rules should be domestically implemented by parties that intend to fund field experiments above a certain threshold or to permit

40 Reliance upon the researchers does not imply complete self-regulation by them. Even in the absence of private intellectual property, they will have other personal interests. See Jane C. S. Long and Dane Scott, 'Vested Interests and Geoengineering Research', 29(3) *Issues in Science and Technology* 45 (2013).

41 The rules should remain general in the agreement, given the dynamic character of research. For emerging norms, see supra note 14. See also Robert Fair, 'Does Climate Change Justify Compulsory Licensing of Green Technology', 6(1) *International Law and Management Review* 21 (2009).

them to occur in (or over) their territory. These researching parties would be required to review and authorize proposed projects in a manner consistent with the agreement, and in a manner that considers the standing committee's advice. Thus, each project would have one or more authorizing states. In the case of a joint project with multiple authorizing states, they should agree beforehand on their relative proportions of responsibility.

Furthermore, all parties would establish and support a compensation fund, with their relative contributions based upon a mixture of their ability to pay, their historical greenhouse gas emissions, and their expected net benefit from climate engineering.[42] A portion of the fund could derive from international carbon-market mechanisms, such as taxes or permit auctions. In the event of harm from climate-engineering research, parties could claim damages for harm from the fund, but would forego any other international legal recourse. These claims would be bounded, in that harm must occur in a party's territory and would be limited in time and in scope, such as loss of life, injury, property damage, impairment of the environment, economic losses, and reasonable preventative and response measures actually taken or to be taken. However, the financial size of a claim would not be limited. An international expert panel would review claims and, using the best available methods, assess the probability that the research caused the harm, and if so, what portion of the harm. Awarded damages would be pro-rated to the probability of causation, but only above a certain probability threshold in order to discourage frivolous suits.[43] A victim would not need to demonstrate fault in order to be awarded compensation from the fund. The victim's contributory negligence, such as failing to practice due diligence and to take reasonable protective measures in light of expected and publicized consequences of field tests, could reduce or eliminate damages.

The expert panel would also review the domestic regulation and approval process of the authorizing state. If the injuring state complied with the agreement, it would not be held individually responsible. The state could be also exonerated in the event of, among other reasons, armed conflict or force majeure, or if the harm was due to a third party. Otherwise, an authorizing,

42 See Horton et al., supra note 5, for a defence of an international compensation fund for climate-engineering implementation based upon existing international environmental law.

43 See Steven Shavell, 'Uncertainty over Causation and the Determination of Civil Liability', 28(3) *Journal of Law and Economics* 587 (1985); Eberhard Feess, Gerd Muehlheusser, and Ansgar Wohlschlegel, 'Environmental Liability under Uncertain Causation', 28(2) *European Journal of Law and Economics* 133 (2009).

non-compliant state would be obligated to reimburse the fund up to some limited amount, perhaps on the order of several hundred million dollars.[44] Although this is not liability in the narrow sense of the injurer paying damages to the victim, it can be considered indirect liability, in that a negligent state would pay something akin to damages beyond its standard contribution to the fund. Of course, the state could choose to fine the researchers or to limit their future funding if they were at fault in some manner. In this way, the indirect liability could implicitly be fully or partially vicarious. Finally, the agreement should contain a mechanism for closing and disbursing the remaining compensation fund when certain conditions are met.

This proposed international regulation not only creates incentives to maximize social welfare while compensating victims, it would also be in the interests of all relevant states to participate in it. On the injurer side, the researching countries would be motivated to participate because the agreement would share, reduce, and clarify researching states' potential liability. The agreement would also give them political cover for a possibly controversial practice, particularly if many states that were vulnerable to harm from research were to also participate. As something like insurance, the compensation fund would face its own moral hazard and adverse selection among researching states, which could be managed and would likely not be a major problem. With respect to the former, the prospect of being responsible for full or partial reimbursement to the compensation fund would encourage researching states to exercise caution, such as through domestic implementation of the general and more specific rules, as well as appropriate review of proposed projects. This is akin to insurance with a high deductible in the event of fault, a mechanism frequently used to reduce moral hazard. Adverse selection would likely not be a problem because the benefits of lesser, shared 'liability' and of political cover would be appealing to researching states. However, one could imagine either a powerful researching state with little to lose in the way of reputation, or a particularly less responsible one, choosing not to participate. Within the participating researching states, the researchers would themselves similarly be motivated to comply out of fear of fines, funding restrictions, and stricter future domestic regulations, as well as their own reputational damage. The latter fear would be important, given the nature of international scientific research. The shared reputational character of research

44 Immediate compensation from a fund followed by possible reimbursement by injurers is somewhat like the US Comprehensive Environmental Response, Compensation, and Liability Act of 1980 ('Superfund') 42 U.S.C. §9601 et seq., and the European Environmental Liability Directive, supra note 38.

would further encourage scientists to monitor one another and to encourage compliance with rules and norms.

On the other side, the advantage for the potentially harmed states to participate is clear: they would have an agreed-upon avenue for full compensation in the event of demonstrated harm. They too would have incentives to take reasonable precautions, which would often bring the additional benefit of greater protection against extreme weather events and climate change itself. Meanwhile, all parties would contribute to compensation in proportions that appear to be roughly appropriate. Although compensation funds are typically supported by the injurers in proportion to their risk generation, in the case of climate engineering, the original source of risk is greenhouse gas emissions. Thus, a broader group of states should contribute. Here, the fund would face a free-rider problem of ensuring the participation of all relevant states. Those that, on the one hand, would benefit from climate engineering and its research or that contributed significantly to historical emissions but that, on the other hand, would not be vulnerable to field tests' negative effects or would not engage in research may not have sufficient incentive to become parties. Formal and informal linkage to other issues could help attract them to the agreement.

This proposal has precedents in international environmental law. For example, space law provides for strict state liability, in part because activities in space are performed, or must be authorized, by states.[45] The regime for nuclear accidents provides for three levels of liability: the operator is held liable up to a certain amount; beyond that the operator's state is liable up to yet another amount; and still beyond that all parties are collectively liable.[46] Additionally, the International Law Commission issued Draft Principles which, although not necessarily binding law, call for compensation for transboundary harm arising from hazardous activities, through mechanisms including liability, industry-wide compensation funds, and state payment of residual damages.[47]

One further possible gap would be compensating victims in a state that either does not participate in the agreement or that does not pursue a claim. This may be due to an undemocratic government that fails to represent the interests of its citizens. Of course, this is a much larger problem than can be addressed here. Nevertheless, the agreement could have a provision for class action by individuals who claim harm. This, though, would grant private actors

45 Supra note 33.

46 Supra note 35.

47 International Law Commission, supra note 37, principle 4.

unprecedented standing in international public legal processes and may open the door to excessive or frivolous claims.[48]

A concern could be that this proposal is contrary to the general rule of strict liability for ultra-hazardous activities. However, note that, as with strict liability, victims would be fully compensated independently of whether the injurer practised a duty of care (assuming some significant probability and portion of causation, and low contributory negligence). The standard of care would only be relevant insofar as determining whether the state would be required to further reimburse the compensation fund. Furthermore, some scholars argue for the advantages of a negligence rule for liability from development risks.[49]

An obvious challenge to implementing such a compensation agreement is the attribution of an extreme weather event to climate-engineering field research, whether a particular project or the activity in general. However, there are strong arguments grounded in efficiency and justice for an international compensation fund for harm from climate change itself, or even from a wide array of natural disasters.[50] That is, compensating a country from the fund for harm from climate-engineering research for harm that was actually due to climate change or a natural disaster may be acceptable. This could be limited to 'accidental' mis-attributions, or the agreement could even be broadened to explicitly include harm from climate change and extreme weather events. This would remove the challenge of attribution. On the other hand, widening the purview of the agreement would make it more contentious, less likely to come into effect, and potentially more difficult to administer.

I wish to consider but reject three possible variations on the suggested agreement. As a first alternative, it could encourage abatement by making parties' relative contributions to the compensation fund also a function of whether they met internationally agreed-upon abatement targets. However, the targets are politically negotiated and often controversial, and such a mechanism could discourage participation in the compensation agreement while encouraging the further manipulation of abatement targets. A second alternative is that states could be motivated to participate by giving parties some sort

48 Excessive or frivolous claims by the parties themselves would be discouraged by the traditional mechanisms of international relations, such as the prospects of reputational damage, reciprocation, and retaliation.

49 Skogh, supra note 27.

50 See Detlef F. Sprinz and Steffen von Bünau, 'The Compensation Fund for Climate Impacts', 5(3) *Weather, Climate, and Society* 210 (2013); Maxine Burkett, 'Rehabilitation: A Proposal for a Climate Compensation Mechanism for Small Island States', 13(1) *Santa Clara Journal of International Law* 81 (2015).

of capacity over future decision-making on climate-engineering implementation.[51] I believe, though, that implementation remains too distant and uncertain to actually motivate states. Third, the agreement could, in theory, be expanded to address harm from climate-engineering implementation. However, the circumstances and incentives regarding implementation will differ from those in the research context. And for each of the last two suggested variations, how countries, individually or collectively, may wish to implement and govern climate-engineering implementation remains unclear. In fact, as discussed above, an advantage of the agreement proposed here is that it sets aside this matter, which is contentious but not yet urgent. In the meantime, it would be preferable if field research could proceed in a responsible, socially optimal manner, and if any victims of its negative effects could be compensated.

Finally, although this proposal strives to be feasible in the sense that all the necessary countries would benefit, or at least not lose, by ratifying it, I recognize that the actual likelihood for such an agreement materializing is small, at least in the short term. This is due to, among other things, the costs of developing it, and a general low desire among states for new international environmental agreements. However, climate engineering itself has gone, in less than ten years, from being considered taboo to being the subject of serious consideration among academics and within certain segments of the climate change community. There is a reasonable scenario leading to large-scale field tests, and possible harm from these would likely be a contested issue. The suggestion for an optimal, feasible regime to compensate for harm may serve as a focal point in any future deliberations over climate engineering, its research, and their negative effects.

This article is premised upon an assumption that climate-engineering field research would not only be a public good, but also a beneficial one. The validity of this assumption relies upon at least two specific future developments. The first is that outdoors research will be able to proceed in reasonable and justified steps in terms of scale, perturbation, and the risks generated. This depends upon both the ability of researchers to design informative, low-risk experiments, and the underlying physical reality of the natural world. The second is that such research is carried out responsibly, in the interests of a broad global public, and consistent with social and legal norms. This remains largely within the sphere of human agency. Scientists, policymakers, and other involved actors can—and arguably have a duty to—act in a manner that maximizes the probability of this path. Compensation for harm as part of a wider international regulatory regime will be necessary for this.

51 This is inspired in part by Edward A. Parson, 'Climate Engineering in Global Climate Governance: Implications for Participation and Linkage', 3(1) *Transnational Environmental Law* 89 (2013).