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#### **Toward ethical norms and institutions for climate engineering research**

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**Abstract.** Climate engineering (CE), the intentional modification of the climate in order to reduce the effects of increasing greenhouse gas concentrations, is sometimes touted as a potential response to climate change. Increasing

interest in the topic has led to proposals for empirical tests of hypothesized CE techniques, which raise serious ethical concerns. We propose three ethical guidelines for CE researchers, derived from the ethics literature on research with human and animal subjects, applicable in the event that CE research progresses beyond computer modeling. The Principle of Respect requires that the scientific community secure the global public's consent, voiced through their governmental representatives, before beginning any empirical research. The Principle of Beneficence and Justice requires that researchers strive for a favorable risk–benefit ratio and a fair distribution of risks and anticipated benefits, all while protecting the basic rights of affected individuals. Finally, the Minimization Principle requires that researchers minimize the extent and intensity of each experiment by ensuring that no experiments last longer, cover a greater geographical extent, or have a greater impact on the climate, ecosystem, or human welfare than is necessary to test the specific hypotheses in question. Field experiments that might affect humans or ecosystems in significant ways should not proceed until a full discussion of the ethics of CE research occurs and appropriate institutions for regulating such experiments are established.

**Keywords:** climate engineering, geoengineering, ethics, research ethics, governance

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## 1. Introduction

Climate engineering (CE), the intentional modification of the climate in order to reduce the effects of increasing greenhouse gas concentrations, is sometimes touted as a potential response to climate change, either alone or as a supplement to emissions mitigation and adaptation. The feasibility and the wisdom of CE have been much debated in a hypothetical context [1–22]. An increasing focus on the topic on the part of climate scientists, engineers, and policymakers has led to proposals for empirical tests of hypothesized CE techniques [9, 10, 23], including planetary-scale experiments. The Royal Society's recent report on climate engineering encourages further research on the topic, and a report by a separate committee of senior scientists proposes a concerted decade-long research program, including field tests of stratospheric aerosol injections [24, 25].

CE research raises serious ethical questions. Large-scale trials of some CE techniques, such as the injection of aerosols into the stratosphere, could affect vast numbers of people in potentially dangerous ways. Today, society questions or condemns as unethical and immoral behavior the actions of past generations of researchers who thought it would be acceptable to endanger people and ecosystems for various scientific purposes related to the welfare of the general public. Examples include people and ecosystems near nuclear weapons testing sites [26–28] and poor rural African–Americans subject to medical experiments [29, 30], among others. Unless we give serious consideration to the ethical dimension of CE research now, we may find future generations looking back at our actions in the same way, repulsed by the nonchalance with which CE researchers experimented with the climate.

The purpose of this letter is to develop a basic framework for discussion of the ethics of CE research, as distinct from the ethics of actually implementing CE. To that end, we propose a set of norms to guide decisions about which large-scale CE experiments, if any, would be ethically acceptable. We also highlight a number of important normative questions that are too big to answer here but must be addressed in deciding how to implement those norms, as well as some preliminary ethical concerns about doing any CE research at all.

We see discussion of norms for conducting CE research as part of a larger discussion about whether society ought to conduct any CE research. We do not assume that such research is ethically acceptable, much less necessary, but we believe that it is important to discuss these norms now for two reasons. First, such discussion may reveal that there would be no ethical way to conduct CE experiments that affect the climate (as opposed to modeling or engineering studies). Second, if society proceeds with such CE research, it would be preferable if discussion of ethical norms for that research were to stay ahead of the research itself. Developing the norms without doing the CE research would be harmless; doing the research without developing the norms might not be.

## 2. Types of CE and CE research

For the purpose of this letter, we distinguish four strategies for limiting or coping with climate change: *abatement* of greenhouse gas emissions, *adaptation* to ongoing climate changes, *longwave CE* (LWCE), and *shortwave CE* (SWCE). We further distinguish between *implementation of CE* and *CE research*, and we recognize three types of CE research: *modeling*, *engineering*, and *climatic*.

We define abatement as limiting climate change by slowing or reversing the growth of greenhouse gas emissions, adaptation as limiting the impact of climate change without altering the climate itself, and CE as intentional measures to offset the climatic effects of increasing greenhouse gas concentrations. LWCE involves measures designed to capture and sequester atmospheric greenhouse gases, thereby reducing the amount of outgoing longwave radiation that is retained by the atmosphere [31], whereas SWCE includes measures designed to reduce the absorption of incoming solar radiation. (We use the terms 'abatement' and 'LWCE' in lieu of the term 'mitigation', which sometimes combines the two.)

An example of LWCE is the creation of large, long-lived carbon sinks on land or in the ocean, as might be achieved through significant afforestation [32] or through the direct air capture of CO<sub>2</sub> [33]. A prominent example of SWCE is the injection of scattering aerosols such as

sulfate into the stratosphere to increase planetary albedo [22]. The distinction between LWCE and SWCE is normatively important because LWCE attempts to either slow or reverse changes in a system (the global carbon cycle) that has already undergone large anthropogenic perturbations, whereas SWCE seeks to produce a novel state that maintains high concentrations of greenhouse gases while attempting to limit their climatic effects. Because it aims at an atmospheric state of which we have limited knowledge, SWCE is riskier. From a practical perspective, the two activities are also distinct because Earth's carbon reservoirs are large and the consequences of any particular LWCE experiment will therefore be minor on a global scale, whereas a single SWCE experiment could produce significant regional or global climatic effects relatively quickly.

We define 'CE research' to be any CE activity whose *primary purpose* is to test specific hypotheses about the effects of one or more CE interventions. Thus, the difference between CE research and CE practice lies in the intentions of those carrying out the CE activity. For instance, scientists who launch aerosols into the stratosphere with a primary intention of cooling the globe are implementing CE, whereas scientists who launch those same aerosols with a primary intention of measuring their effects are conducting CE research. Our method of distinguishing research from implementation parallels the distinction between medical research and medical practice drawn in the Belmont Report [34], a classic statement on the ethics of research with human subjects. As in the case of medicine, there is not always a bright line between research and practice. The distinction is normatively significant, however, because climate engineers would need to maintain their CE activity indefinitely in order to fulfil their intentions, whereas CE researchers need not.

Finally, we distinguish between three kinds of CE research: modeling, engineering, and climatic. Modeling studies have no potential for environmental impacts and raise ethical concerns only regarding allocation of resources. Engineering studies, such as experiments testing the atmospheric lifetimes of different reflective aerosols, employ CE technologies at scales too small to have a climatic impact. Such studies may have environmental impacts and raise ethical issues akin to other research utilizing potentially hazardous materials, as well as issues related to the creation of technologies enabling an ethically ambiguous activity. They do not, however, raise the same concerns as climatic studies, which aim to determine the climatic response to climate engineering and therefore could have widespread impacts on both human populations and the biosphere. Modeling studies are currently ongoing, and the decadal research program proposed in [25] includes both engineering and climatic aspects.

This letter focuses on the ethical concerns surrounding climatic SWCE research, which we believe must be addressed before any such studies take place. In the spirit of the 1975 Asilomar Conference on Recombinant DNA Molecules, which established basic principles governing genetic engineering research prior to the blossoming of the field, we urge that a serious discussion including not just scientists but also ethicists, legal and policy experts, and other stakeholders precede any SWCE research program that extends beyond the modeling stage. We hope that norms like the ones we propose here will become entrenched both in the scientific community and in national and international laws, as has happened in varying degrees with norms governing research in medicine [35, 36] and the social sciences [37], research on animals [38], and various kinds of biotechnology research [39, 40].

### 3. Preliminary ethical concerns about SWCE research

There are four ethical reasons to worry about performing climatic SWCE research at all, over and above its effects on humans, animals, and ecosystems. First, pursuing SWCE solutions to climate change may create a moral hazard, exacerbating the challenge of mitigating emissions [6, 8, 12, 16, 22]. Second, SWCE research may lead to development of technologies that could be used for nefarious purposes [1, 6, 16]. Third, beginning SWCE research in earnest may create interest groups within scientific or business communities that would have strong incentives to push for SWCE (or at least SWCE research) even if it turns out to be unwise [4, 22]. Finally, money spent on SWCE research is unavailable for other kinds of research, such as on the mitigation of or adaptation to climate change.

With regard to the moral hazard, unless scientists take great care in what experiments they do, what they publish, and how they explain their work, the public and policy makers may develop an optimistic bias in their assessment of SWCE's possibilities [12]. If this happens, hope for a technological fix for climate change may cripple efforts to limit greenhouse gas emissions. SWCE has been considered and sometimes even advocated as a substitute for abatement policies [2, 15, 41, 42]. This is particularly troubling because SWCE strategies are not long-term solutions to climate change: a decision to rely upon them to cool a world with high greenhouse gases concentrations would represent a long-term commitment that would require both effort and expense to maintain. If that maintenance were to stop before greenhouse gas concentrations were reduced, a process that will take centuries to millennia in the absence of augmentation by direct air capture technologies [43], rapid warming would swiftly ensue [44, 45]. Furthermore, no existing SWCE proposal can counteract every negative consequence of increasing greenhouse gas concentrations, and all known proposals have side effects, leading some commentators to suggest that a 'cocktail' of interventions would be needed to keep the environment in balance [18, 20]. Thus, by making it harder to implement a fundamental solution to the problem of climate change, undertaking any SWCE research may pose a risk to the long-term welfare of the planet. It is possible, however, that the opposite could happen, since research may reveal that SWCE is unworkable and that we have no practical alternative to mitigation and adaptation.

Furthermore, the technologies developed or made possible through SWCE research may be deployed in ways intended to cause harm. We can foresee some of these ways, but not all. Solar shades placed in geostationary orbit would be potent offensive weapons against any target [6]. Some SWCE technologies have only regional effects and others have different effects on different regions, making possible strategic military uses. The US Defense Advanced Research Project Agency has expressed interest in SWCE [46], presumably because it recognizes these possibilities. Furthermore, the relative ease and affordability of SWCE mean that a rogue state, a terrorist group, or even a disgruntled billionaire could effectively hold the world for ransom. If it paves the way for potentially dangerous technologies, SWCE research would create new dangers even if no SWCE intervention is ever implemented.

Perhaps the most worrying issue at this early stage is that the initiation of serious SWCE research would create interest groups that have strong incentives to continue SWCE research and even implementation. The first interest group would consist of scientists who have devoted significant portions of their careers to SWCE [4]. A secondary group might arise with significant commercial interests in SWCE [22]. Either of these groups would resist efforts to abandon SWCE research, and they might push for SWCE implementation even if it proves to be unwise. Thus, it would be naïve to think that, once SWCE research is undertaken, it could be terminated promptly if proven undesirable.

In many scientists' minds, these worries are outweighed by the need for better information about SWCE [5, 10]. There may come a time, goes the argument, when SWCE is society's only option for averting climate disaster. In order to ensure that society knows enough to deploy SWCE effectively, should the need arise, we need to begin doing SWCE research now. This argument has been challenged on numerous grounds [47], but

its prominence in scientific circles underwrites our assumption that climatic SWCE research may occur in the near future.

For the purposes of this letter, however, we focus not on the important and difficult question of whether SWCE research is justifiable in the abstract but instead on the consideration of ethical norms that should constrain any climatic shortwave SWCE experiments that may be proposed.

#### 4. Norms for climate engineering research

Once it progresses from computer modeling and engineering research into climatic experiments, SWCE research acquires the same ethically dubious features as research on human and animal subjects. It exposes humans, animals, and ecosystems to potentially serious risks in ways that could be coercive or exploitative<sup>Noted</sup>. Though SWCE research differs from canonical cases of ethically dubious biomedical research in that its effects on humans and animals are indirect, the potential severity of its effects merits the application of ethical norms similar to those governing biomedical studies. We suggest that SWCE research is, in this respect, similar to nuclear weapons testing, in which an experiment's indirect effects are dangerous enough to be ethically significant [27].

Scientists have developed a number of basic norms to guide research on human subjects, as well as some principles for research involving animals, which can be extended to encompass SWCE research. These basic principles are expressed in the US Government's Belmont Report [34] and in Russell and Burch's *The Principles of Humane Experimental Technique* [48], among other sources (see [35]).

The Belmont Report enumerates three basic principles for research involving human subjects: (1) *respect* for persons, (2) *beneficence*, and (3) *justice*. As it is usually interpreted in the research ethics literature, respect for research participants requires respecting their autonomy by securing their informed consent prior to their participation [34]. Beneficence requires that 'risks to subjects [their families, and society at large] be outweighed by the sum of both the anticipated benefit to the [individual] subject, if any, and the anticipated benefit to society in the form of knowledge to be gained from the research' [34]. When the expected benefit to society is great enough, 'interests other than those of the [individual] subject may on some occasions be sufficient by themselves to justify the risks [to the individual] involved in the research, so long as the subjects' rights have been protected' [34]. For example, phase I drug trials, which are intended to test the safety rather than the efficacy of new drugs, provide greater benefit to society than they do to the subjects involved [35]. In any case, however, 'the risks and benefits affecting the immediate research subject... carry special weight' [34]. Finally, justice requires that the costs and benefits of the research be fairly distributed.

While no analog of the Belmont Report exists for research involving animals, Russell and Burch advocate three widely-cited principles: (1) *replacement* of animals by non-animals when possible, (2) *reduction* in the number of animals used, and (3) *refinement* in the way(s) that animals are used to minimize the impact on them. Together, these principles dictate that researchers use as few animals and inflict as little suffering on those animals as is needed to test a specific hypothesis. For instance, a study on disease may reduce the number of animals involved by using greater statistical sophistication, and it may refine its treatment by euthanizing the animals as soon as possible, rather than allowing a painful terminal disease to run its course [38].

Few of these principles apply straightforwardly to SWCE research, but there are ways for SWCE researchers to respect the basic values behind them.

##### 4.1. Respect for persons

Applying the principle of respect for persons, as it is typically interpreted in the literature, requires respecting persons' autonomy in deciding whether to participate in a particular study. Respecting persons' autonomy would be particularly challenging for SWCE researchers. Climatic experiments, such as the injection of aerosols into the stratosphere, could affect the climate at regional or global scales. Such experiments would therefore affect anywhere from tens of millions to billions of people. Some would affect every person on Earth. The nature of these experiments effectively precludes individuals from opting out. It would therefore be impossible for SWCE researchers to comply with a strict demand that they obtain individual informed consent from everyone affected by the experiment. The only practicable alternative that we see is to obtain informed consent from representatives of those affected and to create procedural safeguards designed to protect the rights of the individuals affected.

One major question for future discussion is whether representative consent is ethically sufficient in this case. This question raises difficult political questions about the kinds of decisions that national and international representative bodies have the authority to make on behalf of their constituents. It is widely accepted that a representative government may, without universal consent from its citizens, make decisions that have serious consequences for the well-being of all or part of its population. Examples include decisions about military, economic, environmental, and health care policy. It is beyond the scope of this letter to determine whether this authority extends to decisions by international bodies on issues relevant to SWCE research. Thus, while we will work with the operating assumption that, given the proper institutions, some form of representative consent may be ethically sufficient for SWCE research, we recognize that this assumption might be false. If it is, then climatic SWCE research, in the current context, would be ethically unacceptable.

The first step in achieving representative consent would be for the international community to agree on a set of parameters for SWCE experiments. These parameters, which might govern the duration of experiments, specific local and regional climate perturbations, acceptable levels of risk, etc, would need to be established through an international treaty, perhaps as a protocol negotiated under the United Nations Framework Convention on Climate Change. Such a treaty would constitute the international community's consent to the research. Ideally, the treaty would be ratified by every member state of the United Nations. Assuming that consensus would be difficult to achieve, one important question for further consideration is whether it would suffice if the treaty were ratified by some minimum proportion of states and individuals.

In order to ensure that any experiments fell within the range of these parameters, we urge the creation of two separate institutions to oversee any proposed SWCE research. We believe that existing institutions, such as those in universities or national governments, are insufficient because they do not represent the global public. The first would be an International Climate Engineering Research Review Board, perhaps housed within WHO or UNEP and resembling in function the Institutional Review Boards established within universities for the approval of research on human subjects. The Board would ensure that any proposed SWCE experiment falls within the parameters agreed upon by the international community. The Board would also perform or commission scientific reviews of any proposed experiment, in order to determine the scientific validity and importance of the experiment. These reviews would help the Board reach normative judgments about whether the study is important enough to

warrant the risks involved. Though there is no objective standard for making such judgments, existing ethical review panels make them routinely for other kinds of research, calling not only on scientists, but also on ethicists, lawyers, and representatives of the public [35, 49]. The second institution that would be needed would be an International Climate Engineering Research Coordination Board. This board would coordinate the different experiments that had been approved by the review board so as to prevent experiments from interfering with one another, potentially ruining them and exposing the global public to greater or different risks than they agreed to bear.

This is certainly an imperfect approximation of informed consent, but there are three counterbalancing considerations. The first is that existing processes are already altering the global climate regardless of anyone's consent. No one currently has the autonomy to 'opt out' of climate change. Establishing a range of permissible SWCE experiments is therefore an improvement, with respect to autonomy, over the current situation. (Some people may find this symmetry irrelevant because SWCE researchers would be altering the climate intentionally, whereas greenhouse gas emissions are incidental byproducts of the pursuit of other goals. This difference is known to be a psychologically important determinant of moral judgment [50], though its philosophical significance is disputed [51].) The second is that consent by political representatives resembles consent by proxy, which is sometimes recognized as an adequate substitute in medical ethics [35]. The third is that public policies frequently constitute social experiments, though the public expresses its consent only insofar as it elects specific leaders in order to have such policies enacted. The fluoridation of water, educational reforms, and restrictions on foods like salt or trans fats are all examples of such experimental policies. The public as a whole may be able to opt out of these experiments in the next election, but individuals can opt out only at significant expense. Even if such consent is sufficient at the national level, which it may not be, moving to the international level dilutes consent even further, since entire countries may find themselves unable to refuse or opt out of SWCE research.

The difficulty of respecting persons deserves to be center stage in the debate over the ethics of SWCE and SWCE research. Though there are ways to achieve some degree of respect for persons during SWCE research, they are far from perfect. They may not even be adequate and should be a focus of future ethical investigations.

#### 4.2. *Beneficence and justice*<sup>Note 5</sup>

Achieving a favorable, fairly distributed balance of risks and benefits would also be challenging for SWCE researchers. This is chiefly because initial SWCE experiments should, given the current uncertainties and risks involved in climatic experiments, be 'non-therapeutic'. That is, their primary intent should be to test scientific hypotheses, not to attempt to provide relief from the effects of increasing greenhouse gas concentrations [52].

As with any non-therapeutic research, the primary benefit of SWCE research would consist of knowledge gained. The people and ecosystems affected by climatic experiments, however, could face substantial risks. For instance, the injection of particles into the stratosphere could increase water stress due to regional changes in precipitation [44], adversely affect stratospheric ozone chemistry, reduce the productivity of solar power generators [16], and reduce yields in some kinds of crops by reducing photosynthesis [53]. Some of these risks mirror potential benefits to current generations, such as cooler temperatures, which might extend the lifetime of mountain glaciers and the water supplies dependent upon them, or increased yields in some kinds of crops and vegetation [53, 54], but it is important to note that even within current generations, the individuals who might benefit are not generally those who would bear the risks. Therefore, counting such potential benefits as direct counterweights to the risks of SWCE research, or seeking to enhance those benefits to offset greater risk, is ethically questionable. The legitimacy of doing so is another issue that merits further debate.

Also as with any other non-therapeutic research, the problem of balancing risks and benefits is made more difficult by the fact that the majority of the risks from the research fall on individuals who may not benefit significantly from it. The primary beneficiaries, if there are any, of SWCE research that is conducted in the next couple decades will be future persons. Some of those persons may be living now, but many are not. Many persons living now, who would bear the brunt of SWCE experiments' negative consequences, would not live to see any benefits from the research. This is particularly likely for persons living in countries where life expectancies are low and vulnerability to climatic change is high, as in many of the world's least developed countries.

There is currently no generally-accepted framework for weighing the social benefit of knowledge gained against the risks born by individual research subjects or for distributing risks and benefits across long time spans [35]. Recognizing the difficulty of this 'risk-knowledge calculus', research ethicists suggest that such judgments require the input of a wide, interdisciplinary range of experts, including ethicists, lawyers, and representatives of the community—which, in this case, would be the global community [49, 52]. This responsibility would lie with the International Climate Engineering Research Review Board.

In light of these challenges, those who would face the greatest risks and expect the least benefit deserve researchers' greatest ethical concern. Therefore, we advocate a maximin approach to the assessment of risk–benefit ratios. In designing studies, researchers should aim, as far as is possible given sound research design, to minimize the expected harm to those whose welfare is most negatively affected by the study. In identifying those expected to be 'worst off' in any given scenario, it is important to note that identical climatic changes will impact different people's welfare differently, depending on factors such as wealth, source of income, local environmental conditions, etc.

We also suggest that research funders allocate a portion of the study's funding to a climate adaptation fund [55–57]. Contributing to such funds would not only reduce risks by enabling more people to ward off or cope with some of the adverse impacts of SWCE experiments, but it would also distribute risks more fairly by transferring the financial burden of those risks from the global public to research funders. Funding adaptation to all climate-related damages in this way would sidestep scientifically and ethically difficult questions about the likelihood that a particular harm would have happened regardless of researchers' intervention in the climate.

There are two further complications that deserve careful consideration. The first is that some studies might create risks to individuals that cannot be offset by the studies' contributions to the greater good. The Belmont Report states that 'brutal or inhumane treatment' is 'never justified', and that risks to an individual can be outweighed by others' interests only 'so long as the subjects' rights have been protected' [34]. The subsequent research ethics literature provides little refinement of this broad requirement, but one oft-cited part of the United States Code of Federal Regulations (CFR) requires that non-therapeutic research on children present no more than 'a minor increase over minimal risk', where 'minimal risks means that the probability and magnitude of harm... anticipated in the research are not greater... than those ordinarily encountered in daily life' [58]. The notions



of 'minor increase' and 'harms ordinarily encountered in daily life' are left vague. (Research on children is an appropriate analog here because most affected individuals, like children, would have a limited ability to give informed consent, and would therefore merit special protection.)

Devising methods for applying these rough guidelines should be another high priority in future discussions of SWCE research ethics, though devising stricter rules would require the input of the international community. Applying the guidelines would require identifying a list of relevant rights and deciding what it means to protect those rights. As an illustration of the types of rights that the international community might choose to protect, SWCE experiments could endanger the lives, livelihoods, health, property, and personal security of individual around the world, all of which are guaranteed in the Universal Declaration of Human Rights [59]. The international community might operationalize the notion of protecting these rights by drawing on the notion of minimal risk. We might say that an SWCE experiment presents minimal risk if any arbitrary individual would face roughly the same degree of risk (with respect to the relevant rights) during that experiment as any other arbitrary individual would face (with respect to the relevant rights) if the study were not being conducted, within the limits of our abilities to determine and compare those risks.

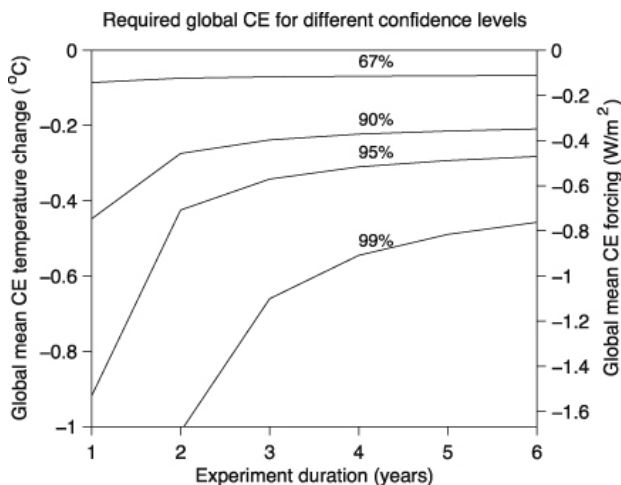
The second complication concerning beneficence and justice has to do with the impact of SWCE research on animals and ecosystems. Animals and ecosystems also stand to benefit and suffer from SWCE research, and as in the case of persons, different animals and ecosystems will face different risks and possible benefits from SWCE experiments. These risks are particularly difficult to capture in quantitative cost-benefit analyses, introducing further subjectivity into judgments about favorable risk-benefit ratios. This is a widely recognized problem in the evaluation of climate change impacts [60] and environmental economics generally [61]. We suggest that SWCE researchers draw on the quantitative and qualitative evaluation techniques discussed in [60] to address this problem.

### 4.3. Minimization

We combine Russell and Burch's principles for the use of animals in research—'replace, reduce, refine'—into a single Principle of Minimization. In order to minimize the impact on people and the environment, no study should last longer, cover a greater geographical area, or have a greater impact on the climate, ecosystem, or human welfare than is strictly necessary to test the hypotheses in question. The rationale behind this principle is that minimizing the extent and intensity of SWCE interventions minimizes risks. It also minimizes infringement of others' autonomy.

One major question concerning this principle is what metrics researchers should use to measure an experiment's effects on the climate, ecosystem, and human welfare. The standard metric for assessing the effects of shortwave SWCE interventions on the climate is radiative forcing, measured in  $W m^{-2}$ . We recommend that SWCE researchers draw on work done by the Intergovernmental Panel on Climate Change on criteria for identifying key impacts and vulnerabilities to climate change in assessing the intensity of an experiment's effects on the ecosystem and human welfare [62].

In many cases, conducting a smaller-scale experiment for a longer period of time can produce results as statistically significant as those produced by a larger experiment run for a shorter period of time. For instance, producing a global reduction in mean summer temperature distinguishable at the 95% confidence level from background variability would require a cooling of about 0.9 °C for one year, 0.4 °C for two years, or 0.3 °C for three years (figure 1). If climate sensitivity is near the median estimate of 3 °C warming per CO<sub>2</sub> doubling [63], then the one-year result would require an engineered forcing of  $-1.5 W m^{-2}$ —about equal in magnitude to 90% of the forcing currently produced by CO<sub>2</sub>. Assuming that longer but smaller experiments minimize net impact because they are less likely to cross dangerous thresholds, we suggest that researchers should be prepared to trade speed for reduction of harm in any climatic experiments conducted in the near future.



**Figure 1.** Magnitudes of engineered global cooling (for instance, as produced by global stratospheric aerosol loading) necessary to produce reductions in global mean June–July–August (JJA) temperatures distinguishable from background variability at different confidence levels. The GISTEMP surface temperature analysis indicates that the background variability of detrended JJA temperatures from 1981 to 2008 was characterized by a standard deviation of 0.15 °C. Estimates of forcing magnitude assume a climate sensitivity of 3 °C/CO<sub>2</sub> doubling. The confidence intervals are given by a *t*-distribution with *N* degrees of freedom, where *N* is the duration of the experiment.

## 5. Conclusions

Scientists may begin climatic SWCE research within the next decade or two. Such research merits careful ethical consideration. We propose that, if

such experiments should be done at all, they should be guided by three principles, derived from the ethics literature on research with human and animal subjects. The Principle of Respect requires that the scientific community secure the global public's consent, which would need to be voiced through their representatives and given for any studies within specified parameters, rather than on a case-by-case basis. The Principle of Beneficence and Justice requires that researchers strive for a favorable risk–benefit ratio and a fair distribution of risks and anticipated benefits, all while protecting the basic rights of the individuals affected. Finally, the Principle of Minimization requires that no study last longer, cover a greater geographical extent, or exert a greater influence on the climate than is necessary to test the specific hypotheses in question.

We see five outstanding questions about these principles. First, what representative bodies, if any, have authority to consent to SWCE experiments on behalf of the global public, and under what conditions is that consent ethically sufficient? Second, under what conditions, if any, does a 'maximin' approach to the distribution of risks, achieved partly by contributions to an adaptation fund, create a favorable, fairly distributed balance of risks and benefits? Third, which rights must be protected in the design of SWCE studies, and what would constitute adequate protection of those rights? Fourth, given the difficulties of assigning monetary values to many of the consequences of climate change and SWCE, how should SWCE's effects on the biosphere factor into judgments about the risk–benefit ratios of SWCE experiments? Finally, which metrics should be most important in guiding decisions about the minimization of experiments' impact on the ecosystem and human welfare?

The next steps in the development and implementation of these norms involve further discussion among scientists, ethicists, and the public about whether and how to carry out SWCE research, as well as discussion in the international diplomatic community about an agreement on parameters for acceptable SWCE research and institutions for ensuring compliance with that agreement. We strongly urge that this discussion and establishment of appropriate institutions precede any effort to move climate engineering research from computer models into the planetary environment, which at this juncture cannot be justified.

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## Notes

[Note4](#) In this context, 'coercion' is defined as compelling someone to face risks created by an experiment without obtaining their informed consent. 'Exploitation' is defined as the recruitment of research participants in such a way that it is difficult or impossible for them to refuse participation or to understand the nature of the research and the risks involved.

[Note5](#) Ethicists often contrast beneficence and justice. The former involves providing benefits to someone, regardless of whether that person deserves the benefits. The latter involves ensuring that someone gets what he or she deserves, regardless of whether that is beneficial to him or her. Because of the long time spans separating the risks and benefits of SWCE research, we believe that the goal of ensuring a favorable risk to benefit ratio (i.e., of acting beneficently) cannot be separated from the goal of ensuring a fair distribution of those risks and benefits (i.e., of acting justly). Thus, we treat beneficence and justice together under a single principle.

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