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"Geoengineering: Assessing the Implications of Large-Scale Climate Intervention"

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1. Summary

Climate change poses a real risk to Americans. The surest way to reduce this risk is to reduce emissions of greenhouse gases.

However, other options may also be available which could in some circumstances cost-effectively contribute to risk reduction. These options can be divided into two categories with very different characteristics:

- Solar Radiation Management (SRM) approaches seek to reduce the amount of climate change by reflecting some of the sun's warming rays back to space.

    - The most promising Solar Radiation Management proposals appear to be inexpensive (at least with respect to direct costs), can be deployed rapidly, and can cause the Earth to cool quickly. They attempt symptomatic relief without addressing the root causes of our climate problem. Thus, these methods do not address the problem of ocean acidification. While these approaches may be able to reduce overall risk, there is the potential that they could introduce additional environmental and political risk. Solar Radiation Management approaches have not yet been given careful consideration in international negotiations to diminish risks of climate change. The primary consideration governing whether such systems would be deployed is our level of confidence that they would really contribute to overall risk reduction.

- Carbon Dioxide Removal (CDR) approaches seek to reduce the amount of climate change and ocean acidification by removing the greenhouse gas carbon dioxide from the atmosphere.

    - The most promising of the Carbon Dioxide Removal approaches appear to be expensive (relative to SRM methods, but perhaps competitive with methods to reduce emissions), slow acting, and take a long time before they could cool the Earth. However, they address the root cause of the problem – excess CO2 in the atmosphere. There is no

expectation that these methods will introduce any new unprecedented risks. Some Carbon Dioxide Removal approaches associated with forests and agricultural practices have received attention in international negotiations and in carbon offsetting schemes. The primary consideration governing whether Carbon Dioxide Removal approaches would be deployed is cost relative to options to reduce greenhouse gas emissions.

We need multi-agency research programs in both Solar Radiation Management and Carbon Dioxide Removal. (Every agency that has something to contribute should be given a seat at the table.) Because Solar Radiation Management and Carbon Dioxide Removal approaches differ in so many dimensions, it seems unwise to link them closely together. In particular, Carbon Dioxide Removal approaches have more in common with efforts to reduce CO2 emissions than they have with Solar Radiation Management approaches.

- Solar Radiation Management research might best be led by agencies that have a strong track record in the highest quality science, with no vested interest in the outcome of such research, such as the National Science Foundation or perhaps NASA.

- Carbon Dioxide Removal research that focuses on storing carbon in reduced (organic) forms might best be led by agencies that are already involved in conventional Carbon Dioxide Removal methods involving agricultural or forestry practices. Carbon Dioxide Removal approaches which employ centralized chemical engineering methods to remove CO2 from the atmosphere might best be led by agencies, such as DOE, already involved in carbon dioxide capture from power plants. It is less clear where research into distributed chemical approaches might fit best, although leadership by the National Science Foundation is a possibility.

2. Background

Climate change represents a real risk to Americans.

It is increasingly obvious that modern industrial society is affecting climate. It is less clear how much this climate change will affect the average American. Nevertheless, it is reasonable to think that there is a significant risk that climate change will be more disruptive to our economy than a few million mortgage defaults.

Economists estimate that it might take 2% of our GDP to squeeze carbon dioxide emissions out of our energy and transportation systems. I believe that the risk is high that, if we continue to produce devices that dump carbon dioxide waste into the atmosphere, climate change will lead to problems that dwarf the subprime mortgage debacle. The recent subprime mortgage crisis, driven by defaults on several million mortgages, led to an approximately 4% reduction in worldwide GDP growth. Therefore, I believe a rational investor would invest 2% of our GDP to avoid this risk.

When I am speaking, I often ask:

If we already had energy and transportation systems that met our needs without using the atmosphere as a waste dump for our carbon dioxide pollution, and I told you that you could be 2% richer, but all you had to do was acidify the oceans and risk killing off coral reefs and other marine ecosystems, all you had to do was heat the planet, and risk melting the ice caps with rapid sea-level rise, risk shifting weather patterns so that food growing regions might not be able to produce adequate amounts of food, and so on, would you take all of that environmental risk, just to be 2% richer?

Nobody I have ever spoken with has said that all of this environmental risk is worth being 2 % richer. (Some years, I have gotten a 2% raise and barely noticed it.) So, I think we have to agree that the main issue with solving the climate-carbon problem is not the cost *per se* – it is that the cost is high enough to make it difficult to generate the necessary level of cooperation needed to solve the problem.

I do not know how much climate change will affect the average American. While I cannot with confidence predict great damage, I can predict great risk.

The carbon-climate problem is about risk management – and the best, surest, and clearest way to reduce environmental risk associated with greenhouse gas emissions is to reduce greenhouse gas emissions.

If you take the risk of climate damage seriously, you want to take action to diminish risk by reducing greenhouse gas emissions, but you would not want to limit yourself to only one risk-reduction approach.

There may be novel approaches that could also help us manage risk associated with greenhouse gas emissions. However, these novel approaches are poorly understood and have been inadequately evaluated. There has been a paucity of the kind of research and development that would let us understand the positive and negative properties of these approaches. These novel approaches are not alternatives to reducing greenhouse gas emissions; they are supplementary measures that might help us reduce the risk of climate-related damage. Some of them are approaches that America might need in a time of crisis.

3. Introduction to the concept of "*geoengineering*"

"Geoengineering" is a catch-all term, used to refer to a broad collection of strategies to diminish the amount of climate change resulting from greenhouse gas emissions. The term "geoengineering" is used in different ways by different authors and there is no generally agreed-upon definition, although features common to strategies referred to by the word "geoengineering" generally include:

(1) Intent to affect climate
(2) Affecting climate at a regional to global scale
(3) Novelty or lack of familiarity

Emitting CO2 by driving a car is not generally considered geoengineering because, while it affects global climate, there is no intent to alter climate. Planting a shade tree to provide a cooler local environment is not generally considered geoengineering because, while there is intent to alter climate, it is not at a sufficiently large scale. Promoting the growth of forests as a climate mitigation strategy involves an intent to affect climate at global scales; however, we are familiar with forest management, so this approach does not have the novelty that would cause most people to use the word "geoengineering" to refer to it.

The term "geoengineering" also has another meaning related to the engineering of tunnels and other structures involving the solid Earth. Furthermore, the term "geoengineering" has been applied to large scale efforts to alter geophysical systems, such as the old Soviet plan to reroute northward flowing rivers so that they would instead flow south towards central Asia.

Because "geoengineering" has been used by different people to refer to many different types of activities, and there is no single universally agreed definition, it is my opinion that the term "geoengineering" no longer has much use in informed discussions. More than that, use of the term "geoengineering" can have a negative influence on the ability to conduct an informed discussion, since there is little that can be said generally about such an ill-defined and heterogeneous set of proposals.

4. An introduction to the major "*geoengineering*" strategies

"Geoengineering" strategies can be divided into two broad categories:

(1) Solar Radiation Management (SRM) and related strategies that seek to directly intervene in the climate system, without directly affecting atmospheric greenhouse gas concentrations.

(2) Carbon Dioxide Removal (CDR) and related strategies that seek to diminish atmospheric greenhouse gas concentrations, after the gases have already been released to the atmosphere.

These two broad classes of strategy are so different, that they should be treated as being independent of each other. Solar Radiation Management approaches (SRM – can also be thought of as Sunlight Reflection Methods) attempt to limit damage from elevated greenhouse gas concentrations – these methods are designed to provide symptomatic relief. In contrast, Carbon Dioxide Removal strategies try to remove the atmospheric drivers of climate change – these methods are designed to address the root causes of our climate problem.

Solar Radiation Management proposals will inherently involve actions by governments, because the primary issues driving deployment of such approaches will involve questions of environmental risk reduction, equity, governance, and so on. (Of course, a clear scientific and technical basis needs to be developed to act as a foundation for these policy discussions.)

In contrast, Carbon Dioxide Removal proposals would likely be driven by actions of private corporations, because the primary factor driving deployment is likely to be a price on carbon emissions. If it is more cost-effective to remove carbon dioxide from the atmosphere than to prevent an emission to the atmosphere, and local environmental issues have been adequately addressed, then there will be an economic driver to remove carbon dioxide from the atmosphere.

Because the issues around Solar Radiation Management (and related approaches) differ so greatly from issues around Carbon Dioxide Removal (and related approaches), it is best to address these two classes of possible activities separately.

4.1 Solar Radiation Management (SRM) and related strategies

4.1.1. Overview of Solar Radiation Management

While proposals to intentionally alter climate go back a half century or more, relatively little research has been done on these strategies. Therefore, everything said about these approaches must be regarded as provisional and preliminary. The recent report on Geoengineering by the UK Royal Society provides a good summary of this preliminary research.

The sun warms the Earth. Greenhouse gases make it harder for heat to leave the Earth. With additional greenhouse gases warming the Earth, one way to cool things back down is to prevent the Earth from absorbing so much sunlight.

There are two classes of proposal that appear to be able to address a significant part, if not all, of globally averaged mean warming: (1) placing small particles high in the atmosphere to reflect sunlight to space or (2) seeding clouds over the ocean to whiten them so that they reflect more sunlight to space.

The leading proposal for reflecting large amounts of sunlight back to space is the emplacement of many small particles in the stratosphere. We have good reason to believe that such an approach will fundamentally work because volcanoes have performed natural experiments for us. It is thought that the rate of particle injection needed to offset a doubling of atmospheric CO2 content is small enough that it could be carried in a single fire hose. The determination of whether we would ever want to deploy such a system would not depend on cost of the deployment, but rather on an assessment of whether it was really able to contribute to overall risk reduction, taking both environmental and political factors into consideration.

In 1991, the Mt. Pinatubo volcano erupted in the Philippines, introducing a large amount of tiny particles into the stratosphere. This caused the Earth to cool by around 1 degree Fahrenheit. Within a year or two, most of this material left the stratosphere. Had we replenished this material, the total amount of cooling would have been more than enough to offset the average amount of warming from a doubling of atmospheric CO2 concentration.

There are questions about how good a short term eruption is as an analogue for a continuous injection of material into the stratosphere. Nevertheless, the natural experiment of volcanic eruptions give us confidence that the approach will basically work, and while there might be negative consequences, the world will not come instantly to an end, and that after stopping a short-term deployment, the world is likely to return to its previous trajectory within years.

Nobody should think that any Solar Radiation Management strategy will work perfectly. Sunlight and greenhouse gases act differently on the atmosphere. Sunlight strikes the surface of the Earth where it can both warm the surface and help to evaporate water. Greenhouse gases for the most part absorb radiation in the middle of the atmosphere. So, changes in sunlight can never exactly compensate for changes in greenhouse gases.

However, preliminary simulations indicate that it should be possible to offset most of the climate change in most of the world most of the time. Climate model simulations show that deflecting some sunlight away from the Earth can make a high CO2 world more similar to a low CO2 world at most times and at most places. However, the climate might deteriorate in some places. This raises important governance issues in that Solar Radiation Management approaches (or Solar Reflection Methods) have the potential to cause harm at some times in some places, even if they are able to reduce overall environmental damage and environmental risk.

4.1.2. Concerns relating to Solar Radiation Management

While there is some expectation that Solar Radiation Management approaches can diminish most of the climate change in most of the world most of the time, it is possible that there could be bad effects that would render this offsetting undesirable. These bad effects could be environmental, or they could be socio-political.

With regard to environmental negatives, it is possible there could be adverse shifts in rainfall, or damage to the ozone layer, or unintended impacts on natural ecosystems. These unintended consequences should be a major focus of a Solar Radiation Management research program. Furthermore, we must bear in mind that Solar Radiation Management proposals do not solve problems associated with ocean acidification (but they do not significantly affect ocean acidification).

With regard to socio-political negatives, some countries might actually prefer their warmer high CO2 climate or perhaps they might be (or believe they are) negatively impacted by a Solar Radiation Management scheme – or perhaps countries might differ in the amount or type of Solar Radiation Management to be deployed. These sorts of issues could cause political tension.

It is also possible that the perceptions that there is a technical fix could lull people into complacency, and diminish pressure for emissions reductions. However, when the UK Royal Society conducted a preliminary focus group, they found that people were even more willing to put effort into emissions reduction after hearing the extreme measures scientists are considering to reduce climate risk. Just because we wear seatbelts, that does not mean we will drive more recklessly. Seat belts can remind us that driving is a dangerous activity.

4.1.3. Governance, regulation, and when to deploy

4.1.3.1. Gradual deployments

Often, in discussions of Solar Radiation Management, there is an assumption that we are speaking about large scale deployments and some system of global governance is necessary. While discussions of governance and regulation of both experiments and deployments are necessary, it is not clear at this time what form that governance or those regulations should take.

For example, it is thought that sulfur emissions from power plants might today be reflecting about 1 W/m2 back to space that would have otherwise been absorbed by Earth. This could be causing the Earth to be about 1 degree Fahrenheit cooler than it would otherwise be. In other words, if we cleaned up all of the sulfur emitted by power plants worldwide, the Earth might heat up another degree.

Because sulfur lasts a year or more in the stratosphere but generally less than a week in the lower atmosphere, if we were to emit just a few per cent of the sulfur now emitted in the lower atmosphere into the upper atmosphere instead, we would get the same average cooling effect with a more than 95% reduction in overall pollution. What if China were to say, "For each power plant that we fit with sulfur scrubbers, we will inject a few percent of that sulfur in the stratosphere – and we will get the same average cooling effect with a greater than 95% reduction in our sulfur emissions."?

Today, ships at sea burn high sulfur oil. These ships can leave white contrails in their wake, reflecting sunlight to space. The International Maritime Organization has requested that these sulfur emissions be curtailed for reasons related to pollution and health – and the expected outcome is additional global warming. What if these ships were retrofitted with cloud seeding devices that would produce these same contrails, but without releasing any pollution? (It has suggested that a seawater spray would do the job.)

It is not clear whether these things would be good things to do or bad things to do. It is not clear what kind of governance or regulatory structures should be built around such activities. One reason why we need a research program and discussions about governance and regulation is so that we can make informed decisions about such issues.

4.1.3.2. Emergency deployments

While such gradual deployments might be one path to implement Solar Radiation Management schemes, there is another possibility.

In every emissions scenario considered by the Intergovernmental Panel on Climate Change, temperatures continue to increase throughout this century. Because of lags in the climate system and the long time scales involved in transforming our energy and transportation systems, the Earth is likely to continue warming throughout this century, despite our best efforts to reduce emissions. Our actions to diminish emissions can reduce the rate of warming and reduce the damage from warming, but it is probably already too late for us to see the Earth start to cool this century, unless we engage in solar radiation management (or related climate system interventions).

What if we were to find out that parts of Greenland were sliding into the sea, and that sea-level might rise 10 feet by mid-century? (Such rapid sea level rises apparently happened in the geologic past, even without the kind of rapid shock we are now applying to our climate system.) What if rainfall patterns shifted in a way that caused massive famines? What if our agricultural heartland turned into a perpetual dustbowl? And what if research told us that an appropriate placement of tiny particles in the stratosphere could reverse all or some of these effects?

That was a lot of “what if’s”, but nevertheless there is potential that direct intervention in the climate system could someday save lives and reduce human suffering. Moreover, direct intervention in the climate system might someday save lives and reduce suffering of American citizens. I do not know what the probabilities of such outcomes are, but I believe that if we take the risks associated with climate change seriously, we must investigate our options carefully and without prejudice.

We do not want our seat belts to be tested for the first time when we are in an automobile accident. If the seat belts are not going to work, it would be good to know that now. If there is something really wrong with thoughtfully intervening in the climate system, we should try to find that out now, so that if a crisis occurs, policy makers are not put in the decision of having to decide whether to let people die or try to save their lives by deploying, at full scale, an untested system.

We need the research now to establish whether such approaches can do more good than harm. This research will take time. We cannot wait to ready such systems until an emergency is upon us.

4.1.3.3. Building governance and regulatory structures

We should proceed cautiously in developing governance and regulatory structures that could address Solar Radiation Management approaches both in the deployment phase and in the research phase.

At this point we know very little. It is very easy to sound as if you are taking the moral high ground by saying, “It is wrong to intentionally intervene in the climate system, so it should be disallowed.” However, every simulation of a Solar Radiation Management method that used a “reasonable” amount of solar offsetting has found that there is potential to offset most of the climate change in most places most of the time. If we really believe that climate change has the potential to cause loss of life and suffering, and we believe that Solar Radiation Management approaches may have the potential to cost-effectively reduce that loss of life and suffering, it could be immoral not to research and develop these options.

Information on Solar Radiation Management approaches is at this point highly preliminary and has not been widely disseminated. Pushing too early for formal agreements may lock political entities into hard positions that will be difficult to modify later. Therefore, what is needed now for governance is a period of discussion, careful consideration, and learning.

With respect to experiments, no additional regulation is needed for small scale field experiments designed to improve process understanding where there is no expectation of any detectable lasting effects and no detectable trans-boundary effects.

Discussions need to begin about how to develop norms that might govern larger experiments where there is potential for detectable climate effects or where significant trans-boundary issues must be addressed.

Since these larger experiments and deployments could affect people in many countries, it is important that these discussions occur both internationally and domestically. Initially, it is probably best if these discussions proceed informally, perhaps with the facilitation of scientific unions or professional organizations.

In short, we need to do the informal groundwork now, so that we can develop the shared understanding that is necessary for the development of good governance and regulatory structures.

4.1.4. Additional Solar Radiation Management strategies

While this discussion has focused on introducing small particles high in the atmosphere, a number of other approaches have been proposed that attempt to reduce the amount of climate change caused by increased greenhouse gas concentrations in the atmosphere. These include proposals to whiten clouds over the ocean, to mix heat deeper into the ocean, to whiten roofs and roads, to put giant satellites in space, and so on.

For a number of reasons, I believe that placing small particles high in the atmosphere is the most promising category of Solar Radiation Management approaches. However, approaches to whiten clouds over the ocean or mix heat downward into the deep ocean, both appear feasible and may be able to be scaled up to offset a large fraction of century-scale warming. Of these two options, whitening marine clouds seems more benign, but neither of these approaches has been subject to sufficient scrutiny.

Most other proposed Solar Radiation Management (and related) approaches, either cannot be scaled up sufficiently (e.g., proposals to whiten roofs and roads) to be a “game changer”, or cannot be cost-effectively scaled up quickly enough (e.g., massive satellites placed between the Earth and Sun) to make a difference this century.

4.1.4. Institutional arrangements for research

Within the United States, agencies such as National Science Foundation or NASA might be in the best position to lead research into Solar Radiation Management, although DOE, NOAA, and other agencies also may have important roles to play.

It is important that this research be internationalized and conducted in as open and transparent a way as possible.

While laboratory and small scale process studies in the field need no additional regulation at this time, larger scale field studies will require some form of norms, governance, or regulation. Discussions need to take place, both domestically and internationally, to better understand how to strike the best balance between allowing the advancement of science and technology while safeguarding our environment.

4.2 Carbon Dioxide Removal (CDR) and related strategies

We emit greenhouse gases to the atmosphere, causing the Earth to warm. Is there potential to actively remove these gases from the atmosphere?

The answer is, ‘yes, we are confident that there are ways to remove substantial amounts of carbon dioxide from the atmosphere.’ By addressing the root cause of the climate change problem (high greenhouse gas concentrations in the atmosphere), Carbon Dioxide Removal strategies diminish climate risk. They also reduce ocean acidification. Carbon dioxide removal methods do not introduce significant new governance or regulatory issues.

I would suggest that within the domain of Carbon Dioxide Removal there are at least two, and possibly three or more, relatively independent research programs.

Because Carbon Dioxide Removal approaches represent a miscellaneous collection of approaches, there is no one taxonomy that would uniquely classify all of these proposals. Nevertheless, Carbon Dioxide Removal approaches can be divided into two categories:

- Strategies that use *biological approaches* (i.e., photosynthesis) to remove carbon dioxide from the atmosphere and store carbon in a reduced (organic) form.
- Strategies that use *chemical approaches* to remove CO2 from the atmosphere.

Biological approaches may be subdivided in several different ways, but one way is to divide them into land-based and ocean-based approaches. Proposed land-based biological approaches include planting forests, changing agricultural practices to result in more carbon storage, and burying farm waste. All of these methods are limited by the low efficiency of photosynthesis, and thus require significant land area, although in some cases this land can be multi-use. Many of these approaches are already the subject of considerable study and are already being considered in discussions about how to limit climate change. Current research indicates that biologically-mediated carbon storage in the ocean is problematic in several dimensions, and is not likely to represent a significant contributor to solving our climate change problems.

Chemical approaches may be divided into two categories: centralized approaches and distributed approaches. Centralized approaches seek to build industrial chemical processing facilities to remove carbon dioxide from the atmosphere and store it in a form that cannot interact with the atmosphere. The most promising avenue appears to be to store the carbon dioxide underground in compressed form, as with conventional carbon capture and storage. Distributed approaches seek to spread chemicals over large areas of the land or ocean, where they can react with carbon dioxide and cause the carbon dioxide to be removed from the atmosphere.

There are additional hybrid approaches that do not fit easily into this taxonomy. For example, it has been suggested that plants could be grown and then burned in power stations to generate electricity, and then the CO2 could be captured from the power stations and stored underground.

More thought needs to be put into finding institutional homes for these research elements. While all of these research efforts are likely to require multi-agency input, it is likely that research into biologically based methods might best be led by agencies that have strong track records in the biological sciences or experience with agriculture and forestry issues. Research into the centralized chemical approaches might best be led by DOE, but this is uncertain.

5. Closing comments

Solving our climate change problem is largely about cost-effective risk management. There are many different ways that risk might be diminished. The most important of these is to diminish greenhouse gas emissions. However, we also need to improve our resilience so that we can better adapt to the climate change that does occur. We also need to understand whether there are ways that we can cost-effectively remove carbon dioxide and perhaps other greenhouse gases from the atmosphere. Lastly, we should try to understand whether a thoughtful intentional intervention in the climate system might be able to undo some of the damage of a thoughtless unintentional intervention in the climate system. This problem is too serious to allow prejudice to take options off the table.

Geoengineering to Shade Earth

Ken Caldeira

In June 1991, Mount Pinatubo in the Philippines erupted explosively—the biggest eruption of the twentieth century. The volcano created a column of ash and debris extending upward 40 kilometers (about 25 miles). The eruption ejected around 20 million tons of sulfur dioxide into the stratosphere, where it oxidized to form sulfate dust particles. The stratosphere is the part of the atmosphere that is higher than where jets normally fly.[1]

As a result, about 2 percent of the sunlight passing down through the stratosphere was deflected upward and back into space. The dust particles were big enough to scatter sunlight away from Earth but small enough to allow Earth's radiant heat energy to escape into space. Earth cooled about half a degree Celsius (almost 1 degree Fahrenheit) the following year, despite the continued increase in greenhouse gas concentrations. This raises an obvious question: Could we similarly put dust into the stratosphere to offset climate change?[2]

Earth is heated by sunlight and cooled by the escape of radiant heat into space. Earth's atmosphere is relatively transparent in the wavelengths that make up sunlight but somewhat opaque in the wavelengths that make up escaping radiant heat energy. As greenhouse gases accumulate, the atmosphere becomes more opaque to outgoing radiant heat. With greater amounts of radiant heat trapped in the lower atmosphere, Earth's surface warms.[3]

The most obvious approach to keeping Earth cool is to reduce greenhouse gas concentrations in the atmosphere, so that heat energy can escape more easily into space. But another strategy involves reducing the amount of sunlight absorbed by Earth. If greenhouse gases accumulating in the atmosphere are like closing the windows of a greenhouse and trapping heat inside, then "geoengineering" approaches seek to keep Earth cool by putting the greenhouse partially in the shade. They try to reverse warming by preventing sunlight from being absorbed by Earth.[4]

A number of modeling and theoretical studies have looked into such climate engineering schemes. The consensus appears to be that these will not perfectly reverse the climate effects of increased greenhouse gases but that it might be technically feasible to use geoengineering to reduce the overall amount of climate change. Obviously, however, these schemes would not reverse the chemical effects of increased carbon dioxide (CO_2) in the environment, such as ocean acidification or the CO_2-fertilization of land plants.[5]

Several approaches have been suggested for deflecting sunlight away from Earth. The most science-fiction scheme would be to place sunlight-blocking satellites between Earth and the sun. But in order to compen-

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sate for the current rate of increases of greenhouse gases in the atmosphere, governments would need to build and put in place more than a square mile (about 3 square kilometers) of satellite every hour. Most people would probably agree that such an enormous effort would be better applied to reducing greenhouse gas emissions.[6]

The placement of sulfur dust particles in the stratosphere appears to be the leading candidate for most easily engineering Earth's climate. (Numerous other approaches have been suggested, including some designed to increase the whiteness of clouds over the ocean with sea salt particles formed by spraying seawater in the lower atmosphere.) Tiny particles have a lot of surface area, so a lot of sunlight can be scattered with a relatively small amount of dust. The full amount of sulfur from Mount Pinatubo, if it had remained in the stratosphere for a long time, would have been more than enough to offset the warming (at least, on a global average) from a doubling of atmospheric carbon dioxide content. The actual short-lived cooling from the Mount Pinatubo eruption turned out to be much less because the oceans helped keep Earth warm despite the reduction in the amount of absorbed sunlight.[7]

The sulfur from Mount Pinatubo remained in the stratosphere only for a year or two. To maintain a dust shield in the stratosphere for the long term would require continual dust injection. It is thought that a small fleet of planes, or perhaps a single fire hose to the sky suspended by balloons, would be enough to keep the dust shield in place. Costs are uncertain, but it might total less than a few billion dollars a year. The amount of sulfur required would be a few percent of what is currently emitted from power plants and so would contribute somewhat to the acid raid problem.[8]

Why might policymakers want to deploy

Karin Jackson, U.S. Air Force

Mount Pinatubo erupting on June 12, 1991, as seen from Clark Air Force base eight miles away

climate engineering systems? The main reason is to reduce climate damage and the risk of further damage from greenhouse gases. Some commentators deny the reality of human-caused greenhouse warming but think it worth developing climate engineering systems as an insurance policy—just in case events prove them wrong. Others accept human-induced climate change but think reducing emissions will be either too costly or too difficult to achieve, so they favor climate engineering as an alternative approach. Some people fear that a climate crisis may be imminent or already unfolding and that these systems are needed right away to reduce negative climate impacts such as the loss of Arctic ecosystems while the world works to reduce greenhouse gas emissions in the longer term. Still others think climate engineering is needed as an emergency response system in case an unexpected climate emergency occurs while greenhouse gases are being reduced.[9]

There are also many reasons not to develop climate engineering, some of them having to do with climate science and some having to do with social systems. These schemes will not work perfectly, for example, and there is some chance that unanticipated consequences will prove even more environmentally damaging than the problems they are designed to solve. Concerns include possible effects on the ozone layer or patterns of precipitation and evaporation. Climate engineering would not solve the ocean acidification problem, although it would not directly make it worse either.[10]

Some observers fear that the mere perception that there is an engineering fix to the climate problem will reduce the amount of effort placed on emissions reduction. Climate engineering could lull people into complacency and produce even greater emissions and ultimately greater climate damage. (On the other hand, such schemes also could frighten people into redoubling efforts to reduce greenhouse gas emissions.) And it might work well at first, with negative consequences manifesting themselves strongly only as greenhouse gas concentrations and the offsetting climate engineering effort both continued to grow.[11]

Climate engineering will affect everyone on the planet, but there is no clear way to develop an international consensus on whether it should be attempted and, if so, how and when. It would likely produce winners and losers and therefore has the potential to generate both political friction and legal liability. Conflict over deployment could produce political strife and social turmoil. (On the other hand, any success at reducing climate damage could lessen strife and turmoil.)

From the perspective of physical science and technology, it appears that climate engineering schemes have the potential to lower but not eliminate the risk of climate damage from greenhouse gas emissions, yet unanticipated effects and difficult-to-predict political and social responses could mean increased risk. Thus the bottom line is that climate engineering schemes have the potential to make things better, but they could also make things worse.