An Opinion Piece for IRGC

# Cooling the Earth Through Solar Radiation Management:

## The need for research and an approach to its governance

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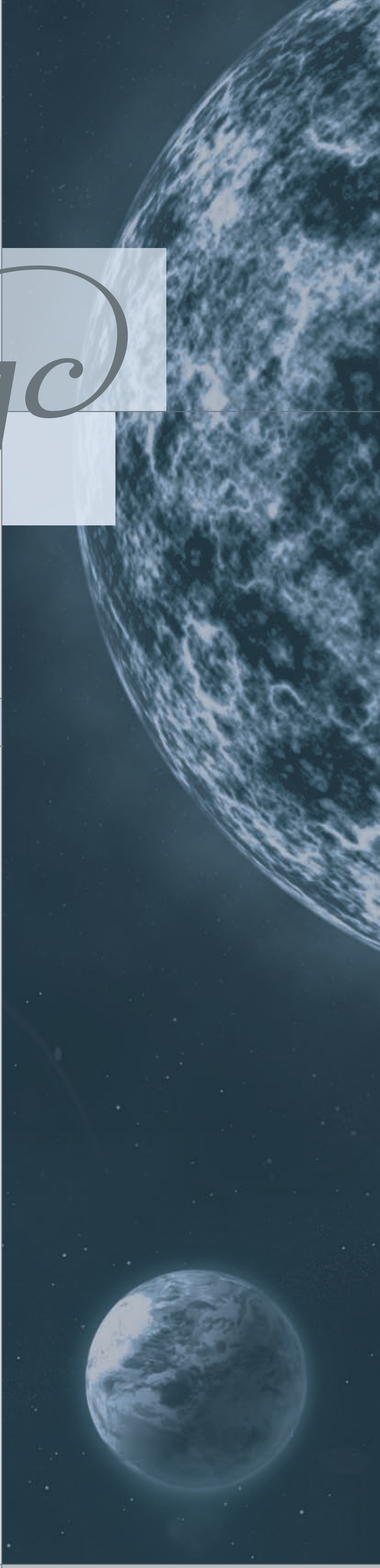


international risk governance council

## About IRGC and Solar Radiation Management

The International Risk Governance Council (IRGC) is an independent organisation based in Switzerland whose purpose is to help the understanding and governance of emerging, systemic global risks. It does this by identifying and drawing on scientific knowledge and the understanding of experts in the public and private sectors to develop fact-based recommendations on risk governance for policymakers. IRGC believes that improvements in risk governance are essential if we are to develop policies that minimise risks and maximise public trust in the processes and structures of risk-related decision-making.

In addition to its work of developing concepts of risk governance, IRGC has in recent years focused on risk governance challenges related to climate change and new technologies, including topics such as bioenergy, carbon capture and storage (CCS), nanotechnology and synthetic biology. It is in light of this portfolio that the project on geoengineering was initiated in 2008. IRGC's objective was to establish a dialogue between scientists and international policymakers on large-scale climate modification – because of the potential international / global impact of some of the proposed technologies – and to build up the capacity of policymakers and provide them with the opportunity to consider the relevant technologies and how they might be regulated. The project's main event was an international workshop held in Lisbon in April 2009. The workshop was convened by IRGC, the Portuguese Ministry of Science, Technology and Higher Education, through the Science and Technology Foundation, and the Calouste Gulbekian Foundation, in collaboration with the Carnegie Mellon – Portugal Programme, the NSF Climate Decision Making Center, Carnegie Mellon University and the Energy and Environmental Systems Group, University of Calgary.

IRGC then narrowed its focus to Solar Radiation Management (SRM). IRGC strongly believes that it is absolutely crucial to mitigate climate change by reducing greenhouse gas emissions. Because SRM does not address this problem, SRM is a controversial topic.

M. Granger Morgan and Katharine Ricke, authors of this "opinion piece" for IRGC specifically target SRM. Their brief is prescriptive, arguing that a first stage of research in this area is needed and outlining a strategy by which it should proceed.

## Acknowledgements

This opinion piece was written for IRGC by Prof. M. Granger Morgan (Chairman of IRGC's Scientific and Technical Council and Head, Department of Engineering and Public Policy, Carnegie Mellon University) and Katharine Ricke (Doctoral Candidate, Department of Engineering and Public Policy, Carnegie Mellon University). The document has benefitted greatly from the comments made during the peer review process, which was coordinated by Dr Warner North (President, Northworks Inc. and Consulting Professor, Department of Management Science and Engineering, Stanford University) on behalf of IRGC's Scientific and Technical Council.

Preparation of this opinion piece was supported by academic funds at Carnegie Mellon University. Research underlying the opinions was supported by the Climate Decision Making Center at Carnegie Mellon University under a cooperative agreement with the US National Science Foundation (SES-0345798) and by a National Science Foundation Graduate Research Fellowship.

### Disclaimer

While they have been informed by the deliberations in an IRGC workshop held in Lisbon, Portugal in 2009, the views and policy prescriptions contained in this document are those of the authors and are not a consensus judgement by IRGC, its reviewers, or its sponsors.

# Contents

# Foreword

I am very pleased to write the foreword to this Opinion Piece on Solar Radiation Management (SRM), one broad category of activity that falls under what is more generally termed “geoengineering”.

No one really is enthusiastic about changing the albedo of the planet through this technology, nor are the authors of this Opinion Piece. But the reality of climate change and the lack of international consensus on how to arrest greenhouse gas emissions makes it imperative for the survival of the planet as we know it that there be a Plan B. The authors of this IRGC Opinion Piece outline the essential elements of what could constitute this Plan B.

I have followed this climate change dossier for many years. The challenges were outlined at UN conferences: Stockholm in 1972; then at Rio in 1992; repeated at New York in 1997; Kyoto in 1997; Bali in 2007 and then last year at Copenhagen. Despite the warning of dire consequences for the planet and for humanity at each of these gatherings and the concerns expressed in each successive report by the Intergovernmental Panel on Climate Change (IPCC), little has been done to arrest and reverse the level of $CO_2$ emissions. Some countries, such as Canada, having undertaken in the Kyoto Protocol to reduce greenhouse gas emissions by 6% below 1990 levels, have in fact increased emissions by at least 26-29% above those levels .

By nature I am not a pessimist, but it requires more optimism than I can generate to believe that there will be an enforceable multilateral agreement in my lifetime that will bring about a reduction of as much as 80% in $CO_2$ emissions by the end of this century so as not to cross the threshold of 450 ppm which we are told will trigger an increase in global temperatures of 2 degrees centigrade.

A more likely scenario is that of “business as usual”, which the International Energy Agency (IEA) says will take us to an atmospheric $CO_2$ concentration of 700 ppm in this century, with horrendous climate change and unthinkable economic and societal consequences. Of course there may be new technologies such as those referred to in this Opinion Piece which might come on stream in time to scrub $CO_2$ out of the atmosphere and sequester it so as to meet emission targets. History makes me very doubtful.

The SRM technology described in this thoughtful analysis may indeed be inevitable as a last resort. But to implement it without serious research being done beforehand would be akin to administering a new drug without clinical trials. In the case of drugs, only those receiving them are at risk. In the case of SRM, the entire planet and all living beings could be affected.

That is why we should endorse the proposal from the authors that…“ the time has come to undertake a systematic programme of research on SRM ”.

**Hon. Donald Johnston**
Chairman of the Board
Formerly Secretary-General 1996-2006, OECD

# Summary

The authors begin this Opinion Piece by outlining the basic science that underlies the climate problem. They explain that when fossil fuels (i.e., coal, oil and natural gas) are burned, $CO_2$ is released to the atmosphere, where much of it remains for 100 years or more. $CO_2$ traps heat with the result that the planet warms, causing changes in the climate. The magnitude of these changes can be reduced if the concentration of $CO_2$ in the atmosphere is lowered.

To avoid a significantly changed and warmer climate, as well as the other impacts of rising levels of $CO_2$, the world needs to achieve roughly an 80% reduction in emissions of $CO_2$. The authors outline a number of ways in which this might be done. All of these strategies to reduce the concentration of $CO_2$ in the atmosphere are relatively slow (decades to centuries) and expensive (perhaps 0.5% to 5% of world GDP).

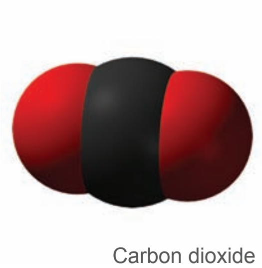
In contrast, if the fraction of sunlight reflected by the earth back into space (the albedo) is slightly increased, then the amount of sunlight that is absorbed by the earth system is slightly reduced and the planet is cooled. This can occur very rapidly – requiring only days to months. Large explosive volcanic eruptions clearly demonstrate this when they add large amounts of fine reflective particles to the stratosphere. Humans could do similar things to increase albedo, perhaps at a cost that is 1/100th or less of the cost of reducing the level of $CO_2$ in the atmosphere. Such activities are called “solar radiation management” or SRM.

Trying to intentionally and rapidly modify the earth’s climate strikes many people as a bad idea. While SRM may be relatively *cheap* and *fast*, it is also *imperfect*. It cannot precisely offset warming. It would lead to changes in the levels and patterns of precipitation and it would do nothing to offset the negative ecological effects of rising levels of $CO_2$ in the atmosphere, in particular the ongoing acidification of the world’s oceans, which will likely result in the demise of most corals and many other ocean ecosystems by the end of this century.

The world has been talking about reducing emissions for decades and has yet to make significant reductions. The authors argue that in order to be prepared in the event of a “climate emergency”, or for the case where someone tries to undertake SRM unilaterally, the time has come for a research programme on SRM that examines: how it might be done; what it would cost; and what intended and unintended impacts and risks might arise. They call on the research community to define a set of limits within which modest low-level field research could be conducted with minimal impact and therefore without formal international approval. They argue that any such research should be open, transparent and loosely coordinated internationally. In parallel with this research, they call for an effort to engage the foreign policy community in discourse to identify and assess the strengths and limitations of alternative possible approaches to the global governance of SRM.

# 1. Background

Our world has a climate problem. Since the early part of the 19th century, first England, then Europe and North America, and later Japan and many others burned ever growing quantities of coal, oil and natural gas. When these fossil fuels are burned, the carbon they contain combines with oxygen from the air to release heat. That heat powers factories, moves goods and people, heats and cools buildings, and makes possible the myriad of goods and services of modern industrialised society. Combustion combines the carbon in fossil fuel with oxygen in the air to create prodigious amounts of a colourless, odourless gas called carbon dioxide ($CO_2$). While the bulk of the $CO_2$ that is in the atmosphere today came from past activities in what is now the developed world, future concentrations will rise even faster because China, India and much of the rest of the developing world are using coal, oil and natural gas to fuel their own development.



Carbon dioxide

$CO_2$ occurs naturally in the earth's atmosphere. Plants use sunlight to convert it (together with water and trace nutrients) into leaves and stems. Animals eat some of those plants, use the energy that the plants stored, and breathe out $CO_2$. Organisms die, and microbes break them down, again releasing $CO_2$. These processes are all very natural.

$CO_2$ is responsible for helping to make earth a warm and pleasant place to live. When the sun shines on the earth about 70% of the incoming energy passes through the atmosphere and is absorbed. But, while the atmosphere is transparent to visible incoming sunlight, it is nowhere near as transparent to the infrared (i.e., radiant heat energy) emitted by the earth after it absorbs this sunlight. Much of this heat radiated back towards space is absorbed by molecules of water vapour, $CO_2$ and a few other gases in the atmosphere. The result of this "greenhouse effect" is that the earth is on average about 33°C (about 60°F) warmer than it would be without the atmosphere.

However, this warming effect is also the source of the world's climate problem. Water vapour doesn't stay in the atmosphere very long before it falls out as rain. As a result its atmospheric concentration remains rather stable. In contrast, once humans release $CO_2$ it is mixed throughout the atmosphere and the concentration remains elevated for more than 100 years. That means that even today when we breathe in $CO_2$ some of what we breathe is a legacy left from Thomas Newcomen's and James Watt's early steam engines. It also means that since those early days, the amount of $CO_2$ in the atmosphere has grown by almost 40% – and as we burn more coal, oil and natural gas the amount of $CO_2$ in the atmosphere continues to grow. As a result, the earth is gradually warming up. Today, mostly due to these higher concentrations of $CO_2$ and other greenhouse gases, the average temperature of the planet is about 0.75°C (about 1.4°F) higher than in preindustrial times[1]. Since heat drives the climate system, the climate is changing – on average warming, but also changing such things as large-scale flows in the atmosphere and the oceans, patterns of rain and snow, and patterns and strength of storms.

(1) Hegerl, G.C., F. W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, N. Nicholls, J.E. Penner and P.A. Stott, 2007: Understanding and Attributing Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

# 2. Needed: An 80% reduction in global emissions of carbon dioxide by later this century

If we want to avoid dangerous changes in the climate of the earth in the coming centuries, the best scientific estimates suggest that we need to reduce global emissions of $CO_2$ [2] by roughly 80% by later in this century, and then probably continue the decrease[3]. Why so much? Because the problem of elevated $CO_2$ is not like the problem of conventional air pollutants such as sulphur dioxide ($SO_2$) or oxides of nitrogen ($NO_x$). If the emissions of these pollutants is stabilised, within a few days their concentration in the atmosphere will also stabilise. If their emissions are stopped, within a few days they will be gone from the atmosphere. *This is not true for* $CO_2$. If we stabilised emissions of $CO_2$ from human activities, the concentration of $CO_2$ in the atmosphere would keep going up – this is because once increased the elevated concentration persists for many years.

To stabilise the concentration we need to dramatically reduce emissions (see Box 1). The energy system releases much of the $CO_2$ that human activities add to the atmosphere[4]. Thus, to make such emissions reductions, the world needs to make two changes in the energy system:

1. Reduce dramatically the amount of energy used to provide goods and services. There are enormous opportunities to improve energy efficiency. Making that happen will require tighter performance standards, better zoning codes, improvements in information provided to the public and to designers and builders, and a number of similar activities.
2. Produce energy in a way that releases little or no $CO_2$ to the atmosphere. Options include:
   - Wind, biomass and other renewables
   - Adoption of “carbon capture and storage” technologies that capture carbon from fossil fuel-burning processes and keep it from entering the atmosphere
   - Nuclear power
   - Conversion of cars, trucks and railroads to use electricity generated from sources that emit little or no $CO_2$ and to biomass fuels.

If all the major industrialised countries set out to systematically improve the efficiency with which they use energy, and convert energy sources to those that do not release $CO_2$, they could probably decarbonise their entire energy systems over the next 50 years for a cost of at most a few percent of their GDP[5].

(2) There are a few other “greenhouse gases” that also contribute to global warming. Once emitted they also stay in the atmosphere for many years. However, because $CO_2$ is the biggest contributor to warming, to keep things simple, here and in what follows, we ignore these other gases.

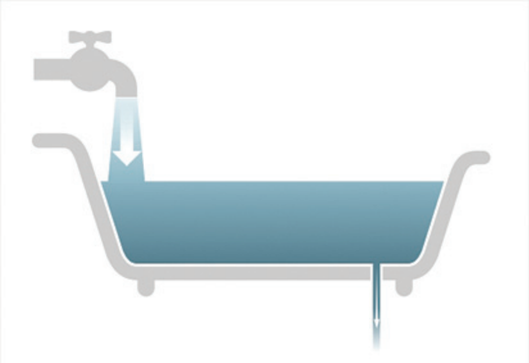
(3) See, for example: Parry, M. et al. “Squaring up to reality” *Nature Reports: Climate Change.* pp 68-71, 2008.

(4) R.E.H. Sims, R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, J. Torres-Martínez, C. Turner, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, X. Zhang. 2007: Energy Supply. In: Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

(5) See the cost calculation in Box 3. See also IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp. For an estimate focussed on just the cost of decarbonising the US electricity system see Granger Morgan, Jay Apt, Lester Lave, “The U.S. Electric Power Sector and Climate Change Mitigation,” a report prepared for the Pew Center on Global Climate Change, 84pp, June 2005.

A third option – directly removing $CO_2$ from the atmosphere – is now being explored. This strategy is called carbon dioxide removal or CDR. Of course, nature already removes $CO_2$ from the atmosphere, much of it through absorption into the waters of the world's oceans, and some of it into trees and plants. One way to do CDR might be to find ways to speed up these processes and make them more efficient.

## BOX 1: A few details about carbon dioxide and climate change



$CO_2$ gas is released to the atmosphere whenever coal, oil, or natural gas are burned. $CO_2$ and other heat trapping "greenhouse gases" are not like ordinary air pollutants. When pollutants like sulphur dioxide or oxides of nitrogen enter the atmosphere, they only stay there for a few hours or days. That means that if the level of emissions is stabilised, concentrations in the atmosphere quickly also stabilise.

This is *not* true of $CO_2$ and most of the other greenhouse gases humans release into the atmosphere. A useful analogy[1] is to think of the atmosphere as being like a bathtub with a big faucet (sources of $CO_2$ and other greenhouse gases) and a much smaller drain (processes that remove $CO_2$ and other greenhouse gases from the atmosphere). Unless the faucet is closed quite tightly (i.e., emissions are reduced by roughly 80%), the level of water in the bathtub will continue to rise.

For an additional semi-technical discussion of climate change and the role of $CO_2$ and other greenhouse gases see:
www.ncdc.noaa.gov/oa/climate/globalwarming.html#q3

For a more detailed technical discussion see:
www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1

1) The bathtub is not a perfect analogy because there are also massive natural flows of $CO_2$ into and out of the atmosphere. However it is a useful way to get an approximate understanding of the problem.

In the surface waters of the oceans, there are many plankton that can take up $CO_2$. The rate at which they do this is often limited by the availability of trace nutrients such as iron. For this reason, one of the strategies that people have talked about is to add iron or other nutrients to the surface waters of the ocean as a fertilizer to speed up the rate at which these plankton can absorb $CO_2$. A number of experiments have now been run from ships at sea. So far the results don't look very promising[6]. Reforestation is another strategy that will take up $CO_2$. Similarly, changing agricultural practices to build up more carbon in soils (e.g., with no-till methods) is also a way to remove some $CO_2$ from the atmosphere. While these may be useful short-term strategies, neither can remove anywhere near as much $CO_2$ as is needed to stabilise atmospheric concentrations. There are scientists exploring the possibility of using modern methods

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(6) See for example: P. Boyd et al., "The Decline and Fate of an Iron-induced Subarctic Phytoplankton Bloom," *Nature,* 428, 549-553, 2004; S. Blain et al., "Effect of Natural Iron Fertilization on Carbon Sequestration in the Southern Ocean," Nature, 446,1070-1075, 2007.

of genetic engineering to dramatically increase the efficiency with which trees or plants can remove $CO_2$ from the atmosphere. These ideas are still a long way from becoming a practical reality.

There are several scientists and engineers now working to develop engineered systems that could directly scrub $CO_2$ out of the atmosphere. Once captured, the $CO_2$ would be sequestered deep underground in stable geologic formations. In the future, if new technology can be developed, it might also be possible to convert the $CO_2$ into some form of solid (essentially carbonate rock).

At the moment, direct air scrubbing is still in the early stages of development, although there are several start-up firms working to perfect the technology. If the cost of capturing $CO_2$ could be reduced to something like USD150 to USD200 per ton (a target that experts working in this field think might be within reach), then direct air capture may become an important part of a portfolio of technologies to decarbonise the world's economy. For example, it could become the most cost-effective way to offset $CO_2$ emissions from some vehicles and from aircraft.

Given the evidence to date, and the potential for ecosystem disturbance, we do not see a need for governments to make more than modest research investments in CDR that involves enhanced natural removal of atmospheric $CO_2$. On the other hand, we believe that direct air scrubbing shows sufficient promise to warrant a considerable expansion in government and private research support. Policies should also be developed to promote private sector interest in developing and implementing this technology. Facilities engaged in direct air scrubbing would, of course, be subject to the same sorts of local and national regulation that apply to all large facilities. However, because it is local, inherently slow and similar to conventional abatement strategies in its climatological impacts, we see no need for any global governance framework[7].

# 3. If we know what we should be doing – why aren't we doing it?

The problem is not that we don't know how to dramatically reduce the world's emissions of $CO_2$. We can do that with a portfolio of dramatic improvements in the efficiency with which we use energy to produce goods and services, and the wide adoption of energy sources that do not emit $CO_2$. Nor is the problem that the world's largest emitters can't afford to make the needed changes. Rather, the problem is threefold:

1. Both in the industrialised and in the industrialising world, there are many pressing short-term issues that demand attention and resources (e.g., economic development, public health and national security). Since the most serious consequences of climate change lie decades in the future, it is expedient to procrastinate;
2. There are powerful short-term economic interests that are investing hundreds of

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(7) The one possible exception might lie in the area of how to account for the $CO_2$ that has been captured in a future international accounting scheme.

millions of dollars to keep the public confused and thus block the emergence of the needed collective social commitment[8]; and

3. Nobody wants to go first, as any country acting alone faces significant national costs for relatively lower internationally distributed benefits. A few leading developed countries need to start making serious deep cuts. If they did that, then we believe, either as a result of moral suasion or diplomatic and economic pressure, others would be induced to follow. But while there has been a lot of rhetoric, at least until now, national leaders in the major countries have judged that short-term domestic interests and concerns prevent them from taking such a lead.

So, while atmospheric concentrations of $CO_2$ continue to rise at an ever faster rate, the world has continued to procrastinate. Reducing atmospheric concentrations of $CO_2$, either by reducing emissions or by scrubbing it directly out of the atmosphere, is an inherently slow process. Making a dent in the problem will take decades. That means that even if the entire world got serious about reducing emissions of $CO_2$ tomorrow – something that all signs suggest is not about to happen – the world would still likely undergo significant climate change. This will happen both because all of these emissions reductions policies take time to implement and because inertia in the ocean-atmosphere system has already committed the earth to some climate change, the consequences of which are still uncertain.

## BOX 2: A word about definitions

Various authors have used the term “geoengineering” to refer to many different things, including methods of reducing emissions of $CO_2$, methods to remove $CO_2$ from the atmosphere, or methods to increase the amount of sunlight that is reflected back into space. Lumping all of these very different things together, some of which are local and slow, others of which are global and fast, has been the source of considerable confusion. Recently the Royal Society[1] helped to clarify this confusion by defining two broad categories of activity:

- CDR or carbon dioxide removal: activities that aim to directly remove $CO_2$ from the atmosphere
- SRM or solar radiation management: activities that aim to direct a higher fraction of incoming solar radiation back into space before it is absorbed by the earth’s surface. In technical terms this is called increasing the earth’s “albedo”.

In addition to cooling the planet much faster than CDR (i.e., weeks not decades) many SRM methods are both more poorly understood and more controversial than CDR because the impacts can be rapid and global.

We think these two terms (CDR and SRM) offer a big improvement over the much too general term “geoengineering” and so have now adopted them in our work.

(1) The Royal Society, Geoengineering the Climate: Science, governance and uncertainty, 82pp., September 2009. Available on line at: royalsociety.org/WorkArea/DownloadAsset.aspx?id=10768.

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(8) See for example Naomi Oreskes and Erik M. Conway, Merchants of doubt: how a handful of scientists obscured the truth on issues from tobacco smoke to global warming, Bloomsbury Press, 2010.

# 4. Solar Radiation Management (SRM)

There is a way to cool the planet quickly. A few times every century, nature provides a practical demonstration of this fact when an explosive volcanic eruption lofts millions of tons of $SO_2$ gas and ash high into the stratosphere. Once there, the $SO_2$ is converted into fine sulphate particles. These particles reflect sunlight before it has a chance to penetrate deeper into the atmosphere and get absorbed. For example, the eruption of Mount Pinatubo in the Philippines (Figure 1) in 1991 produced global scale cooling of about 0.5°C.

**Figure 1:** The eruption of Mount Pinatubo (left and centre) lofted large quantities of fine particles and $SO_2$ gas (which became fine sulphate particles) into the stratosphere. These particles reflected enough sunlight back to space to cool the planet by about 0.5°C. Had there not been an El Niño event going on at the same time, the cooling would probably have been closer to 0.6-0.7°C. Such cooling is observed every time a large explosive volcanic event occurs. (Credits: Left, U.S. Geological Survey; Centre, NASA STS043-22-11; Right, IPCC AR4)

The fraction of sunlight that is reflected back into space is called the “planetary albedo”. There is nothing new about the idea of modifying the climate by increasing albedo. Scientists have known for many years that this could be done[9]. However, until very recently, there has been almost no serious research on how to do SRM, on what it might cost, on how well it might work, or what its undesirable side effects and risks might be. We believe that there are two reasons the climate research community has not devoted serious research attention to these issues:

- Scientists have been reluctant to divert scarce research funds away from the urgent task of studying the climate system, climate change, and its impacts.
- Scientists have been legitimately concerned that studying this topic might increase the likelihood that someone might actually do it. Humans have a dismaying track record of changing their intentions as their capabilities change.

In our view, today the world has passed a tipping point and there are two reasons why it is too dangerous *not* to study and understand SRM:

1. There is a growing chance that some part of the world will find itself pushed past a critical point where, for example, patterns of rainfall have shifted so much that agriculture in the region can no longer feed the people. Believing this shift is the result of rising global temperatures, such a region might be tempted to unilaterally start doing SRM to solve its problem. If this situation arises, and no research has been done on SRM, the rest of the world could not respond in an informed way.

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(9) In addition to adding small reflective particles to the stratosphere, other methods such as increasing marine cloud brightness or placing mirrors in space, have been proposed. Here we concentrate on reflective particles in the stratosphere, though many of the climatic effects would be similar with other SRM methods.

2. With luck, the major effects of climate change will continue to occur slowly, over periods of decades. However, if the world is unlucky and a serious change occurs very rapidly, the countries of the world might need to consider collectively doing SRM. If this situation arises, and no research has been done, SRM would involve a hopeful assumption that the uncertain benefits would outweigh the uncertain and perhaps unknown costs.

While there is great uncertainty about SRM, we are confident that it has "three essential characteristics: it is cheap, fast and imperfect"[10].

**CHEAP:** The classification of SRM activities as "cheap" doesn't just refer to the low economic costs associated with cooling the planet with these mechanisms, but also to the fact that only a little bit of material is necessary to implement these planetary-scale changes, which can offset the influence of tons of $CO_2$. For example, under the current understanding of SRM technologies, the mass of fine particles needed to counteract the radiative effects of a doubling of atmospheric $CO_2$ concentrations is approximately 2.6 million tons per day of aerosol if injected into marine stratus clouds or 13,000 tons per day of sulphate aerosol if injected into the stratosphere. By comparison, to achieve the same radiative effect (whether by artificial or natural means), we would need to remove 225 million tons per day of $CO_2$ from the atmosphere for 25 years straight[11].

While few realistic engineering analyses have been done on the economic costs of SRM, a 1992 report of the U.S. National Research Council[12] estimated the potential costs of a programme of stratospheric albedo modification based on the use of a standard naval gun system dispensing commercial aluminium oxide dust to counteract the warming effect of a $CO_2$ doubling. Undiscounted annual costs for a 40-year project were estimated to be USD100 billion. More recent analyses[13,14], have suggested that well designed systems might reduce this cost to less than USD10 billion per year – clearly well within the budget of most countries, and much less costly than any programme to dramatically reduce the emissions of $CO_2$. For additional details on costs see Box 3.

**FAST:** While cutting emissions of $CO_2$ and other greenhouse gases would slow or halt their rising concentrations in the atmosphere, much of the $CO_2$ released through past emissions will reside in the atmosphere for 100 years or more. In addition, inertia in the climate system means that global temperatures will continue to rise. Reducing planetary temperatures through emissions reductions will take many decades to centuries. In contrast, increasing planetary albedo by doing SRM can reduce planetary temperature

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(10) The quote is from David W. Keith, Edward Parson and M. Granger Morgan, "Research on Global Sun Block Needed Now," *Nature,* 463(28), 426-427, January 2010.

(11) David Keith. "The Case for Geoengineering Research," Presentation at MIT, October, 30, 2009.

(12) NAS Panel on Policy Implications of Greenhouse Warming, *Policy Implications of Greenhouse Warming: Mitigation, adaptation and the science base*, National Academy Press, 918pp., 1992.

(13) A. Robock, A. Marquardt, B. Kravitz, and G. Stenchikov, "Benefits, Risks, and Costs of Stratospheric Geoengineering," *Geophys. Res. Lett.*, 36, L19703, doi:10.1029/2009GL039209, 2009.

(14) S. Salter G. Sortino J. Latham, "Sea-going Hardware for the Cloud Albedo Method of Reversing Global Warming," *Phil. Trans. R. Soc.* A, 366, 3989–4006. doi:10.1098/rsta.2008.0136, 2008.

## BOX 3: How much might SRM cost?

Nobody knows exactly what the cost of a full-scale implementation of SRM would be. We can, however, make a crude estimate. A 1992 National Research Council report[1] estimated the undiscounted annual costs for a 40-year project to be USD100 billion. A report from Lawrence Livermore National Laboratory[2] suggested that well designed systems might reduce this cost to as little as a few hundred million dollars per year.

We can use those two reports to estimate cost to be between USD100 million and USD100 billion per year. The size of the global economy is roughly USD$60 \times 10^{12}$ per year. So:

$(0.1\text{-}100 \times 10^9$ USD/year$)/60 \times 10^{12}$ USD/year is roughly 0.0002% to 0.2% of world GDP/year.

How does this compare with the cost of reducing emissions of $CO_2$ and other greenhouse gases? Today, the world is emitting about $50 \times 10^9$ tons per year $CO_2$ equivalent of greenhouse gases (of which about $30 \times 10^9$ is $CO_2$).

The IPCC 4th assessment[3] reports that: "Modeling studies show that global carbon prices rising to USD20-80/t$CO_2$-equivalent by 2030 are consistent with stabilization at around 550ppm $CO_2$-equivalent by 2100. For the same stabilization level, induced technological change may lower these price ranges to USD5-65/t$CO_2$-equivalent in 2030." So:
$(50 \times 10^9$ t$CO_2$-eq$)($5 to 65USD/t$CO_2$-eq$)$ = 250 to $3300 \times 10^9$ USD/year.

(0.25 to $3.3 \times 10^{12}$ USD/year$)/60 \times 10^{12}$ USD/year is roughly 0.4% to 5.5% of world GDP/year

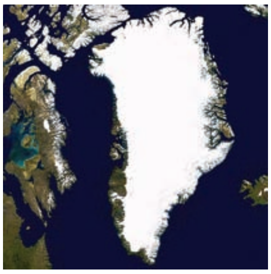
In short, it is probably safe to assume that the direct monetary cost of doing SRM would be *at least* 100 times less than the cost of a full programme of greenhouse gas abatement…*and perhaps even cheaper than that!*

(1) National Academy of Sciences, "Chapter 28: Geoengineering" in *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base,* 433-464, National Academies Press, 1992.

(2) Teller, E., L. Wood and R. Hyde, *Global Warming and Ice Ages: I. Prospects For Physics-Base Modulation Of Global Change,* University of California Research Laboratory Report UCRL-JC-128715, Lawrence Livermore National Laboratories, August 1997.

(3) IPCC, 2007, *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)], IPCC, Geneva, Switzerland, 104pp.

in days or months. This fast response cuts two ways. On the one hand, it means that SRM could be used to rapidly cool the planet in the event of a "climate emergency", such as the rapid deterioration of the Greenland ice sheet[15] or the sudden release of large amounts of methane from arctic tundra or the deep edges of the coastal oceans. On the other hand, if SRM were started and then stopped before greenhouse gas concentrations in the atmosphere were drastically reduced, then global temperatures could shoot up dramatically[16]. This would be devastating for many ecosystems.



**IMPERFECT:** Because the mechanisms by which blocking sunlight cools the planet are different from those by which greenhouse gases warm it, SRM cannot reverse climate change in a perfect way at either the global or local level. Global warming from

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(15) There is some chance that the loss of much of Greenland's ice might be irreversible once it has started.

(16) Matthews, H. D. & Caldeira, K. "Transient Climate-carbon Simulations of Planetary Geoengineering," *PNAS, 104*, 9949-9954, 2007.

rising greenhouse gases changes the level of global precipitation in a number of ways. First, rising global temperatures cause more evaporation. More water vapour in the atmosphere produces more precipitation. But, higher concentrations of greenhouse gases in the atmosphere also modify how the temperature of the atmosphere changes with altitude, dampening the "convective instability" that drives the way that water is cycled in and out of the atmosphere (what scientists call the hydrological cycle). With rising concentrations of greenhouse gases and rising global temperatures, the precipitation-increasing effect dominates and precipitation will increase globally. But, when SRM is used to lower global temperatures in a world with high $CO_2$, only the dampening effect remains. Thus, SRM necessarily weakens the global hydrological cycle[17]. This effect would affect different regions of the planet differently, with SRM compensating for climate changes in some regions reasonably well and potentially exacerbating changes that would occur with global warming in others. It is almost certain that the benefits and costs of global climate stabilisation would not be equitably distributed among regions[18].

In addition to such imperfections, a number of negative side effects could result from the various proposals for implementing SRM. Injecting aerosols into the stratosphere could provide reaction sites that might lead to significant destruction of stratospheric ozone[19]. And, because SRM does nothing to stop the rise of $CO_2$ from anthropogenic activity, it will not slow the associated acidification of the surface ocean, the continuation of which could lead to profound changes in ocean and terrestrial ecosystems, including the likely demise of many or all coral reefs[20]. Box 4 provides a few additional details on some of the imperfections and risks of SRM.

## BOX 4: Some undesirable aspects of SRM

Even if it could be shown to work as intended, SRM would not be able restore the future climate to its present state. It would also not be able to reverse many of the consequences of rising atmospheric concentrations of $CO_2$:

- An SRM-modified world that held average global temperature to today's level would result in reduced precipitation globally, and in changes in the patterns of precipitation.
- Unless special care were taken in the design of the particles used in stratospheric SRM, the surfaces of the particles could become chemical reaction sites at which ozone might be broken down. Ozone in the stratosphere is responsible for shielding life on the planet from harmful ultraviolet radiation.
- If SRM were implemented for awhile to offset the effect of rising levels of $CO_2$ but were then suddenly stopped, the

(17) G. Bala, G., P.B. Duffy and K.E. Taylor, "Impact of Geoengineering Schemes on the Global Hydrological Cycle," *PNAS.*, *105*, 7664-7669, 2008.

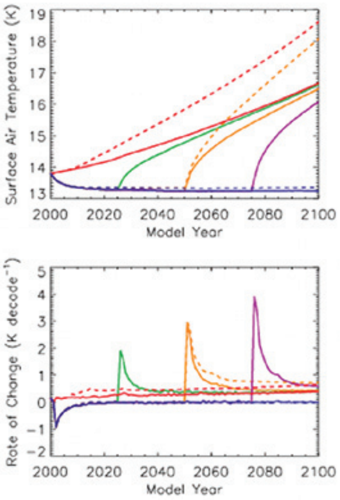
(18) See for example: A. Robock, L. Oman and G.L. Stenchikov, "Regional Climate Responses to Geoengineering With Tropical and Arctic SO2 Injections," *J. Geophys. Res., 113*, 2008; or K. Ricke, M.G. Morgan, M. Allen, "Regional Climate Response to Solar Radiation Management," *Nature Geoscience, 3*, 537-541, 2010.

(19) S. Tilmes, R.R. Garcia, D.E. Kinnison, A. Gettelman, P.J. Rasch, "Impact of Geoengineered Aerosols on the Troposphere and Stratosphere," *J. Geophys. Res., 114*, D12305 , 2009.

(20) S.C. Doney, V.J. Fabry, R.A. Feely, J.A. Kleypas, "Ocean Acidification: The other $CO_2$ Problem," *Annu. Rev. Marine. Sci., 1*, 169-192, 2009.

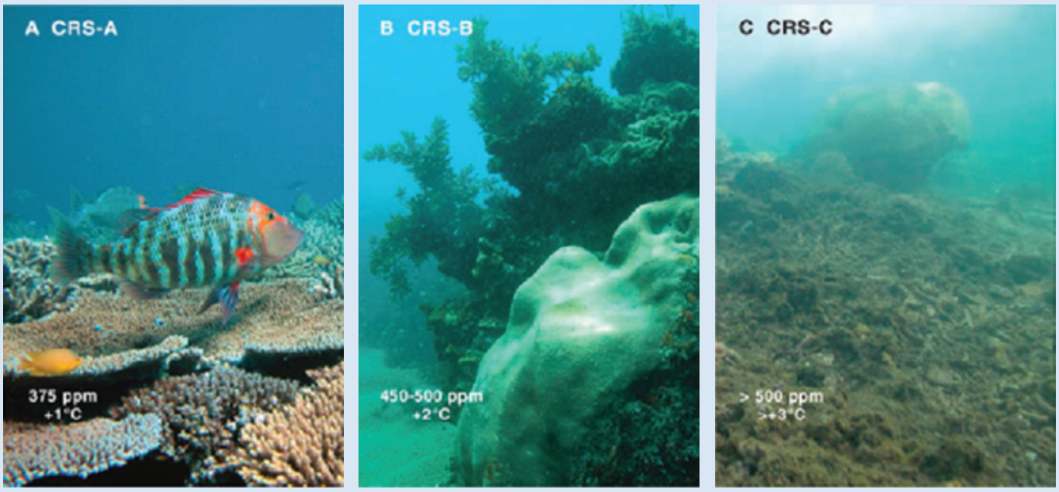
result would be very rapid warming. Ecosystems have difficulty adapting to even gradual warming. Substantial warming that occurred rapidly over a period of weeks or months, rather than over the course of decades, would be devastating to many ecosystems. That means that once the world started serious SRM, and ran it for years to offset rising $CO_2$ concentrations, it would become increasingly risky to stop.

- Plants use $CO_2$ and sunlight to build plant tissue. Many greenhouses use elevated levels of $CO_2$ to increase yields. However, not all plants use $CO_2$ with the same efficiency. Thus, as the atmospheric concentration of $CO_2$ increases, some plants in terrestrial ecosystems will have an advantage over others. The result will likely be shifts in the make-up of some ecosystems.
- Much of the $CO_2$ that enters the atmosphere ultimately ends up being absorbed by the oceans. As a consequence, today the surface waters of the oceans are about 30% more acidic than they were before the start of the industrial revolution. Because SRM does nothing to stop the rise in the atmospheric concentration of $CO_2$, the oceans would continue to acidify. If emissions continue upon their present trajectory, late in this century, most coral reefs will be gone (see figure below), and many other aquatic organisms with shells will no longer be able to maintain them. Of course, this is not a problem caused by SRM. Unless the world reduces its emissions of $CO_2$ dramatically we will have more acidic oceans with or without SRM. But while SRM can probably offset warming, it will not reduce this problem.



Computer models show the very rapid temperature increase that could occur, if SRM were done for a while and then suddenly stopped.

Source: H.D. Matthews and K. Caldeira, Transient Climate–carbon Simulations of Planetary Geoengineering, *PNAS, 104,* 9949-9954, 2007. © 2007 by The National Academy of Sciences of the USA



375ppm +1°C

450-500ppm +2°C

>500ppm >3°C

From O. Hoegh-Guldberg et al., “Coral Reefs Under Rapid Climate Change and Ocean Acidification,” *Science, 318*, 1737-1742, December 14, 2007. Reprinted with permission from AAAS.

# 5. The need for research and an approach to its governance

In our experience, the reaction of most people when they first hear about SRM is that "messing with the planet" like this is a terrible idea. Indeed, it is tempting to say we should create a global taboo against all efforts to study or engage in SRM, much as we've done for chemical and biological weapons. However, given the very wide uncertainty bounds on our present knowledge about climate change and its impacts, there is unfortunately some small chance that the world will face a global climate catastrophe that places billions of people at risk. If that were to happen, the countries of the world might collectively need to do some SRM to limit the damages. It is also plausible that a major country, suddenly experiencing a serious local or regional climate disaster such as prolonged drought, could decide to do SRM unilaterally, thus imposing its consequences on the entire planet. In both these cases, if the world has not studied SRM and its impacts, it won't be able to make informed decisions or muster informed counter arguments.

In 2008, we and a number of colleagues decided that the time had come to begin to inform leaders in the foreign policy community about the issue of SRM, so that they could begin to think about how best to approach the issues of global governance. Our first step was to organise a workshop at the Council on Foreign Relations (CFR) in Washington, DC that brought together a group of leading U.S. and Canadian climate scientists and foreign policy experts. The deliberations of that workshop helped to inform a paper we subsequently published in the journal *Foreign Affairs*[21].

Because the participants in that first workshop were all from North America, in 2009, we organised a second more international meeting under the auspices of IRGC, which was hosted in Lisbon by the Ministry of Science, Technology and Higher Education of the Government of Portugal. Participants in this meeting came from Canada, China, several Member States of the EU, India, Russia and the U.S.

There was a general consensus by many participants in both these workshops that the time has come to undertake a systematic programme of research on SRM[22]. There was a strong consensus that such research should be open and transparent and coordinated informally within the international scientific community. There was also a strong consensus that it would *not* be appropriate to conduct such research through defence or intelligence agencies. Finally, most participants argued that until research had yielded a better understanding of the issues, it would not be appropriate to develop a treaty or any other formal regulatory scheme to govern research or the potential future deployment of SRM. Moving quickly to a formal treaty could make it difficult or

(21) David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner and Katharine Ricke, "The Geoengineering Option," *Foreign Affairs, 88*(2), 64-76, March/April 2009. A pdf of this paper is available at http://iis-db.stanford.edu/pubs/22456/The_Geoengineering_Option.pdf

(22) This argument is further elaborated in: M. Granger Morgan, "Why Geoengineering?," *Technology Review,* 14-15, January/February 2010. David W. Keith, Edward Parson and M. Granger Morgan, "Research on Global Sun Block Needed Now," Nature, 463(28), 426-427, January 2010.

impossible to undertake the needed initial research or could leave unanticipated gaps that would result in even less desirable forms of climate modification than the ones such a treaty was designed to prevent.

In 2009, the Royal Society in London convened a small group of experts to conduct a study on the broad topic of geoengineering. Two of the experts (David Keith and Ken Caldeira) who had participated in both the CFR and IRGC workshops were members of the Royal Society group. The conclusions about global governance in the resulting Royal Society report[23] strongly parallel the conclusions from the earlier workshops. The Royal Society has now launched a follow-on activity, in which IRGC is a participant. This new study will specifically focus on issues of governance of research and possible future implementation.

# 6. Defining a framework for SRM research

If natural scientists, engineers and social scientists are going to start a programme of research, what should it look like? In our view, such a programme should begin with expanded computer simulations and laboratory studies. However, because there are many important questions about these technologies that can only be answered by observing the real world, within a few years it will likely be necessary to also conduct modest low-level field testing in a way that is transparent and coordinated informally within the international scientific community. The objective of such research should be to learn:

- What methods and strategies might work to implement SRM?
- How well are these various proposed methods likely to work and how well could they be controlled?
- How much would these different methods cost?
- What undesired side effects might arise and what new risks might be associated with these various methods?
- How will the direct effects of these various methods be distributed over time and across the world?
- What uncertainties remain because of incomplete understanding of the complex climate system?

So long as modest low-level field studies designed to answer these questions are done in an open and transparent manner, we believe they should not be subject to any formal international process of vetting and approval. Countries and firms routinely fly various aircraft in the stratosphere, or send rockets through the stratosphere into space. These activities release significant quantities of particles and gases. A requirement for formal prior approval of small field studies, just because they are directed at learning about SRM and its limitations, is probably unenforceable because judging intent is often impossible. Such a regulation would, at best, make conducting modest low-level SRM

Source: NASA ISS015-E-14611

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(23) The Royal Society, *Geoengineering the Climate: Science, governance and uncertainty*, 82pp., September 2009. Available on line at: royalsociety.org/WorkArea/DownloadAsset.aspx?id=10768.

research extremely difficult and, at worst, impossible[24].

That said, clearly one of the first objectives of an SRM research programme should be to give more precise meaning to the phrase “modest low-level”. This definition is important both to begin to create clear norms within the international scientific community, and also to provide technical input to the diplomatic and foreign policy community as it begins to think about how it might best regulate larger-scale experimental activities or proposals for actual implementation.

One possible approach would be to define, based on research, an “allowed zone”. Once a proposal for such a zone has been developed through research, it would need to be informally vetted within the international research community (for example, through a process such as the one the Royal Society is initiating, through the IAC – Inter Academy Council of the world’s science academies, ICSU – International Council for Science, or some similar group[25]). After vetting, while experiments may still be subject to any number of regulatory requirements within the country funding or hosting them, scientists should be able to proceed with studies that fall inside this zone without formal international approval, subject only to the requirements that their studies are publicly announced and all results are made public. They should also be informally assessed and coordinated within the scientific community. Once an “allowed zone” has been defined, a norm should be created that the further an experiment ventures outside such a zone, the more extensive the international vetting should be before it is conducted. In the future, such a boundary of allowed activities might be formally incorporated in an international treaty or other agreement.

An “allowed zone” might be defined in terms of a number of different variables or factors, such as the amount of radiative forcing, the duration of the forcing, and the impact that the experiment might have on ozone destruction. Figure 2A, provides an illustrative example. The initial research to define an “allowed zone” should examine what factors (axes) should be included to define the space, where the limits should be set, and what shape the “allowed zone” should have within that space.

Research by the scientific community might identify a variety of benign experiments that could add complexity to the shape of such a space. For example, David Keith has recently suggested that it might be feasible to develop artificial particles that would be self-orienting and self-levitating[26] – thus, making it possible to focus on a specific

(24) While early experimentation involving SRM would involve changes in albedo and other impacts that would be *much* smaller than those imposed by natural volcanic eruptions, and in some cases only comparable to the impacts of aircraft and rockets that frequently fly in or through the stratosphere, there might be a temptation on the part of some to attribute unusually climatic events to SRM field studies. Lest this seem implausible, we note that in studies conducted in the US in the early 1990s, and again almost two decades later, over 10% of lay respondents indicated that they believe the space program is or might be a cause of climate change. (See: Ann Bostrom, M. Granger Morgan, Baruch Fischhoff and Daniel Read, “What Do People Know About Global Climate Change? Part 1: Mental models,” *Risk Analysis, 14*, 959-970, 1994.; Daniel Read, Ann Bostrom, M. Granger Morgan, Baruch Fischhoff and Tom Smuts, “What Do People Know About Global Climate Change? Part 2: Survey studies of educated laypeople,” *Risk Analysis, 14*, 971-982, 1994; and Travis William Reynolds, Ann Bostrom, Daniel Read, and M. Granger Morgan, “Now What Do People Know about Global Climate Change? Survey Studies of Educated Laypeople,” *Risk Analysis*, in press.)

(25) While the IPCC’s 5th Assessment will include some consideration of SRM, several people have suggested to us that the IPCC might also supervise and coordinate SRM research. We believe that research design and coordination is not compatible with the IPCC’s role of reviewing the literature, or their system of elaborate government review of all products.

(26) David W. Keith, “Photophoretic levitation of engineered aerosols for geoengineering,” *PNAS, 107*, pp 16428-16431, 2010.

range of latitudes, and perhaps move the particles high enough to be above the ozone layer. Since such particles could likely persist in the stratosphere far longer than other particles, testing the behaviour of a very small quantity of such particles could require an extension of the zone along the "duration" axis as shown in Figure 2B.

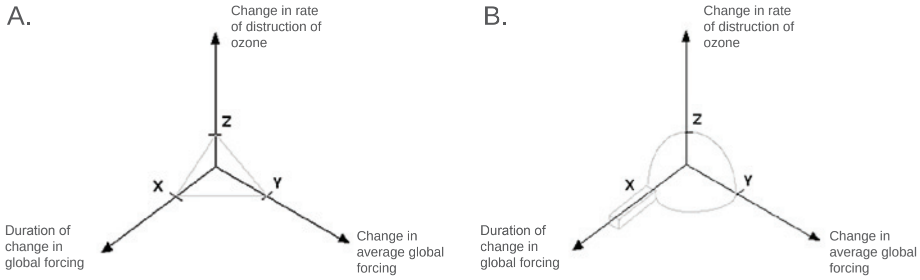

**Figure 2: A (left) -** Illustration of an "allowed zone" within which small scale experiments should be able to proceed without formal international approval. One of the first tasks that the global scientific community should address is to identify the axes that should be used to define such a zone and the shape it should have. This will likely require an iterative process. **B (right) -** For example, it might be desirable for the zone to have a slightly convex shape or to include an extension along the "duration" axis to allow studies of the behaviour of very small quantities of long-lived particles.

Of course, sometimes nature runs large natural experiments (in the form of volcanic eruptions) that lie well outside any plausible "allowed zone". Thus, a second focus of the early stages of an SRM research effort should entail investing in establishing sufficient observational infrastructure to do comprehensive field studies as soon as possible, should such an event occur in the near future.

Institutional funding arrangements for the early stages of SRM research will necessarily be different in different countries and regions. Since in the early stages we should encourage as diverse a set of ideas as possible, it would be best to provide initial support through agencies that are good at encouraging investigator initiated proposals. Since in many cases social, behavioural, legal and ethical issues will be important, it would be best to choose agencies whose tradition and experience also includes supporting such work.

Above we argued that it is important to encourage private for-profit funding of direct air scrubbing to implement CDR. In our view, however, governments should look for ways to actively discourage private for-profit funding for SRM research since it holds the potential to create special interests that might push to move beyond research into active deployment. While private firms might be used as contractors in government funded studies, any intellectual property developed in that work should not be held in private hands, and to the extent possible, policies should be adopted that minimise or prevent any private stake in promoting deployment.

# 7. Decisions that the world may face with and without SRM research

Figure 3 provides a simplified illustration of the decisions about whether and what research to conduct and what might be learned from that research. Along the top is a timeline. Up until now very little research of any kind has been conducted on this topic. That, of course, is understandable since, as we argued above in Section 4, investigators have been reluctant to divert scarce research funds from the pressing need to make progress in improving the understanding of climate science and abatement technologies. They have also been concerned that engaging in research that improves our knowledge about *how* to do SRM might increase the likelihood that someone facing significant local/regional adverse effects from climate change might actually do it.

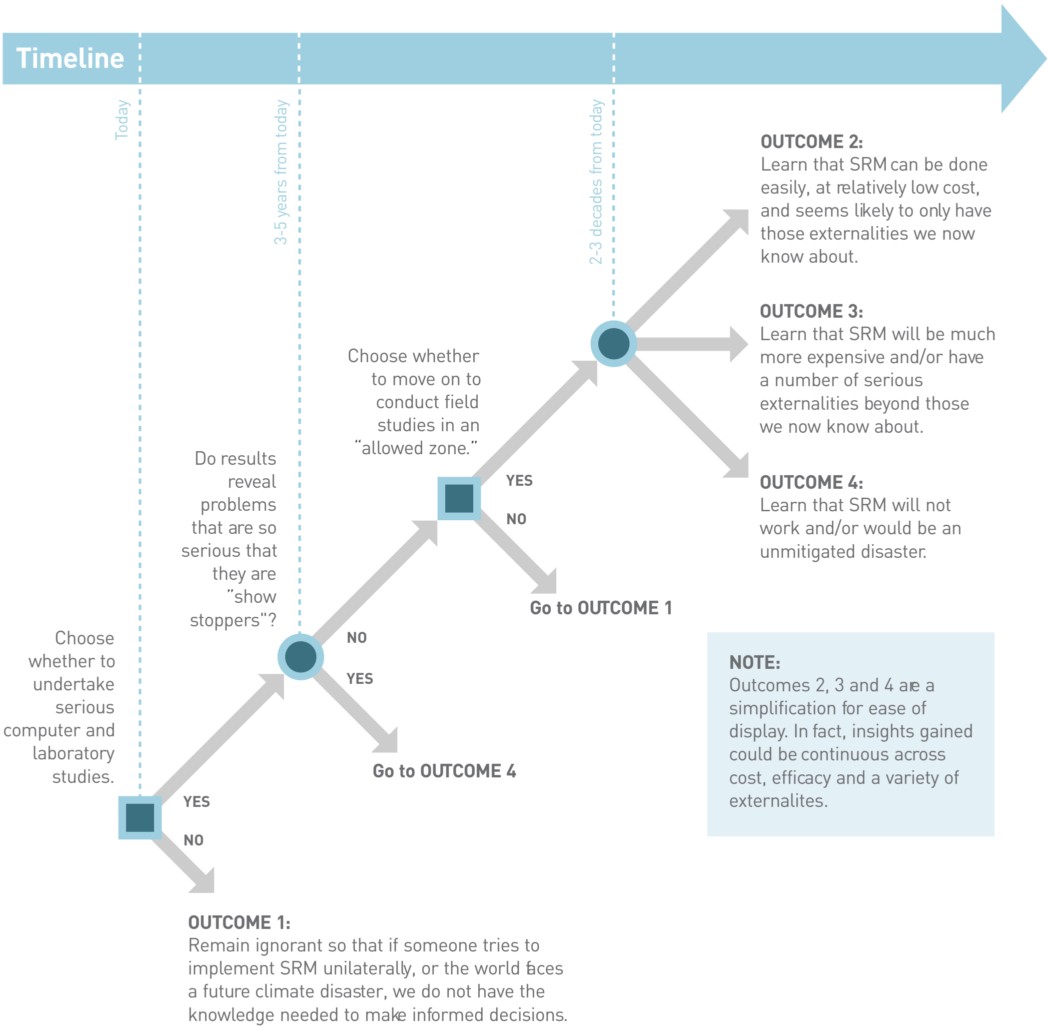

**Figure 3:** Timeline and simplified decision tree for research on SRM.

If we[27] decide today to engage in a programme of computer and lab studies, we might then, on the basis of what is learned in those studies, choose to conduct a set of field studies. Figure 3 simplifies what might be learned from those studies into three broad outcomes. At worst, we could learn that SRM would not work to reduce the negative effects of global warming or would result in unmitigated climate or ecological disasters. At best, research may indicate that SRM can be done easily and inexpensively, both in terms of direct costs and known externalities. Alternatively, we may learn that SRM is more expensive to implement than anticipated or would have previously unforeseen negative side effects. In either case – or in any case in between – such information would allow the world to more realistically compare costs and side effects of an SRM-modified world with those associated with one with no SRM.

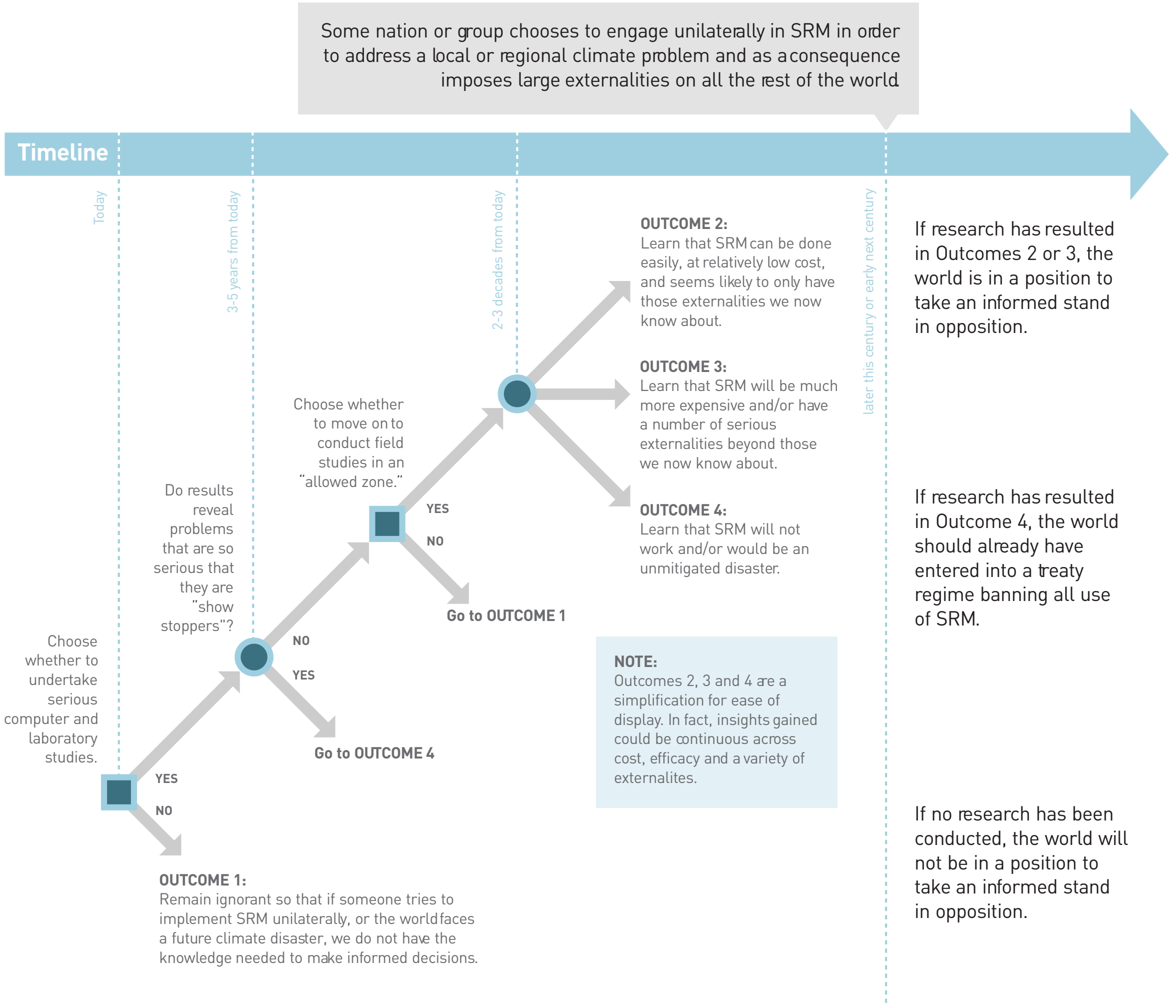

**Figure 4:** The situation that results if in the future some major state decides to deploy SRM unilaterally in order to address a local or regional impact from climate change.

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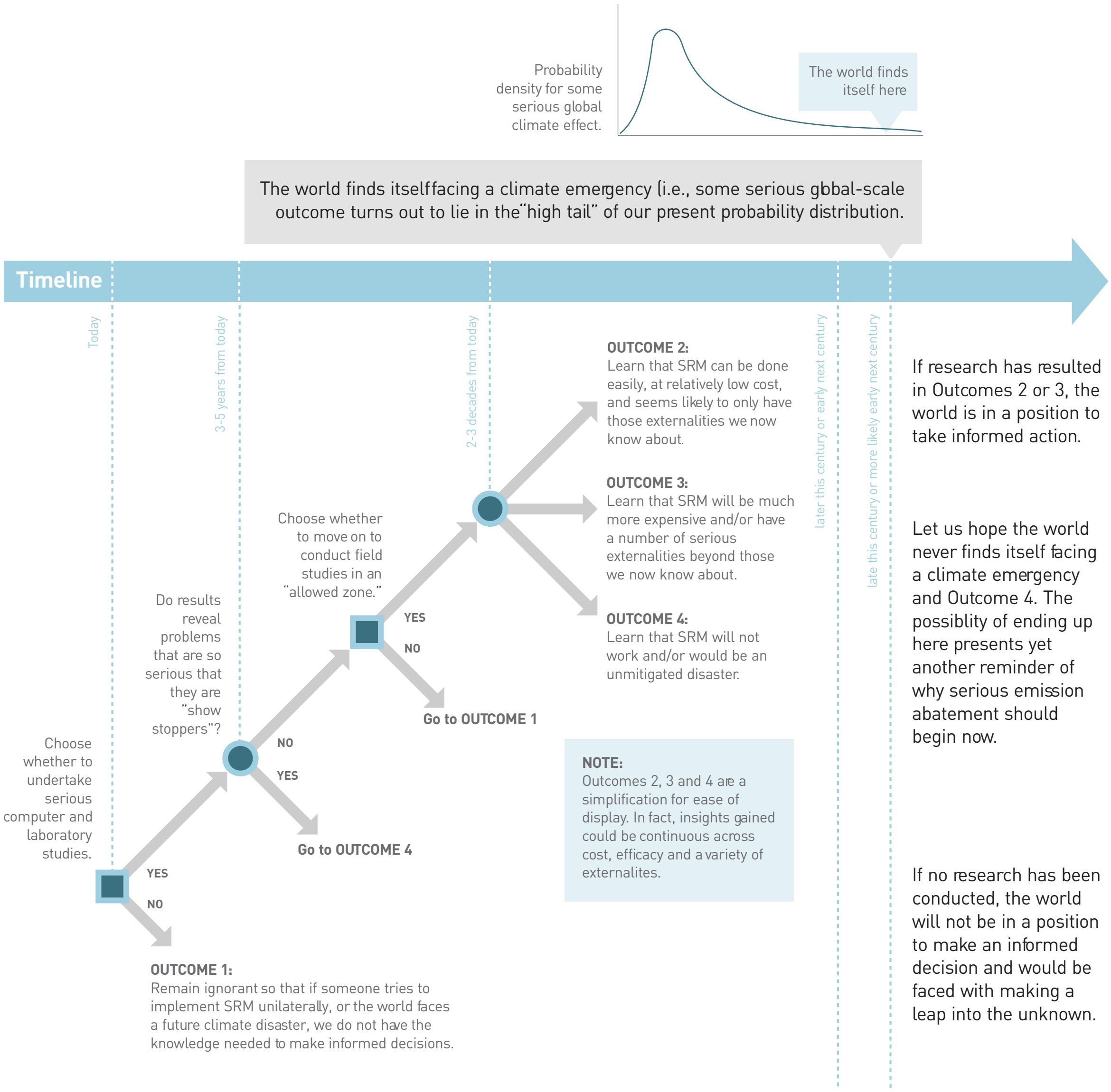
(26) It is standard practice in discussions of decision analysis to use the term "you" to refer to any decision maker. Since in this case it is essentially the countries and citizens of the world that would make the decisions being discussed, here and in what follows, the term "we" is used.

Suppose now that at some time in the future a country or region finds itself facing a serious local or regional problem caused by climate change. While the rest of the world might take action to aid that region (for example, by providing food aid in the event of a profound drought), suppose that instead the nation or region chooses to take matters into its own hands and unilaterally "solve" its problem by engaging in SRM. In this case, it would impose any associated effects and externalities upon the rest of the world. Figure 4 summarises in very simple terms the situation in which the rest of the world would find itself as a function of what had been learned as a result of the previous programme of research. In the case of an anticipated "unmitigated disaster", the world should have taken action to formally restrict such activities. If the research programme produced outcomes 2 or 3, the international community will be in a position to take an



The world finds itself facing a climate emergency (i.e., some serious global-scale outcome turns out to lie in the "high tail" of our present probability distribution.

Choose whether to undertake serious computer and laboratory studies.

Do results reveal problems that are so serious that they are "show stoppers"?

Choose whether to move on to conduct field studies in an "allowed zone."

**OUTCOME 1:**
Remain ignorant so that if someone tries to implement SRM unilaterally, or the world faces a future climate disaster, we do not have the knowledge needed to make informed decisions.

**OUTCOME 2:**
Learn that SRM can be done easily, at relatively low cost, and seems likely to only have those externalities we now know about.

**OUTCOME 3:**
Learn that SRM will be much more expensive and/or have a number of serious externalities beyond those we now know about.

**OUTCOME 4:**
Learn that SRM will not work and/or would be an unmitigated disaster.

**NOTE:**
Outcomes 2, 3 and 4 are a simplification for ease of display. In fact, insights gained could be continuous across cost, efficacy and a variety of externalites.

If research has resulted in Outcomes 2 or 3, the world is in a position to take informed action.

Let us hope the world never finds itself facing a climate emergency and Outcome 4. The possiblity of ending up here presents yet another reminder of why serious emission abatement should begin now.

If no research has been conducted, the world will not be in a position to make an informed decision and would be faced with making a leap into the unknown.

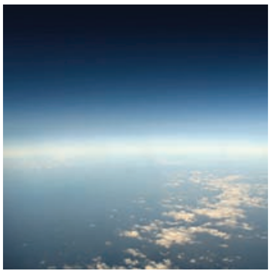
**Figure 5:** The situation that results if, in the future, the world finds itself facing a climate disaster and needs to consider collectively deploying SRM. Scientific uncertainty about many of the impacts of climate change involves distributions with low probability "high tails".

informed stand in opposition to such unilateral action, on the grounds that, in the view of the authors, no single nation or region should have the right to unilaterally impose the externalities listed in Box 4 on the rest of the world. If no research is conducted, any opposition would be uninformed and therefore less legitimate.

Finally, Figure 5 illustrates the situation in which, in the future, the world finds itself facing a very serious global climate disaster. In this case, if the research has demonstrated that SRM is feasible, the world would be in a position to weigh the relative costs of engaging in SRM or suffering the consequences of the climate change.

The probability of this extreme outcome may not be entirely independent of whether or not the world does research on SRM. We suggested above that one reason that many scientists have been reluctant to engage in SRM research is concern that knowing more about it may increase the chance that someone relies on it as an alternative to reducing emissions of $CO_2$ and other greenhouse gases. However, there is also the possibility that if we conduct research that shows that SRM will not work, and/or would be an unmitigated disaster, this might induce a more serious global effort to engage in dramatic reduction of emissions. And, without research, if a climate disaster does arise, the world may end up faced with the decision to take a leap into the unknown and deploy SRM despite ignorance of the consequences.

# 8. Conclusion



It is likely to take the foreign policy community at least as long to become informed and develop a strategy on SRM as it will take the scientific community to do the needed research. *We need to start now on both fronts*. Specifically, we need to:

1. Establish a modest and transparent international research programme that is informally coordinated within the scientific community to examine how SRM might be done, what it would cost and what the intended and unintended impacts and risks could be. Because SRM would do nothing to stop the rising atmospheric concentration of $CO_2$, it is also important to expand research on the implications of that rise for terrestrial and oceanic ecosystems.

2. Engage the foreign policy community in discourse to identify and assess the strengths and limitations of alternative possible approaches to the future global governance of SRM.

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ISBN 978-2-9700672-8-3