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Geoengineering Framework and Case Study

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1) Abstract

Geoengineering (technological modification of the climate) has been suggested as a path to mitigate some of the effects of anthropogenic climate change. A worst-case climate change scenario was developed, based on a realistic (if pessimistic) view of future emissions patterns, whereby a single state actor could be motivated to pursue a geoengineering policy. In the highly uncertain context of climate change, how might this actor go about changing the climate? A framework for evaluation of geoengineering technologies (under conditions of uncertainty) is developed, including an order-of-magnitude cost analysis. Sulfur dioxide (SO_2) atmospheric injection is found to be the most cost-effective and technically feasible geoengineering technique. The policy implications of such a geoengineering strategy are discussed, as well as possible frameworks for governing geoengineering at the multinational level. An implementation roadmap is proposed, tying the scientific and operational realities of geoengineering to the political context in which this policy would be carried out.

2) Introduction

*"Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. * * * It is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in [greenhouse gas] concentrations and [equivalents]." [1]*

2.1) Context

Humans, via our emissions of greenhouse gases, are causing the Earth to warm. The quantity, location, and trend of this warming is uncertain, but the warming itself is unmistakable. The IPCC, an international organization that supports the United Nations Framework Convention on Climate Change, [2] has produced five assessment reports since 1990 that aim to collect, analyze, and propagate research about the potential causes and effects of climate change. Each successive report has introduced new models, data, and insight into the climate and human effects upon it, but the scientific conclusions have remained roughly static since the very first report: the Earth is getting warmer, and human emissions are the most likely culprit.

One part of each set of IPCC reports includes recommendations, in the form of suggested mitigations and adaptations. For the most part, these recommendations can be boiled down to one simple theme: reduce carbon emissions through increased use of renewable energy sources, including biofuels, and continue to invest in energy technology (such as storage). This strategy is generally accepted to be the most technically sound method to reduce future climate change. Unfortunately, it has proven difficult to coordinate an effective greenhouse gas reduction policy. Fossil fuels are, quite simply, quite cheap. The alternatives are more expensive, and sometimes technically immature. In short, a comprehensive plan of CO_2 reductions would be among most expensive non-military collective action projects in human history. The IEA has estimated [3] a cost of $44 trillion through 2050 in the form of power system upgrades, new power plants, additional spending on technology, and forgone consumption. While this particular number is not authoritative, most models of this mitigation cost are strongly sensitive to the availability of certain technologies (carbon capture and storage in particular). Many of these technologies are *not* currently available, which suggests that the true mitigation costs could be far higher than estimated.

What's more, our atmosphere is the canonical example of a true public good; [4] indivisible and freely accessible, it suffers from the ultimate free rider problem. Everyone benefits from marginally cleaner air, but the costs to provision that air accrue to single actors. The game theoretic equilibrium is a world where everyone emits as much as they please.

Unfortunately, climate change is not harmless. In fact, most of the content in the past three IPCC reports details the potential negative consequences from climate change, and some of these outcomes are undeniably severe. If humans continue to emit without restriction, these severe outcomes become more likely, and true "worst-case scenarios" become possible. These include events like the melting of Greenland's ice caps, the cessation of important sea currents, and the desertification of [5] much of the world's farmland. While these predictions are also subject to significant uncertainty, and some occur far in the future, they are possible.

Perhaps in light of this, the IPCC has recently seen fit to include some analysis of technologies that might help reduce some (but not all) impacts from anthropogenic warming. Any such methods could be very valuable, considering the cost of reductions in greenhouse gas emissions, and the consequences from unmitigated warming. These methods are typically and collectively defined as "geoengineering."

2.2) Purpose

In this white paper, we have explored the potential for humans to engineer the climate. Within, we discuss potential technologies, decision making under uncertainty, and the circumstances required to motivate an actor to geoengineering (with India as a hypothetical case study). Finally, we propose a "path forward" for geoengineering that might present the least risk and the most benefit.

Much of the ongoing discussion on Geoengineering has discussed the moral hazard of geoengineering knowledge, or the ethical implications of meddling with "Mother Earth." This white paper is not intended to reject these arguments – it will not help to determine whether geoengineering is "good" or "bad" in some normative sense. Instead, we propose another mental model.

2.3) Scenario

We ask the reader to consider a future world that has gotten much hotter (much earlier) than scientists had expected. We've based this world on the RCP 8.5 scenario, [5] which assumes that humanity continues to get richer, but also that we do not substantially reduce greenhouse gas emissions ("business-as-usual" emissions). In fact, these emissions rise dramatically throughout the scenario period ending in 2100, and continuing beyond 2100. Based on the available models, we believe that the RCP 8.5 scenario could result in a mean surface temperature increase from pre-industrial times of up to 3.2 °C by 2050. Since mean *land* temperatures are ~1.4 to 1.7 times hotter than sea temperatures, this paper assumes a mean land surface temperature increase of 4.5 °C relative to preindustrial times. This temperature increase could subject humans in this future to pervasive droughts, extreme heat waves, crop failures, more severe weather events, and potentially the failure of the Asian monsoon. [6]

With this in mind, imagine a scenario where:

- The consequences of climate change have already started to occur (~2050),
- one country is experiencing disproportionate effects, and

- they decide something must be done.
- What might they decide to do? What’s the best way to do it?

3) Geoengineering Technologies

3.1) Potential Technologies

There are a variety of potential technologies that a state actor could choose to implement a geoengineering policy. These can be broadly grouped into two categories: Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM). CDR technologies involve removing carbon dioxide from the atmosphere in order to stabilize the climate and reduce future radiative flux. SRM technologies involve decreasing the amount of sunlight reaching earth's surface, reducing radiative flux without directly changing the amount of carbon dioxide in the atmosphere. While SRM methods may mitigate the warming impacts of excess carbon dioxide in the atmosphere, they do not solve other problems caused by excess carbon dioxide, such as ocean acidification or changing weather patterns due to changes in the distribution of heat within layers of the atmosphere. [7-10]

3.1.1) Technology Plausibility Criteria

In our initial survey of these technologies, we utilized two criteria to screen out technologies that did not fit the scenario described in §2.3. First, the technology selected had to be something a single state actor could undertake. Technologies that did not fit these criteria include ground based solar reflectors, roof whitening, and reforestation, as these would require mass global adoption to have any significant impact. Secondly, the underlying science had to be understood to a sufficient extent that we could qualitatively address whether such a method could actually work. Technologies excluded for this reason include cloud brightening and cirrus cloud thinning, as there is still debate on the mechanism on which these potential methods would work, according to the IPCC. [11] (§7.7.2.2)

3.1.2) Carbon Dioxide Removal (CDR)

CDR can be accomplished by a variety of methods. Reforestation is one such method, planting more trees to remove CO_2 from the atmosphere. Another option – accelerated weathering, whereby silicates added to the oceans absorb CO_2, turning into solid carbonate that sinks to the ocean floor. Ocean seeding requires the use of a biological accelerant of some kind, such as iron dust, that increases algae growth – these algae would consume CO_2 during photosynthesis. When these algae die, they would sink to the ocean floor, permanently removing the carbon dioxide from the atmosphere. A final method would be to remove carbon dioxide directly from the air either via a direct air capture (DAC) system, or through combining biofuel-fueled power plants with carbon capture and storage (CCS) system. Aside from costs (to be discussed later), this category of mitigation faces the additional challenge that any removal of atmospheric carbon dioxide would eventually be partially offset by releases from natural carbon dioxide sinks in the land and oceans. That is, the CO_2 released after the beginning of the industrial revolution resides not only in the atmosphere, but also in these additional CO_2 sinks.

Many of these options will be discussed in more detail below. While several other strategies have been proposed, these are believed to be the most plausible technologies at this time, after filtering for the criteria mentioned in §3.1.1.

3.1.3) Solar Radiation Management (SRM)

Several plausible SRM technologies have been proposed. One such method would be to increase the reflectivity of earth's surface, such as painting the roofs of buildings white or installing solar reflectors that would reflect solar radiation. These methods would require mass adoption across the world however, and would not be feasible for a single state actor. [12] Methods that could be implemented by a single actor include space-based solar reflectors and atmospheric aerosols. The space-based solar reflector method would require launching large mirrors into space to shade the earth. These could be placed into low earth orbit, or at the L1 Lagrange orbital point. Low earth orbit mirrors face the challenge of only being active during half their orbit, when they are between the earth and the sun. Mirrors based at the L1 Lagrange point are able to stay roughly in one location relative to the earth and sun, since the gravity of the earth and the sun interacts to enable a stable orbit around a point in space. NASA has already used this orbital point with its Solar and Heliospheric Observatory Satellite (SOHO), which remains fixed at this point so it constantly observes the sun. [13] It should be noted that either location would involve some risk from asteroids or other orbital debris impacts, though Low Earth Orbit would be riskier.

The final option, atmospheric aerosols, involves seeding the upper atmosphere with particles such as sulfur dioxide (SO_2) that would increase earth's albedo, reducing the solar radiative flux reaching earth. Any release of aerosols into the upper atmosphere would be distributed east and west by wind at the latitude at which it is released, but north-south dispersal does not occur as readily. Releases would need to be coordinated across all latitudes in order to achieve global coverage. While this may require action from multiple countries, it could also be accomplished through airspace passage rights, in which a single state actor operates the system by which the SO_2 is dispersed, requiring only airspace passage from other nations. Therefore, this method still fits our criterion for applicability to a single state actor. [14]

Sulfur dioxide is released naturally when volcanoes erupt, such as the 1991 eruption of Mount Pinatubo. Global temperatures have been observed to fall in the wake of eruptions such as this, so the correlation between sulfur dioxide release and temperature change has been well documented. Again, these methods will be examined in more detail below.

3.2) Feasible Technologies

Using the feasibility conditions, we chose six potential technologies, four CDR methods and two SRM methods, for further investigation. We prepared a Rough Order of Magnitude (ROM) estimate of the cost for each of these technologies (Table 1), to determine which would be most likely to be selected by a developing country (such as India) for deployment. We also evaluated their capacity to mitigate warming, as some methods, such as ocean seeding, are bound by physical limits on the amount of carbon dioxide they can capture per year. The goal of this table is only to show notional order of magnitude estimates, in order to decide which method would most likely be used. The discount rate of all calculations was assumed to be 4%.

3.2.1) Biofuels + CCS

This method has been described, with some cost estimates, by Howard Herzog, Senior Research Engineer at the MIT Energy Initiative. Under this system, biofuels generation (such as algae mats) would draw CO_2 from the atmosphere, which would then be burned in power plants for electricity. The carbon dioxide generated would then be captured and sequestered in underground geological formations. The advantage of this system over a direct air capture system is that the carbon dioxide concentrations are much higher coming out of the smokestack of a power plant than in the atmosphere, decreasing the capture cost.

In preparing our cost estimate, we used the optimistic side of Herzog's range, at $55 per metric ton. [15] We further assume that world electricity consumption continues to grow proportionally to GDP, and that GDP growth and the energy intensity of GDP continue to move at historical rates (3.5% and -1.4%, respectively). Given this rate of economic growth, we were able to estimate a removal rate of approximately 3 ppm of CO_2 per year in 2050, or 159 ppm over 50 years, assuming all electricity production was switched to biofuels at the start of the scenario described. [16, 17] We also did not include the additional cost of using biofuels over fossil fuels or the cost of storing the carbon in our estimate.

3.2.2) Direct Air Capture

The Direct Air Capture estimate uses some similar assumptions, gathered from the electricity and plant construction costs in the American Physical Society paper on this topic. [18]. For this estimate, we assumed enough direct air capture plant capacity would be built to reach the desired carbon dioxide concentration at the end of 50 years of operation. This estimate only includes the construction and electricity operating cost of the plants, a substantially optimistic approximation. Given our assumptions in the Biofuels + CCS method above, we did not do additional analysis of this method, as it was clear that this method would be significantly more expensive than capturing carbon directly from a power plant (given the relative concentrations in the air).

3.2.3) Ocean Fertilization

Ocean Fertilization is one of the cheaper options, since it only involves the cost of iron dust and the cost of distributing it over the ocean. We used the cost of iron dust commercially available currently on Alibaba.com, and used commercial fishing prices per ton as a proxy for distribution cost. [19] Although this this yielded a small present value cost, it is limited to 30 ppm reduction at the end of 50 years. It should be noted that there remains considerable uncertainty over the efficacy of this method, as there is a range of three orders of magnitude of the amount of iron required per ton of CO_2 captured. [20] Our estimate used a realistic assumption for the ratio of iron to carbon captured of one ton of iron per 1000 tons of carbon captured. An important consideration left out of this analysis is the potential for environmental disruption to the oceanic biosphere due to massive amounts of new algae growth; blooms are already disturbing many habitats, such as the Gulf of Mexico

3.2.4) Enhanced Weathering

Enhanced weathering also faces a similar challenge, where the 50 year limit of CO_2 reduction is set by geophysical realities at 5 ppm, and it would result in serious environmental consequences at that level. [21] A cost estimate conducted by the Oxford University Department of Earth Sciences gave a wide range for the cost per ton of silicate material introduced to the ocean, from $50 - $578. [22] We used the average of this range for this analysis, and limited the scope to the physical limit set forth in the IPCC report of a 5 ppm reduction in CO_2. Similar to the Ocean Fertilization method, we did not include an analysis of the potential oceanic environmental disruption in this estimate.

3.2.5) Space Mirrors

The space based reflectors method, while one of the most innovative solutions posited, is also one of the most expensive. Estimates for the mass of material required to build a space reflector are on the order of 20 million tons. [23] For launch cost, we used $3,400 per pound, the cost currently reported by SpaceX for the Falcon9 rocket delivering payload to earth geosynchronous orbit. [24] While launch costs may fall in the future, the L1 Lagrange orbital point is further than geosynchronous orbit, and it is unlikely future launch costs to this point would fall by the orders of magnitude required to change this method's cost relative to the others.

3.2.6) SO_2 Aerosols

Sulfate aerosols are a current component of the stratosphere and troposphere. Following volcanic eruptions, we have witnessed sulfates in the stratosphere influence the Earth's radiative budget by reducing the incoming solar radiation that reaches the Earth's surface. In the troposphere, sulfate aerosols also reflect solar radiation, but in addition, affect the size and persistence of clouds, which in turn affect cloud reflectivity [25]. Figure 1 is a rough budget of various aerosol precursors that exist in the troposphere and stratosphere during volcanic inactivity.

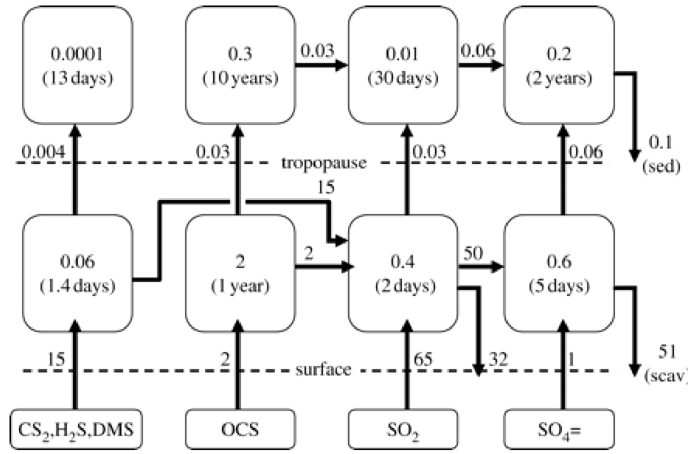

Figure 1: An approximate model of the evolution of atmospheric sulfur species during volcanically dormant times. Numbers inside the boxes are the amount of sulfur in Tg S and the approximate lifetime. Numbers beside arrows indicate net source or sinks (transformation, transport, emissions, and deposition processes) in Tg S yr^{-1}. The aerosol precursors are dimethyl sulfide (DMS), carbonyl sulfide (OCS), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S). These gases are oxidized to produce products with the sulfate ion (SO_4^{2-}) such as ammonium sulfate ($(NH_4)_2SO_4$), bisulfate ($(NH_4)HSO_4$), sulfuric acid (H_2SO_4), and nitric acid (HNO_3) [25]). See. Rasch [25] for an in depth explanation of the science and technology of using sulfate aerosols for geoengineering.[1]

The lifetime of aerosols in the troposphere is only a few days, compared approximately a year in the stratosphere. The net source of sulfur to the atmosphere is about 0.1 Tg S yr^{-1} with volcanic eruptions increasing the source. The 1991 eruption of Mount Pinatubo in the Philippines released the largest cloud of SO_2 in the stratosphere, resulting in measurable global temperature changes. This eruption released about 10 Tg S over a few days, making it 100 times greater than usual sources throughout the year. “The life cycle of these particles is thus controlled by a complex interplay between meteorological fields (like wind, humidity and temperature), the local concentrations of the gaseous sulfur species, the concentration of the particles themselves and the size distribution of the particles” [25]. After Mount Pinatubo erupted, global temperature cooled by about 0.7°C for about three years due to the released aerosols in the stratosphere [26]. Figure 2 shows some of the interactions that SO_2 has when it is released into the stratosphere after a volcanic eruption.

[1] 1 Tg = teragram = 10^{12} g

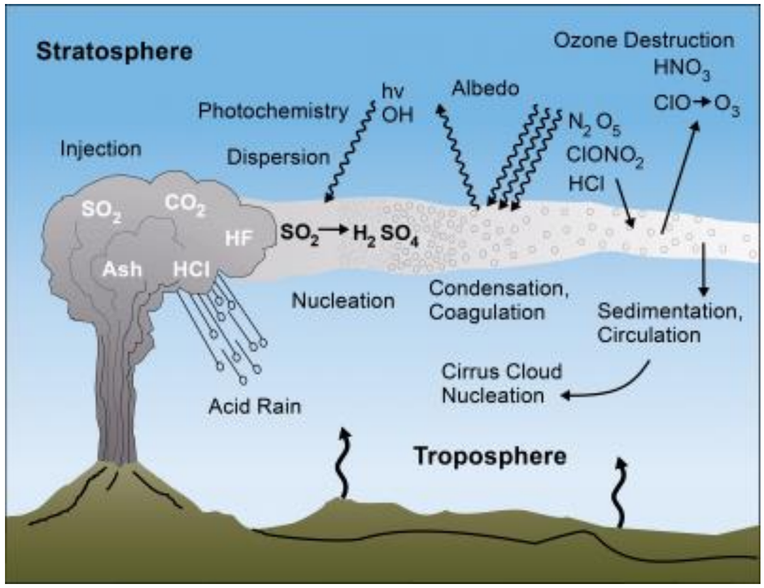

Figure 2: Interactions of the SO_2 interaction is the atmosphere after a volcanic eruption, including the conversion from SO_2 to H_2SO_4 [26].

3.3) Economics of Feasible Technologies

The sulfur dioxide aerosols method presents the lowest cost, by four orders of magnitude, of any of the methods described. The cost estimate for this method relied heavily on data compiled by Aurora Flight Sciences, an experimental aerospace company that has worked with DARPA on a variety of projects, and published through the University of Calgary. [26] The cost of this method depends heavily on the altitude at which the sulfur aerosol is deployed. Release at altitudes in the range of currently operating aircraft would be much more cost effective than developing a new aircraft. For this estimate, we assumed that a new aircraft would be required to release the aerosol at the altitude where it would be most effective (100kft). The Aurora estimates only included a fleet capable of delivering 5 MT of sulfur dioxide per year, so this number was doubled to account for delivery of 10 MT of sulfur dioxide, the amount posited by researchers at Stanford as the amount required to offset a doubling of CO_2 from pre-industrial concentrations. [27] This number was then scaled over time to mitigate the increasing warming each year over the scenario described above. We did not include any efficiency gains for this scaling, in order to keep the estimate conservative.

Table 1: ROM Estimates of GeoEng Methods

	Rough Order of Magnitude (ROM) Estimates of GeoEng Methods ($B)						
		Annual Cost per metric tonne CO2 (whole $)	Total Solution Cost (PV)	Up-Front Fixed Costs	Variable Cost (Annual)	End State (CO2 PPM)	Equiv. CO2 PPM Radiative Forcing
CDR	Biofuel + CCS	$ 55	$ 31,600	N/A	$ 1,470	805	805
CDR	Direct Air Capture	$ 116	$ 224,000	$ 197,000	$ 1,240	500	500
CDR	Ocean Fertilization	$ 3.5	$ 466	N/A	$ 22	905	905
CDR	Enhanced Weathering	$ 324	$ 6,960	N/A	$ 324	930	930
SRM	SO2	$ 0.11	$ 212	$ 8.08	$4 - $19	935	500
SRM	Space-Based Reflectors	$ 77	$ 149,000	$ 149,000	N/A	935	500

1. 2100 CO2 935ppm
2. Baseline CO2 500pmm, 2 deg. C warming

The figures in the "Total Solution Cost (PV)" column of Table 1 represent the cost of 50 years of warming mitigation, at a discount rate of 4%. While this is instructive for comparing methods, we also investigated what the present value of an SO_2 intervention would be across a variety of discount rates and timeframes. The following charts summarizes our findings, showing that even in the worst case scenario, where SO_2 is deployed for 1000 years at a 1% discount rate, the present value of this solution comes out to roughly $1.6T, an amount that is feasible for most world governments to finance over 1000 years. In terms of the cost per ton of CO_2 emitted that would be mitigated by the SO_2 intervention, the cost comes to $0.36 per ton of CO_2.

Table 2: Present Value of SO_2 *Intervention across Timeframes & Discount Rates*

		Discount Rate		
		1%	3%	5%
Timeframe	50	$457	$268	$172
Timeframe	100	$902	$378	$201
Timeframe	250	$1,436	$410	$204
Timeframe	1000	$1,591	$410	$204

Table 3: Cost per Ton of CO_2 *Mitigated by* SO_2

		Discount Rate		
		1%	3%	5%
Timeframe	50	$0.10	$0.06	$0.04
Timeframe	100	$0.20	$0.08	$0.04
Timeframe	250	$0.32	$0.09	$0.05
Timeframe	1000	$0.36	$0.09	$0.05

For the base case scenario in Table 1, the annualized cost of SO_2 injection comes to less than 1% of the annual budgets of the US, China, and the EU, and 3% of the annual budget of India. This indicates that SO_2 injection is well within the financial capabilities of a variety of state actors

After conducting this analysis, it is clear that sulfur dioxide is the lowest cost option that a single state actor could implement to completely offset the warming effects of excess carbon dioxide. The efficacy of this method is also at least partially known due to natural experiments that have been conducted via volcanic eruptions. This method also has the advantage of being largely scalable, as a fleet of sulfur dioxide delivery aircraft could be developed and left unused unless required, and more aircraft produced if the need arose. There are uncertainties for a number of factors, including: 1) the lifetime of sulfuric particles in the atmosphere, 2) the amounts required for proper radiative flux change, the interactions between sulfur dioxide and ozone, and 4) the possibility of excess atmospheric sulfur increasing acid rain. (IPCC, 7.7.2.1) Current estimates of all these factors make sulfur dioxide the most likely option, (in our opinion), that a single state actor, especially a developing country like India, would pursue in a geoengineering policy.

4) Climate Change Decision Making

The climate change problem presents policy makers with a unique and complex set of considerations. If we assume they begin their investigations with a cost-benefit analysis – an assumption with its own complex implications [28] – they still must find a way to arrive at the appropriate solution when the risks are uncertain, the costs of intervention are substantial, and the main benefits of intervention accrue to the distant future. We discuss these factors below, and present a proposed path forward based on the work of C. Sunstein [29] that balances these factors while optimizing for average *and* minimum human welfare.

4.1) Uncertainty

The climate change literature is unequivocal – there is significant uncertainty in the character and quantity of risk to human welfare. [1, 30] This uncertainty is present in every tier of risk evaluation.

Future anthropogenic radiative forcing (greenhouse gas emissions and influences) is unknown, since policy, technology, and economic conditions will all influence the quantity and character of emissions, and these are difficult to predict (especially over centurial time scales).

For a *given anthropogenic radiative forcing*, the climate response is uncertain, with various models predicting different results.[2] For example, if we consider a collection of models using the same forcing inputs (in this case the RCP6.0 scenario, which roughly corresponds to the lower-end of "business-as-usual" emissions), [31] they predict mean surface temperature increases in 2100 compared to the 1986–2005 period of between 1.4°C and 3.1°C.[3] Each model makes different physical assumptions and approximations, and there is currently no way to quantify their accuracy relative to each other and to the future climate.[4]

For a *given climate response*, the set of physical impacts to humans (and the biosphere more generally) are uncertain. For example, the glaciers upon Greenland could irreversibly melt if the climate warms by 2.5°C, but they might instead melt only at 4°C. Ocean biodiversity will likely decrease as the climate continues to warm, but the magnitude of this reduction is unclear, and some locations are projected to see increased species richness. Terrestrial food production is generally at risk, but the welfare impact is unclear, especially since new land will become arable and total world precipitation will likely increase.[5]

Decision-making under conditions of pure uncertainty has been studied [32] and that work argues against policy-making based on ad-hoc (read: "made up") probabilities when well-

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[2] These models collectively are called the ensemble in IPCC reports, and the ranges provided are simply the lowest and highest predicted mean temperature from the ensemble.

[3] "The period 1986–2005 is approximately 0.61 [0.55 to 0.67] °C warmer than 1850–1900."

[4] That said, most models do include ranges based on things like sensitivity analysis.

[5] We might also say that human adaptation to a *given set of physical impacts* is uncertain.

defined probabilities don't exist. Further, Woodward and Bishop believe well-defined probabilities are not a necessary condition for rational policymaking. In a world where those probabilities are missing, a somewhat complete understanding of the possible outcomes would suffice. However, under these conditions, predictions may not provide useful information about the *mean* of the possible outcomes, though the model that produced the *median* prediction is a tempting proxy. The true mean could potentially lie near or beyond edge cases predictions. Absent some probability density, "additional attention should be focused on potential adverse effects … toward the extreme end of the spectrum." These "effects" might otherwise be called catastrophes.

4.2) Catastrophic Risk

Uncertainty is only one of several factors that make climate change a uniquely difficult problem. For example, even given such uncertainty, it is clear that truly catastrophic consequences are possible, especially at the higher levels of emissions (e.g. RCP 8.5). In particular, large sea level rises (~7m), pervasive crop failures, and massive migrations could occur, with corresponding drastic reductions in human welfare. Economic modeling of these catastrophic outcomes is limited, and could understate the risks (discounted or otherwise) of unmanaged climate change [33, 34] and their welfare impact [35].

It has also been argued [36] that catastrophes also exhibit greater-than-proportional impact on welfare than smaller events (relative to their direct proportional losses). This effect can be characterized (in part) by the social amplification of risk inherent to events that impact an entire society. This suggests that catastrophes must be weighted more heavily in a cost benefit estimate relative to a naïve analysis.

4.3) Irreversibility and Cost of Delay

What's more, while many of the consequences of exceptional warming are unknown, there are several possible "tipping points" [37-39] (such as ice sheet melting or methane hydrate deposit destabilizing) after which warming would accelerate and biologic impacts would become irreversibly severe. Further, biologic and geologic systems could be irretrievably damaged or lost after a period of intense anthropogenic warming. Unfortunately, radiative forcing due to CO_2 emissions is permanent over centurial time scales, and the extremely high costs of direct CO_2 air capture seem to preclude rapid reduction of CO_2 concentrations.

Worse, the potential for irreversible consequences becomes more likely each day without CO_2 mitigation, as the long-term equilibrium temperature continues to increase. This will increase the expected cost of damages from climate change, even assuming that humans hold the long-term equilibrium CO_2 concentration constant (via more severe interventions after the delay). [40] Uncertainty about the precise temperature associated with these tipping points only serves to increase the expected costs. Of course, postponed mitigation will increase the cost of mitigation required to meet a certain climate target as well. [41]

4.4) Distribution and Fairness

The hypothetical costs of inaction are not perfectly distributed among the world population. In fact, "[g]reenhouse gas emissions and vulnerability to climate change show a strong negative correlation." [42] Briefly, developing countries have contributed much less to the total CO_2 stock than developed countries. Unfortunately, in order to prevent dangerous climate, developing countries cannot now start to emit CO_2 at western levels, since this would make developed countries' mitigation plans ineffective. Even determining the correct future level of emissions is complicated by questions of equity, since poorer countries are will have much lower willingness to pay for some interventions (given their relative poverty, and preference for growth). Restated, why make someone pay more for insurance than they'd like? Many of these countries argue instead that the rich world should reduce their emissions, and pay the poorer countries in exchange for further emissions reductions.

This reality was acknowledged in the Framework Convention [2] but firm agreements that shared this philosophy were not forthcoming. This question of equity will not be solved here. We merely propose to consider the question of equity while evaluating proposed interventions, borrowing from the "maximin principle" [43], which argues that manageable inequalities should be arranged "to be of the greatest benefit to the least-advantaged members of society." Restated – the poor shouldn't bear the brunt of the negative effects of climate change.

4.5) Future Generations and Discounting

It is natural to discount future returns to investments and future expenditures, especially in the context of one's own life. However, intergenerational discounting is a subtler matter. [44] While there is now more academic consensus [45] objections remain. Some of these objections would be leveled at any regulatory action that might permit harm after a cost-benefit analysis, since these harms might be considered rights violations, torts (which would permit recovery), or even value-system conflicts (a reverence for nature, for example).

Other objections relate to the practice of discounting itself, specifically the long-term benefits from climate mitigation. R. Revesz explored this topic extensively, [46] and came to two conclusions. First, one of the main justifications for discounting cash flows does not apply to risks to life and health: lives and health cannot be directly invested to produce future returns of life and health (though he agrees that an individual human may have a pure time preference for health today rather than tomorrow). Second, while a single person may have an internalized time preference for health and life, the argument to apply the same logic between generations is quite fragile. "Why should the death of a ten-year-old in 2040 count less than the death of a ten-year-old today?" Revesz concludes that there is not a good answer to that question, and that risk reductions/improvements ought not to be discounted at all between generations.

Regardless, technologies that increase our future options are valuable, since they might mitigate some irreversibilities, and permit the delay of other mitigations into the future (reducing their cost, due to discounting).

4.6) Precautionary Principle and Geoengineering

Building upon the above, we can justify a precautionary principle best suited for questions of climate change. The concept itself has a long history of application in environmental policy [47, 48]. The principle has often been described as having one of two forms. A weak form might suggest "a lack of evidence of harm should not be a ground for refusing to act." [29] This is sensible, but not especially useful in the context of global warming, since ample evidence already exists. Stronger versions, while more directive, require action at given any possibility of risk. Sunstein correctly argues that such a strong policy is paralytic and incoherent – the interventions themselves carry risks, some uncertain; the cure might be worse than the disease. Instead, policy makers should base their decisions on a guideline that recognizes the cost-benefit balance inherent to catastrophic risks: The Catastrophic Harm Principle. Summarized, this principle suggests the following:

> *Under circumstances of uncertainty, regulators should eliminate the worst-case scenario if,*
>
> - *The worst-case scenario under one course of action is much worse than the worst-case scenario of the alternative, and*
> - *It is not extraordinarily burdensome [costly] to take the course of action that eliminates the worst-case-scenario*

Admittedly, this is vague guidance, but it is a start.

4.7) What about Geoengineering?

As we've seen, geoengineering methods (and specifically SO_2 injection) are not without risks. Many of these projected risks (such as uneven cooling, weather system impacts, or severe droughts) [49-51] are both plausible and salient. What's more, the existence of a comprehensive geoengineering solution is likely to decrease the commitment of CO_2 emitters to reduce emissions (at least in the short term). [52-54] More than a few researchers, policy makers, and members of the public have examined these risks and concluded that they are too great, and that the scientific and policy communities should focus solely on CO_2 reduction. While we agree that these risks are substantial (though uncertain), we believe that geoengineering tools would provide substantial benefits relative to CO_2 reduction alone.

4.7.1) <u>Cost</u>

We have estimated that SO_2 injection could cost about $20 billion per year, providing most of the benefits of CO_2 reductions at about 2% of the cost. This is substantially less than any published estimates for the cost of climate change mitigation based on emissions reductions alone.

4.7.2) Insurance and Option Value

In the case of climate change, being faced with the potential for an unpredictable irreversible loss, policy makers "should be willing to pay a sum – the option value – in order to maintain flexibility for the future." [29] Geoengineering solutions could be "optioned" and subsequently made available purely as an "insurance policy," in the event that the other mitigations chosen fail to prevent costly states of the climate. Additionally, geoengineering provides a tool for humanity to respond relatively quickly to consequential climate shifts proportional to the observed shift, avoiding some potential for over or under investment.

4.7.3) Out of Options

In certain states of the world, climate change may reach a tipping point, after which reductions in anthropogenic GHG emissions would not prevent a further increase in warming. In this case, geoengineering may be the only tool remaining with any plausible hope of restoring the climate to a tolerable equilibrium.

4.7.4) Zero carbon feasibility

Most energy policy proposals that aim to reduce global warming do not propose an immediate end to CO_2 emissions, but instead set the date for carbon-free economy for 2050 or 2070. Even then, these proposals assume the existence of a variety of technologies that are currently immature. Most important would be some form of Carbon Capture and Sequestration (CCS). If these technologies are not available, then "mitigation costs can increase substantially." In particular, unavailability of CCS has been modeled to increase mitigation costs by ~40% to 140% depending on the CO_2 concentration target. [1] Further, solar power deployment (which has the greatest potential energy generation capacity) is limited by land use considerations and technological development [55, 56].

Complicating matters, it would be difficult or impossible to produce enough energy to sustain western-level energy consumption for every human on Earth. The international cooperation and cost sharing required to sustain a CCS infrastructure might also be difficult, and act as another barrier to a true zero-carbon economy.

Finally, if bioenergy substitutes for transportation fuels are likewise not available, then climate change mitigation plans may be simply infeasible without the reverse forcing provided by geoengineering technologies.

4.7.5) Going it Alone

Many examples of inter-state collective action suffer from the free-rider problem. Climate Change is no exception, and the substantial abatement costs exacerbate the problem. Geoengineering tools (and SO_2 in particular) are simply so much cheaper than CO_2

reductions alone (as above, about 50 times cheaper) that a single actor could be motivated to invest in a program of climate mitigation, since the benefits that accrue to that single actor might be greater than of the costs of "going it alone."

4.7.6) Moral Hazard

It is straightforward to believe that the existence of geoengineering options is likely to reduce incentives for GHG emissions – clearly, a method to avoid the most costly emissions reductions (and still be protected against catastrophic climate change) would distract from efforts to develop a zero-carbon economy. [57] However, it is plausible (if not defended here) that a program that mixes geoengineering technologies and some CO_2 emissions abatement may be welfare maximizing. Regardless, some authors have argued that these abatement and geoengineering technologies are complements and best used together. [58]

4.7.7) Reasonable and Plausible

For these reasons, we believe that the use of geoengineering, and specifically, SO_2 albedo modification, could be worth the risks in the scenario we describe. It may be that this technology would only be used in an emergency, or perhaps it would be used over decades or centuries to postpone the eventual necessary reduction in atmospheric CO_2. In short, SO_2 injection used to modify the climate,

- Has potential to eliminate some catastrophic risks,
- Could prevent climate reaching tipping points (or make them reversible),
- Cheap enough to be implemented by relatively poor countries (improving fairness),
- Permits delay of other mitigations (reducing cost), and
- Presents risks, but much smaller ones than unmitigated climate change

Therefore, we think SO_2 injection is worth consideration as an insurance option.

5) Policy Landscape

5.1) Current Policy Landscape

The answers to questions surrounding the potential implementation and management of geoengineering regimes undoubtedly require a great deal of scientific understanding. However, the implementation and on-going maintenance required to implement a geoengineering strategy must also take into account non-science values and political will of various stakeholders. Political legitimacy, the speed of deployment and subsequent ability to change course, and the desire and economic and technical feasibility of implementation are examples of hugely important aspects of geoengineering policy. Ensuring that such values, coupled with the best available scientific data, are taken into consideration when implementing geoengineering policies is critical, especially in terms of designing appropriate political bodies to oversee this implementation and maintenance.

Currently, there are no international laws explicitly governing geoengineering. In fact, geoengineering research and development had not been explicitly addressed by the IPCC prior to the IPCC's Scientific-Technical Assessment for its Fifth Assessment Report (AR5) released on September 26, 2013. Some existing international agreements mention the possibility of geoengineering, such as 2010 Convention on Biological Diversity, which states that "until there is an adequate scientific basis on which to justify such activities [geoengineering] and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts…"geoengineering should be avoided [Gao citation]. However, some existing international agreements and legal instruments have been subsequently interpreted to apply to geoengineering principals. Examples include:

- The Vienna Convention for the Protection of the Ozone Layer, which could regulate stratospheric aerosol injections deemed harmful to ozone;
- The Convention on Long-Range Transboundary Air Pollution (CLRTAP), which bans the human introduction of substances to the air that could have a negative effect on human health or the environment; or
- The Convention on the Prohibition of Military or Other Hostile Use of Environmental Modification Techniques (ENMOD), which prohibits "any other hostile use of environmental modification techniques which have widespread, long-lasting, or severe effects...to any party..."

In addition, we were unable to find literature evaluating existing domestic policy governing geoengineering, suggesting that few, if any, laws currently exist explicitly pertaining the implementation or deployment of geoengineering in the United States. Like the international regulations above, there exist state and federal law or statutory authority that could potentially be used to regulate geoengineering in the future. However, no examples of any of these regulations have been used to significantly affect the research and development of geoengineering policy to date. Whether geoengineering can be adequately regulated though amendments or addendums to existing law or if new domestic and international laws will be necessary remains unclear.

5.2) Possible Governance Structures

Geoengineering policies could be implemented by one or more of the following institutions: (1) a far-reaching and vastly representative international body such as the United Nations (UN); (2) a smaller coalition of countries specifically convened for the purpose of geoengineering management; or (3) unilateral action by one state or private sector actor. Each of these broad categories include potential advantages and disadvantages for geoengineering implementation, although in our opinion the most likely scenario involves action driven by single actor. Additionally, other non-governmental organizations such as nonprofits are likely to play a critical role in geoengineering policy.

5.2.1) United Nations Framework

One possible method for the governance of geoengineering on an international level is to create or modify an existing regulatory body associated with the UN. This body would likely resemble that of the UNFCCC—a large-scale organization with near-universal international representation. Benefits of this type of governance are increased legitimacy and transparency, and greater access to technology and financing.

However, significant disadvantages are associated with this type of governmental structure, especially as it would relate to geoengineering. First, this method of governance is inherently conservative, requiring massive amounts of time and political capital to come to consensus on issues. In contrast, geoengineering is by nature a radical action that would ideally only be implemented under extreme scenarios (i.e. in the tails of the climate model distributions). Additionally, much remains unknown about the practical implementation and unintended side effects of geoengineering. As more information becomes available about the how geoengineering regimes work in the field or the effects of geoengineering as it is scaled-up, a suitable governing body would need be able to adapt quickly to new information and developments. A slow-moving political body like the UN would likely not be able to react quickly enough to change course, thus making it unsuitable for the regulation and on-going maintenance of geoengineering.

Lastly, most large political bodies lack the compulsory jurisdiction to enforce international agreements should one party violate the agreement's terms. A commonly cited concern among geoengineering detractors is the idea that some actors could choose to implement geoengineering in a hostile manner. Such actors would likely not be party to any kind of geoengineering agreement, yet even if they were, the legal instruments of the treaty would likely be unable to punish the rouge actor.

5.2.2) Unilateral Action

Unlike many other pressing environmental challenges facing the international community, geoengineering, particularly SRM, does not require collective action or cooperation among state actors. In fact, the risk of one state taking unilateral action without the consent or involvement of the international community is often perceived as a far greater political challenge than managing the collective actions of an international coalition. Unilateral action, especially unilateral action that is taken without the consent or involvement of other affected parties, has a negative connotation. While some examples of unilateral action are perceived by others to be appropriate, it is extremely difficult to define what appropriate unilateral action looks like. Rather, actors routinely rely on the subjective "you know it when you see it" designation to classify unilateral action deemed threatening.

The issue of unilateral action and the inherent tensions surrounding it are related in large part to the idea of national sovereignty. Independent nations have the right and responsibility to enact policies which would benefit their people. In fact, most environmental regulations are enacted unilaterally and are rarely contested by neighboring countries (i.e., effluent discharge limits, air pollution standards). However, this issue is complicated by problems that are trans-boundary by nature, including many environmental issues. As environmental issues become more international in scope, and the economy becomes more global, issues such as CO_2 emission will likely require more international coordination than in the past.

We see unilateral action as an unavoidable part of the geoengineering policy debate. It seems likely that one country, when faced with potentially dire effects of climate change, would act alone in an effort to combat those effects. In fact, based on economic analysis of sulfur dioxide injections previously described in this paper, it is conceivable that a wealthy private actor acting alone could also decide to deploy SO_2 into the atmosphere. In this case, for unilateral action to result in a positive effect, the action must support shared, impartial interests rather than parochial national or personal interests.

The association of unilateral action with illegitimacy and mistrust is troubling, not least because effective international coordination on climate change may not be possible. Although the recent climate agreement in Paris is considered to be a victory by many, some in the international and environmental communities fear that this agreement does too little to ensure that CO_2 emissions stay at a manageable level. In any event, the agreement does not contain any enforcement mechanism, which would seem to be necessary to discourage free riding in the face of the high costs of mitigation.

In this case, it is worthwhile to think of unilateral action as compared to inaction. In the scenario that we have presented previously, it is possible to imagine a state of the world where geoengineering implemented unilaterally is preferable to political deadlock in a UN framework.

5.2.3) Multi-Party Coalition

Creating a multi-party coalition of international actors could help to bridge the gap between efficiency and legitimacy. A multi-party coalition in this context should have two main components: (1) small membership, and a (2) minimal formal structure (in the form of enforceable treaties, for example). Small membership would allow the coalition to react quickly to new information and change course if necessary. A weak legalization structure is necessary to encourage participation in the coalition. One drawback to a small membership, multiparty structure is that it is wholly reliant on the behaviors of the few nations that are members, and could be drastically affected if one member drops out of the coalition. Virgoe predicts that this type of governance would be most beneficial for the early research and development stages of implementation, but may not be stable enough for full deployment or long-term maintenance. [59]

5.2.4) NGO Involvement

The growing involvement of NGO actors in the international political arena could have a significant impact on the development of geoengineering policy. Increasingly, NGO's have become organizations known for building and maintaining the most current "best practices" and expertise on a given subject. We expect that NGOs advocating for geoengineering research and policy could be created in the coming decades. In addition to providing expertise, NGOs could also add legitimacy to the research and development process. NGOs are often associated with grass-roots movements and might appear to give the implementation of geoengineering a participatory feel.

6) Implementation

6.1) Why India?

Although climate change is expected to affect different regions in vastly different ways, and regional-specific issues will largely determine the policy decisions made by various state actors, we want to highlight one country – India – to use as an example of how a state might approach the issue of geoengineering and its implementation. India provides an interesting example in which to evaluate a country's decision-making process surrounding geoengineering because:

a) India is projected to experience significant effects from climate change
b) India will likely be facing other socioeconomic stressors which might complicate the issue of climate policy, and
c) India is projected to have enough economic and political capital to be an active player in international politics.

6.1.1) India is Particularly Vulnerable to Climate Change

According to the World Bank, India is particularly vulnerable to climate change and by 2050 will likely have experienced serious effects as a result of increased CO_2 in the atmosphere. For example, Mumbai, home to one of the planet's largest coastal populations and with a significant portion of the city built on salvaged land below the high-tide mark, is expected to be seriously affected by sea level rise, even more so than countries located at higher latitudes. (Analytics 2013) Climate models tend to agree that increased CO_2 will result in both higher average temperatures (2 °C on average, ranging from 1 °C – 4 °C at extremes) and increased rainfall in India. [60] Additionally, extreme weather events such as droughts and heavy monsoon rains are expected to increase in frequency. For example, intense monsoon rains previously experienced every 100 years on average are expected to occur on average every 10 years as a result of increased atmospheric CO_2. However, regional variability in climate effects, even within the Indian subcontinent, is likely to be significant.

6.1.2) Major Effects Likely on the Agricultural Sector

The most substantial effects of climate change on India will impact the country's agricultural system. The latest (2015) figures from the World Bank estimate that the agricultural sector comprises approximately 17.8% of Indian GDP. (The World Bank n.d.) Furthermore, 68% percent of India's population relies economically on the agricultural system in some way, meaning that disruptions to this sector could have lasting ripple effects on both the Indian economy and the livelihoods of millions of people. [61] However, the extent to which different regions within the Indian subcontinent will be affected as well as how these changes in temperature and precipitation will affect agriculture and growing seasons remains unclear. Some academics suggest that increased average temperatures will decrease crop yields; however, increased average temperature could also simultaneously lengthen the growing season for many crops. Kumar and Jyoti [62] estimate that increased temperatures will have a net negative effect on crop yields, especially among winter crops such as cereals, which are typically grown in northern states like Haryana, Punjab and western Uttar Pradesh. Additionally, this analysis predicts that greater negative impacts are likely to be experienced as temperatures increase.

Increased variability in precipitation are also likely to result from increased CO_2 levels in the atmosphere, and are projected to contribute to increased frequency and intensity of natural disasters such as floods and droughts. In India, changes in precipitation are expected to vary across the country, however, most regions are predicted to experience fewer, higher intensity rain days, [60, 63]. Bird et al. estimates that "the impact of such variability could undermine the water security of over one billion people, globally…"

6.1.3) Policymakers Must Also Deal With Other Stressors

In addition to adapting to changes in temperature and precipitation, India will also be faced with additional socioeconomic stressors that political leaders will have to consider, notably economic development and globalization. According to the World Bank, approximately 21% of Indians live below the global poverty line, which is defined as living on $1.90 USD or less per day. Pressure on policymakers to grow the economy, provide jobs and social services, and modernize – actions which many feel is inextricably linked to CO_2 emissions – needs to be recognized and balanced with the global need to reduce CO_2 emissions.

6.1.4) India Possesses the Economic and Technological Capabilities

Unlike other developing countries predicted to be severely affected by climate change, India is also projected to be one of the largest economies in 2050, making the economics of research and deployment of geoengineering feasible. Harvard economists have predicted that India will experience the largest annual growth rate of any country over the next decade, surpassing China and other fast-growing Asian countries. Additionally, a recent report by Price Waterhouse Cooper estimates that India could become the second largest economy in the world according to purchasing power parity (PPP) by 2050 and that India's GDP could potentially reach 10 trillion dollars by 2035. [64] Mitigation and adaptation to climate change, especially the research and development of new technologies to combat such effects, will require substantial monetary investment as well as the technological capabilities and human capital to implement them.

6.2) Implementation Road Map

An important aspect of geoengineering is designing the implementation. David Keith lays out a "Scenario for Deployment" in his book *A Case for Climate Engineering*. The steps are: 1) Theory and Lab Work 2) Experiments in the Atmosphere 3) Minimal Deployment 4) Gradual Deployment [65]. These four steps are general guidelines for any country to follow if deciding to inject aerosols in to the atmosphere. Another factor to consider is how this country will choose to act in relation to the rest of the world. Will they execute all of the steps unilaterally, with alliances, or with universal consent? If India chooses to act unilaterally, India opts to research, fund, experiment, deploy, and monitor without officially consulting other countries. For this to occur, India would have to be in a true crisis because there are many factors working against them. Not only would put the entire financial burden fall on India, but they risk conflicts with other nations who oppose injecting aerosols in to the atmosphere. With India already experiencing the negative consequences of climate change, India choosing to act rather than wait for universal cooperation that may never happen, might temper some of the negative effects.

The second choice India has, is to form alliances with countries who are also feeling the effects of climate change. This allows the countries to share the financial burden, utilize greater resources, and is a greater deterrence for countries to act against the deployment.

The last choice is for India to wait for universal cooperation and consensus on any action. When India is experiencing frequent extreme weather events, disruption in their agriculture, and increased poverty levels due to climate change, universal consensus is not an option because India needs to act immediately. Any sort of treaty or convention would take months if not years to plan, and even so, a consensus on how to act may never be reached.

6.2.1) Step 1: Theory and Lab Work

At this stage, there are four main questions that India has research before they are ready to deploy:

- How much SO_2 needs to be injected and at what rate?
- What method of deployment?
- Where should India inject the SO_2?
- How will India monitor the effectiveness and negative consequences?

6.2.1.1) How much SO_2 and at what rate?

In our scenario, we are mitigating all warming above 2°C, with SO_2 injection levels increasing every year to compensate for the increasing CO_2. We estimate that between 1.9 Mt and 10.97 Mt of SO_2 yr^{-1} need to be injected at around 20-30 km in the stratosphere at a cost of $4 - $19 billion per year. There is uncertainty around this estimate due to the degree of radiative forcing of SO_2 scientists use, among other factors. For example, a study by the Max Plank Institute for Meteorology found that in order to maintain the predicted 2020 temperature, about 45 Mt of SO_2 yr^{-1} needs to be injected into the stratosphere [66]. That amount is at least 5 times the SO_2 injected by Mount Pinatubo, meaning we are unable to use any natural phenomenon to predict the consequences of injected aerosols in the stratosphere at such high levels.

6.2.1.2) Method of Deployment

Many deployment technologies currently being developed including, gas pipes, guns, rockets, and various aircrafts. The type of deployment method used is heavily dictated by the height of injection. No current aircraft flies at the altitude required for aerosol injection in the stratosphere. According to the Aurora Flight Sciences study, a new aircraft is required for our estimated injection height of 20-30 km, with a hybrid airship required for higher deployment heights [26]. At this height, it would cost about $4-$19 million per year to continuously inject SO_2. It is important for India to start developing their method of deployment well in advance, as they have to design and build new aircrafts.

6.2.1.3) Where should India inject SO_2

There are two aspects of where India should inject the aerosols. The first is the altitude of deployment that we have previously discussed. The second is spatially across the earth. Should India distribute the aerosols uniformly over the earth? There is evidence of asymmetric forcing of stratospheric aerosols, specifically evidence of general east/west distribution but less of a north/south distribution [25]. In addition, the amount distributed latitudinally varies based on whether India wants to optimize temperature or net precipitation (precipitation minus evaporation) to preindustrial conditions [28]. To regain preindustrial temperature, a parabolic distribution of aerosols is optimal with injections at lower altitudes at the equator and higher altitudes at the poles. However, to reach preindustrial net precipitation, a more uniform latitudinal distribution is optimal. These are a couple of the factors that India has to consider when deciding where to distribute the SO_2.

6.2.1.4) How will India monitor the effectiveness and negative consequences?

One of the biggest oppositions to any geoengineering, including aerosol injections, is the unintended consequences. Many of those consequences are being researched such as asymmetrically decreasing the ozone and the resulting increase in UV-B radiation [67], changing the rainfall/monsoon with a potential decrease in global-mean precipitation [68], the various impacts of aerosols asymmetric forcing [69], increasing the terrestrial photosynthesis rate which increases the carbon sink [70], and many more. One common concern about injecting sulfate aerosols in the potential for increases in acid rain. However, studies show that the amount of sulfur injected is such a small percent of the total sulfur in the troposphere and stratosphere that it can be offset with a decrease of emissions in the troposphere [25]. Still, more research in these and other known potential negative consequences needs to continue. Unfortunately, even if India is able to optimize deployment for all of these consequences, there are still the unknown negative consequences that could occur after deployment that scientists did not consider researching. Therefore, developing monitoring technologies is extremely important, so that at each stage of deployment, scientists can detect not only the known but also the unknown unintended consequences.

During the research and development stage, India has the capability and resources to unilaterally research each of these four main questions. However, it would benefit India to partner with other countries and research institutions to explore these fundamental aspects of sulfate aerosol injections because pooling data and resources will expedite the process. An example of international geoengineering research cooperation is the Geoengineering Model Intercomparison Project (GeoMIP). GeoMIP was created out of the need to compare the results between geoengineering models. As research groups created different models, it was difficult to determine whether the varying results were due to the geoengineering technology or the model the simulation was based on [71]. Hence, GeoMIP was created to "organize geoengineering simulations by prescribing the experiments which all participating climate models will perform" [71]. As a result, scientists and research institutions from around the world collaborate through GeoMIP. Model results using GeoMIP can be more easily compared than those with different starting assumptions.

6.2.2) Step 2: Field Experiments

Field tests are necessary before deployment because models and laboratory experiments give limited results. With these experiments, India can determine some level of efficacy and feedback loops, and identify where more research needs to be done. David Keith proposed two field experiments in 2014: the Stratospheric Controlled Perturbation Experiment (SCoPEx) and the Mesoscale Stratospheric Geoengineering Experiment (MSGX) [72]. The purpose of ScoPEx is to "quantify the risks posed by SRM to activation halogen species and subsequent erosion of stratospheric ozone" [73]. They propose to use a balloon to inject small amounts of water vapor and aerosols, and then measure responses to those perturbations. MSGX "aims to test sulfate aerosol geoengineering at a scale sufficiently large to enable quantitative tests of stratospheric mixing, aerosol dynamics, the impact of aerosol heating rates on dynamics, ozone chemistry and radiative forcing, and to enable comparison of *in situ* and remote sensing observations" [72]. In this experiment, Keith proposes to use five aircraft to deploy 500 t S over 1000 km spatially and a few kilometers in the atmosphere. These are the type of field experiments India has to conduct in order to quantify the feedback loops and unintended consequences that are difficult predict using models alone. One important factor that comes in to play at this stage and even more during actual deployment is other countries' opposition. Deployment of anything into the atmosphere, even if it is minute, temporary, and above India's own airspace, can cause resistance. Since conducting field experiments is the step before deployment, countries against geoengineering or sulfate aerosols injections specifically will oppose India progressing at this stage. Therefore, it is beneficial for India to partner with other countries who have an interest and will benefit from aerosol deployment. This not only allows for shared financial and physical resources, but creates a deterrent from any intervention from an opposing country.

6.2.3) Step 3: Minimal Deployment

Minimal deployment is important because if negative consequences appear that were unobserved in the field experiments, the damage will be limited and there is the opportunity to cease deployment. One characteristic of injecting aerosols into the atmosphere is the requirement to continue deployment indefinitely. Abruptly halting deployment can result in temperature, precipitation, and sea-ice cover changing more rapidly than the situation with the expected increase in greenhouse gases without any geoengineering [74]. Essentially, starting aerosol deployment and then suddenly stopping it is more dangerous than if the aerosols were never deployed, because it is the rate of deployment that matters. Swiftly starting or ending injections will rapidly change the temperature, precipitation, and sea ice level, which will impede adaptation by ecosystems and people. With minimal deployment at say 3 Mt yr^{-1}, if severe negative consequences occur, India will be able to halt injections sooner than if they started deploying the full 11 Mt in the first year. India has to determine a minimal deployment level and the rate at which they want to increase to full deployment. In addition, once deployment commences, opposition is almost guaranteed. With the Step 2 Field Experiments, there was a possibility that other countries would not intervene, especially if India is allied with other countries. However, with minimal deployment, there are at least two sources of conflict. Because aerosol dispersion occurs east/west spatially, India can generally deploy north/south. If India decides they want to deploy unilaterally, their deployment planes will have to fly above the countries north of them. This is definitely a source of conflict not only for countries who oppose injecting aerosols, but also for those who suspect that the planes are being used for espionage or military purposes, rather than to deploy aerosols. Therefore, it is beneficial for India to form alliances with countries to their north in order to deploy above those countries without immediate military retaliation. Luckily, the Indian Ocean is south of India, so there are no countries to the south that Indian planes will have to fly over. It will be difficult for India to reach an agreement with every country or even a majority of countries north of them, but in this situation where Indian planes are crossing borders, there is a better chance of successful deployment with some alliances. The second source of conflict is due to the dispersion of the aerosols east/west. Even though Indian planes will not be flying over those countries, they will experience the effects of aerosol injection, albeit positive and negative. While the effects of aerosol injection could benefit those countries, the fact that a country or even a coalition is doing something that will affect the entire earth will result in strong opposition. This is compounded by the fact that once the aerosols are deployed, they have to continuously be injected, so it would be unwise to simply shoot down all of the deployment planes and suddenly halt deployment. At this stage, and especially at Step 4, it is imperative that India form alliances with multiple countries before deploying. They will want to form a military deterrent that will prevent an opposing country from intervening.

6.2.4) Step 4: Gradual Deployment

India should develop criteria for when it is safe to transition from minimal deployment to gradual deployment. How long should they monitor for negative consequences in the minimal deployment stage before they declare it safe to transition? What is their criteria for consequences that are severe enough to halt injections? It is important to remember that in our scenario, India is already experiencing serious effects of climate change. They are motivated to complete each step of deployment as efficiently as possible. At each stage they are going to have to balance risking military intervention and conflict with other countries with the time it will take to form alliances. Countries will disagree each of those four main questions in the research and development stage because they are feeling different effects of climate change to different degrees. When India injects aerosols into the stratosphere to positively affect their monsoon, this could negatively affect China's monsoon, creating a new type of conflict over the ability to control regional climate. For these reasons, when India decides to transition to gradual deployment, they should also work towards forming a universal agreement.

7) Recommendations and Conclusion

The technical and economic analysis of geoengineering methods presented in this paper suggests that SO_2 injections are a viable option for preventing future temperature increases likely to result from increased levels of CO_2 in the atmosphere. However, despite the low relative cost of implementing and deploying this technology, uncertainty still remains regarding the unintended effects of SO_2 deployment, and more research (particularly real-world field testing) should be done to further evaluate this technology.

Of all the available geoengineering methods, SO_2 is the only technique plausible today that is reasonably within the reach of a single state actor. Many nations, and possibly even a collection of motivated affluent individuals, could fund the type of intervention needed to limit earth's warming to no more than 2°C relative to preindustrial on a multi-decadal timescale. SO_2 injection is also tunable, so the magnitude of the intervention can be scaled to match the size of the temperature anomaly faced, as well as tuned to the desired degree of warming to be mitigated. While SO_2, like any other SRM method, does not mitigate all negative effects of excess CO_2 concentrations, such as ocean acidification and disrupted weather patterns, it can act as a complement to general CO_2 reduction.

Critics of geoengineering research point to the moral hazard issue, or the idea that merely knowing of technologies that could prevent the negative temperature effects of climate change exist might reduce incentives to curb CO_2 emissions. While this may be true, we believe that the "cat is already out of the bag," meaning that enough information is already known about geoengineering or the potential for geoengineering that state actors already may decide to forgo mitigation in the hopes that a technology such as SO_2 injections might be deployed. Additionally, under the extreme climate scenario we have presented, runaway climate effects could make further mitigation impossible or impractical.

This paper does not examine the economic and moral issues surrounding substituting SO_2-based mitigation for aggressive CO_2 reductions, but the results of our analysis indicates that this may be an area for further research. While this paper focuses on the implementation of an SO_2 geoengineering policy based on an extreme scenario in which it is already too late to mitigate warming via CO_2 emission reductions, further research may suggest that some amount of SO_2 injection is preferable over drastic reductions in CO_2 emissions, given the extremely low relative cost of SO_2 intervention.

Within the bounds of the climate scenario that we have described, including possible tipping points, we conclude that it is possible that a state actor could maximize welfare by implementing an SO_2 injection program aimed at stabilizing the Earth's mean surface temperature anomaly to less than 2° C. In this case, unilateral action would likely be justified, although international coordination in some fashion would make SO_2 injection "easier" and could result in a more scientifically-sound deployment. Equally important, an actor must be able to commit to the long-term monitoring and implementation of geoengineering, which is essential to avoid rebound effects.

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