Preparing for the Worst:

The Case for Solar Geoengineering Research and Oversight

2019

AUGUST 6

Bradie S. Crandall
American Institute of Chemical Engineers

"The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand."

-Carl Sagan

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Executive Summary

As global carbon dioxide emissions continue to rise, the looming threat of a climate crisis is becoming a growing concern. To avoid the intensification of geo-political, health, economic, and environmental risks, the world may begin considering more drastic measures to address climate change. One of these drastic measures that has been discussed is solar geoengineering. This strategy involves taking measures to intervene with the earth's climate by modifying the planet's albedo. A variety of key conflicts and concerns related to the prospect of solar geoengineering will be considered in this work. These concerns include the potential of a research echo chamber that may occur in this esoteric field which could amplify false notions, the existence of a fine line between solar geoengineering research and implementation, a lack of understanding of the risks associated with this technology, and the possibility of rogue actors implementing solar geoengineering unilaterally. Additionally, the issue of termination shock (if solar geoengineering efforts were to abruptly stop following implementation) will be addressed along with the possible conflation of the climatic effects of climate change with the effects of solar geoengineering. Finally, the lack of public understanding about solar geoengineering technologies and the moral hazard of replacing efforts to reduce emissions with solar geoengineering efforts will be discussed.

Policy recommendations to address the growing interest in solar geoengineering include mechanisms to prioritize climate change mitigation and adaptation, to promote federally funded research, to establish international oversight, to encourage transparency, and to fill the legal void. It is critical for the U.S. to prioritize climate change mitigation and adaptation strategies prior to advancing federal solar geoengineering efforts to avoid being accused of a moral hazard. This prioritization should be accomplished by rejoining the Paris Agreement as soon as possible and enacting policy to achieve the goals established by the international treaty. A road map will be needed to generate robust climate change policies that will strive to attain the Paris Agreement goals. It is suggested that a bipartisan "Green Deal" framework consisting of the commonalities between the Green New Deal and Green Real Deal be constructed. If these efforts fail to address climate change and solar geoengineering is needed, the establishment of international oversight is critical to ensure multilateral deployment. It is recommended that the previously established United Nations Intergovernmental Panel on Climate Change (IPCC) perform annual risk evaluations on the implementation of solar geoengineering. It is also recommended that a U.S. Federal Solar Geoengineering Research Program be created to gain a better understanding of this emerging technology. The DOE's Office of Science should oversee this program by providing research grants to universities and national laboratories. Additionally, NASA and NOAA would provide their satellite resources to aid research efforts while the EPA would provide environmental impact assessments to ensure all environmental risks are minimized during experimentation. It is critical for solar geoengineering research to be transparent to prevent public backlash. This should be accomplished via improved public education and the establishment of national and international research clearinghouses. Finally, the solar geoengineering legal void should be filled by outlawing unilateral action outside of the IPCC's oversight framework and expanding international environmental impact assessment law.

Foreword

About the Author

Bradie S. Crandall is a senior at the University of South Carolina and will graduate in May 2020 with a B.S. in Chemical Engineering, a minor in Chemistry, and with leadership distinction in research. Upon graduating, he intends to further his education by pursuing a PhD in Chemical Engineering. His interests include sustainable energy production, emission reduction, climate change mitigation policy, and science education. He currently serves as the treasurer of the University of South Carolina's student chapter of the American Institute of Chemical Engineers. He also works to promote inclusivity in the field of engineering as a member of the Society of Women in Engineering. He is a recipient of the Magellan Scholar Grant and was appointed to Oak Ridge National Laboratory by the Department of Energy in 2018. He has over three years of environmental catalysis experience at the University of South Carolina's Strategic Approaches to the Generation of Electricity Research Center. His research projects have included work on the tri-reforming of methane, adsorptive desulfurization of liquid fuels, and photocatalytic hydrogen production via water splitting.

About the WISE Program

The Washington Internships for Students of Engineering (WISE) program was founded in 1980 through the collaborative efforts of several professional engineering societies and has become one of the premier Washington internship programs. Each summer, the WISE societies select outstanding 3rd or 4th year engineering/computer science students, or students in engineering/computer science graduate programs, from a nation-wide pool of applicants. The students spend nine weeks living in Washington, D.C. during which they learn how government officials make decisions on complex technological issues, and how engineers can contribute to the legislative process and regulatory public policy decision-making.

Acknowledgements

First and foremost, I would like to express the sincerest of gratitude to my parents, Brad and Jodie Crandall. Without them, I would not be the man I am today. The sincerest of thanks is also given to my longtime girlfriend, Rachel Margolis, for supporting me in all my endeavors. I would like to recognize the American Institute of Chemical Engineers for their sponsorship and aid this summer with a special thanks to Dr. Dale Keairns and Heather Yuengling. I owe the opportunity to have such a positive experience in DC to the Institute of Electrical and Electronics Engineers and I would like to especially thank Diana Librizzi and Erica Wissolik for hosting the other interns and I this summer. All my professors at the University of South Carolina, especially Dr. John Weidner, Dr. Johen Lauterbach, and Dr. Erdem Sasmaz should be recognized for imparting their engineering knowledge upon me. I would also like to thank the interns whom I worked alongside in DC this summer. Finally, I would have never become a chemical engineer had my high school chemistry teacher, Victor Senn, not inspired me to do so. May he rest in peace.

Acronyms

CCS – Carbon capture and sequestration

CDR – Carbon dioxide removal

CIA – Criminal Intelligence Agency

CTBT – Comprehensive Nuclear-Test-Ban Treaty

DOE – Department of Energy

EIA – Environmental Impact Assessment

EPA – Environmental Protection Agency

IPCC – Intergovernmental Panel on Climate Change

NAS – National Academy of Sciences

NASA – National Aeronautics and Space Administration

NOAA – National Oceanic and Atmospheric Administration

SCoPEx – Stratospheric Controlled Perturbation Experiment

SPICE – Stratospheric Particle Injection for Climate Change Engineering

SRM – Solar radiation management/modification

UNEP – United Nations Environment Programme

UN – United Nations

UV – Ultraviolet

1. Introduction

1.1 The Climate Crisis

The ability of human beings to modify the composition of earth's atmosphere on a global scale to an extent that it warms the planet via the greenhouse effect is now certain (*Fig. 1*). The amount of carbon dioxide in the atmosphere today is the highest it has been in 3 million years, before humans walked the earth [1]. Even more alarming, carbon dioxide levels in the atmosphere are increasing over 100 times faster than the increase observed at the end of the last ice age, more rapidly than has ever been recorded in earth's history [2]. In 2018, the United Nation's Intergovernmental Panel on Climate Change (IPCC) reported that the world has only until 2030 to avoid potentially irreversible climate change [3]. However, it has recently become clear that the models used by the IPCC to assess the impacts of climate change have historically underestimated warming projections [4,5].

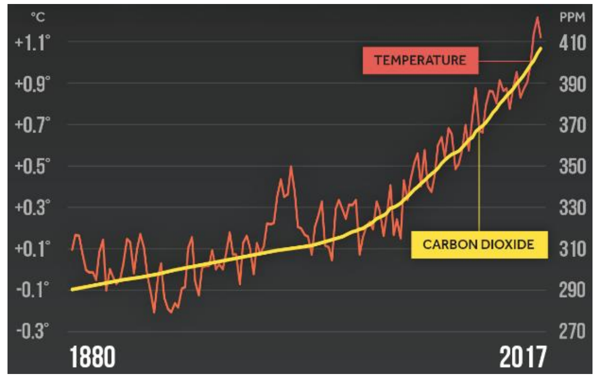

Figure 1. Human caused global temperature and carbon dioxide increase [6].

In 2018, the IPCC reduced the holding requirement for the temperature rise from 2 to 1.5 °C after realizing this was necessary to avoid some of the worst, most irreversible consequences of climate change [3]. Over a 1 °C increase in temperature has already occurred [6-7]. This new 1.5 °C holding temperature requires that global carbon dioxide emissions peak in 2020, are halved in 2030, and halved once again by 2040. Leading climatologists have predicted that global average temperature is likely to rise 5-6 °C by 2100 based upon current trends (fig. 2). In 2018, U.S. emissions rose by about 3% from the previous year and are expected to rise again in 2019 following President Trump's rescindment of President Obama's emission reduction initiatives [8-9]. Although not impossible, it is unlikely that U.S. carbon dioxide emissions will plateau in 2020 as needed to achieve the IPCC's 1.5 °C holding requirement.

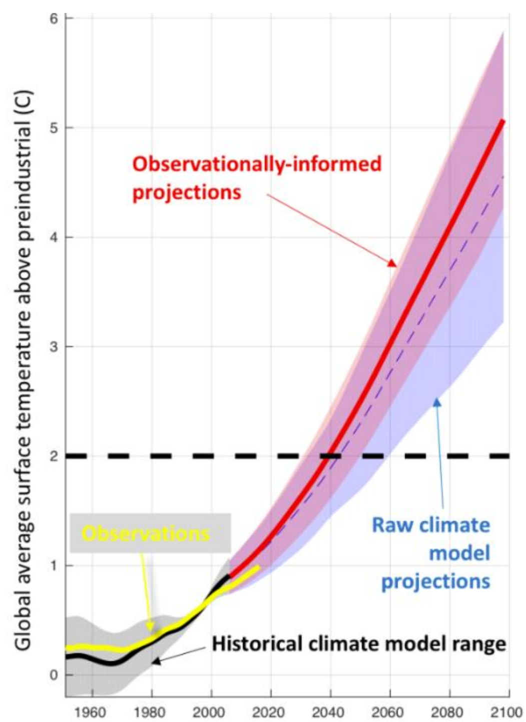

Figure 2. Comparison of raw and observationally-informed climate model projections [7].

The extent to which climate change will impact society remains unclear. However, sufficient evidence exists to identify the following outcomes: temperature rise, ocean acidification, sea level rise, loss of biodiversity, artic sea ice loss, increase in extreme weather events, increase in drought frequency, more heat waves, extreme changes in precipitation patterns, and increased forest fire activity [10]. These outcomes will have wide-ranging geopolitical consequences and will act as conflict intensifiers that pose serious threats to national security. Over the next 20 years, the effects of climate change have the potential to lead to global perturbations, increased risk of political instability, heightened tensions between countries for resources, a growing number of climate-linked humanitarian crises, emergent geostrategic competitive domains, and adverse effects on militaries [11].

The economic cost of climate change to the United States is incredibly difficult to quantify, but the Environmental Protection Agency (EPA) predicts it will exceed $500 billion annually [12]. This cost is likely a gross underestimation since a variety of factors including the potential for an outbreak of war, the true value of human life, and foreign humanitarian aid cannot be predicted. However, the EPA's estimation provides an indication that climate change will have a significant impact on the U.S. economy.

There is no longer a serious debate about the existence or the cause of the changes in the climate currently being experienced. Climate change is now here, and its effects are being observed across the globe in real time. Scientific consensus has concluded that human activity, specifically the emission of greenhouse gases, is the driving force behind climate change. The debate now lies in the hands of elected officials to decide how the United States will respond to this crisis.

1.2 Global Decarbonization Efforts

Under the looming threat of climate change, the developed world is currently undergoing a transition away from fossil fuels towards renewable energy sources. This transition is necessary to cut emissions and meet the targets established by the United Nations Paris Agreement in 2015 [13]. Although some nations are on pace to meet their proposed targets, many are not. Additionally, global carbon emissions are still on the rise as global energy demand continues to increase more rapidly than renewable energy infrastructure is being deployed.

As the undeveloped world pursues the standard of living enjoyed by the developed world, they are becoming consumers of coal and oil to meet their increased energy needs. The undeveloped world's energy demands will continue to grow with improved standards of living, further exacerbating climate change. Renewable energy technologies have failed to be implemented in the undeveloped world largely due to a lack of government funding for research and development and poor infrastructure. Although drastic improvements in affordability have been made in renewable energy technologies, deployment has been sparse in the undeveloped global south.

A significant amount of effort to decarbonize the energy sector has been put forth; however, agricultural, manufacturing, and transportation sectors will also need decarbonized to curb climate change. Efforts to decarbonize the energy sector at a rate greater than the rate at which energy demand is increasing have largely fallen short. Only drastic action to decarbonize the economy on a global scale within the next decade will prevent significant damage caused by climate change. At the current level of ambition, the world will continue suffer from unfavorable changes in the climate that will only worsen. If a technology emerged that could buy society more time to decarbonize in an economical fashion, the deployment of this technology should be seriously considered.

1.3 Solar Geoengineering

Geoengineering, also known as climate intervention, can be defined as the intentional modification of the earth's climate to mitigate climate change. Geoengineering should not be conflated with baseless chemtrail conspiracy theories. The field of geoengineering research is based strictly upon factual and scientific grounds. Geoengineering strategies fall into two categories, carbon dioxide removal (CDR) and solar radiation management (SRM). A significant amount of effort has recently been focused on CDR strategies such as carbon capture and sequestration (CCS) in the United States. CCS typically involves capturing carbon from large point sources; however, CCS can be employed as a CDR geoengineering strategy via direct air capture that scrubs carbon dioxide from the ambient atmosphere. Since CDR does not pose the same geopolitical issues and international relation challenges as SRM, the focus of this work is on the latter.

Solar radiation management, or albedo modification, relates to strategies designed to reduce the amount of solar radiation that contacts the surface of the earth. SRM does not affect the concentration of greenhouse gases in the atmosphere, it simply reduces global warming via solar reflection. The most commonly discussed SRM method involves the addition of aerosols to the lower stratosphere to reflect about 1% of incoming solar radiation.

SRM addresses the warming symptom of climate change but does not resolve all the changes in the climate caused by the release of greenhouse gas emissions. Therefore, some symptoms of climate change such as ocean acidification will not be affected by SRM [1]. It must be made clear that the potential for SRM implementation should not hinder efforts to reduce greenhouse gas emissions. SRM should be viewed as an extreme measure to be employed as a last resort to mitigate climate change. The feasibility and environmental impacts of SRM still remain unclear [14].

2. Background

2.1 History

There have been a variety of attempts scattered throughout human history to manipulate weather. However, these attempts should not be confused with geoengineering since they deal with weather rather than the climate. Solar geoengineering was first seriously considered in 1965 by President Lyndon B. Johnson's Science Advisory Committee in the first high-level government statement on global warming. This committee issued a report that considers, "deliberately bringing about countervailing climatic changes," by "raising the albedo, or reflectivity, of the Earth" [15]. Nearly a decade later, in 1974, Soviet climatologist Mikhail Budyko investigated the potential to reverse global warming by burning sulfur in the stratosphere to mimic the climatic effects of a volcano [16]. In 1976 the term "geoengineering" was first coined by Cesare Marchetti as a kind of system synthesis that took a global perspective to the carbon dioxide problem [17].

As the potential to avoid the consequences of climate change appeared less likely at the turn of the millennium, interest in solar geoengineering begins to surge. In 2006, Paul Crutzen, winner of the 1995 Nobel Prize in Chemistry for his ozone research, advocates for solar geoengineering over emission reductions [18]. This advocacy faced widespread criticism from the scientific community. In 2006, Pentagon weapons designer, Lowell Wood proposes a scheme to use artillery to launch sulfates into the Artic stratosphere to cool the planet at a NASA conference. 3 years later, while referring to geoengineering as one of the potential strategies to address climate change, President Obama's chief science adviser stated, "It's got to be looked at" [19].

The desire to begin conducting serious real-world solar geoengineering research begins to appear in 2011. The Stratospheric Particle Injection for Climate Change Engineering (SPICE), a British academic consortium, attempts to plan the first real-world solar geoengineering experiment [20]. However, this field test was called off in 2012 due to controversy caused by a lack of public engagement and transparency. That same year, The National Natural Science Foundation of China begins prioritizing geoengineering research [21]. In response, the Central Intelligence Agency (CIA) partners with the National Academy of Sciences (NAS) to begin performing an evaluation of SRM geoengineering techniques [22]. In 2014, solar geoengineering strategies were first considered by the UN in the IPCC's fifth assessment report [23]. The sum of the events over the past few decades have built the foundation for the research currently being conducted on solar geoengineering and will continue to provide valuable insights to this emerging technology.

2.2 Recent Interest

In 2019, the prospect of solar geoengineering was being seriously considered as an option to mitigate climate change. In March 2019, Switzerland and nine other nations requested that the United Nations Environment Programme (UNEP) open an inquiry into potential geoengineering governance options [24]. The United States, along with Brazil and Saudi Arabia, blocked this resolution. However, geoengineering will be a key part of the IPCC's Sixth Assessment Report to be published in 2021.

In the United States, the NAS will be issuing a report in the first half of 2020 on solar geoengineering that will build upon their previous 2015 report. The motivation of expanding this report is based upon the lack of time remaining for humanity to mitigate climate change and the reality that climate intervention strategies may need to be considered in the future [25]. Additionally, there are a handful of research groups at universities that are dedicated to addressing the technological, socio-economic, and political challenges related to geoengineering. These research groups include Harvard's Solar Geoengineering Research Program and the Carnegie Climate Governance Initiative.

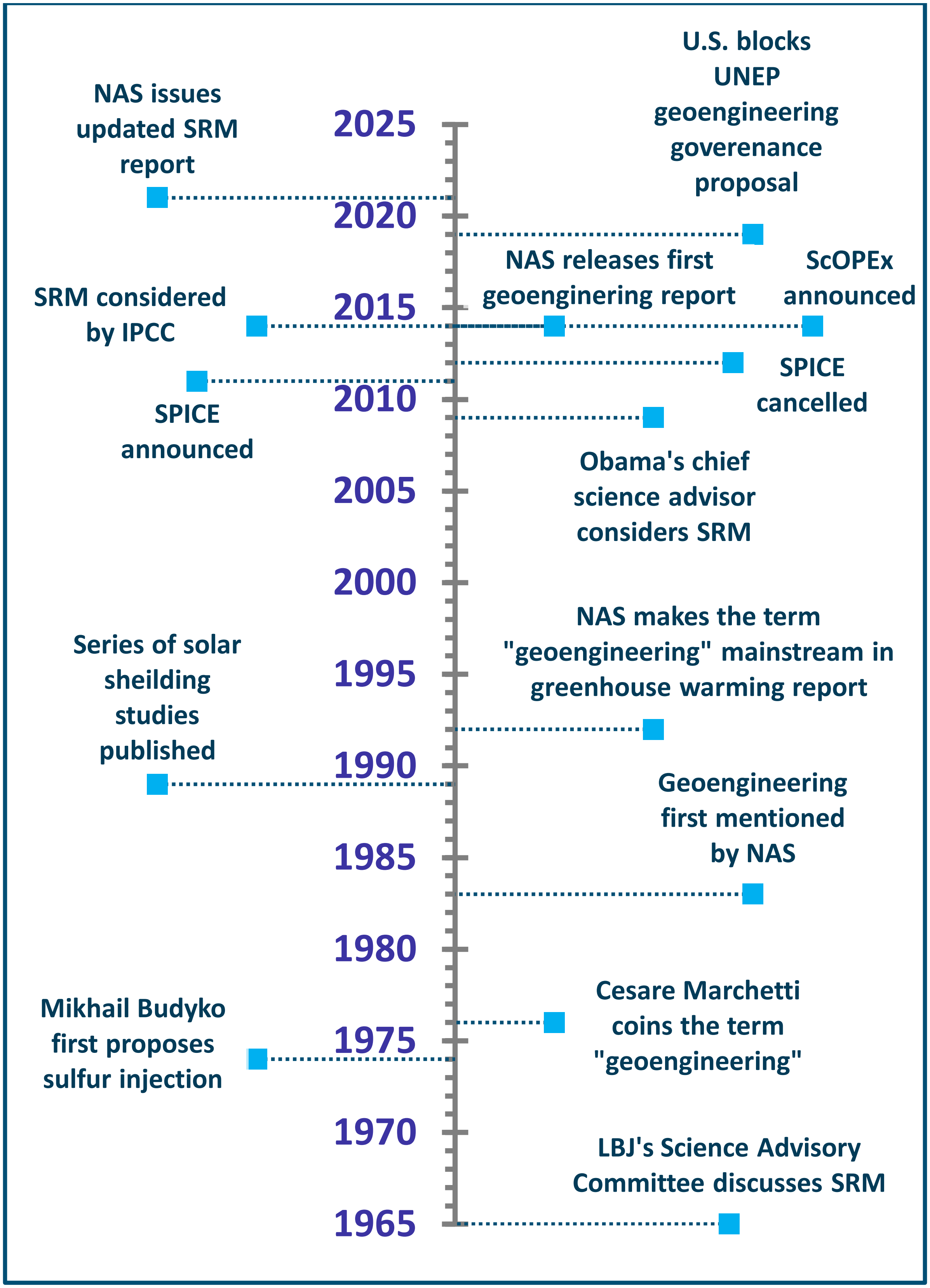

Figure 3. Timeline of geoengineering research and interest.

2.3 Technological Readiness and Feasibility

It is important to consider not only how ready solar geoengineering technology is for implementation, but also how practical implementation would be. The degree to which each solar geoengineering strategy has satisfied the issues of technological readiness and feasibility varies widely. The most prominent solar geoengineering strategies can be placed into four categories:

(1) **Stratospheric Aerosol Injection** – Reducing temperatures by injecting a reflective aerosol into the lower stratosphere

(2) **Marine Cloud Brightening** – Whitening clouds on land or seeding clouds above the ocean to increase planetary albedo (reflectivity)

(3) **Cirrus Thinning** – Decreasing the resistance to the escape of infrared radiation from the earth by thinning cirrus clouds

(4) **Surface Albedo Modification** – Brightening earth's surface (land or ocean) to increase reflectivity

Stratospheric Aerosol Injection appears to be the most promising solar geoengineering approach in terms of practicality and cost. By some estimates, the cost of this strategy could be as low as $1 billion/year [26]. Most recent research on solar geoengineering has been focused on the stratospheric aerosol injection approach. Stratospheric aerosol injection research has been purely based upon computer models and naturally occurring analogues, such as volcanoes, thus far. However, field tests may begin as soon as 2020. Harvard University's Keutsch Research Group is currently in the process of planning what has been dubbed the Stratospheric Controlled Perturbation Experiment (SCoPEx). This first of its kind experiment involves the injection of up to one kilogram of calcium carbonate into the stratosphere. Although most focus in stratospheric aerosol injection research has been on sulfates [27-31], calcium carbonate was chosen for the first trial of this experiment since it is a naturally occurring mineral dust. "SCoPEx will address questions about how particles interact with one another, with the background stratospheric air, and with solar and infrared radiation" [32]. This experiment will likely provide valuable information about the implementation of stratospheric aerosol injection and could improve the current models.

Marine Cloud Brightening research, like stratospheric aerosol injection research, has solely consisted of computer simulations and observations of naturally occurring phenomena. The general idea behind marine cloud brightening is to seed stratocumulus clouds with small seawater particles to enhance the clouds' albedo [33]. Marine cloud brightening has low technological readiness due to the historical lack of success associated with cloud seeding [34].

Cirrus Thinning is still technologically theoretical with most research being conducted via computer simulations. Cirrus clouds differ from other types of clouds in that they have a net warming effect rather than a cooling effect since they trap heat. Cirrus clouds can be thinned by seeding them with aerosols that will stimulate ice formation causing the clouds' ability to trap heat to be diminished [35]. Like with stratospheric aerosol injection, the cloud seeding technology needed to accomplish cirrus cloud thinning is far from perfected. Additionally, there is some evidence suggesting that over-seeding cirrus clouds may lead to warming rather than the desired cooling effect [36].

Surface Albedo Modification involves strategies to increase the reflectivity of earth's surface. Examples of surface albedo modification strategies include brightening roads and roofs, planting high albedo crops, snow forest clearance, and artic ice coverings [37-40]. Surface albedo modification is the simplest and most technologically ready of the selected solar geoengineering technologies, but this does not imply it is the most feasible or that the consequences of implementation are understood. There are considerable economic challenges associated with each surface albedo modification strategy. Until these economic challenges can be overcome, surface albedo modification has relatively low feasibility.

3. Key Conflicts and Concerns

3.1 Research Echo Chamber

A key challenge to obtaining reliable estimates of the pros and cons of solar geoengineering is that most solar geoengineering research is currently conducted by a relatively small group of people. The conversations surrounding solar geoengineering are often dominated by individuals such as Dr. David Keith of Harvard's Solar Geoengineering Research Program. Although there is no reason to doubt Dr. Keith's expertise in this field, additional perspectives from researchers with a more diverse set of backgrounds would be more conducive to advancing solar geoengineering research. The promotion of science relies upon problems to be approached in unique ways. A diverse group of individuals tends to accomplish this best [41].

Another danger of relying upon a small group of individuals to produce quality science is the potential for an echo chamber effect. This effect is characterized by an amplification of an idea within a closed system. This becomes dangerous when a false idea enters the closed system and is amplified to an extent that it is accepted as fact and no longer questioned. Since the same authors appear on most academic publications on solar geoengineering, the probability of the reinforcement of a false idea is high. A larger, more diverse group of researchers can help mitigate the echo chamber effect by rigorously questioning scientific ideas before they are amplified and considered common knowledge in the field.

3.2 Research vs Implementation

There is a fine line between solar geoengineering research and implementation. It is challenging to precisely establish a clear boundary between solar geoengineering research and implementation so these two ideas may be best represented on a spectrum (fig. 4).

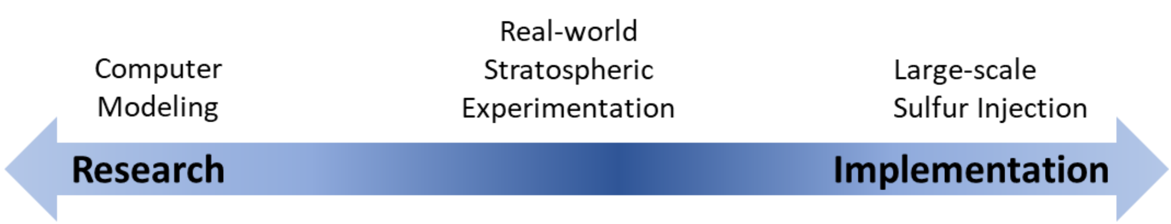

Figure 4. Solar Geoengineering Research/Implementation Spectrum

Solar geoengineering research that is conducted via computer modeling can clearly be categorized as research rather than implementation. However, real-world stratospheric experiments are much more difficult to categorize, and the categorization may vary from experiment to experiment. Small scale real world stratospheric experiments such as Harvard's SCoPEx likely fall more towards the research side of the spectrum than the implementation due to the innocuous nature of the experiment, but other experiments may fall closer to implementation.

Any real-world solar geoengineering experimentation must be performed very cautiously and on as small of a scale as possible to avoid crossing over into implementation territory. Stratospheric experimentation will inherently involve regional implementation, but global implementation must be avoided during such experiments. Real-world solar geoengineering experiments will be incredibly valuable to improving scientific understanding, but when probing uncharted territory, ensuring these experiments are low impact is critical to risk management.

3.3 Health and Environmental Risks

There is a plethora of unintended consequences associated with solar geoengineering implementation. Amongst the most concerning of these consequences are potential health and environmental risks. These risks are currently understood relatively poorly, but computer modeling has identified a handful of potential negative impacts worth considering. Specific consequences of these potential risks will be discussed further, but the potential risks of solar geoengineering can be summarized as:

- Changes in UV exposure and air quality
- Loss of tropical rainforest productivity
- Altered stratospheric circulation and jet stream destabilization
- Variations in ozone concentration
- Increase in methane lifetime
- Disproportionate temperature changes
- Deviations in natural precipitation patterns

Two of the possible negative implications of solar geoengineering are changes in ultraviolet (UV) exposure and air quality. One model has found that solar geoengineering may lead to a large stratospheric ozone increase that induces a significant reduction in surface UV-B irradiance [42]. UV-B irradiance is important since it is necessary for the body to naturally produce vitamin D, an essential nutrient for human life. This model has demonstrated that solar geoengineering may hinder the production of this nutrient possibly leading to exacerbated vitamin D deficiencies. Additionally, the model demonstrated a significant change in the composition of the troposphere. These changes were primarily driven by decreased humidity and a reduced UV-A and UV-B flux; however, it is difficult to predict how these tropospheric changes may further impact the earth's climate.

Another negative impact relates to the loss of tropical rainforest productivity. Two computer models have revealed that the gross primary productivity of tropical rainforests may decrease as a result of marine sky brightening [43]. This is troubling since tropical rainforests act as natural carbon sinks that aid in climate change mitigation by sequestering carbon from the air back into the earth. Further understanding of the impact that marine cloud brightening could have on tropical rainforests is necessary prior to considering implementation.

A third potential negative implication of solar geoengineering is a change in stratospheric circulation. One model has revealed that stratospheric aerosol injection may generate thermal winds in the lower stratosphere causing stratospheric vortices to intensify [44]. Since the troposphere and the stratosphere are intimately coupled, this shift in stratospheric circulation may lead to a shift in tropospheric jet streams. This shift is already occurring in the polar jet stream as a result of greenhouse gas emission driven climate change, but solar geoengineering may intensify this shift and cause further destabilization. A consequence of the destabilization of the polar jet stream is that warm air will travel further towards the pole and cold air will travel further towards the equator causing extreme temperature changes (fig 5).

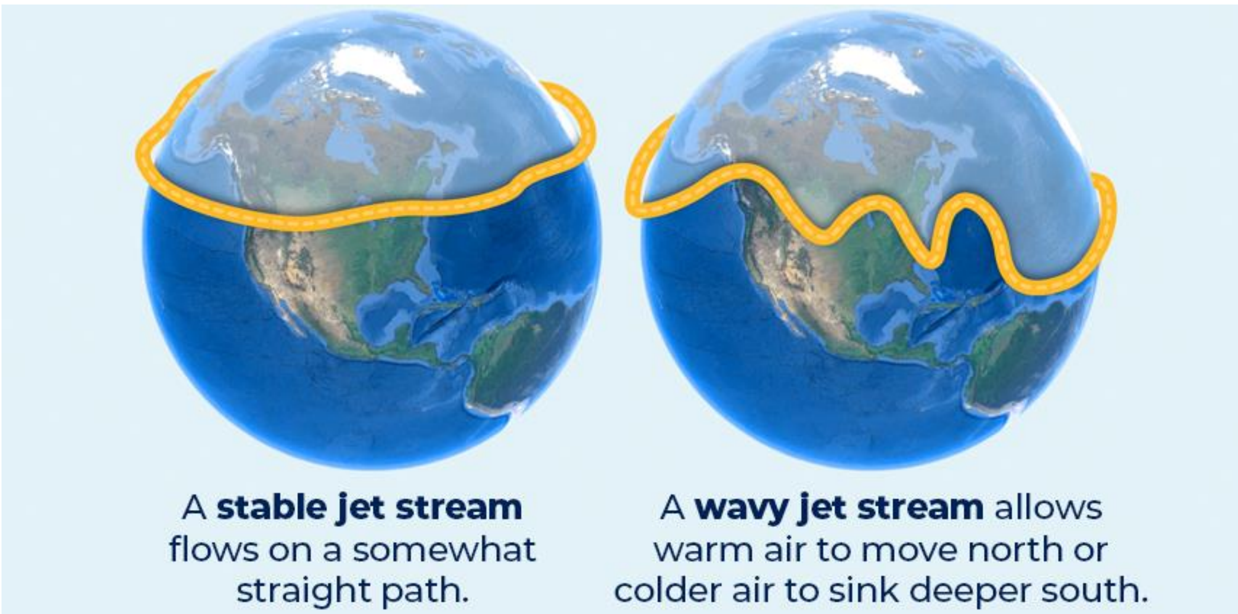

Figure 5. The Changing Jet Stream [45].

A fourth potential risk is the impact solar geoengineering may have on ocean life. A large portion of the world relies upon the ocean for food and solar geoengineering may decrease the net positive production of the ocean [46]. This could intensify the already worsening food shortages of the ocean caused by overfishing. Solar geoengineering may negatively impact net positive ocean production by changing physical factors, such as temperature, radiation, and ocean mixing; however, the effect of each of these individual factors is still relatively unclear.

A fifth risk associated with solar geoengineering are changes in ozone concentration. Balancing ozone concentration is important because if ground-level ozone becomes too concentrated, it can cause respiratory damage and harm crop production and vegetation. If ozone levels become too low, then more UV irradiation will reach earth's surface causing skin cancer rates to increase. One model has determined that solar geoengineering may either reduce or increase surface ozone levels depending upon which solar geoengineering strategy is implemented [47]. If stratospheric aerosol injection is deployed, then global surface ozone levels were modeled to decrease. If one of the other solar geoengineering strategies were deployed, then global surface ozone levels were modeled to increase. Stratospheric sulfates were found to decrease global surface ozone levels by disrupting the transport of stratospheric ozone to the troposphere via the disruption of natural photochemical reactions.

A sixth potential negative effect of solar geoengineering, specifically stratospheric aerosol injection, is an increase in methane lifetime. A computer simulation has found that the lifetime of methane, a potent greenhouse gas, may become significantly longer (approximately 16%) [28]. This is problematic since the global warming impact of methane is 28-36 times greater than that of carbon dioxide [48]. The potential of increasing the amount of time it takes for methane to naturally degrade in the atmosphere is an important consideration to make before implementing stratospheric aerosol injection.

In addition to a potential increase in methane lifetime, stratospheric aerosol injection may also lead to an extreme temperature and precipitation response. Two models have demonstrated that more extreme decreases in minimum land temperatures in comparison to minimum ocean temperatures may be experienced [49]. This shows that solar geoengineering implementation could lead to a disproportionate temperature decrease, creating the potential for winners and losers as a result of global solar geoengineering implementation. It was also found that maximum 5-day precipitation increases over subtropical oceans, warm spells decrease in the tropics, and the number of consecutive dry days decreases in the desert. A second study found an increase in peak precipitation duration over the subpolar climatic region, a decrease in peak precipitation duration over the tropical rain belt, and 1-3 month shift backwards in peak precipitation in much of the northern hemisphere [50]. This study illustrates the complexity of weighing the costs and benefits of solar geoengineering implementation.

A very limited amount of solar geoengineering research has been performed to gain an understanding of potential health and environmental consequences. Further research, beyond modeling work, is needed to better elucidate many potential problems. Additionally, many of the specific atmospheric mechanizations of the climate are poorly understood, further exacerbating the difficulty in quantifying the risks of solar geoengineering implementation. At the very least, it can be stated with near certainty that unintended health and environmental consequences will arise following implementation due to the difficulty of their prediction.

3.4 Rogue Actors

If the cost of solar geoengineering is as low as many researchers predict, the technology will be accessible to most somewhat developed nations and even a few wealthy individuals. This potential low cost, coupled with a lack of international laws restricting solar geoengineering, could enable rogue actors to act unilaterally to implement solar geoengineering. Unilateral deployment is highly undesirable given that earth's climate is a resource shared by all and should therefore, only be manipulated in a manner that maximizes the benefit for as many people as possible. If a single entity were to unilaterally implement solar geoengineering, it would likely be designed to solely benefit that individual rogue actor at the possible expense of other nations.

The probability that a rogue actor may attempt to deploy geoengineering is not negligible. Previous attempts have been made by rogue actors to geoengineer the climate. The most notable being the infamous case involving Palnktos, a Canadian “ocean restoration” startup. In July 2012, the director of Planktos, Russ George, dumped 100 tons of iron sulphate into the Pacific Ocean in an attempt to mitigate climate change. He claimed that the iron would stimulate algae growth that would remove additional carbon dioxide from the atmosphere via photosynthesis; however, this claim has been highly disputed by many experts [51]. Prior to the event, Canada’s environment ministry warned George that the venture would violate international agreements [52]. Since international law is unequipped to deal with rogue actors, George’s actions never got him into any legal trouble [53].

This legal void surrounding geoengineering efforts may encourage rogue actors to pursue unilateral implementation. The Planktos case has now set a dangerous precedent that there are no legal teeth in international law to grapple with rouge geoengineering. With the predicted low cost of geoengineering and the legal immunity precedent established, the chance of rogue actors unilaterally implementing solar geoengineering could be high.

3.5 Termination Shock

One of the most prominent concerns associated with solar geoengineering is termination shock. If solar geoengineering efforts were implemented over a long period of time and then suddenly stopped, a dangerous spike in global temperature could occur if emissions continue to rise after implementation [29, 54-57]. There are a variety of potential reasons the implementation of SRM may suddenly stop including war, a major shift in global politics, or if the cost were to become too high. The potential for termination shock should not be ruled out when implementation considerations are being made.

Although the impact that termination shock could have on the climate is unclear, it is incredibly likely that negative impacts may be experienced if atmospheric carbon dioxide concentrations continue to increase following solar geoengineering implementation. The most likely of these potential impacts is rapid global warming, but this may not be the only impact. Some of the other potential negative impacts that have been identified include an increase in global mean precipitation, decreased sea-ice cover, faster warming in high-latitudes and over land, and increased threats to biodiversity [54, 58].

In addition to the negative impacts, additional research is needed to determine how long it would take for termination shock to be experienced. One study estimates that 1-2 years after implementing stratospheric aerosol injection, the aerosol loadings would decrease and cause potential termination shock if additional aerosols were not injected within that time frame [54]. However, the maximum time of dormancy following the implementation of marine cloud brightening, cirrus thinning, or surface albedo modification solar geoengineering strategies before termination shock could occur remains unknown.

3.6 Climate Tug of War

Deciding where the global thermostat should be set via solar geoengineering is an incredibly difficult challenge. Due to the high probability of unintended consequences, it is likely that some nations could be unhappy with the effects of solar geoengineering implementation.

Many academics are considering the possibility that nations may choose to deploy counter-geoengineering efforts to reverse or neutralize solar geoengineering efforts, creating a climate "tug of war" [59-60]. Ultimately, a climate tug of war could lead to an oscillation between climate extremes causing a myriad of unintended consequences. Additionally, geoengineering efforts that are in opposition of each other is an extremely inefficient use of nations' resources.

Due to variation in geographic position of different nations, there may be disparity amongst climatic preferences. The environmental effects of climate change and their political and economic impacts are distributed unevenly globally. For example, Russia may gain access to oil and other natural resources as global warming causes the artic to melt, whereas African nations may experience crippling droughts [61-62]. Solar geoengineering efforts could be highly undesirable to Russia but may provide significant benefits to African nations. This is just a single example of the complications that must be considered to minimize the potential for counter-geoengineering efforts.

Additionally, counter geoengineering efforts have the potential to generate conflict between nations. This conflict may result in a climate war where nations compete to gain control of the climate via geoengineering. The Environmental Modification Convention, introduced on May 18th, 1977 in Geneva and ratified by the Unites States in 1980, bans the weaponization of weather [63]. However, it is unclear whether this treaty would apply to counter-geoengineering efforts.

3.7 Damage Attribution

Determining which climatic consequences are a direct result of solar geoengineering may prove to be challenging. Simple measurements of global average temperature would be an insufficient method to detect the effects of solar geoengineering. Moreover, it could take years to detect the effects solar geoengineering with a high level of confidence [64]. A wide variety of parameters would need to be measured to effectively determine the effects of solar geoengineering including global average temperature, precipitation, stratospheric circulation, UV exposure, and ozone concentration. Additionally, solid baselines of these parameters would need to be established prior to implementation. This may be difficult as many of these parameters have been rapidly changing due to anthropogenic climate change [23].

Another consideration that needs to be made is the potential for causal conflation between the effects of climate change and solar geoengineering following deployment of solar geoengineering. This issue could add another level of complexity to damage attribution. If solar geoengineering is implemented, it may be difficult to determine which consequences should be attributed to climate change and which should be attributed to the effects of solar geoengineering. This issue is also exacerbated by the difficulty associated with establishing baselines for climatic parameters. Error associated with poor baselines could compound error elsewhere since all measurements would be in comparison to this baseline. Furthermore, determining the amount of solar geoengineering to deploy in the future to mitigate damages following implementation becomes problematic due to the possibility of casual conflation. This issue must be addressed prior to the first implementation of solar geoengineering to ensure proper monitoring and verification of deployment.

3.8 Moral Hazard

Many commentators on solar geoengineering have expressed a fear that policy-makers and the fossil fuel industry may view this technology as an alternative to emission reduction efforts. It is well understood that the phenomena of risk compensation can arise when people respond to risk-reducing innovations by behaving less cautiously [65-70]. In the context of climate change, society may choose to emit additional greenhouse gases into the atmosphere if they feel that the risk of climate change has been reduced by solar geoengineering technology.

It has been argued that effective solar geoengineering may justify decreased mitigation efforts on the basis that a net decrease in global temperature may still be achieved without emission reductions [71]. The premise of this argument is flawed since it assumes that the only symptom of climate change that needs to be addressed is global warming. Solar geoengineering addresses the global warming symptom but fails to address other symptoms of climate change such as ocean acidification. The only effective strategy to mitigate ocean acidification is to reduce carbon emissions. Therefore, solar geoengineering implementation alone is not a strong justification to relax emission reduction efforts.

3.9 Public Reception

Prior to making any policy decisions related to solar geoengineering, the public reception of the technology must be understood. The primary issue related to the public reception of solar geoengineering is that most of the general public in the U.S. is unfamiliar with the technology (fig. 6). This is troubling given the likelihood that solar geoengineering discussions amongst policy-makers will begin in the near future, yet policy-makers lack information on the public perception of the issue.

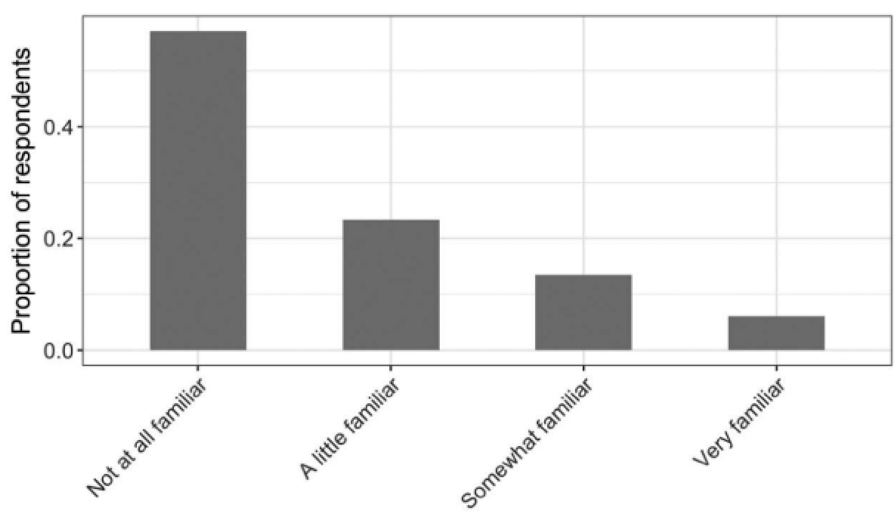

Figure 6. Familiarity with geoengineering in the U.S. [72].

Although public knowledge about solar geoengineering is low, it has been found that once the public is educated, they generally support solar geoengineering research (fig. 7). The American public tends to agree with solar geoengineering research regardless of where they fall on the political spectrum. This indicates that solar geoengineering research has the potential to receive bipartisan support. However, before bipartisan support can be garnered, the knowledge gap between solar geoengineering researchers and the general public must be abridged.

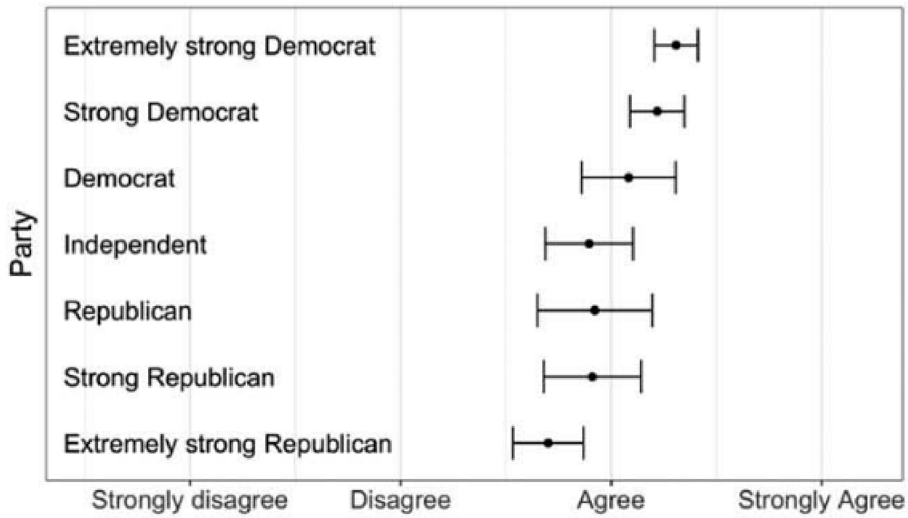

Figure 7. Support for solar geoengineering research by party [72].

Another relevant issue related to the public perception of solar geoengineering is how opinions on solar geoengineering compare to other geoengineering techniques such as CDR. A small study on New Zealanders found that CDR is generally favored over SRM geoengineering techniques [73]. This may indicate that when the public is presented with CDR, they may view solar geoengineering less favorably.

4. Policy Recommendations

4.1 Prioritizing Mitigation and Adaptation

4.1.1 The Paris Agreement

It is important to focus on emission reduction efforts in conjunction with solar geoengineering research efforts. Solar geoengineering efforts should neither overshadow nor be viewed as an alternative to emission reduction efforts. The best way to avoid this moral hazard is to commit to climate change mitigation and adaptation efforts prior to beginning solar geoengineering investigations.

Demonstrating a commitment to emission reductions to the international community prior to conducting solar geoengineering efforts is vital to avoid being accused of moral hazard. An investment in solar geoengineering research without reassuring the international community that the U.S. does not intend to implement solar geoengineering as an alternative to emission reductions could draw criticism. The UN has already established a framework via the Paris Agreement that would allow the U.S. to publicly commit to reducing emissions [23]. The Trump administration verbally withdrew from this voluntary agreement on June 1st, 2017 citing the "America First" policy as justification [74]. It is important to note that the earliest possible official withdrawal date by the United States, in accordance with Article 28 of the Paris Agreement, is not until November 4th, 2020 [23].

In 2017, President Trump stated, "I'm willing to immediately work with Democratic leaders to either negotiate our way back into Paris, under the terms that are fair to the United States and its workers" [74]. There has been no indication that such negations have been conducted yet; however, the possibility of these negotiations occurring behind closed doors cannot be ruled out. It is advised that the United States verbally rejoin the voluntary Paris Agreement to publicly demonstrate the nation's commitment to reducing greenhouse gas emissions. If necessary, the terms of the Paris Agreement should be renegotiated, but this should be done in a timely fashion. The verbal commitment to rejoin the Paris Agreement should be made as soon as possible since indicating the United State's commitment to emissions reductions is recommended prior to commencing any solar geoengineering efforts.

4.1.2 The Green Deal

In 2019, two bills were proposed in the House that outlined a general path forward to mitigate and adapt to climate change. The Green New Deal was proposed by Democratic Representative Occasio-Cortez on February 7th, 2019 as a set of goals to build climate change policy around [75]. Similarly, Republican Representative Gaetz proposed the Green Real Deal in response to the Green New Deal less than a month later April 3rd, 2019 [76]. Upon close examination of these bills, there is a significant overlap in the goals proposed by Representative Occasio-Cortez and Representative Gaetz. It is recommended that the overlap in these bills be combined to create a new bipartisan framework, tentatively dubbed "The Green Deal" (fig. 8).

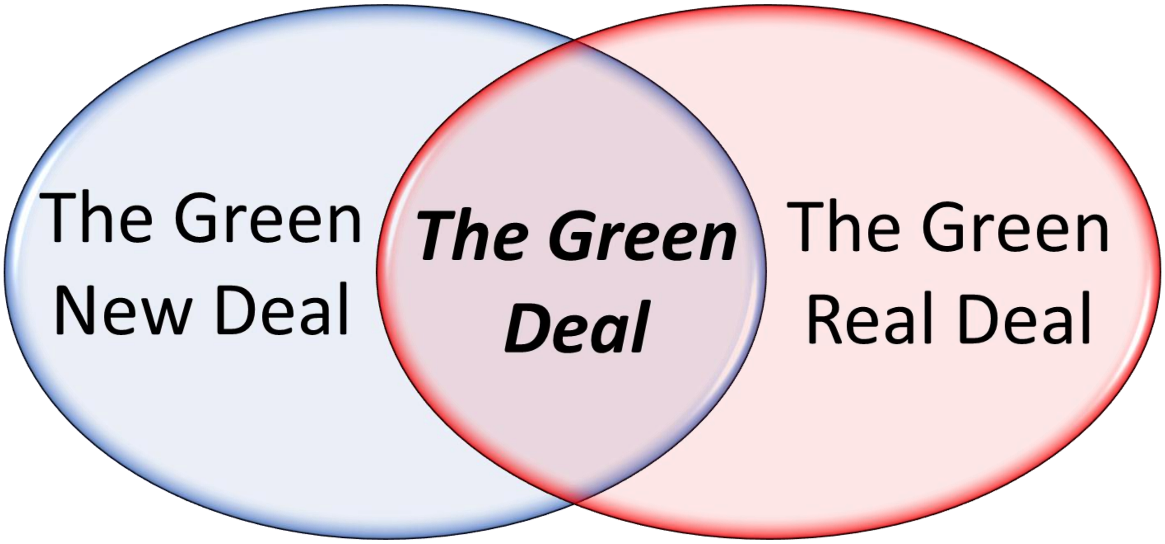

Figure 8. Coupling the “Green New Deal” with the “Green Real Deal” to establish “The Green Deal”

Although, these two documents were not identical, there is enough in common between the two to create a new cohesive set of goals. This new set of goals established by proposing “The Green Deal” could be used as an outline for a set of bipartisan policies that would ensure the prioritization of adaptation and mitigation. The goals of “The Green Deal” should include:

- Investment in clean energy infrastructure
- Economy-wide decarbonization
- Greater resiliency against climate change related disasters
- Modernization of the electric grid
- Improvements in building energy efficiency

4.2 International Oversight

4.2.1 Risk Evaluation

Since solar geoengineering is a global issue, international oversight on implementation efforts is recommended to avoid conflicts. International oversight may help mitigate the risk for the potential of a climate tug of war, rogue actors, and termination shock. It is advised that the framework previously established by the UN IPCC be used as the vehicle for international solar geoengineering oversight.

The IPCC was initially created to provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options [77]. It accomplishes this through a structure that includes four technical support units (TSU) that each have a specific set of goals (fig. 9). If the IPCC were to begin more closely examining the risks associated with solar geoengineering, at least three of these four TSU’s would likely be needed.

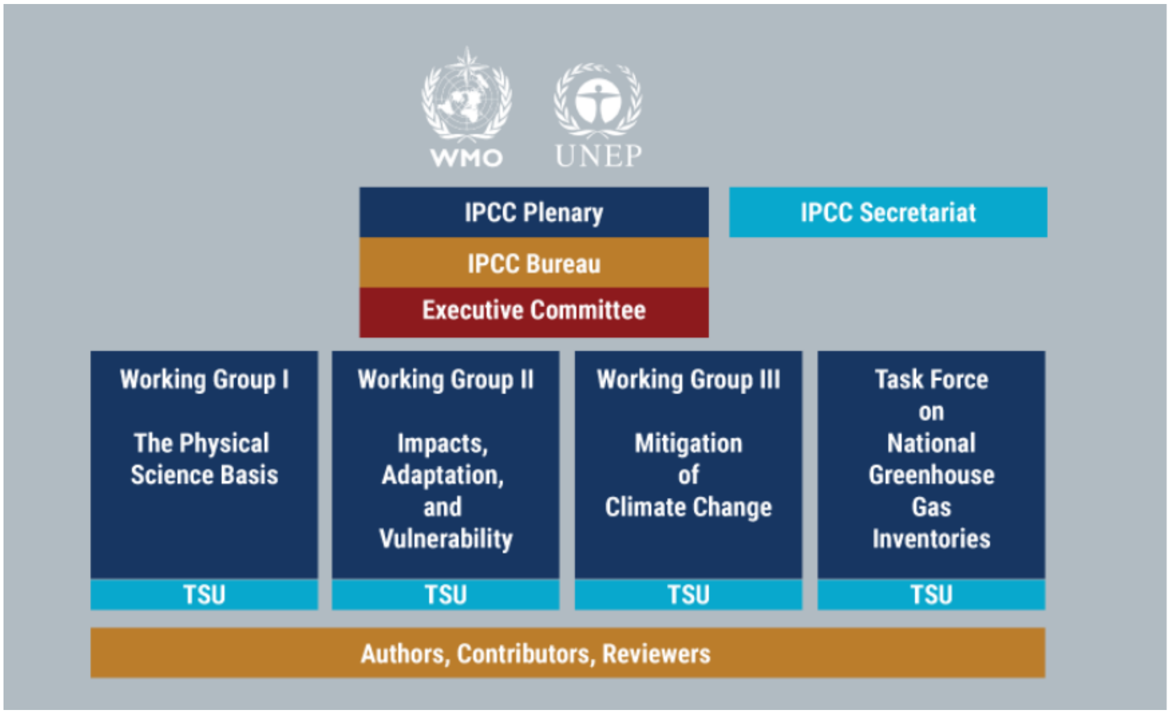

Figure 9. Structure of the IPCC [77].

Working Group I, on the physical science basis, would continue to provide information on greenhouse gases and aerosols in the atmosphere; temperature changes in the air, land and ocean; the hydrological cycle and changing precipitation (rain and snow) patterns; extreme weather; glaciers and ice sheets; oceans and sea level; biogeochemistry and the carbon cycle; and climate sensitivity [77]. This TSU already studies the effects of aerosols in the atmosphere so the investigation of the effect of stratospheric aerosol injection would be a natural extension of their current scope. Additionally, this TSU will provide valuable information for addressing the damage attribution problem previously discussed. Working Group II, on impacts, adaptation, and vulnerability assesses the global and regional effects of climate change. This assessment will provide reliable baseline data to which the effects of solar geoengineering can be compared. Working Group III, on the mitigation of climate change provides an objective evaluation of technical feasibility, cost, and enabling environments. This TSU could be expanded to assess potential solar geoengineering strategies.

One of the primary responsibilities of UN IPCC oversight on solar geoengineering should be to perform an annual risk evaluation on the emerging technology. Further evaluation of potential risks needs to be achieved prior to any consideration of deploying solar geoengineering. The environmental, health, social, and economic risks associated with solar geoengineering are still poorly understood and need much elucidation. A risk evaluation could provide more information on these risks that allow a proper cost/benefit analysis to be performed on solar geoengineering.

4.2.2 Insurance

There is a significant amount of uncertainty associated with the risk of solar geoengineering implementation even if it is implemented through a robust international framework. The establishment of international financial risk pools could help mitigate any unanticipated damages caused by solar geoengineering deployment.

Additionally, it is likely that disagreements between states may arise while discussing solar geoengineering implementation due to conflicting interests. An international risk pool could be used as a mechanism to settle disputes between nations [78]. This risk pool will also provide incentivization to limit opposition to other nations' concerns. A risk pool ensures that it would be in the international community's best interest to set the "global thermostat" to provide the most benefit to the most people. A risk pool would provide financial incentive for all participating nations to minimize solar geoengineering risks. Support for this type of insurance could also provide nations with an opportunity to demonstrate their confidence in solar geoengineering technology.

The World Bank's parametric climate insurance could serve as the model for a solar geoengineering risk pool [79]. The World Bank's index-based insurance uses objective environmental indices to protect parties from significant financial losses. Aspects of this parametric insurance should be adopted when designing a solar geoengineering risk pool. The World Bank's parametric climate insurance can be distinguished from conventional insurance by the following five key advantages [79-82]:

- It does not require causation to be demonstrated—attribution is a nonissue
- It can cover catastrophic losses
- It is oriented toward protecting against future harms (rather than resolving disputes over past damages)
- It is fundamentally contractual in that the insured agrees to pay a premium to the insurer in exchange for coverage against one or more contingencies (as opposed to the adversarial nature of legal liability)
- It is predictable

It is recommended that a solar geoengineering risk pool be established within the existing UN IPCC framework as a damage management tool. The UN IPCC Secretariat manages all funds agreed to by the IPCC, so this entity would be the most natural fit for managing the risk pool. Joining the risk pool would have to be mandatory for all participating nations for it to be effective. This could pose cost challenges to developing nations who want a say in solar geoengineering but cannot afford to participate in the risk pool. To address this challenge, the amount each nation would fund the risk pool should be proportional to their GNP. This would ensure a level playing field for all nations.

4.2.3 Deployment Monitoring and Verification

In the event that the UN IPCC were to decide to implement solar geoengineering multilaterally, a new regime will be needed to provide verification of deployment and effectiveness monitoring. This regime is needed to confirm solar geoengineering has been implemented to the degree previously agreed upon and that the deployed solar geoengineering strategy is interacting with the climate as expected. It is recommended that an international body within the UN conduct deployment monitoring and verification to ensure data reliability.

This international deployment monitoring and verification regime should be based upon the well-developed Comprehensive Nuclear-Test-Ban Treaty (CTBT) model [83]. Monitoring stations should be established across the globe and in space that will measure a variety of climatic variables. It is recommended that these stations be run by many different nations while overseen by the UN to promote robustness of collected data. The overlap between the stations owned by different nations will allow for cross-examinations of collected data to verify their accuracy.

Additionally, there are a variety of parameters that will need to be determined and agreed upon within the UN prior to solar geoengineering implementation. The following parameters will need to be confirmed prior solar geoengineering deployment (specifically stratospheric aerosol injection) to guarantee that the terms agreed upon within the UN will be properly carried out [84]:

- type of material released
- particle size
- amount released
- release altitude
- release/dispersal mechanism and area over which this is done (initial density)

4.2.4 Code of Conduct

There are a variety of ethical challenges that may be encountered while conducting solar geoengineering research. To help resolve ethical challenges, many scientists and engineers often turn to ethical codes. It is recommended that the UN IPCC establish a code of conduct for all solar geoengineering researchers to promote ethical practices. This ethical code should encourage researchers to focus on performing solar geoengineering research to benefit humanity rather than nationalistic or financial motives. It is recommended that a "Solar Geoengineering Research Code of Ethics" be established by the UN Ethics Office. This international code of conduct should be modeled after the Geoengineering Research Governance Project's "Code of Conduct for Responsible Geoengineering Research" [85].

4.3 U.S. Federal Solar Geoengineering Research Program

Internationally, China has one of the world's largest federally funded geoengineering research programs with a budget estimated to be about $3 million [86]. It is recommended that the United States establish a "U.S. Federal Solar Geoengineering Research Program" that is on par with China's research program. It is important that the United States lead the way on this innovative technology via a new research program to maintain the upper hand in international discourse. The recommended structure of the "U.S. Federal Solar Geoengineering Research Program" can be seen below (fig. 10).

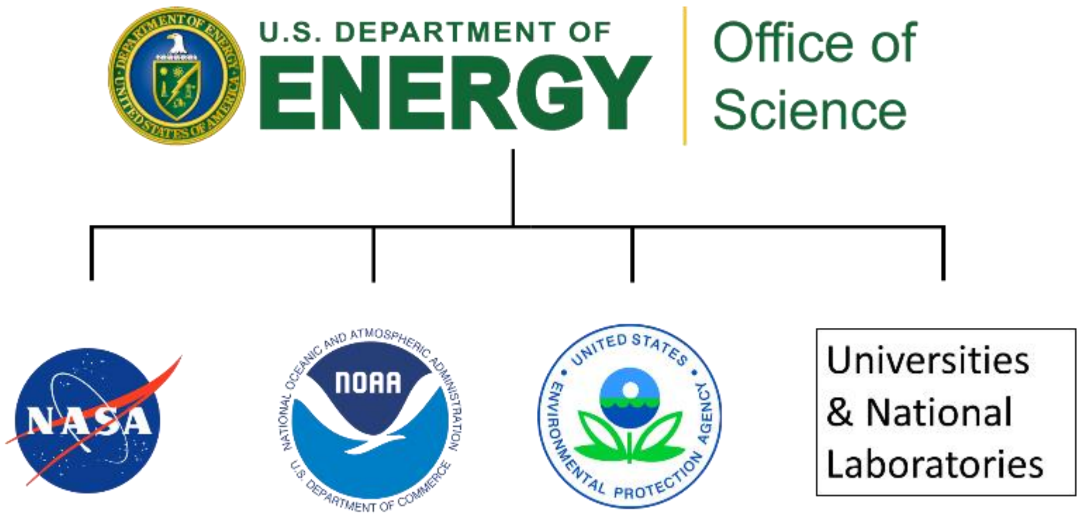

Figure 10. U.S. Federal Solar Geoengineering Program structure

It is suggested that the Department of Energy (DOE) oversee the "U.S. Federal Solar Geoengineering Program" through the Office of Science. The DOE Office of Science would distribute around $3 million in grants to national laboratories and universities to pursue a better fundamental understanding of the interaction of solar geoengineering with the climate. In addition, the grant would fund efforts to study solar geoengineering deployment mechanisms. The National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) would provide their satellite resources as directed by the DOE to aid in research efforts as needed. For all real-world atmospheric experimentation that would occur outside of a laboratory setting, it would be required that the EPA perform and environmental impact assessment (EIA) prior to conducting the experiment. After performing the EIA to determine the potential health and environmental risks of the experiment, the EPA would have the discretion to either shut down or green light each real-world experiment.

4.4 Transparency

4.4.1 Public Education

To prevent public backlash, significant effort needs to be put forth to ensure solar geoengineering efforts are transparent. However, it is important to first educate and inform the public about solar geoengineering so that they possess an understanding of the technology. This type of public education would need to involve a variety of channels by which information could be consumed. These channels could be in the form of a mass media campaign, online resources provided by the U.S. government, or even a part of school curriculum. It is likely that the combination of multiple channels will be needed to reach most Americans with this important information. It is critical for researchers and politicians to engage with the American public on concerns they may have with solar geoengineering, so that research efforts are not undermined by uninformed critics.

4.4.2 Clearinghouses

One way the public could access information on solar geoengineering research efforts is through publicly accessible clearinghouses. These clearinghouses should be based upon the structure that is outlined in the Harvard Project on Climate Agreement's "Governance of the Deployment of Solar Geoengineering" [59]. It is recommended that the DOE establish such clearinghouses as part of the U.S. Federal Solar Geoengineering Research Program that would catalog all federal solar geoengineering research in the U.S. Additionally, as much privately funded research should be cataloged in the clearinghouse as possible to provide a comprehensive database of solar geoengineering information. Each study provided in the clearinghouse should have its funding publicly clarified and it is also important that the DOE summarize the state of solar geoengineering research periodically so that it is more easily digestible by the American public and politicians.

The United States' national clearinghouse should feed into an international clearinghouse overseen by the UN. The UN and the U.S. should also encourage other nations with federal solar geoengineering research programs, such as China, to follow suit. This international clearinghouse would enhance the UN's ability to properly assess the risks associated with solar geoengineering in their annual reports. Additionally, the international clearinghouse could be shared amongst nations to promote collaboration. The establishment of not only a national, but international clearinghouse is vital to preventing mistrust amongst nations and individuals.

4.5 Establishment of Legal Regime

Currently, no U.S. or international law exists to govern the implementation of solar geoengineering to mitigate climate change. As previously discussed, Russel George demonstrated the presence of this legal vacuum when he was not prosecuted for dumping 100 tons of iron sulphate into the Pacific Ocean to geoengineer the planet. This legal void should be filled both in the U.S. and internationally to promote safe, well thought out, solar geoengineering research and implementation.

It is recommended that both the U.S. and the UN outlaw individuals from implementing solar geoengineering outside of the UN IPCC's oversight. This would discourage unilateral deployment that could potentially degrade the environment, human health, and international relations. Furthermore, the UN should enact a law to prevent individual nations from implementing solar geoengineering outside of the IPCC's framework for this same reason. Finally, it suggested that the scope of the current international EIA legal rules be expanded to encompass solar geoengineering. It has been found that the current international EIA law is inadequate to grapple with the emerging technology of solar geoengineering [87]. The expansion of international EIA law could help address the environmental and social risks associated with solar geoengineering.

5. Conclusion

Whether it is decided to implement solar geoengineering or not, one must recognize that humans are already geoengineering the planet via unintentional climate change. It is not inconceivable that one day humanity may decide to modify the climate intentionally to mitigate the damages caused by greenhouse gas emission induced climate change. However, it is critical that the United States does not fall into the moral hazard of allowing future solar geoengineering efforts to undermine emission reduction efforts. Solar geoengineering should not simply be used to mask the effects of climate change given the potential for termination shock and continued ocean acidification. Solar geoengineering should instead be used as a tool to buy humanity precious time to reduce our emissions so that irreversible climate change may be avoided.

A better understanding of the underlying mechanisms of the climate and the effects solar geoengineering may have on them must be gained. A proper cost vs benefit analysis cannot be performed to determine whether solar geoengineering should be implemented without improving this understanding. A federal program designed to pursue information on the effects of solar geoengineering could achieve this desired understanding. This information should be shared with the international community in a transparent manner so that proper oversight can be conducted by the United Nations. Since the deployment of solar geoengineering will impact everybody, the United Nations must promote cooperation and provide a framework to facilitate multilateral implementation. Simultaneously, the United Nations has a responsibility to strongly discourage unilateral implementation.

The idea of modifying the atmosphere of the earth via albedo modification is no longer radical. The unprecedented rate of the release of greenhouse emissions is creating unfavorable circumstances for a growing human population. If habitability is to be ensured, the climate must be restored to be more conducive to human life. As the window closes to prevent the release of greenhouse gases from causing irreversible warming, drastic measures such as solar geoengineering may be considered. A firm understanding of this technology must be acquired within the next ten years, before climate change could become irreversible, to evaluate the risks of its implementation and a robust framework must be established for safe deployment. The actions humanity takes over the course of the next decade will determine whether solar geoengineering will be needed. Ideally, humanity will address the global climate crisis and solar geoengineering will be unnecessary; however, if humanity fails, preparations should be made to use solar geoengineering as a last resort.

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