A Shadow of the Future: A Proposal for Construction of A Solar Shade and its Implementation through International Cooperation

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Abstract

Over the past century, climate change due to anthropogenic forcing has rapidly increased the temperature of the globe. The rate of warming has outpaced the ability of Earth systems to adapt, and as rates of emissions continue to increase, the Earth is quickly reaching a climate tipping point. As political agreements fail to efficiently mitigate this danger, it is time to turn to other solutions. This proposal will advance the creation of a solar shade, in order to reduce the amount of sunlight the Earth receives, and thus employ geoengineering to counter anthropogenic warming. Advancements in drone technology, reusable first stage rockets, and foldable space structures mean a space shade is now actionable, as well as feasible. This paper will discuss the materials and methods of construction, as well as including an in-depth cost analysis of solar shade deployment. There will also be a detailed outline of a control organization, to be instituted along with the technical aspects of a solar shade. Finally, this proposal examines the policy issues inherent to geoengineering projects, and how this proposal resolves those concerns. In its entirety, this proposal will present a scientific and politically minded solution to combat global climate change.

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Introduction

Starlight flickers through an atmosphere increasingly polluted by carbon dioxide and other industry emissions. It has long been recognized that climate change is an issue threatening humanity's normal way of life, and that a solution is needed, quickly. Nations argue and quibble over responsibility and power, as aeration of carbon from lithospheric reserves forces carbon dioxide levels over 400 PPM, levels not seen in hundreds of thousands of years. Climate change has prompted the sixth mass extinction, while even the most advanced climate agreement between nations will fail to keep global warming levels under the target 2 degrees Centigrade above pre-industrial levels. The climate change that Earth is currently undergoing is occurring more rapidly than any natural process would inspire.

Climate change has begun to be seen as more and more of a threat to the security of citizens of the world, but it is seemingly impossible to curb this threat. Fossil fuels are the foundation of economic industries across the globe, and make it political suicide to ban their use. Additionally, emissions mitigation is highly subject to free riders, and no country wants to put themselves in the vulnerable position of being the only country curbing emissions, while the rest get rich off industry and pollution. Globally, attempts to involve all states in emissions reduction are laudable, but have no real mechanisms of enforcement, as that would compromise state sovereignty. Climate change is going to cost the world billions, and current solutions will not stop it, or even slow it.

Due to the history of ineffective emissions reductions goals and the modeled predictions that the Earth's climate is racing towards a point of no return, there has been rising interest in a new proposed solution – geoengineering, or the intended alteration of Earth's climate. Geoengineering is essentially an experiment on the global scale, using technology in a new way to try and reduce, and possibly reverse, the ill effects of climate change. A database analysis revealed that there are only 234 abstracts that make mention of geoengineering – only 55 between 2006 and 2013 (Linner and Wibeck, 2015). In the literature of geoengineering, there are two main focuses: the technical science, and policy questions and implications that arise when it is considered as a solution to climate change.

The first focus, the scientific aspect of geoengineering, concentrates on the research of how to alter Earth's climate directly. There are several ways to do this, due to the nature of how many inputs Earth's climate has. One option is solar radiation management, which reflects incoming light, either before the light has reached Earth, or when the light has already passed through part or the entire atmosphere. Additionally, there are still many questions about the scientific aspects of geoengineering that have yet to be answered. These include price estimates, as well as safety estimates – there is no concrete model to predict the exact reactions of the climate if geoengineering is implemented. This also contributes to a challenge in the field – several attempts to implement a research project have been blocked before they could begin. The science of geoengineering is exciting, but is hampered by a lack of public interest, blocking of research, and cost of some technologies.

The second focus of geoengineering involves the policy issues of altering whole-globe systems. Specifically, there are arguments over what actors, and for what ends, have the right to manipulate the Earth's climate. Additionally, there are questions about how such a system would be overseen and regulated. The majority of open questions on the policy of geoengineering revolve around the issue of equity between all actors, and the issue of liability. There are also those who view geoengineering as the ethically wrong option, because it addresses the effect of carbon pollution rather than the cause itself. However, it is still early in the discussion of climate change, and a majority of ethical concerns associated with geoengineering can be resolved by a specific execution of geoengineering.

Scientific research into solar radiation management is the most comparable to the technology that will be advocated for in this proposal. In particular, Robert Angel (2006) investigates the possibility of positioning a swarm of crystals at the Lagrange 1 Point in space to reflect incoming solar radiation. Unfortunately, his delivery system relies on technology not yet in hand. Paul Crutzen (2006) proposes the reflection of light when it reaches Earth's stratosphere, by spraying sulfur in the stratosphere to mimic the effects of volcanic eruptions. There has been large outcry at the amount of acidification this would cause as sulfur percolates out of the atmosphere, as well as the unpredictability of externalities from an additional input to an already particulate-saturated atmosphere. A final solar radiation management technique is albedo modification; Singaryer et al. (2009) assess the impacts on climate that would arise from substituting typical food crops with lighter-leafed counterparts. Geoengineering can also be carbon mitigation, however, the technological, economical, and political challenges and questions that arise for carbon mitigation differ from those that arise due to solar radiation management. This proposal is focused solely on the discussion of solar radiation management as a geoengineering technique.

Along with investigations into the specific technologies that could produce climate alterations, Donohoe and Battisti (2011) investigate the coupling between atmospheric and surface albedo contributions, concluding that atmosphere strongly attenuates any ground-based attempt to alter albedo. *Atmospheric Transmission, Emission, and Scattering* by Thomas Kyle (1991) provides photochemical knowledge for different gases and layers of the atmosphere. This book allows for deeper investigation of the cascade effects that may occur due to solar radiation management by a solar shade in space. Finally, Levine (1985) provides a compilation of three papers on the specific properties of the troposphere, stratosphere, and upper atmosphere. These papers, coupled with Kyle (1991), provided a solid base for the chemical and physical understanding of the atmosphere, as well as enabling the prediction of effects that would occur due to solar radiation management. The scientific aspect of geoengineering thus is composed of base chemical and physical analysis of the atmosphere, as well as a few papers on precise technical projects.

Continuing, there is a litany of literature for the policy issues that would accompany geoengineering as well. Barrett (2007) argues the need for oversight of geoengineering, as well as that geoengineering, or not, are both Nash equilibriums for an international collective. Additionally, he highlights the necessity that any geoengineering experiment must be able to be halted if negative or unintended externalities appear in force. *The politics of global atmospheric change* by Rowlands (1995) uses the Montreal Protocol to analyze different hypotheses on why some collective action problems are solved and others are not. He highlights the fact that states are reactive entities, as well as the large interplay between politics, public perception, and industry that influences the creation of any climate policy. Bodansky (2013) discusses that international rules vary in effectiveness depending on their legal form, precision of language, and legitimacy of organization. He additionally examines how to govern both private and unilateral actors in geoengineering. Jasanoff (2003) highlights the need for the inclusion of global citizens in science, particularly a need for interactive decision-making when it comes to geoengineering. Finally, Dilling and Hauser (2013) conclude that, as of yet, there is no proposed geoengineering governance framework that adequately addresses the policy issues of geoengineering.

There is a great amount of stigma surrounding discussions of geoengineering, as most scientists still consider it an erratic and impractical possibility. However, due to the nature of technological advancement in the past century, geoengineering no longer resides solely in the purview of science fiction.

This thesis is a comprehensive proposal for a solar shade as a solution to climate change. A shade located in space, composed of multiple units, would be effective in reducing the received flux of Earth and would result in a global cooling to counteract anthropogenic forcing. A solar shade is technologically feasible, currently actionable, and does not add any inputs to an already over-saturated climate system. Additionally, a solar shade is the only form of current proposed geoengineering techniques that includes a mechanism to disengage the geoengineering technology – it has an undo button. In order to comprehensively address the multifaceted issues that accompany the concept of geoengineering, this thesis will also include a discussion of policy implication and general global politics. It will be concluded that a space based solar shade would be effective in cooling the Earth, is not so expensive as to make it unachievable, while incurring the least amount of risk compared to other geoengineering techniques.

1. Global Temperature Rise

The mean temperature of the Earth is rising, that is a quantitative truth. The rate of the rise, and its causes, are what the following section will examine. Evidence will be presented that the temperature of the Earth is rising at an unprecedentedly high rate. It will also be shown that this deviation from normal is due to anthropogenic forcing, largely in the form of carbon pollution. Solar variability and the Milankovitch cycles will also be overviewed and discarded as current contributors to global warming.

1.1 Rate of Temperature Rise

Since formation, the Earth has undergone many different climate changes. After differentiation and the evolution and proliferation of life, these changes began to settle into predictable patterns. Certain global events, such as the evolution and expansion of fauna, or the breakup of supercontinents, create large-scale climate forcings. These differ from what the natural cycles would have produced. Currently, another global event is deviating climate evolution - human activity.

A number is hard to understand when there is little context. This is especially true in the field of climate change, where defined 'averages' can vary dramatically depending on the time scale analyzed. Therefore, to put the rate of climate change in perspective, data from NASA asserts: "As the Earth moved out of ice ages over the past million years, the global temperature rose a total of 4 to 7 degrees Celsius over about 5,000 years. In the past century alone, the temperature has climbed 0.7 degrees Celsius, roughly ten times faster than the average rate of ice-age-recovery warming." (Riebeek, 2010, np.) The rate of temperature increase in the modern world is unprecedented, and only growing.

Analysis of the rate of climate change is also the purview of the International Panel on Climate Change (IPCC)[1]. In their most recent report, published in 2014, they calculated that, "The globally averaged combined land and ocean surface temperature

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[1] The IPCC is a body established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program that "is an international body for assessing the science related to climate change…to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation," (*Intergovernmental Panel on Climate Change,* 2013, np.).

data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] degrees Celsius over the period 1880 to 2012, for which multiple independently produced datasets exist," (Climate Change 2014, 2014, p. 40). Their assessment shows a greater increase in temperature than the NASA report due to the four-year difference in end dates of data sets.

Reports from these two accredited bodies alone create a strong argument for alarm at how quickly the Earth's climate is warming. Even more alarming are the reasons for this shift in the slope of climate change.

1.2 Reasons for Temperature Surge

1.2.1 Anthropogenic Forcing: The Industrial Revolution and After

There are those that argue that climate change is an intrinsic property of the Earth, and that humans have not impacted the rate of climate change drastically. They say that the planet would be warming to match observations, regardless of human existence or not (Cook , 2017, np.). While it is important in science to never say never, there is extremely small chance that climate change is not anthropogenically driven. "The current warming trend is of particular significance because most of it is extremely likely (greater than 95% probability) to be the result of human activity since the mid-20th century and proceeding at a rate that is unprecedented over decades to millennia," (*Climate change: How do we know?,* 2017, np.). A more than 95% percent probability: in science, a confidence this high is the gold standard. It implies science is as certain as feasible that climate change is anthropogenically driven. 100% seems like it would be better obviously, but in science, that does not happen – the measurement of the speed of light, and accepted constant, is not known to 100% certainty either. Scientifically, 95% is accepted as truth, only to be refined, not recanted.

The beginning of notable human impact on Earth's climate started with the Industrial Revolution[2]. Abram et al. (2016) used paleoclimate reconstructions and

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[2] "The Intergovernmental Panel on Climate Change (IPCC) uses 'industrial era' to refer, somewhat arbitrarily, to the time after AD 1750, when industrial growth began in Britain, spread to other countries and led to a strong increase in fossil fuel use and greenhouse gas emissions," (Abram et al., 2016, p. 411).

assessments to model global continental and oceanic warming post-1500s. “Our regional palaeoclimate assessments suggest that widespread climate warming observed during the twentieth century forms part of a sustained trend that began in the tropical oceans and over some Northern Hemisphere land areas around the 1830s.” This time frame aligns with the beginning of the industrial age in Great Britain. Large quantities of coal and other fuels for new machines of industry began being burned and aerated, the pollutant byproducts of combustion pumped into the atmosphere.

It is arguable that the warming in the 1830s was part of a natural progression towards a warmer Earth. However, the study by Abrams et al. addressed this as well. They examined ‘time-of-emergence’, a term for when climate change slope exceeds the range of climate variability. Their study used a larger timeline (1500s to current) than previous studies (usually 18th century to current) in order to establish a baseline temperature with higher accuracy. While warming trends began in the 1830s, they found that time-of-emergence began almost 100 years later. The Artic reached this rate of warming in the 1930s, followed by the tropical oceans, Northern Hemisphere mid-latitude continents, and Australasia in 1960[3]. All other regions, excluding Antarctica, pass the time of emergence threshold by the start of the twenty-first century. This analysis shows that while warming began in the 1830s, warming that could not be explained by natural climate variability alone began in the 1930s. Conclusively, the Earth’s climate is experiencing a temperature increase of anthropologic creation.

1.2.2 Carbon Contribution from Industry

One of the most common quantities used to examine global warming is the amount of carbon dioxide that is present in the atmosphere[4]. This is because carbon dioxide is a greenhouse gas, so the more PPM (particles per million), the more effective the atmosphere is at trapping heat in. “Humans tap the huge pool or fossil carbon for energy and affect the global carbon cycle by transferring fossil carbon – which took

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[3] Australasia is a term to describe a region of land and ocean, most commonly defined as including Australia, New Zealand, New Guinea, and Papua New Guinea, and thus a large portion of the southeast Pacific (Australasia, 2016, np.).

[4] This quantity does vary on any given day as weather patterns and systems operate, typically a monthly or annual mean is used for scientific comparison.

millions of years to accumulate underground – into the atmosphere over a relatively short time span. As a result, the atmosphere contains approximately 35% more CO_2 today than prior to the beginning of the industrial revolution (380 ppm vs 280 ppm)," (Folger, 2008, p. 1). Note that this report to the US Congress was written in 2008. This measurement has increased since 2008, as polluting has not decreased but instead continues to grow. "Last year [2016] will go down in history as the year when the planet's atmosphere broke a startling record: 400 parts per million of carbon dioxide. The last time the planet's air was so rich in CO_2 was millions of year ago," (Jones, 2016, np.). This means the atmosphere now contains almost 43% more CO_2 than before the industrial revolution.

Below is a very useful graphic for visualizing climate forcing that is natural, versus climate forcing that is anthropogenic in origin.

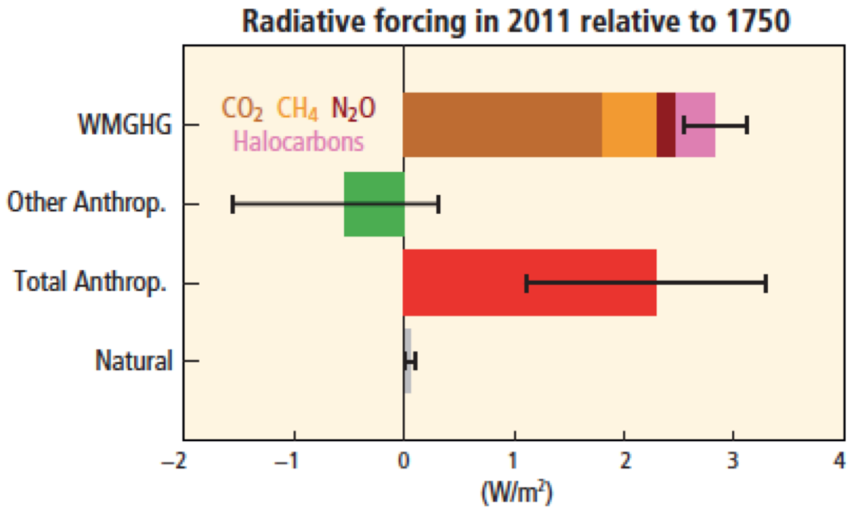

Figure 1.4 | Radiative forcing of climate change during the industrial era (1750–2011). Bars show radiative forcing from well-mixed greenhouse gases (WMGHG), other anthropogenic forcings, total anthropogenic forcings and natural forcings. The error bars indicate the 5 to 95% uncertainty. Other anthropogenic forcings include aerosol, land use surface reflectance and ozone changes. Natural forcings include solar and volcanic effects. The total anthropogenic radiative forcing for 2011 relative to 1750 is 2.3 W/m^2 (uncertainty range 1.1 to 3.3 W/m^2). This corresponds to a CO_2-equivalent concentration (see Glossary) of 430 ppm (uncertainty range 340 to 520 ppm). *{Data from WGI 7.5 and Table 8.6}*

Figure 1: Natural versus Anthropogenic forcing comparison, 1750 to 2011. (Climate Change 2014, 2014, p. 45).

The Synthesis Report published by the IPCC in 2014 corroborates the conclusion that carbon dioxide levels in the atmosphere are now exceptionally high. "Atmospheric concentrations of GHGs [greenhouse gases] are at levels that are unprecedented in at least 800,000 years. Concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have all shown larger increases since 1750 (40%, 150%, and 20% respectively)," (p. 44). The same report also examines specifically the amount of carbon dioxide increase. "Cumulative anthropogenic CO_2 emissions of 2040 (+/- 310) $GtCO_2$ were added to the atmosphere between 1750 and 2011," (p. 45).

It is also important to recognize which part of 'industry' emissions come from, because today's industries encompass many different sectors. As can be supposed, industries where a large amount of fuel is consumed are the ones that emit the most carbon dioxide into the atmosphere. "CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% to the total GHG emission increase between 1970 and 2010, with a contribution of similar percentage over the 2000-2010 period (high confidence)," (*Climate Change 2014*, 2014, p. 46). Below is an infographic for the year of 2010, illustrating which economic sectors contributed what percentage of the total 49 Gt of CO_2 added to the atmosphere in 2010.

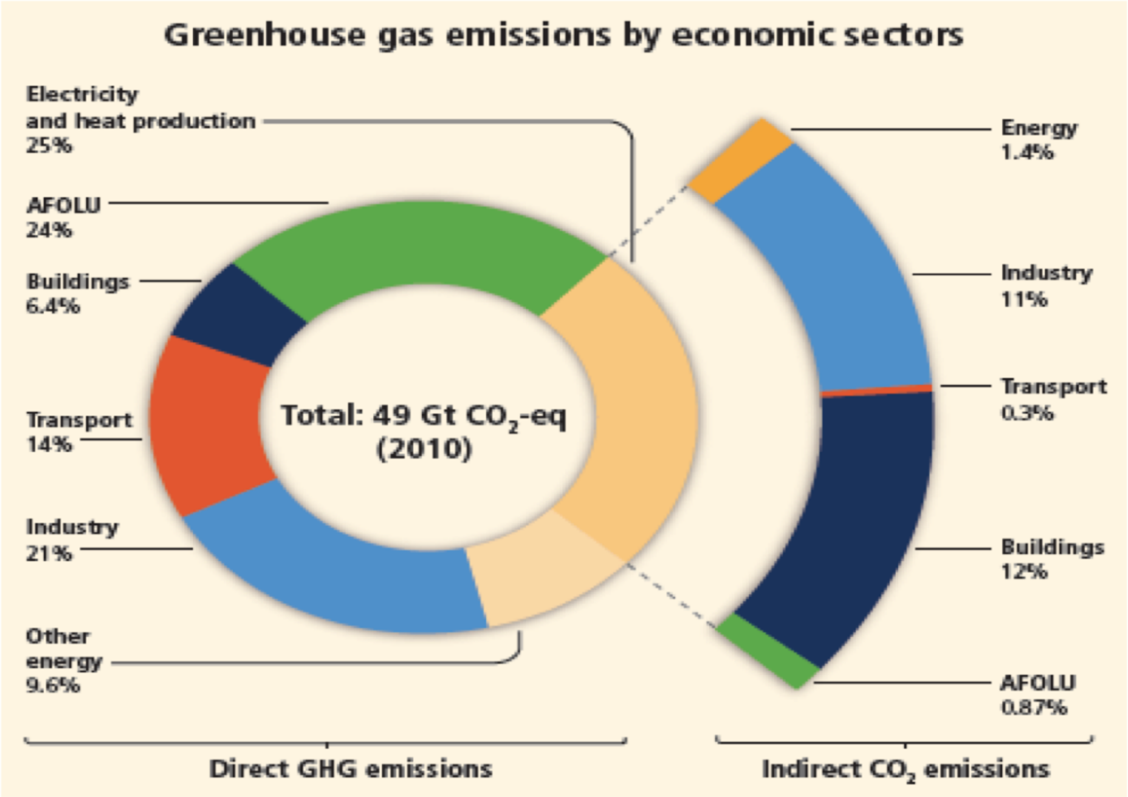

Figure 1.7 | Total anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$-eq/yr) from economic sectors in 2010. The circle shows the shares of direct GHG emissions (in % of total anthropogenic GHG emissions) from five economic sectors in 2010. The pull-out shows how shares of indirect CO_2 emissions (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. 'Other energy' refers to all GHG emission sources in the energy sector as defined in WGIII Annex II, other than electricity and heat production *{WGIII Annex II.9.1}*. The emission data on agriculture, forestry and other land use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from the sub-sectors of forestry and other land use (FOLU) as described in Chapter 11 of the WGIII report. Emissions are converted into CO_2-equivalents based on 100-year Global Warming Potential (GWP_{100}), taken from the IPCC Second Assessment Report (SAR). Sector definitions are provided in WGIII Annex II.9. *{WGIII Figure SPM.2}*

Figure 2: Contributions of CO_2 to atmosphere by specific industrial sectors. AFOLU is an abbreviation for "agriculture, forestry, and other land use".
(Climate Change 2014, 2014, p. 47).

It is undeniable that the aeration of different fuels for utilization by industry adds enormous amounts of carbon dioxide and other GHGs to the atmosphere.

1.2.3 Carbon Reservoirs and the Carbon Cycle

The Earth has natural mechanisms that work to stabilize climate, historically keeping the Earth in relative equilibrium. These cycles, such as the water cycle and the rock cycle, all interact to try and resolve climate perturbations, and return to equilibrium. However, if pushed too far from equilibrium, these systems will not be able to re-establish climate equilibrium - this is commonly referred to as the climate “tipping point”.

The carbon cycle is the Earth’s mechanism for processing carbon. It has different carbon reservoirs, which are bodies with certain permeability for how much carbon they can hold. Carbon, through different processes, is moved from one reservoir to another. The four main reservoirs of carbon are typically defined as the ocean, Earth’s crust (rock), the atmosphere, and terrestrial ecosystems[5]. ‘Terrestrial ecosystems’ is chiefly constituted by plants and soils, where organisms transform carbon into organic compounds (*Carbon Pools and Fluxes*, 2008, np.) The fast and slow carbon cycles act to create a net flux of carbon between different reservoirs.

In the slow carbon cycle, “through a series of chemical reactions and tectonic activity, carbon takes between 100-200 million years to move between rocks, soil, ocean, and atmosphere,” (Riebeek, 2011, np.). The lithosphere (rock) is the net recipient of carbon flux in the slow cycle. Carbon is taken out of the atmosphere, chemically processed in water, runs to the ocean, and is processed into calcium carbonate by organisms that are shell-building. When these organisms die, they sink to the bottom of the ocean, and eventually, the silt is turned into limestone (Riebeek, 2011, np.). Limestone is the largest reserve of carbon on the planet, and constitutes 80% of carbon-containing rock. The other 20% is shale, natural gas, oil, etc., carbon that essentially got sandwiched between rocks or mud while it was still largely organic matter (dead things) (Riebeek, 2011, np.). Lithospheric carbon is eventually subducted into the mantle, melted, and can be re-released into the atmosphere by outgassing of volcanoes.

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[5] Considering four main reservoirs is an acceptable generalization due to the scope of this paper. However, the fact that the carbon cycle permeates almost every aspect of Earth means that many more than four reservoirs can be specified, depending on the depth of analysis required.

The fast carbon cycle is largely based on fluxes in the terrestrial reservoir, and thus is measured in a lifespan. “The fast carbon cycle is largely the movement of carbon through life forms on Earth, or the biosphere. Between 10^{15} and 10^{17} grams (1,000 to 100,000 million metric tons) of carbon move through the fast carbon cycle every year,” (Riebeek, 2011, np.). Every living thing on Earth needs carbon, because organisms on this planet are by definition carbon-based. This means plants intake carbon for energy. Hence, during a global growing season, it is possible to see a large dip in carbon in the atmosphere, as plants intake it for nutrients. This carbon is then re-released to the atmosphere as organisms eat plants and outgas, plants die and decay, or a fire happens. Regardless of the route, it is recognizable that the nature of the fast carbon system creates a very large flux of carbon on a very short basis.

The amount of carbon released into the atmosphere by humans is such a serious issue because it is overwhelming the natural rate of the carbon cycle. “On average, 10^{13} to 10^{14} grams (10-100 million metric tons) of carbon move through the slow carbon cycle every year. In comparison, human emissions of carbon to the atmosphere are on the order of 10^{15} grams, whereas the fast carbon cycle moves 10^{16} to 10^{17} grams of carbon per year,” (Riebeek, 2011, np.). The fast carbon dioxide cycle can be visualized as breathing; the moving of this carbon is not re-uptake and storage, but annual fluctuation between reservoirs. Carbon in the fast carbon cycle is easily and readily reintroduced to the atmosphere. Slow carbon is not. Human industry is pulling fuel out of the lithospheric carbon reservoir and vaporizing it, re-introducing it to the atmosphere. The issue is this amount of carbon was not supposed to exit the slow carbon cycle at the rate that humans are extracting and burning it. “…humans emit about 30 billion tons of carbon dioxide per year – 100-300 times more than volcanoes – by burning fossil fuels,” (Riebeek, 2011, np.). The lithospheric process cannot reprocess and rebury carbon at the rate humans draw it out in shale and oil – what is vaporized in minutes will take thousands of years to reintroduce to rock.

Unfortunately, reintroduction of lithospheric carbon to the atmosphere at an abnormally and egregiously high rate is not the only way humans are detrimentally impacting the carbon cycle. Rampant rates of deforestation effectively destroy the instrument through which carbon in the fast cycle is removed from the atmosphere. To add insult to injury, the plant matter that is burned during deforestation adds to the increase in atmospheric carbon as well.

Humans are disrupting the equilibrium the carbon cycle has worked to preserve over millions of years. Never before in Earth's history has a creature been able to alter geology on the scope that humans now do. These sustained perturbations since the 18th century happen too fast for natural cycles to reconcile completely. Hence, the carbon dioxide in the atmosphere is growing at an epoch-making rate, and humanity is destroying the functionality of Earth's correction mechanism.

1.2.4 Possible Climate Change through the Milankovitch Cycles

The Milankovitch Cycles play a role in determining global climate and must be discussed as well. These cycles are generated due to three aspects of Earth's orientation in space: the Earth does not orbit the Sun in a perfect circle, the Earth is tilted on an axis, and the Earth wobbles around that axis. "Milankovitch cycles are classically divided into the precession, the obliquity, and the eccentricity cycles. These cycles modulate the solar insolation (i.e. the total energy the planet receives from the sun at the top of the atmosphere) or its geographic distribution," (Colose, 2011, np.). However, these cycles act over an extremely long time frame. Eccentricity cycles about every 2.1 million years, obliquity shifts between a 22-25 degree axial tilt every 41,000 years, and precession changes the direction of the North Pole about every 26,000 years (Colose, 2011, np.).

This all means that the Earth modulates between a naturally warmer period, and a naturally cooler period, based on the phase of cycles. "The Holocene temperatures peaked around 8,000 years ago. This temperature peak was associated with the perihelion phase of the Milankovitch cycles. That was when it is estimated that the natural cycle climate forcing was at maximum, including associated climate feedbacks. Since then the forcing levels have been slowly dropping and the temperature has been following the slope of forcing in line with the changes in the Milankovitch cycle forcing combined with system feedbacks. Recent significant changes in climate forcing due to human caused factors have produced a net positive forcing, causing temperatures to rise. This is a departure from the natural cycle," (*Global Warming Natural Cycle*, 2017, np.). Considering temperatures for this warm period have already peaked, the Earth, if following just the Milankovitch cycles, should be in a period of cooling. All records indicate it isn't.

1.2.5 Solar Variability Contribution to Warming

The luminosity of the Sun at this point in its life is very steady. Nevertheless, there are periodic and small changes in stellar luminosity that must be understood and discussed, as they are mechanisms that have the possibility to affect Earth's climate.

The slowest mechanism of change in stellar luminosity is due to the evolution that stars undergo as they age. A star begins its life fusing hydrogen into helium – this process generates energy along with way. In the process, commonly referred to as the proton-proton chain, four hydrogen nuclei are combined to form one helium nucleus. This combining means that there are less independent particles in the core of the star, resulting in a shrinking of the solar core. As the core shrinks, it is still fighting the same gravitational effect that is trying to compress it from the outside – this means that the star must generate more heat inside its core to stay in gravitational equilibrium. This increase in energy output corresponds to an increase in luminosity output. "Theoretical models indicate that the Sun's core temperature should have increased enough to raise its fusion rate and the solar luminosity by about 30% since the Sun was born 4.6 billion years ago," (Bennett et al, 2002, p. 472). One study by Foukal et al (2006) investigated whether changes in stellar luminosity (and thus changes in flux) are at fault for recent climate change[6]. They concluded that, "Overall, we can find no evidence for solar luminosity variations of sufficient amplitude to drive significant climate variations on centennial, millennial, and even million-year timescales," (p. 165). While it is clear that this process results in a change in solar luminosity, the change is so inconsequential due to the amount of time the change occurs over[7]. It is irrelevant to the discussion of current global warming.

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[6] The premise of the paper was to explore whether variation in the total solar irradiance (a measure of the Sun's output as wavelength-integrated radiation flux illuminating the Earth at its average distance from the Sun) [TSI] was likely or not to have significant impacts on global warming since the 17th century.

[7] At a rate of 30% change in 4.6 billion years, this means that there is a 0.000065% change in luminosity every million years. [0.3/4600Mya = 6.52e-5]

The next mechanism that alters the luminosity of the Sun are sunspots and faculae, both of which come about because of contortions in the Sun's magnetic fields. A sunspot is a cooled region[8] on the sun, and is darker than the surrounding area. This is because the strong concentrated magnetic field lines block solar plasma from entering them (Weier and Cahalan, 2003, np.). Sun spots migrate across the surface of the Sun, usually occurring in pairs, and multiple can appear at one time[9]; this would affect total irradiance, as sunspots represent a surface area producing less flux.

Faculae are, in a sense, the opposites of sunspots. They too are the result of concentrations of magnetic lines, but much smaller concentrations than that of a sunspot. "During the sunspot cycle the faculae actually win out over the sunspots and make the Sun appear slightly (about 0.1%) brighter at sunspot maximum than at sunspot minimum," (*Photospheric Features*, 2014, np.). Faculae actually become warmer and brighter than the average Sun output, meaning that they have a higher irradiance. Additionally, while a sunspot must exist with faculae, faculae can also exist independently and are usually more numerous than sunspots (*Facula*, 2009, np.).

A paper by Claus Frölich (1993) titled "Relationship between Solar Activity and Luminosity" analyzed the effect of sunspots and faculae on luminosity over different lengths of time (days, months, many years). He concluded that on the month-long time scale, "modulation is indeed due to the bright network and faculae and not due to sunspots." Thus, in the consideration of changes in solar irradiance, it is reasonable to conclude that the change from sunspots is negligible, and faculae are the real proponents of change. However, overall, this change still results in a minimal perturbation of the solar luminosity, typically only causing a 0.1% variation in output over the course of the 11 year cycle (Phillips, 2013, np.).

Conclusively, stellar luminosity changes due to the aging of the sun are not a driver of current climate change. Luminosity is increasing at a much slower rate than what would be needed to influence global warming. However, sunspots and faculae do

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[8] The average surface temperature of the sun is 5800 K, whereas sunspots are only about 4000 K (Bennett et al, 2002).

[9] Sunspots appear in what is known as the Sunspot cycle. This is an 11-year period between maximums and minimums in the number of sunspots that are present on the Sun at one given time.

create a stellar forcing of climate as they change luminosity. While this may contribute to global warming, it is not the driving mechanism. The quantity of sunspots present on the Sun's surface cycles on a regular basis between a minimum and maximum over a 22 year period. Hence, if global warming was being driven primarily by stellar flux perturbations, it should vary with the sunspot cycle. It does not. During a solar maximum, it is reasonable that sunspot and faculae presence will contribute a net positive forcing to global warming. But this forcing is only an addendum to the climate change already being driven by anthropogenic activity here on Earth. It is in no way strong enough to produce the global warming trends that have been growing since the 18th century.

1. Global Temperature Rise – Conclusions

The Earth is warming, at a rate ten times faster than that of the previous thousands of years. Since the 1880s to 2012, it is calculated that the Earth has warmed 0.85 degrees Celsius. This warming is not natural, is not a result of tectonic activity or geology, or even stellar variations. This warming is a result of anthropogenic forcing – the extraction and aeration of greenhouse gases. This is coupled with the destruction of important facets of the carbon cycle that would naturally remove carbon from the atmosphere. And it's not stopping, or even slowing. "Total anthropogenic GHG emissions from 2000 to 2010 were the highest in human history and reached 49 (+/- 4.5) $GtCO_2$ –eq/yr in 2010," (*Climate Change 2014*, 2014, p. 45). Decisively, anthropogenic forcing is the cause of current, exasperated, global warming.

2. Effects of Global Temperature Rise

Global warming seems like a rather harmless term, especially when the warming has been a mere 0.85 degrees Celsius (*Climate Change 2014*, 2014, p. 40) – the number seems trifling. But the truth of the matter is that the problem is the rate at which climate is being forced to change. If warming were gradual, many systems could adapt; the fossil record proves that species are highly adept at fighting for survival. But the warming is rapid, alarming, and only increasing. There will be consequences.

The effects of a global temperature rise of 0.85 degrees Celsius since 1880 are multifarious, and increasingly harsh. The future does not look particularly welcoming: "Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise," (*Climate Change 2014*, 2014, p. 58). It is important to investigate many facets of the issue in more detail, so that a realistic picture of the future is painted.

This paper will look a different predicted phenomenon in a broad approach. Behind every conclusion about the effects of climate change, there are many researchers and many papers. However, the exact science of each facet is not within the purview of this proposal. It is acknowledged that specific effects are amplified or diminished depending on the area of the world in which they present; the Northern and Southern hemispheres have different experiences based on the current distribution of land mass, just as land and water heat and cool at different rates. Rather, the focus of this section is to construct a general picture of how climate change will impact the globe as a whole.

2.1 Melting of Sea Ice and Sea Level Rise

As the planet warms, ice is melting en mass. Namely, sea ice. The Arctic and Antarctic of course have seasonal fluctuations in ice coverage, but as global warming continues, what was once 'permanent' ice is now being affected as well. "Over the past two decades, the Greenland and Antarctic ice sheets have been losing mass (high confidence). Glaciers have continued to shrink almost worldwide (high confidence)," (*Climate Change 2014*, 2014, p. 42). The increasing loss of what were once considered permanent structures of ice is greatly concerning.

Melting ice is bad for two reasons. The first is the effect on albedo. Snow and ice have a very high albedo, anywhere from 0.5 – 0.9, meaning that these surfaces scatter a large amount of sunlight. Scattering sunlight is desirable, because then the light is not absorbed by the ground and re-radiated in the infrared (which is when it gets trapped by GHGs). Thus, high albedos contribute to global cooling. Less ice means less cooling, which is undesirable when combatting climate change. Additionally, melting ice contributes to global sea level rise. Unfortunately, the ratio of volume increase when ice melts is not 1:1. When ice melts, it is warmed, and as a liquid, expands to fill a larger volume than it did as a solid. On top of that, global warming is heating the whole ocean, meaning that the volume of the ocean as a whole is expanding.

Sea level rise is an issue because of the habitats that are being distressed, or even lost. Additionally, a large percentage of the global population lives near seas and oceans, and is thus placed at risk to the ill effects of rising sea levels. "Over the period 1901 – 2010, global mean sea level rose by 0.19 [0.17 to 0.21] meters. The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (high confidence)," (*Climate Change 2014*, 2014, p. 42). To exacerbate the problem, as illustrated earlier in this paper, the rate of climate change is increasing. Improved climate models predict that, "…the rate of sea level rise will very likely exceed the observed rate of 2.0 [1.7 – 2.3] mm/yr during 1971 – 2010," (*Climate Change 2014*, 2014, p. 62). To put this in perspective, the IPCC predicts that if there is sustained warming, and the Earth's temperature rises 0.5 – 3.5 degrees Celsius more, the complete Greenland ice sheet will melt, and add 7 *meters* to global mean sea level rise (*Climate Change 2014*, 2014, p. 72). Since coastal cities are some of the most populous on the planet, this figure represents an imminent threat to humans and their way of life across the globe.

Not only will sea level rise threaten human life, it will largely impact the global economy. Nations will try to protect their receding coasts and the inhabitants of those regions, sinking monies into risk aversion and disaster relief. "Previous research estimated the damages from coastal flooding could soar to $1 trillion a year by 2050," (Carrington, 2017, np.). In the US alone, if the rate of pollution stays on its current trajectory, real estate losses due to a rising tide are projected to reach as high as $360 billion a year in 2100 (Ackerman and Stanton, 2008, p. v). For countries with large GDPs, such as the US, this economic burden is most likely bearable. But for small island nations, this may not be the case. "Some low-lying developing countries and small island states are expected to face very high impacts that could have associated damage and adaptation cost of several percentage points of gross domestic product," (*Climate Change 2014*, 2014, p. 67). As flooding and coastal weather events recur and strengthen yearly, and as sea levels continue to rise, the expenditure on flood mitigation and damages will grow to astronomical proportions.

There is one positive externality that may come about because of melting Arctic Ice. "…a host of countries – including Russia, China, Iceland, Canada, and the United States – continue to make preparations to turn the rapidly warming Arctic into a busy global shipping route," (Struzik, 2016, np.). Russia seems to have the highest interest in this shipping possibility, as well as having the greatest number of cargo ships that have ice-breaking capabilities. The possibility of a passage is still being explored, but the economic draw is obvious, as the journey cuts time from Asia to the US by negating the need for the Panama Canal. "…a Danish bulk carrier, saved $200,000 and four days' transit time by shipping 15,000 metric tons of coal from Vancouver to Finland via the Northwest Passage in 2013," (Struzik, 2016, np.). The idea of a passage does have its drawbacks, as environmentalists are concerned about the impact on local wildlife, from noise creation to the possibility of oil spills. Additionally, there is a possibility of coal soot coating ice and snow, further decreasing Arctic albedo and contributing to global warming. If well regulated, the possibility of a transpolar shipping route may be an economic silver lining to the cloud of global warming, for those countries with Arctic access.

Melting ice has to go somewhere, and as it trickles to the ocean, sea levels continue to rise. There are only 44 countries that don't have ocean access (Rosenberg, 2017, np.). This means that there are 151 countries in the world that have some stretch of coast. 151 countries that are likely to lose capital already in place along seaboards as sea levels rise. 151 countries that will have physical land swallowed up by the ocean, unable to be used for development. Melting ice caps and glaciers are problems that have localized and global effects, and the extent of these effects is yet to be felt in full force, as the rate of sea level rise continues to escalate.

2.2 Melting of Permafrost

Probably one of the most frightening aspects of global warming is the predicted melting of permafrost. "There is high confidence that permafrost temperatures have increased in most regions of the Northern Hemisphere since the early 1980s, with reduction in thickness and areal extent in some regions. The increase in permafrost temperatures has occurred in response to increased surface temperature and changing snow cover," (*Climate Change 2014*, 2014, p. 42). The fear is not solely over losing permafrost ecosystems, but because of what lies beneath permafrost. Permafrost is a soil that has been frozen for two or more years, but it may have an active upper layer that periodically warms. Recall from the previous section, soil is a carbon reservoir, as it includes roots of plants, decaying organic matter, and other materials such as leaf litter, all organics rich in carbon. If permafrost warms more than usual annual fluctuations, there is danger of frozen, buried organic matter decaying and releasing all of the carbon it currently stores.

The issue of thawing permafrost is new to the climate change table, and it has been asserted in some literatures that the Climate Change 2014 report published by the IPCC does not adequately assess the issue. A paper by Schaefer et al., (2014) investigates the issue in a more thorough matter. They estimate that permafrost soil contains about 1700 gigatons of carbon, nearly twice as much as is in the atmosphere. "If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO_2) and methane (CH_4) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions," (Schaefer et al., 2014, p. 3). Additionally, if climate change does perpetrate the thawing of permafrost on mass scales, the result is irreversible.

There is no way to reconvert the carbon released from permafrost soil into organic matter and then to re-bury it beneath the ice (at least not with current technology). The research estimated a loss of permafrost area by 2100 of 52 (+/- 23) %. Especially alarming is that permafrost melting and decaying releases a portion of emissions as methane, not carbon dioxide. This is alarming because methane is a 33x more effective greenhouse gas than carbon dioxide, and after its short lifetime of 8 years, it decays into carbon dioxide (Schaefer et al., 2014, p. 4). After analyzing multiple models, Schaefer and his team estimated an additional 120 +/- 85 Gt of carbon from thawing permafrost by 2100, increasing global temperature by 0.29+/- 0.21 degrees Celsius (2014, p.8) from permafrost contribution alone. However, the models also indicate that 60% of permafrost emissions will occur after 2100, implying that an increased forcing of 0.29 degrees

Celsius from permafrost melt is only a portion of the forcing that will occur if the Earth warms enough to melt all permafrost (Schaefer et al., 2014, p. 8). Clearly, keeping permafrost frozen is a necessity, lest climate change spiral out of control.

2.3 Ocean Acidification

The oceans are saving humanity from the true cost of carbon pollution that has been created thus far. The ocean, as a carbon reservoir, holds 38,140 gigatons of carbon. In comparison, the atmosphere is a reservoir of 780 gigatons of carbon. This means the ocean has a huge capacity for carbon absorption, and annually is a net receiver of 1.7 Gt/C from the atmosphere (Folger, 2008, p.8). This huge capacity as a carbon sink means that the ocean is delaying the onset of climate change, and is effectually the only thing giving the Earth a margin of time to adapt. “The oceans represent a major heat reservoir, taking up more than 90% of the total global energy imbalance since the 1950s. Internal variability of ocean circulation mediates the global climate,” (Abram et al., 2016, p.1). Life was at one time sheltered and nurtured in the ocean, fragile in its evolution; the ocean continues to protect, even now.

While the ocean is a great time delay, the opportuneness of this carbon sink is quickly diminishing. “…as the absorption of the CO_2 emissions from human activities increases, this reduces the efficiency of the oceans to take up carbon. Carbon dioxide exchange is a two-way process, with the oceans and atmosphere absorbing and releasing CO_2. A decrease in the amount of CO_2 absorbed by the oceans will mean that relatively more CO_2 will stay in the atmosphere,” (*Ocean acidification*, 2005, p.9). As ocean water warms, it becomes less able to hold dissolved carbon. Additionally, while the ocean is currently acting as a thermal sink, this process isn’t permanent. “Recent weather trends suggest that uptake mechanisms like subsurface heat burial in the tropical Pacific and vertical heat transfer to the ocean depths could already be declining,” (Katz, 2015, np.). New research has shown that much of the ocean’s heat has been sequestered into the deep currents in the Southern hemisphere. However, the heat will not just stay there perpetually, “More heat stored in the ocean now means more will inevitably return to the atmosphere,” (Katz, 2015, np.). If the ocean starts eschewing heat while humans are still aerating gigatons of greenhouse gases, it will severely exasperate the rate of warming.

The ocean is an amazing carbon sink, but it is only a delay of the effects that the carbon dioxide will produce as warming continues. A solution to climate change must be implemented before the ocean changes from a dampener to an accelerator of global warming.

Ocean absorption of carbon dioxide is good news for the delay of global warming, but it is horrible news for the biodiversity of the ocean. "Carbon dioxide plays an important natural role in defining the pH of seawater…when CO_2 dissolves in seawater it forms a weak acid, called carbonic acid. Part of this acidity is neutralized by the buffering effect of seawater, but the overall impact is to increase the acidity," (*Ocean acidification*, 2005, p. 9). Why is acidic salt water bad? Because a giant scope of organisms live in that salt water. Carbonic acid inhibits the creation of shells by marine life, and is causing the dissolution of shells and loss of biodiversity (*Ocean Acidification*, 2017, np.). These shellfish are at the base multiple food chains, and a rapid decrease in populations could have incredibly detrimental effects on whole food systems within the ocean.

Beyond acidification, marine biodiversity is also being affected by the dramatic warming of the upper ocean. "Warmer water holds less oxygen and other gases. On top of that, warming increases ocean stratification, which blocks the movement of oxygen-rich surface waters to lower depths. The resulting low-oxygen zones are now spreading, and climate models predict they could be 50% larger by the end of this century," (Katz, 2015, np.) The 'lucky' animals that are mobile have the possibility of trying to adapt to new regions of the ocean. However, coral is not one of the lucky, and is currently being devastated by the heating seen in the upper meters of ocean water. "Corals are unable to cope with today's prolonged peaks in temperatures – they simply haven't been able to adapt to the higher base temperatures of the ocean. Although reefs represent less than 0.1 % of the world's ocean floor, they help support approximately 25% of all marine species," (*Global Coral Bleaching*, 2016, np.). The ocean as a carbon sink is a blessing, but the life within this carbon sink is suffering as the ocean acts to mitigate the inadaptable level of climate change produced by anthropogenic climate forcing. The IPCC summarizes the interplay of ocean acidification well, pointing to the fact it will only worsen an already devolving situation, "Ocean acidification acts together with other global changes (e.g., warming, progressively lower oxygen levels) and with local changes (e.g., pollution, eutrophication) (high confidence), leading to interactive, complex, and amplified impacts for species and ecosystems," (*Climate Change 2014*, 2014, p. 67). Continued global warming, coupled with ocean acidification, will perceivably alter the world's oceans if nothing is done to decrease these two causes.

2.4 The 6th Mass Extinction

Another alarming phenomenon being propagated by climate change is the increasing rate of extinction in the biosphere. Indeed, there is now a wealth of research to indicate that the world is entering the period of its sixth mass extinction. In the geological record, there have been five recorded mass-extinction events. From asteroid impact to glaciation to volcanism, the causes have been multifarious, but in the fossil records there are clear distinctions of when rates of extinction of different periods skyrocketed above the normal background extinction rates[10]. This century, humanity has entered a sixth mass extinction. "…biologists have found that the Earth is losing mammal species 20 to 100 times the rate of the past. Extinctions are happening so fast, they could rival the event that killed the dinosaurs in as little as 250 years…they assert that human activity is responsible," (Kaplan, 2015, np.). This uptick in extinction rate is not prompted by climate change alone, but it is amplified by it.

Species extinction and decline is due to a number of factors. "In the last few decades, habitat loss, overexploitation, invasive organisms, pollution, toxification, and more recently climate disruption, as well as the interactions among these factors, have led to the catastrophic declines," (Ceballos et al., 2017, p. 2). One of the largest issues, habitat loss, is due to human sprawl. The others can be highly exasperated and invigorated by climate change. "The multiple components of climate change are anticipated to affect all the levels of biodiversity, from organism to biome levels…At the most basic level of biodiversity, climate change is able to decrease genetic diversity of populations due to directional selection and rapid migration, which could in turn affect ecosystem functioning and resilience," (Bellard et al., 2012, p. 1). As the Earth warms,

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[10] Extinction is a natural phenomenon, and never truly ceases. The background extinction rate is the term for normal levels of extinction, for example, the expected extinctions to happen over 10,000 years. Different models give different rates.

the natural timing and responses that plants and animals have - such as when to migrate, breed or pollinate - are being affected. "In a meta-analysis of wide range of species including animals and plants, the mean response across all species responding to climate change was a shift in key phenological events of 5.1 days earlier per decade over the last 50 years," (Bellard et al., 2012, p. 3). Shifting phenological events can mean that plants and their insect pollinators are no longer on the same schedule, resulting in decreased populations and likely extinction of either or both symbiotic partners. Organisms need time to adapt; the fact that some can't is causing death, less genetically varied populations, and mistiming previously symbiotic events, to the detriment of all.

Extinction events are alarming in themselves, as one laments any loss in variation of life on the only planet known to be hospitable to life. "Species extinctions are obviously very important in the long run, because such losses are irreversible and may have profound effects ranging from the depletion of Earth's inspirational and esthetic resources to deterioration of ecosystem function and services," (Ceballos et al., 2017, p.1) The desires of humanity go far beyond a pathos to preserve and a desire for esthetics; they enter the realm of economics, as well as food source stability. "Genetic diversity provides the raw material for plant breeding, which is responsible for much of the increase in productivity in modern agricultural systems," (*Perspectives on Biodiversity*, 1999, np.). Genetic diversity is what allows humans to bioengineer plants to be better producers for the main food staple crops. Beyond that, wild ecosystems are economically valuable. Gross revenue from world marine fisheries was $69 billion in 1989, forest-product exports in 1993 valued $100 billion, and nature tourism netted a cool $250 billion in 1990 (*Perspectives on Biodiversity*, 1999, np.). Clearly the economic benefits derived from sustained biodiversity are large, and a significant motivator to protect what biodiversity remains on Earth.

Earth warming not only impacts the phenology of plants and animals, it also impacts different habitats. As climates change, ecosystems try to migrate spatially in order to find a new area similar to their accustomed habitat. "Latitude and altitudinal range shifts have already been observed in more than 1,000 species – especially those with high dispersal capabilities like birds, insects and marine vertebrates, leading to a reduction in range size particularly in polar and mountaintop species," (Bellard et al., 2012, p.3). For species already on the tops of the mountains, there will be nowhere left to go as other species push upwards to try and find cooler climates. "…the responses of many populations are likely to be inadequate to counter the speed and magnitude of the current climate change. In addition, unlike in past periods of climate change, species have now to cope with additional threats, some of which may act in synergy with climate change," (Bellard et al., 2012, p.4). Mitigating climate change won't solve human encroachment on biomes, or ocean acidification, or pollution, but it will stop rising temperatures from exasperating additional problems, and hopefully give life the time it needs to effectively adapt.

2.5 Impact on Human Health

Another worrying impact of climate change is the effect it has on human life. Humans now number almost 8 billion, and proliferation across the globe means exposure to all of the detriments of global warming. These include not only increasingly limited access to food and water, but also extreme temperature changes, economic mitigation costs for all countries, and the pressures of human migrations.

Just like other species, humanity's food and water supply are in danger from global warming. "All aspects of food security are potentially affected by climate change, including food production, access, use and price stability," (*Climate Change 2014*, 2014, p. 69). It is true that some areas of the world may see increased returns from agriculture as previously harsh climates become more temperate. Globally, the yield of food crops will remain essentially constant across models. Population demand, however, will continue to rise, and shifting agricultural bands will serve to exacerbate problems of access to food. Perhaps more alarming is the effect that climate change will have on the accessibility of water. "The interaction of increased temperature; increased sediment, nutrient and pollutant loadings from heavy rainfall; increased concentrations of pollutants during droughts, and disruption of treatment facilities during floods will reduce raw water quality and pose risks to drinking water quality," (*Climate Change 2014*, 2014, p. 69). Drinkable water is the essence of life, and by perpetuating climate change, humanity is amplifying the scarcity of drinking water while concurrently amplifying the drought.

The same weather that threatens food production and access to clean drinking water is also the weather that will have direct impacts on human health. "The mean warming over land will be larger than over the ocean (very high confidence) and larger than global average warming. It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases. It is very likely that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur," (*Climate Change 2014*, 2014, p. 60). There is already sobering evidence of this weather impacting human health as, for example, the average temperature for the subcontinent of India has risen 0.5 degrees Celsius in recent years. "Heat waves killed 1,300 people there in 2010, 1,500 in 2013 and 2,500 in 2015, according to researchers. About a quarter of the country's population, totaling 1.3 billion people, doesn't have electricity and lives on less than $1.25 a day. Air conditioners are seen as a status symbol – a luxury of the middle class – and many of those most likely to die from heat have no way to keep cool," (Waldman, 2017, np.). For the US alone, if emissions continue on their same trend, energy costs are projected to reach $141 billion a year in 2100 (Ackerman and Stanton, 2008, p. v). Those are energy costs for primarily air conditioning and refrigeration. Luckily for most of the population in the US, climate control is an everyday amenity. In countries where that is not the case, death tolls will continue to rise as climate change plays havoc with the weather at an ever-accelerating rate.

One fact, as illustrated above, is that the risks of climate change will be disproportionately large for those populations that are poor or live in lesser developed countries (LDCs). "Climate change will amplify existing risks and create new risks for natural and human systems. Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development," (*Climate Change 2014*, 2014, p. 64). The Northern Hemisphere, where most of the more developed countries (MDCs) are located, is slated to have less drastic and less damaging shifts in climate as the planet warms. Not so for the south. "The projected temperature increase of 2.2 to 5.5 degrees Celsius by the end of the century could make parts of developing nations in Asia, the Middle East, Africa and South America "practically uninhabitable" during the summer months," (Waldman, 2017, np.). The ethics of this distribution of detriment are a discussion for another paper. However, it must be noted that MDCs traditionally have a section of national budget dedicated to global aid and relief. This means, though not directly drastically impacted, MDC monies will still pay for at least some of the harm visited upon poorer, more vulnerable populations and states. In fiscal year 2017, the US Agency for International Development (USAID), the department responsible for administration of humanitarian funds, had a budget of $22.7 billion (*FY 2017 Development and Humanitarian Assistance Budget*, 2016, np.) The United Nations also has a budget for humanitarian aid: in 2016, they requested $22.2 billion, in order to try and assist 92.8 million of the most vulnerable people in 33 countries (Taylor, 2016, np.). While MDCs may be some of the most environmentally protected and stable countries when it comes to suffering effects of climate change, climate change will still incur costs.

Another issue that is commonly tied to the contrast between LDCs and MDCs and will be exasperated by climate change is that of migration. Specifically, the displacement of populations at risk, usually within LDCs, and their attempts to move or seek refuge in MDCs. "According to a Pew Research Center analysis of U.N. data, 0.8% of the world's population was forcibly displaced at the end of 2015 – the highest percentage since record-keeping began in 1951," (Taylor, 2016, np.). 0.8 percent of the world population is equivalent to 600 million people. That is twice as large as the population of the United States. A displaced or migratory person still needs food, water, and shelter. An example of the strain that migrant populations put on countries can be seen in the refugee crisis that has been occurring in the European Union since 2015. "In total, the EU has dedicated over 10 billion euros from the EU budget to dealing with the refugee crisis in 2015 and 2016. Many people arrive in the EU needing such basics such as clean water, food and shelter…In order to support refugees in Turkey, the EU and its Member States are providing 6 billion euros," (*The Refugee Crisis*, 2016, np.). Granted, this migration has been started primarily by conflict, but the response mechanisms are the same nonetheless, and illustrate that mass population migrations are costly for the receiving nations, usually MDCs. Climate change will only serve to displace more people, as livable habitats shift latitude. As stated above, it is predicated that parts of Asia, the

Middle East, Africa, and South America will become unlivable in summer. It has yet to be seen what the scale of migration due to climate change will be, but undeniably it will generate a substantial economic cost.

2. Effects of Global Warming – Conclusion

Something needs to be done to stop the Earth from melting. "…the average global temperature on Earth has increased by about 0.8 degrees Celsius (1.4 degrees Fahrenheit) since 1880. Two thirds of the warming has occurred since 1975, at a rate of roughly 0.15 – 0.20 degrees Celsius per decade," (Carlowicz, 2010, np.). Notice, this study was written in 2010. An updated study measures that a net warming of 0.95 degrees Celsius has occurred from 1880 – 2016 (Dahlman, 2017, np.). That is an alarming change in temperature to happen in such a short period of time, and the effects will echo through decades to come if nothing is done to abate or correct this aberration.

Predicting the amount that global temperature will continue to rise is a difficult thing. A large amount of temperature increase depends on how much pollution continues to take place. Optimism is always a good trait to have, but hard data predicts a different future, as the levels of pollution continue to rise. "Multi-model results show that limiting total human-induced warming to less than 2 degrees Celsius relative to the period 1861 – 1880 a probability of more than 66% would require cumulative CO_2 emissions from all anthropogenic sources since 1870 to remain below about 2900 $GtCO_2$. About 1900 Gt CO_2 had already been emitted by 2011," (*Climate Change 2014*, 2014, p. 10). The 'allowance' of carbon dioxide emissions is being met sooner and sooner every year, as different factors continue to drive the pace of pollution. This means predictions are forced to chose between the optimism of emissions regulation effectiveness, and the pessimistic data trends. Predicting warming generates large warming, but one thing is certain - the equilibrium temperature of Earth is not done rising.

As already stated, projecting climate change temperature impact too far into the future is amazingly difficult and does not create reliable results. There are too many factors to consider, such as volcanic eruptions and the possibility of unseen gas releases or other such events happening. The IPCC, with medium confidence, using corroboration between different models, predicts a 0.3 – 0.7 degrees Celsius increase in global temperature relative to the temperature in 1986 – 2005 (*Climate Change 2014*, 2014, p.10). And this is the moderate prediction. Emissions caps and attempts to halt the rate of climate change are marvelous, and show humanity is beginning to comprehend the impacts of pollution. But the solutions presented to this point are not large enough, are not enforceable, and are not desirable enough to inspire caretaking of the planet to the level that is needed. It is time to think outside the box.

3. What Affects Global Temperature

For a discussion of climate alteration, it is important to understand the main way in which the Earth receives energy, and then how that energy is propagated by the planet. To do this, an equation called the 'energy balance equation' is employed. The energy balance equation is an equivalency formed by adherence to the law of conservation of energy. For planets, it means that the energy emitted must be equal to the energy absorbed, when the planet is matured and no longer in the process of forming but has reached an equilibrium state.

3.1 The Energy Balance Equation

As applied to the Earth, "Over a given period, the Earth and atmosphere combined must emit as much energy back into space as they absorb from the sun, corresponding to the balanced state or radiative equilibrium. This is the only way the planet can maintain a constant temperature," (Frederick, 2008, p. 60). Therefore, the equation can be set up as: [energy absorbed] = [energy radiated][11]. The Earth, consequently, emits from the *top* of its atmosphere[12] the same amount of energy that is being absorbed.

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[11] "The balance expressed…applies when averaged over the entire planet for at least a full year," (Frederick, 2008, p. 61).

[12] This is called effective radiating temperature, and is the temperature a satellite would record for the temperature of Earth if measuring its output into outer space.

Earth receives its energy as light produced by the sun. The Sun emits primarily in visible wavelengths, peaking around 500 nanometers[13]. "The visible surface of the sun has a temperature of 5700 to 5800 K, and material at this temperature emits a substantial fraction of its radiant energy in the visible and shorter wavelength infrared portions of the spectrum," (Frederick, 200, p. 50). Thus, incoming solar radiation is called 'shortwave', as 500 nanometers is a small width for a wavelength. The incoming radiation, if it makes it through the atmosphere, is absorbed by the surface of the Earth. This heats the ground, making it re-emit energy in infrared, a longer wavelength.

When the light is re-radiated, it now has a longer wavelength, and is primarily infrared light. IR has a longer wavelength than visible, and thus re-radiated energy is referred to as 'longwave radiation'. Infrared light has the correct level of energy to interact with greenhouse gases. Greenhouse gases are asymmetric molecules, capable of stretching and bending their chemical bonds. "As a general result, a molecule constructed of two identical atoms (e.g. N_2, O_2, H_2) is not radioactively active in the longwave part of the spectrum. However, gas-phase molecules that consist of three or more atoms, commonly called "polyatomic molecules," have the potential to absorb and emit longwave radiation very efficiently. Prime examples of radiatively active gases in the Earth's atmosphere are CO_2, H_2O, and O_3," (Frederick, 2008, p. 56). After absorption, the greenhouse gas molecule is excited for some time, but then 'releases' the energy, still in IR wavelengths, and radiates it back into the atmosphere. This radiation can occur in any direction – the energy does not necessarily continue up and out of the atmosphere. The longwave radiation can then be absorbed by another greenhouse gas molecule, and play ping-pong through greenhouse gases until it eventually completes a random-walk out of the atmosphere. This is why greenhouse gases are responsible for the heating of a planet – they trap longwave radiation and bounce it around before letting it back out into space,

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[13] The Sun does emit some light in all wavelengths of the EM spectrum (approximately 8% of the solar constant is in the ultraviolet, 46% is in the visible, and 46% is in the infrared (Frederick, 2008, p. 51)). However, because of the temperature and type of star the sun is, the peak of its emissions occurs in the visible, in 'green' around 500 nm. This peak is due to Planck's Radiation Law: "on a qualitative level…hot objects preferentially emit high-energy photons, whereas colder objects preferentially emit lower-energy photons," (Frederick, 2008, p. 57). Essentially, the peak wavelength is tied to how hot an object is – the Sun, at an average temperature of 5700 to 5800 K, peaks in green.

effectively heating the atmosphere, and thus planet by forestalling the release of energy back to space.

Once the re-radiated light reaches the top of the atmosphere, it can finally escape into space. Again, to follow the law of conservation of energy, the amount of energy that escapes from the *top* of the atmosphere must be equal to the amount of incoming solar radiation for planets in equilibrium. However, the amount of energy at *lower* levels in the atmosphere is not subjugated to this. Due to the greenhouse effect, the lower atmosphere is warmer than the effective temperature of Earth as would be measured from space.

Armed with an understanding of the transformation of energy once it reaches Earth, the completely energy balance equation can now be discussed. The Earth is understood to be in energy equilibrium: it is on a stable orbit and is no longer receiving energy from sources other than the Sun (such as collisions when planets are first formed).

The amount of energy received is calculated by a fairly straightforward equation.

$$E\ absorbed = (1 - A)\pi R^2 S)$$

The part of the equation that looks like it belongs to a circle does in fact come from that. The πR^2 value is the measurement of the area of a circle, or in this case, the portion of the Earth that is receiving flux from the sun. Only half of the Earth’s surface faces the sun at one time, and an image of that surface would appear to be a circle.

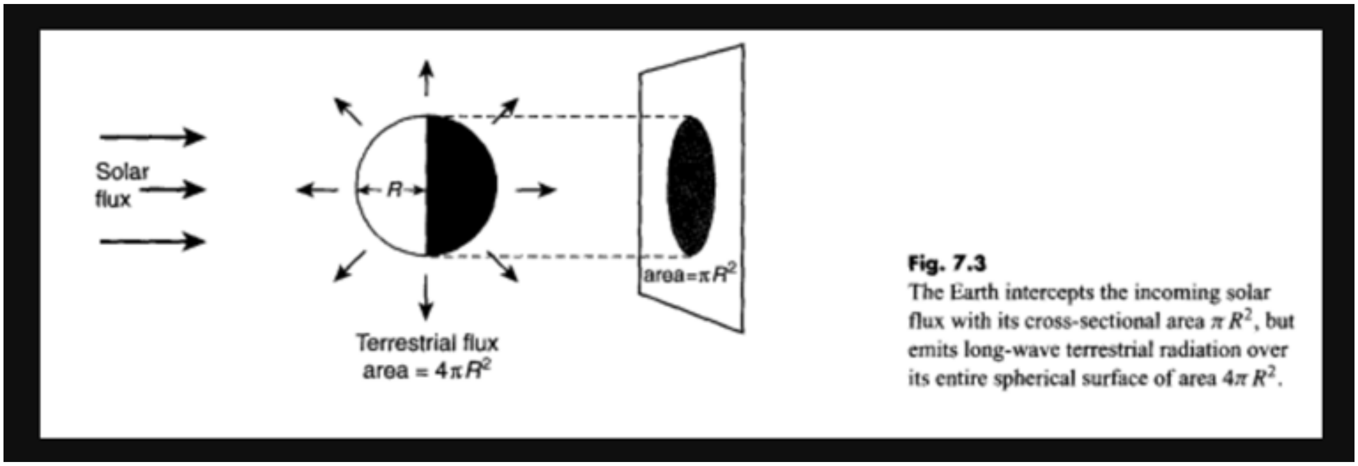

Fig. 7.3
The Earth intercepts the incoming solar flux with its cross-sectional area πR^2, but emits long-wave terrestrial radiation over its entire spherical surface of area $4\pi R^2$.

Figure 3: Solar Flux Received at Earth - Area Illustration
(https://scienceofdoom.com/2010/02/06/the-earths-energy-budget-part-one/)

The variable ‘S’ is the measure of stellar flux, usually measured in watts. Flux diminishes as an object gets farther away from the source by the relationship $1/r^2$ (where r is the distance from the emitter to the object). For example, a planet at 2 AU will receive 4 times more flux than a planet at 4 AU; flux diminishes as an inverse square law. The last part of the equation (1-A) is to measure reflectivity of the planet. ‘A’ is the variable for albedo. Albedo is the measure of how much a surface will reflect[14]. A value of 1 means that it will reflect all of the light that is received – picture an amazingly white surface. An albedo value of 0 means that an object is a perfect black body – it is absorbing all light and not reflecting any. Earth has an average albedo of 0.3, meaning 30% of all incoming radiation is scattered back into space before being absorbed. In the absorption equation, the value is (1-A) to multiply incoming solar radiation by the amount of the radiation that is absorbed, and disregard the radiation that is simply reflected due to albedo. To summarize, incoming radiation is effected by albedo, the amount of flux received, and size of the planet.

To balance energy received, the other half of the equation is energy emitted.

$$E\ out = 4\pi R^2 \sigma {T_E}^4$$

R for this half of the equation is also the planet’s radius - hence, when the two sides are set equal to each other, radius cancels; it can be concluded a planet’s radius does not have an impact on received flux energy. Sigma is the Stefan-Boltzmann constant, and is equal to 5.67e-8 W m^{-2} K^{-4}. This constant originates from the Stefan-Boltzmann law, which is a thermodynamic law in which the intensity of all wavelengths at which a blackbody radiates increases as temperature increases. T_E is the effective radiating temperature of the planet - the energy measured as looking at the planet from space. While energy radiated out of a system is important, this half of the energy equation will not factor greatly into the rest of this proposal, as the interest is in changing the amount of energy received by the system.

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[14] This is bond albedo.

3.2 Changing Variables in 'E Absorbed'

Clearly, in order to change the amount of energy that is being received, and thus change the temperature of the Earth, one of the variables in the energy balance equation needs to be altered. Therefore, the variable change must occur in the energy-absorbed equation. This leaves four variables: albedo, planet size, distance between the Sun and Earth, and insolation (incoming solar flux). The next sections will exam each variable in turn and the feasibility of altering them.

3.2.1 Changing Albedo

The first variable that might seem the easiest to alter is albedo. Radiative forcing associated with carbon dioxide increase would be equivalent to a 0.01 decrease in albedo. Therefore, raising albedo 0.01 would counter carbon dioxide radiative forcing (Donohoe & Battisti, 2011, p.4402). There are two ways to alter albedo; atmospheric alterations, and ground-based alterations.

The largest problem with relying on ground-based albedo alterations to combat climate change is the fact that they would not have a significant effect on overall albedo. Atmosphere strongly attenuates the impact of surface albedo on overall planetary albedo. "…atmospheric processes are found to be the dominant (88%) contributor to global average planetary albedo while surface processes make a much smaller contribution to the global average planetary albedo," (Donohoe & Battisi, 2011, p. 4407). Even if surface albedo were increased to reflect more shortwave radiation before it was absorbed, the effects would be so attenuated by varying atmospheric conditions to render the project inefficient and unpredictable. However, this is not to say that ground-based albedo alterations are entirely useless. On the contrary, if coupled with another tactic to combat climate change, ground-based albedo alterations would prove a valuable secondary line of attack. Some alterations are as simple as substituting regular crops with a lighter-leafed variant, or painting rooftops white. These methods are regionally effective, but not modeled as effective enough to be solely relied on to combat climate change. Ground-based albedo modifications would be a secondary solution to strengthen a primary one.

The other way to alter albedo is to change atmospheric albedo. Volcanoes do this when they erupt - the more particles there are in the atmosphere, the more light is scattered by the particles before reaching Earth's surface. Atmospheric albedo alterations as a solution to combatting climate change are possible, but as will be shown in the section "Other Suggested Solutions", they are not advisable.

3.2.2 Changing Area of the Planet

The next variable in the equation to consider is radius of the Earth. Considering there is no easy way to increase the mass of the Earth, or to make Earth less dense and thus 'puffier' and thus increase radius, this is not a realistic option. Indeed, when the equation is considered as a whole for global energy balance, radius cancels out. Thus, changing area or radius of the planet would have no effect on received energy.

3.2.3 Changing Distance Between the Sun and Earth

The distance between the Sun and the Earth is also a variable in the equation. Fundamentally, changing the orbital parameters of a planet is not a viable option to mitigate energy at this time, and is thus readily discarded from consideration.

3.2.4 Changing Incoming Solar Flux

The last variable in the equation is incoming solar radiation. Changing incoming solar radiation sounds like it would be a science fiction option – change the amount of sunlight Earth receives? But this is just the option. The following sections will illustrate how such a solar shade would be constructed and implemented. It will not be easy, it will not be cheap, but the only alternative is to watch the world grow more polluted and warmer while the technology to solve climate change from the ground lags far behind the need.

4. The Science of Changing Insolation

Changing insolation. An idea that sounds like science fiction at first – reducing the amount of sunlight a planet receives? Hogwash.

But the idea isn't crazy, not anymore. All of the required technology exists: the engineers, the materials, the mathematicians, and the models. The following section will lay out the required technological pieces for a solar shade, and calculate how to achieve the desired drop in insolation.

This is not a permanent fix. This is not a license for the world to continue massive emissions of pollutants that are acidifying oceans. Instead, this is a way stop the Earth's temperature equilibrium from deviating so far from the mean that natural mechanisms cannot restore balance. This is a solution to give humanity time to develop the technology needed to remove carbon dioxide from the atmosphere. This is necessary.

[All calculations are available in Appendix D, with explanations]

4.1 The Considerations of Changing Insolation

To begin, an important definition is that insolation is the amount of solar radiation reaching a given area. Changing insolation of Earth will change the amount of heat Earth re-radiates into its atmosphere as longwave radiation, decreasing the amount of energy into the system, and thus the temperature.

As discussed in "Global Temperature Rise: Solar Variability Contribution to Warming", solar luminosity fluctuates with the sunspot cycle, as well due to stellar aging. This may have an impact on a solar shade because a change in luminosity correlates to a change in insolation. Luminosity is the total energy (light) radiated by a blackbody, and insolation is the amount of light received over an area. So, changing light output changes light received over an area.

One of these mechanisms, change in luminosity over the age of the Sun, is of no concern on a time scale of less than thousands of years. The Sun has increased luminosity 30% over 4.6 billion years – this equates to a 0.000065% change in luminosity every million years. Notable, yes. Concerning for this project or impactful on the variation of insolation received, no. The second mechanism, sunspots and faculae, must be discussed as well. The Earth experiences changes in irradiance regularly due to both, but that is not something that this proposal is aiming to correct. Putting a solar shade between the Earth and Sun will decrease the amount of insolation the Earth receives as determined by what change in temperature of the Earth's climate is desired[15]. It will do this regardless of whether the Sun is in a sunspot minimum or maximum, regardless of how many faculae are present. Total solar irradiance is not a specific number – it has fluctuations on day and month-long time scales. A solar shade is not correcting for these, so there need not be concern over adapting a shade daily based on whether the irradiance is slightly higher or lower than average. The Sun is at a steady *average* total irradiance, and this average value is what will be used in all the following calculations.

4.1.1 Calculation – Percentage Drop in Sunlight

The first computation is how much of Earth's warming is to be countered. It is desirable to re-establish a temperature that the biosphere is accustomed to, and that would preserve ice sheets and permafrost areas. The goal of this proposal is to counter anthropogenic warming, as this warming is contrary to what climate should be if in adherence with the Milankovitch cycles, and is instead due to unnaturally high flux into the atmospheric carbon reservoir. "The total anthropogenic radiative forcing over 1750 – 2011 is calculated to be a warming effect of 2.3 [1.1 to 3.3] W/m^2," (*Climate Change 2014*, 2014, p. 44). Given the purview and the sophistication of IPCC climate models, this proposal will utilize their conclusions. Therefore, the calculation will determine how much total irradiance must be decreased, in order to counter a warming of 2.3 W/m^2.

4.1.2 Area Coverage at L1

As shown in the calculations, there needs to be coverage of area totaling 2.0996x10^{11} m^2 at the L1 point to counter anthropogenic warming of 2.3 W/m^2. Notice, this is the total area that needs to be covered. However, it does not mean that there must be one shade of this size. Instead, this proposal advocates of fleet of satellites, positioned

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[15] Irradiance is the instantaneous measure of solar power over an area. Insolation is solar energy over an area for a certain period of time.

over a given area, to block sunlight. Nevertheless, this would still require a very large number of units. If each sunshade were 1200 m^2 [16], 175 million spacecraft would be required. The feasibility of this will be addressed in a later section.

There should be further investigation into the exact dispersion pattern of these shades. Insolation is also affected by latitude. To better understand, imagine the Earth orbiting the Sun. Due to the inclination of the poles, the Northern Hemisphere is pointed away from the Sun in winter, and towards in summer. This means that the higher latitudes have more 'glancing' sunlight than direct sunlight.

A good companion study for this proposal would be how insolation is dispersed across the globe, and how to keep that same ratio of insolation during deployment of a solar shade. The comprehensive mathematics to model these shadowing relationships are beyond the extent of this proposal, but such a relationship would be valuable to understand and model in further research.

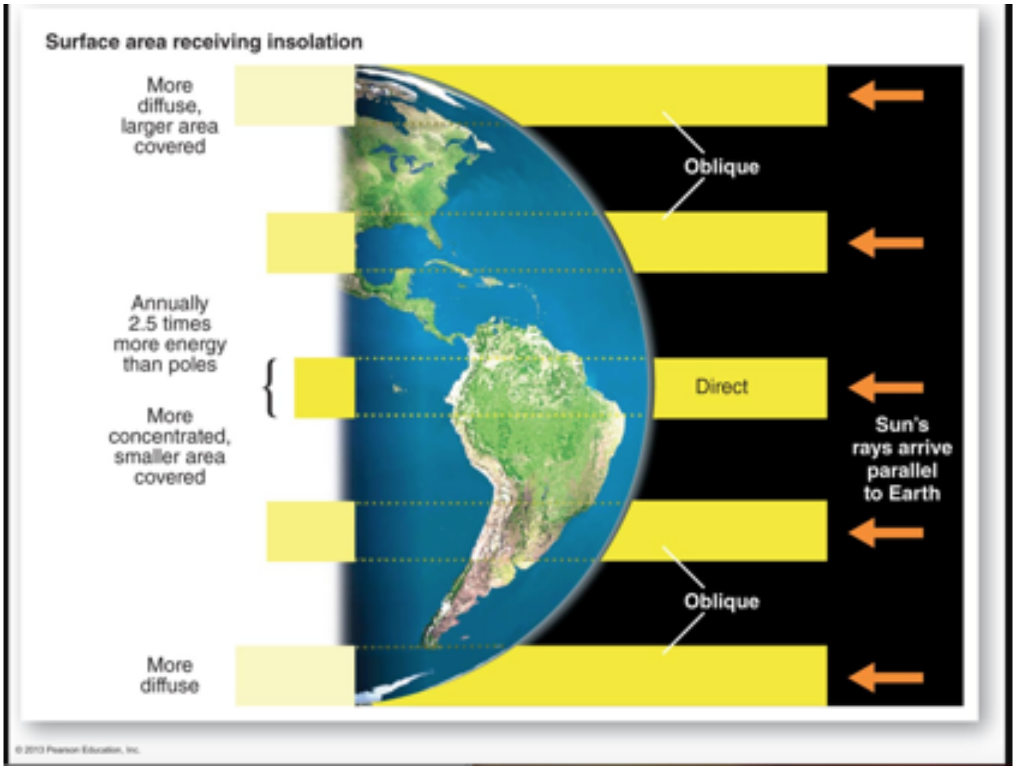

Figure 4: Illustration of Insolation differing with Latitude (http://www.geogrify.net/GEO1/Lectures/EnergyAtmosphere/SolarEnergy.html)

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[16] This number is not arbitrary, it is the size of the solar-sail Sunjammer, originally commissioned by NASA (the contract was not renewed after expiration in 2013) (Leone, 2013, np.).

4. 2 Construction of Solar Shade – Elements

This proposal will now outline the suggested assembly and dispersion mechanism of the solar shade. However, this proposal is not an in-depth engineering model, and as such will be moderately vague when it comes to assembly specifics. Nevertheless, it will be illustrated sufficiently that this model is executable – all of the required technology currently exists in the world, and if not commonplace as of yet, is still currently functional.

4.2.1 A Fleet of Drones

The first image that comes to mind for many when the word ‘solar-shade’ is thrown around is that of a giant umbrella or some such in space. This is a shade, true, but it is by no way the best way to do things. Instead, a solar shade should be constructed of multiple individual bodies that each have a deployable shade (this will be discussed in detail in a following section). Having multiple bodies is of benefit for a few reasons. The first is that multiple repeating systems to construct a whole means redundancy. “An element is redundant if it contains backups to do its work if it fails; a system is redundant if it contains redundant elements,” (Downer, 2009, p. 4). A single shade the size needed for Earth shading is huge, and technologically not feasible at this point. A whole solar shade, constructed of multiple mini-shades, accomplishes the same effect of shading while being more reliable. Multiple small shades, though, are entirely possible, and have the added benefit of being redundant. If one shade breaks, it is only a small percentage error and can be easily fixed or replaced, versus the catastrophe of an error in a large and complicated single structure. “Redundancy has served as a central tenet of high reliability engineering for over 50 years,” (Downer, 2009, p.4). As a system, multiple shades acting together to shade a required area is not only feasible, it is reliable.

The second benefit to having multiple shades is the ability to construct and place them over a longer period of time. Normally, when something like a telescope goes into space, it is all one payload. This means there are no results until 100% of the body has finished construction. With a multi-piece solar shade, this is not so. Different pieces can go up at different times, and effects begin with the first piece in place; it is not required to wait until 100% of the units are built to launch and begin blocking sunlight. This flexibility thus allows, concurrently, immediate action, funds to be solicited over a period of time, and proposals for better shade deployment to be developed and considered – this solar shade is not something to wait around for 50 years to be assembled. The parts are simple enough, the mechanisms are already employed on other spacecraft, the materials are already sold by companies. This is a solution to climate change that is currently actionable.

This multi-pieced, space based system, has a third added benefit. One large and reasonable hesitation to geoengineering is the fact that there may be unintended consequences. The proposed solar shade is of such construction as to assuage those fears. For one, this geoengineering does not actually take place as any form of input into to Earth. No chemicals sprayed in the atmosphere, no land lost to giant whitewashing in an attempt to bolster albedo. Only 0.00168% of incoming light is being blocked - as such, this should not have a detrimental impact on plant photosynthesis, and will not even be noticeable to the naked eye (Singarayer et al., 2009, p. 2). The final fail safe? All sails are variable, meaning that they can be expanded and contracted at will. If there is an unforeseen circumstance in which an Earth system responds by an extreme perturbation, the solar shade can be effectively withdrawn. And, on the other end of the spectrum, if it turns out there is not enough shading, more solar shades could be added to the whole to increase shaded area. Overall, a total solar shade constructed of redundant parts not only assures higher reliability, it enables an increase or decrease in the amount of shading, allowing flexibility as changes in the Earth's systems are observed and geoengineering technique becomes more developed.

The last point to be addressed for construction is how to coordinate so many moving parts. The answer is cutting-edge drone technology. "An arm of the Pentagon charged with fielding critical new technologies has developed a drone that not only carries out its mission without human piloting, but can talk to other drones to collaborate on getting the job done. The Perdix autonomous drone operates in cooperative swarms of 20 or more, working together towards a single goal," (Mizokami, 2017, np.). This quote says 20 or more, whereas the operation reported on in the article involved 103 drones. The fact that the technology is the purview of the Pentagon may make it seem inaccessible. In reality, the US has a highly intertwined military and civilian space program, and it has been since the conception under Eisenhower. "Space was likely to be just such a 'big ticket' enterprise, and Eisenhower accordingly pursued an apparatus for space R & D that was subservient to the White House, isolated from its most powerful claimants, but still adequate to discharge legitimate space missions for science and defense," (McDougall, 1997, p.165). Just because the Pentagon controls a technology at the moment does not mean it would be unusable for a space shade. In fact, it is probably quite the opposite: after all, global warming is a national security crisis.

Drones on Earth have to contend with all of the problems that the atmosphere poses, such as gas drag, thrust, etc. This in turn means programmers and engineers must figure out how to address such issues. "Flight is energetically expensive, particularly when the size of the device is reduced. This is often due to practical issues that arise when scaling a vehicle down," (Floreano & Wood, 2015, np.). Luckily, space is a zero-g environment, so what electronics would usually be taken up by flight/power considerations can be left open for other necessities. For example, communication must also be considered. The shades in space will have a communication setup much like the one utilized in the drone project HANCAD. "A heterogeneous communication architecture is necessary in many real-world task scenarios. In HANCAD, all drones have short-range communication capabilities used for local coordination, while few are equipped with long-range communication technology, and serve as gateways between the operator and the swarm," (Velez et al., 2015, p.1). Essentially, the shades will communicate with each other, while main 'heads' are directed by ground control. An example of such a 'head' is NASA's Tracking and Data Relay Satellite (TDRS), "TDRS serves as a way to pass along the satellite's information. Nine TDRS sit about 35,4000 kilometers above the Earth and are able to forward information from a satellite," (Campbell, 2017, np.). As should be sufficiently clear by now, the logistics for coordination and communication for a venture involving many bodies already exists, and is highly applicable and desirable for a solar shade design.

4.2.2 CubeSat Cores

In order to maximize shading while minimizing mass, it would be ideal to have small control bodies with very large shades that unfold from them. CubeSats, a novel type of compact and inexpensive satellite, are perfect for integration with solar technology. "CubeSats are a class of research spacecraft called nanosatellites. The cube-shaped satellites are spacecraft size in units or U's, typically up to 12U (a unit is defined as a volume of about 10 cm x 10 cm x 10 cm and typically weighing less than 1.33 kg)" (Jackson, 2017, np.). CubeSats are small, lightweight, and would only need to be a 'head' for a solar shade – no other instrumentation is required. They have the capacity for cold gas thrusters or chemical propulsion, and electric propulsion is in development (*CubeSat*, 2017, np.). While the majority of satellites are relatively large, with masses in the low thousands of kilograms, CubeSats are small and lightweight. Since no instrumentation is required for solar shade units besides propulsion, communication, and the shade itself, CubeSats would be the perfect platform for the 'head' of each shade in the conglomeration.

4.2.3 Shade Movements and Material

In addition to drone technology, the advent of deployable space structures is what enables this solar shade construction. This ability is most recently highlighted in the construction of the new James Webb Telescope. "The tennis court-sized sunshield, which is the largest part of the observatory, will be folded up around the Webb telescope's mirrors and instruments during launch. As the telescope travels to its orbit one million miles from Earth, it will receive a command to unfold and separate the sunshield's five layers," (Loff, 2014, np.). For a deployed sun shade, there is no need to be five layers thick[17], only one is needed. The James Webb sun shield will be comparable to a solar shade, in that it has a large area and is deployed after launch.

From the James Webb example, it can also be concluded that materials which are durable and deployable on spacecraft are already invented and have been successfully produced. A recommendation would be to highly consider the same material used in the

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[17] The sunshield is five layers thick to effectively disperse all heat and thus take higher-resolution infrared images.

James Webb solar shield - Kapton. Kapton has been around since the 1960s, and is a polyimide film that can remain stable from negative 269 degrees Celsius to 400 degrees Celsius (*Kapton*, 2017, np.). To increase the reflectivity of the Kapton, and to increase longevity, the material can be coated in aluminum, much like the James Webb. Aluminum has a close to 100% reflectivity, making it ideal for a solar shade. "Aluminum was used because it is widely available primarily as ore bauxite that makes 8% of the earth's solid surface…Aluminum films used as metallization contacts have low specific resistivity, good thermal stability, high uniformity across the flat substrate, low particle contamination, and good adherence to substrate. These properties have led aluminum to be irreplaceable and its demand is on increase in many areas of today's rapidly developing technologies especially optical industries. Highly specular aluminum films made in an ultrahigh vacuum deposition process have a solar reflectance of 92%," (Lugolole & Obwoya, 2015, p. 3). Aluminum would be most desirable for a reflective coating on Kapton, and the current market price for aluminum is $0.94 per pound, making it a cheap material to acquire and utilize (*Aluminum Prices*, 2017, np.).

Table 1: Reflectivity of Pure Uncoated Aluminum at Normal Incidence

Wavelength	% Reflectivity
248 nm	92.6
400 nm	92.0
532 nm	91.6
633 nm	90.7
800 nm	86.8
900 nm	89.0
1 um	94.0
3 um	98.0
10.6 um	98.7
20 um	99.0
100 um	99.4

(Reflectivity of Aluminum, 2014, np.)

The table above indicates the reflectivity of aluminum at specific wavelengths. More research should be done into the feasibility of reaching 100% reflectivity, or into what additional materials may block wavelengths where aluminum is not as highly reflective[18].

In addition to being readily accessible, the materials needed for the construction of the shade are lightweight. On the James Webb, the aluminum coating applied to the solar shield was ~100 nm (3.93 microns) thick (Lynn, 2016, np.). Kapton comes in a range of thicknesses, from 7.6 micrometers to 127 micrometers. This means it varies in weight from 1 kg per 93 m^2 to 1 kg per 4.7 m^2 (*DuPont Kapton*, 2017, p.17). For another comparison of thickness, the sail for the Sunjammer project was 5 micrometers thick (Leone, 2014, np.). The shade for the solar shade will have very minimal mass for its size, making it cheap to launch while effectively shading a large area.

Furthermore, the durability of the shade, and thus its materials, must be considered. Kapton holds its shape very well and is extremely durable – a 25 micrometer-thick film has only 0.17% shrinkage at 150 degrees Celsius, and a folding endurance of 285,000 MIT[19]. There are also additional treatments to increase durability. For the James Webb telescope, a technology called Thermal Spot Bond was used to ensure the solar shield would not become unusable if struck by space debris. This method is recommended for utilization in the solar shades; as it ensures a hole does not enlarge if a shade is pierced, further ensuring the longevity of the shade (Lynn, 2016, np.). The durability of Kapton, the fact it is already manufactured and being used in another spacecraft, and ability to be treated with Thermal Spot Bond makes it a perfect candidate for the material construction of solar shades.

Another exciting technology that may be applied to constructing solar shades is that of origami. While origami has a very long historical tradition, it is newly being integrated with space technology. Origami is valuable because the mathematical precision and intricacies of developed folds allow material to be folded for launch, and then reliably unfolded in space, resulting in very large spacecraft. “Last year, Zirbel and

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[18] As will be presented later, due to atmospheric composition, reflectivity is of primary concern in UV and visible light. This is wavelengths 10-400 nm for UV, and 390-700 for visible.

[19] Folding endurance is calculated by F = log 10d, where d is the number of double folds that are required to make a test piece break under standardized conditions (*Folding Endurance*, 2014, np.).

Trease collaborated with origami expert Robert Lang and BYU professor Larry Howell to develop a solar array that folds up to be 2.7 meters in diameter. Unfold it, and you've got a structure 25 meters across," (Greicius, 2015, np.). Even more exciting is the fact that for some folds, only one 'chord' needs to be pulled for deployment, meaning only one input is required, greatly simplifying the mechanism. "Trease envisions that foldable solar arrays could be used in conjunction with small satellites called CubeSats…It could be especially appropriate for spacecraft applications where it's beneficial to deploy an object radially," (Greicius, 2015, np.). Clearly, the concept of origami in conjunction with solar shades is highly applicable, and would be an advantageous route to explore. It is highly recommended to employ folding techniques in solar shades to maximize shade area per unit, and thus effectively reduce cost per area shaded.

4.3.4 Position in Space – Lagrange 1 Point

One main issue for construction of a large space body is the decision of where to place it. With gravitational forces at play, a shade would be worthless if it became misaligned due to the passing gravitational interactions with another body. Luckily, there are 5 mathematical positions around the Earth, where gravitational balances between the Earth and Sun occur. It is proposed that these points offer the best position for a solar shade.

The solar shade should be placed at a position called the Lagrange 1 point. "A Lagrange point is a location in space where the combined gravitational forces of two large bodies, such as Earth and the sun or Earth and the moon, equal centrifugal force felt by a much smaller third body. The interaction of the forces created a point of equilibrium where a spacecraft may be 'parked' to make observations," (Howell, 2017, np.). The L1 point is the position that lies directly between the sun and the Earth, at about 1.5 million km. The L1 point, as opposed to L4 and L5, is a 'saddle', meaning the point of gravitational balance is rather precarious. It is possible to keep spacecraft there (the Solar and Heliospheric Observatory Satellite is there currently), but it is required that they have some propulsion system to occasionally re-balance them. This means that every solar shade piece will need some form of propulsion.

A benefit of being positioned at the L1 point is that the shadow of the solar shade will not directly darken any region of Earth with an umbral shadow. "The preferred location is near the Earth-sun inner Lagrange point (L1) in an orbit with the same 1-year period as the Earth, in line with the sun at a distance >/= 1.5 million km. From this distance, the penumbra shadow covers and thus cools the entire planet," (Angel, 2006, p.1). As mentioned above, insolation may be affected, but overall the diffusion of penumbral shadow will equally shade the entire Earth.

[See appendix E for this calculation.]

A final consideration for solar shade placement is what impediment it will have upon Earth. The L1 point minimizes any impact, specifically on the field of astronomy. Most astronomers would take issue with any more items being placed in orbit, as they further interrupt already difficult ground-based observations. Putting objects in low Earth orbit is also becoming more difficult and potentially dangerous, as over 50 years of contributing satellites and other space junk has increased the possibility of interspace collisions. Since the solar shade will be placed at L1, it will never be in view of night-side Earth, and will never block field of view for observations as well as not adding to near Earth space debris. Unfortunately, solar observatories will be impacted. The Dunn Solar Telescope in Sacramento will likely not be able to continue its observations. However, its necessity is drawn into question by the placement of SOHO in space in 1995, as its imaging of the Sun is not attenuated by Earth's atmosphere. As recently as November of 2016, NOAA's GOES-16 satellite was launched and now tracks solar weather, among other things, from space. While the loss of ground based solar observations may be lamentable, they will not be of the magnitude to adversely affect the research and development of solar science.

Overall, the placement at L1 is the most desirable position for a solar shade. The distance from the sun means the size of the solar shade is less than if it were located at Earth. The equilibrium of gravities at the position will keep the solar shade continuously between the Earth and sun, while requiring only minimal orbital corrections. L1 shading will be far enough away to not eclipse any specific portion of the Earth (even if the solar shade were one collective body instead of multiple pieces), and will not negatively impact ground-based astronomical observations. L1 is the most economic and feasible position for a solar shade.

4.3.5 Engineering with Current Technology

The main selling point for a solar shade at L11 as a way to confront climate change is that the technology for a solar shade solution *currently* exists. Geoengineering seems far-fetched, because a majority of the time it is – far in the sense that the technology required for the solution is still waiting to be invented. For example, another paper that proposes cooling Earth using crystals at the L1 position, suggest implementing the system through electromagnetic launch, (i.e. a rail-gun as it is commonly referred to in literature). The theory and designs for such a device exist, but have never been constructed or implemented on such a scale due to high cost, unlikelihood of payloads to survive extreme acceleration, and air drag issues due to low launch angles (Angel, 2006, p. 3). In juxtaposition, this proposal employs existent and actionable materials and methods; waiting for future solutions to correct global warming is ill advised when the Earth is already rapidly approaching a climate tipping point.

The technology, in summation, is as follows. Drone configuration and communication is in its infancy, but exists. As proven by the aforementioned Department of Defense deployment, it is even possible to configure over 100 drones to run autonomous missions. NASA has relay satellites that communicate commands to multiple other orbiters, proving only few ‘heads’ are needed to control a whole. Rockets to achieve orbit exist. CubeSats are a condensed and simplistic satellite that will be perfect for integration with folding solar shades, hopefully using origami techniques. A possible shade material is already in production by Kapton, and the methods for improving its durability and reflectivity have been modeled by the James Webb Telescope. All together, none of this technology is something that is missing theory, or needs time for development. All of the pieces to construct cheap, lightweight, and effective solar shades exist today. And today is when the world needs a solution to climate change.

4. The Science of Changing Insolation – Conclusion

It has been thoroughly demonstrated that the possibility of changing Earth's insolation is not in the realm of science fiction: it is implementable technology. The technologies and materials recommended in this section are to provide a baseline investigation. This does not mean that every technology or material mentioned in this section is necessary for final construction – this proposal does not assume to be a detailed blueprint. Rather, this section presents a rough jigsaw of the pieces needed to fabricate a solar shade. The stage for a solar shade at the L1 point is thus set.

5. The Science of Controlling Earth's Temperature

This section of the proposal will delve into the specifics of how to affect the temperature of Earth. To begin, a survey or the atmosphere, which will include its layers and composition. In addition, some atmospheric chemistry will be mentioned. This will be followed by a commentary on modeling the atmosphere. This section will end by examining other geoengineering methods that have been proposed.

5.1 The Atmosphere

To begin a discussion of the atmosphere, it is important to first understand the composition and reactions that occur there. The atmosphere is (by mass) 76% nitrogen, 23% oxygen, 1.3% argon; the main trace gases are carbon dioxide (0.05%), neon (1.2×10^{-3} %), helium (8×10^{-4} %), krypton (2.9×10^{-4} %), hydrogen (0.35×10^{-5} %), xenon (3.6×10^{-5} %), and ozone (0.17×10^{-5} %) (Saha, 2008, p. 10). As can be seen in the diagram below, due to the composition of the atmosphere, some wavelengths of light are transmitted all the way to the ground, while many are not.

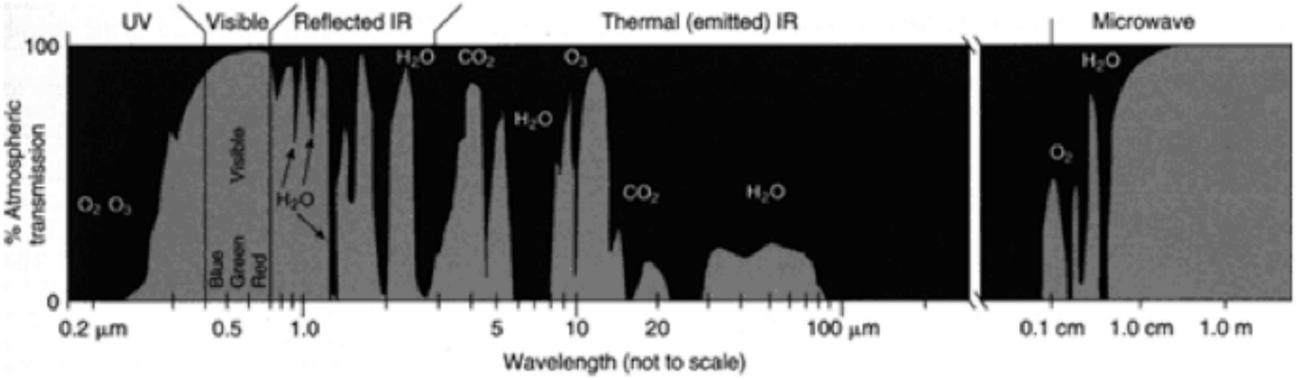

Diagram of atmospheric windows—wavelengths at which electromagnetic radiation will penetrate the Earth's atmosphere. Chemical notation (CO_2, O_3) indicates the gas responsible for blocking sunlight at a particular wavelength.

Figure 5: Atmospheric Windows
(https://earthobservatory.nasa.gov/Features/RemoteSensing/remote_04.php)

One of the reasons most animals see in the visible portion of the spectrum is because these are the wavelengths that penetrate all the way to Earth's surface – if eyes were constructed to 'see' x-rays, the whole world would essentially look dark, as the atmosphere is not transparent to that wavelength. Therefore, for a solar shade, it is of import to block light that will be transmitted all the way to the surface, while it is permissible to allow other energies of light to be attenuated by the upper atmosphere.

5.1.1 Distinctions of Each Layer of the Atmosphere

The atmosphere of Earth is typically divided into five layers. The bottommost layer is the troposphere, typically defined to reach to an altitude of 6 – 20 km. The troposphere, being the lowest layer, is where most particles of the atmosphere reside – the troposphere contains 75-80% of the mass of the whole atmosphere. This is also the layer were most clouds are found, and where almost all weather occurs (*The Troposphere – overview*, 2011, np.). It is transparent to wavelengths in the visible spectrum, and microwave. The troposphere behaves essentially like a turbulent fluid, moving particles constantly as pressure, temperature, and forces all fluctuate with local weather systems. This means that any aerosol, instead of being confined to one local area, is quickly transported, usually large distances. Additionally, gases in the atmosphere also have specific lifetimes. The result of atmospheric lifetimes and mixing due to weather is that, "…few gases react rapidly enough for their effects of be confined to the local scale. Most are primarily global in effect…therefore, the effects of local emissions are felt throughout the troposphere," (Graedel, 1985, p.49). This is pertinent to climate change, as it emphasizes that the effects of emissions from one entity will be felt by the whole world.

The next layer of the atmosphere is the stratosphere, extending to 50 kilometers. The stratosphere is where the majority of photochemistry happens due to a sufficiently high concentration of molecules coupled with energetic photons. The stratosphere is most notable for containing the ozone. Ozone is chemically O_3, and effectively absorbs ultraviolet radiation. Far UV light is effectively absorbed by the stratosphere (and upper atmosphere) that a shade would still be effective, even if transparent to these wavelengths. However, longer-length UV would need to be shaded, as the longer wavelength UV is mostly transmitted through the atmosphere.

The mesosphere is next, extending to 85 kilometers. The composition and chemistry of the mesosphere is more difficult to study than that of other layers because of its height – it is not accessible by weather balloon, and satellites orbit above it, and are not able to directly measure it. As altitude increases, temperature decreases in this layer, indicating that it does not contain UV absorbers. Additionally, because this is the layer where meteorites and space debris burn up, it has a higher concentration of iron and affiliated metals than do the other layers (*The Mesosphere – overview*, 2008, np.).

The thermosphere is the next layer, extending to 600 kilometers. The upper atmosphere is the section that most strongly mitigates short wavelengths, less than 0.2 micrometers (the far UV and x-ray). The thermosphere is responsible for absorbing 0.02 – 0.1-micrometer wavelengths, creating ionization (Torr, 1985, p. 167). While important in UV absorption, the thermosphere (and ionosphere) is transparent to visible wavelengths. As such, if a solar shade were to not reflect extreme UV and x-ray, they would still be effectively abated by the thermosphere. This implies solar shade materials would still be effective even if these wavelengths were not reflected.

Finally, the exosphere is last, and is the upper limit on the atmosphere. It extends to (up to) 10,000 kilometers (Zell, 2015, np.). All of the different layers of the atmosphere are interesting and intriguing in their own right. For a more in-depth relation of the different layers and their functions, see Appendix A.

Chemical differences in layers of the atmosphere and different photochemical reactions that occur in those layers are of high import. Responsible science requires that the differences and sensitivities be understood and investigated before directly implementing systems that may affect these layers and the chemistry within. The exact research into such is beyond the scope of this paper. However, it is arguable that due diligence has been done, because at most, insolation would be decreased by 0.00168% - a fraction of a percent. It would be foolish to argue that a diminishing of sunlight will have no atmospheric or photochemical effect; however, it is equally thoughtless to presume that such a marginal change in sunlight would have sizeable atmospheric repercussions.

5.1.2 Material of Shade Construction and Photochemistry

The material for shade construction must be required to block visible light and low-energy UV light. Atmospheric chemistry is energized by wavelengths in the range of visible to UV; it is important that if photochemical reaction rates decrease, they should ideally decreases proportionally and equally across all reactions. Additionally, cost should be taken into account when choosing materials for construction – if two materials reflective abilities vary by a marginal amount, the cheaper material should be given preference.

As mentioned in the “Construction of Solar Shade” section, aluminum coated Kapton material would be a strong candidate for such a shade. Unfortunately, the exact engineering of materials is outside the purview of this proposal, so it is suggested that there be an in-depth investigation into possible materials. Another material that would be a strong candidate is silver coated polymer. There is a significant increase in papers discussing the uses of silver coated polymers around the 1980s, likely due to a U.S. Department of Energy interest in their development. Unfortunately, no new (and therefore appropriate) sources on the subject are available. However, in one resource it is reported, “The hemispherical reflectance of a freshly deposited silver film weighted over the solar spectrum (250-2500 nm) is greater than 97%,” (Mittal et al., 1989, p. 79). This is a very large range of wavelengths blocked with amazing completeness. However, the paper goes on to report that the durability of silver-coated materials is less than five years. There may be hope that this material has become more durable with technological advances since the 1980s, but clearly more investigation of material sciences for a solar shade is needed.

5.2 Modeling Earth's Atmosphere

One of the largest issues that any geoengineering proposal must contend with is the fact that affecting global systems means modeling hundreds of interactions and interplays between variables. There are so many components to consider in atmospheric modeling that no future model can be 100% accurate in its predicted outcome (as of yet).

Clouds are one of the trickiest components of the atmosphere to model correctly in any global model. This is because the 'reservoir' of cloud cover is not constant, but varies as water vapor, water vapor saturation pressure, condensation nuclei[20], and freezing nuclei[21] vary. Indeed, "without condensation nuclei high degrees of supersaturation would have to occur before droplets could form and not immediately evaporate away," (Kyle, 1991). The multitude of factors that go into cloud production would make it difficult to predict cloud formation patterns. To make matters even worse, all variables change from region to region of the Earth, as temperature, weather systems, and particle movement in the atmosphere change. Hence, clouds remain one of the toughest challenges when creating an atmospheric model.

Attempts to conquer the challenge of modeling clouds and cloud formation are estimable, because clouds have great consequences on the atmosphere. Specifically, different types of clouds affect the absorption and radiation of incident solar radiation. "At any given time, clouds cover some 40% of the earth's surface. Their effect on radiation varies greatly with wavelength." However, "the overall effect of all clouds together is that the Earth's surface is cooler than it would be if the atmosphere had no clouds," (Graham, 1999). This phenomenon is often referred to as cloud forcing.

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[20] Condensation particles are those tiny particles, be it dust or other fragments, which allow water to conglomerate around them and thus serve as the 'seed' for clouds.

[21] Like condensation nuclei, freezing nuclei are seeds for clouds that are made primarily of ice particles. However, they are more specialized in the fact that there is a shortage of freezing nuclei as compared to condensation nuclei. "Water clouds can continue to exist at -5 or even -10 degrees Celsius because of a lack of nuclei. Freezing nuclei have a range of activation temperatures that depends on the materials themselves…In order to characterize how freezing will proceed in a cloud, the distribution of the number of freezing nuclei as a function of temperature is needed," (Kyle, 1991).

Now it must be observed that different types of clouds actually have different effects on the overall energy budget of the Earth. High clouds (above ~6 km), mainly cirrus clouds, are composed of ice particles and are highly transparent to shortwave radiation[22] (Graham, 1999, np.). This means that they do not contribute greatly to the albedo of Earth, and reflect minimal shortwave radiation. Additionally, the water within cirrus clouds is an amazingly efficient greenhouse gas, absorbing a large portion of outward-bound longwave (IR) energy. After absorption, this outgoing energy is reradiated in all directions, not just up and out, but back to Earth too. This means that, "the overall effect of the high thin cirrus clouds then is to enhance atmospheric greenhouse warming," (Graham, 1999, np.).

Another point must be considered is in reference to high-altitude cirrus clouds. Recall from the section "Melting of Permafrost" the fact that a significant percentage of permafrost outgassing due to thawing is in the form of methane. It just so happens that methane presence in the stratosphere produces a large amount of water[23]. "In fact, CH_4 is a major source of stratospheric H_2O above ~20 km. Globally, about 6×10^7 metric tons of H_2O are formed in the stratosphere each year from CH_4," (Turco, 1985, p. 100). An increase in stratospheric water is equivalent to an increase in greenhouse gases, and contributes to increased cirrus cloud formation. This should be just another added weight to an argument for solar irradiance mitigation: if the permafrost is allowed to melt, global warming will be amplified not only by an increase in methane, but also by the reactions methane enables. Essentially, methane is an extremely effective greenhouse gas, while also being a catalyst for formation of stratospheric greenhouse gases (water).

Additionally, one problem with predicting the formation of high, icy clouds is that the process of their formation is not fully understood. This is because there has not been sufficient investigation into what condensation nuclei will serve as freezing condensation nuclei. "…Experience has shown that all kinds of nuclei are not equally effective, for injection of particles of quartz, salt, and many other substances were found to have no

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[22] In discussions of the energy balance of Earth, shortwave radiation is the name give to incident solar radiation, as it peaks in the visible, or 'shortwave'. Re-radiated energy is radiated in the infrared, and thus referred to as 'longwave' radiation.

[23] This water production occurs as methane decomposes within the stratosphere. Other products are CO_2 and H_2 (Turco, 1985, p. 100).

effect on production of ice particles in supercooled spaces…Apparently, the nature of the surface and the crystal structure of the sublimation nuclei play a great role in this business," (Saha, 2008, p. 68). The obscuration of the mechanism of high cloud formation adds one more challenge in the seemingly insurmountable process of trying to model cloud effects on the planet.

In the middle range of high (ice) and low (water) clouds, there lies another enigma of clouds. This puzzle is that water-composed clouds have been found to form at altitudes so high that the water in these clouds is supercooled, but has not transformed into ice. "The surprising fact is that clouds consisting even entirely of water droplets are found on high mountain tops and in airplane ascents even when the temperature is much below the freezing point, and are found to be the same size as the fog droplets. These droplets are 'supercooled' and are, therefore, in unstable equilibrium. They generally transform themselves into ice-particles as soon as they strike against any hard surface or obstacles, like airplane sides," (Saha, 2008, p. 66). Essentially, the correlation between temperature and formation of water or ice clouds is not understood. As ice and water have different impacts on energy radiation, ignorance of the correlation means inaccuracies in models.

Finally, low clouds tend to have the exact opposite effect as high clouds on trapping radiation. Low clouds are most commonly stratocumulus clouds, which are much thicker and therefore not transparent. Much less solar radiation is able to penetrate these clouds to reach the ground in areas covered by these clouds. The tops of these clouds create an albedo forcing, reflecting visible light before it can be absorbed. Additionally, these clouds are generally so low that radiated longwave only marginally contributes to warming. Overall, these clouds have a net cooling effect, (Graham, 1999).

It can be concluded from the above evidence that modeling clouds in the Earth's atmosphere is, at best, a hazy issue. It is a valid concern that reducing incoming insolation to the Earth would have a moderate to extreme effect on cloud formation. These fears may be addressed by the following: decreasing insolation will not have effect on condensation nuclei or freezing nuclei for clouds. Decreasing sunlight is not an immediate impact on the amount of particulates in the atmosphere, so it may be assumed that the cloud cycle will continue without any drastic changes. There is always a possibility that a change in insolation will alter atmospheric patterns, but a watchdog program will be implemented to minimize the impact. In-depth models for cloud cover do not yet exist, but global averages do, and these will be the mean and standard deviation to which cloud data will be compared after the placement of a solar shade. Thus, it would be possible to react to cloud coverage perturbations that may occur before they cause drastic changes.

Atmospheric modeling is still a rapidly growing area of understanding. It wasn't until the late 1950s that scientists even realized what a complex and multilayered system the atmosphere is (Rowlands, 1995, p. 66). With that being said, it is still within the ability of current models to account for how large-scale systems will respond, especially as new models are developed and tested against each other. Unfortunately, the access and ability to use these models is beyond the author's ability; nevertheless, they would be a valuable asset in the assessment of the outcomes of solar irradiance alteration.

5.2.1 Controlling How Insolation is Modified

The primary reason that this solar shade proposal is of acceptable design, regardless of climate modeling ability, is because of the ability for revocation. A cornerstone of this solar shade design is that shades can be deployed *as well as refolded*. This means that there will be continuous control, and the ability to continuously alter the amount of insolation being blocked. If an unpredicted detrimental effect begins to emerge, insolation reduction can be halted or reversed. Abdusamatov, Lapovok, and Khankov have a marvelous paper "Monitoring the earth's energy balance from Lagrange point L1" (2014) which details the requirements for a telescope at the L1 point to monitor the Earth, with the possibility of recording variations of bond albedo at the 0.1% level. Such a telescope could be launched along with the solar shade, enabling real-time feedback at a highly detailed level.

There is always some risk involved with cutting-edge science. The makers of the atomic bomb half thought that setting off one explosion would cause a chain reaction of splitting all atoms, effectively ending the world. Luckily, constructing and implementing a solar shade is nowhere near that risk level. It is true that the climate is a complicated monstrosity, and that as of now there are no 100% accurate models for such a system. The strength of this proposal is that it has acceptable risk levels because of self-mitigation that will be built into every system. It is a system that can be monitored and corrected in real time, with a high capacity for risk minimization.

5.3 Other Suggested Solutions

As the world grows more desperate for a solution to climate change, the literature on geoengineering has been growing. Indeed, interest was greatly increased by a paper published in the journal *Climate Change* in 2006 by Nobel Prize-winning Paul Crutzen, an atmospheric chemist. His paper, although not the first to propose the idea, became an acclaimed proposal for stratospheric aerosol injection. This paper prompted a wider scientific interest into geoengineering, "The climate engineering literature has expanded rapidly since 2006, as indicated by growth from six abstracts in WoS in 2006 to 55 in 2013, for a total of 234 abstracts," (Linner & Wibeck, 2015, p. 258). If one assumes that the majority of climate engineering, to be feasible, must be up to date with atmospheric and technological knowledge, the majority of papers written before the 21st century are readily disregarded. This means there is a rather limited field of research into geoengineering, leaving room for innovation. To highlight how this proposal is innovative and practical in its approach, a fair examination of other proposed geoengineering tactics is required. Following are three options that represent the other primary archetypes of research in the field of solar-radiation management (SRM). Carbon dioxide removal is not examined in detail because it does not have the same foundational science as this proposal, but will be mentioned briefly. This section will conclude with a summation of why this solar shade proposal advances the most advantageous geoengineering design.

5.3.1 Method 1 – Stratospheric Aerosol Injection

The most common example toted when geoengineering is mentioned is the one first proposed in 1977 by Russian scientist Budyko, but made famous by Paul Crutzen: stratospheric aerosol injection. The crux of this idea lies in emulating the effect that volcanic eruptions have on Earth's climate system. When volcanoes erupt, they send gigatons of various particles into the air, one of which is sulfur. The sulfur particles then backscatter light to space, essentially reducing solar radiation during their atmospheric residences. Sulfur, out of the multitude of elements deployed by volcanoes, was singled out because it has a relatively isolated atmospheric chemistry. Unlike constituents such as odd-hydrogen or odd-nitrogen, sulfur is not a catalyst for any major atmospheric reactions, and has a limited range of atmospheric molecules. Thus, sulfur particles seem enticing for atmospherically increasing albedo, without inducing significant interactive photochemistry with other particles.

Another facet of volcanoes that made them icons for emulation is that they spew particles to great heights in the atmosphere. The majority of atmospheric particles reside in the troposphere (~80%), but volcanic eruptions place materials into the stratosphere, which extends from 20-50 kilometers. Stratospheric residence time of particles is extended as compared to tropospheric residence times, due to limited weather and mixings, which act to percolate molecules out of the atmospheric system. Thus, those who advocate for solar radiation management through sulfur injections advocate injections into the stratosphere. "Although climate cooling by sulfate aerosols also occurs in the troposphere, the great advantage of placing reflective particles in the stratosphere is their long residence time of about 1-2 years, compared to a week in the troposphere. Thus, much less sulfur, only a few percent, would be required in the stratosphere to achieve similar cooling as the tropospheric sulfate aerosol," (Crutzen, 2006, p. 212). On top of that, stratospheric sulfur injection would be relatively cheap, about $8 billion per year by some estimates (Barrett, 2008, p. 47). This seems pretty good so far. The fact that sulfur injection naturally occurs via volcanoes, their limited atmospheric chemistry, and low cost, all make stratospheric sulfur injections seem a reasonable possibility for a geoengineering technique.

The major issue with sulfur atmospheric injections lies in the unpredictability of one main factor: the atmosphere. Humans can split the atom, can send machines to distant worlds, alter the courses of rivers, but one major thing that still eludes definition is an accurate working model of the atmosphere system as a whole. Even an atmospheric model that is slightly off is still unobtainable – all models currently used for current or future projects have major error bars in their analyses.

But here's what it is possible to know will happen, should sulfur be injected into the stratosphere. First, the sulfur will eventually percolate out of the atmosphere, causing ecological and economical damage. If it does this through water, it forms acid rain. Acid rain destroys the natural pH of ecosystems, greatly increasing ecological damage that is already happening. Corrosive interactions with solids can also pull sulfur out of the atmosphere. "The principal agents of atmospheric corrosion are compounds of chlorine and sulfur, aided by high humidity, solar radiation, and the presence of atmospheric oxidants…losses may amount to 70 billion dollars annually," (Graedel, 1985, p. 73). Second, sulfur is a catalyst for ozone destruction. It can be seen from post-volcanic event data that whenever large amounts of sulfur are injected into the atmosphere, there is ozone loss. "Local ozone destruction in the El Chichon case was about 16% at 20 km altitude at mid-latitudes. For Mount Pinatubo, global column ozone loss was about 2.5%," (Crutzen, 2006, p. 216). The Earth has just barely begun to rebuild ozone since the Arctic ozone hole incident– does it really need more destruction? Finally, sulfur in the stratosphere will also act to form more cirrus clouds, as it is an effective cloud nuclei. As mentioned in the previous section, cirrus clouds act as a positive forcing on atmospheric warming, meaning sulfur injections will create externalities that contribute to warming.

The final overwhelming reason sulfur injections are a poor idea? There is no undo button. If the technology doesn't exist in large capacities to scrub CO_2 from the atmosphere, it surely doesn't for sulfur. This is the risk that is so pivotal to so many arguments against geoengineering, and is highly applicable to this idea. "Once we put aerosols in the air, we cannot remove them," (Robock, 2008, p. 16). Climate change and pollution have already introduced enough extraneous particles into Earth's atmosphere – compounding the issue is not the way to solve it.

5.3.2 Method 2 – Space-Based Reflection

The next idea, which is the most similar to the one presented in this proposal, is advanced by Roger Angel, in a paper called "Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1)" (2006). One can extrapolate from the title that the subject matter is similar. However, Angel proposes using small crystals as the 'spacecraft', populating an area at L1 with them to create a 'cloud' that diffracts and reflects sunlight. The failure in the paper is to utilize present technology and thus have an immediately implementable plan – Angel proposes using an electromagnetic propulsion system (commonly called a 'railgun') to cheaply deliver crystals to the L1 point. Unfortunately, the technology for these types of propulsion systems has yet to reach the efficiency or have the range required for this project. A final drawback in the paper is, again, the absence of an 'undo' button. True, crystals would eventually drift from saddle point at L1 and exit the geosynchronous orbit, but lag time for this exit is still a concern. The novelty of geoengineering requires that, in order to be actionable and receive public approval, there needs to be a failsafe built into the system. Earth climate models have yet to be perfected, or even within the range of acceptable error, and until they are, it is unfeasible and immoral to enact a geoengineering plan that is not immediately stoppable.

5.3.3 Method 3 – Albedo Enhancements

The last solar radiation management technique that is most often suggested to combat global warming is that of changing ground-based albedo. As was previously explored in the "Changing Albedo" section, a major issue with this idea is that ground-based albedo alterations have minimal effect on the overall albedo of the Earth. "Qu and Hall (2005) found that surface reflection accounts for less than 25% of the climatological planetary albedo in the ice- and snow-covered regions of the planet and the remainder is due to clouds. They also found that, although the year-to-year variability of planetary albedo in cryospheric regions is mainly due to changes in surface albedo, atmospheric processes attenuate the effect of the surface albedo changes on the local planetary albedo by as much as 90% (i.e. the change in planetary albedo is 10% of the change in surface albedo)," (Donohoe & Battisti, 2010, p. 4403). The sad reality is that any albedo changed that is enacted on the ground will be marginally successful regardless of the extent, due to strong atmospheric attenuation.

This is not to say that ground-based albedo alterations cannot help combat climate change on the local scale. On the contrary, there is research to suggest that supplementing a generic food crop with its lighter-leafed counterpart would have noticeable seasonal/regional impacts. For example, "albedo variations of up to 0.01 and 0.08 have been observed between several different commercial varieties in barley and maize," (Singarayer et al., 2009, p. 2). The same paper went on to conclude that, "Because bio-geoengineering provides its greatest cooling benefits during summer in many regions closely associated with arable regions, it provides a focused mitigation benefit disproportionate to the modest global average temperature reduction," (Singarayer et al., 2009, p. 6). Increased reflectivity during solar maximums (summer) results in a higher regional cooling than would otherwise occur. It may be commendable to couple this method of solar radiation management with the implementation of a solar shade. More research is needed – the authors of the paper were unable to conclude whether or not climate variations would still occur if the substitution was enacted only regionally, and not globally.

Overall, ground-based albedo modification does not promise to be a globally effective field. The atmosphere attenuates the effects too strongly for any forcing to be consistent or reliable. However, if coupled with a solar shade from space, the method could prove effective and perhaps more successful on a region-by-region basis, while being reasonably low-cost. More research is needed, but the promise of a shade/albedo coupled mitigation technique may prove highly effective in combating global climate change.

5. The Science of Controlling Earth's Temperature – Conclusion

To conclude, a solar shade would be the optimal geoengineering approach for four reasons. The first is that it does not add any particulates to the atmosphere. Stratospheric sulfur injection would mimic a 'natural' process, but little is known or reliably modeled about the full effects that such an action would have. To compound upon that, any geoengineering solution, to globally assuage implementation fears, should have an 'off' switch. A solar shade has this – shades can be expanded and contracted as needed. Sulfuric injection, cloud seeding, and many other solar forcing techniques do not – once something is in the atmosphere, it is there for its natural lifetime. Thirdly, when a solar shade is put in place, it would be able to be 'tweaked' as needed. Less shade?

Possible. More shade? Simply launch more shade elements. With methods that inject particles, there is no way to tweak the amount, only increase it. Finally, a solar shade at the L1 point does not contribute to the space debris already prominent in low Earth orbit. Overall, a solar shade is controllable, 'undoable', and has maximum effect with zero particle input into an already polluted climate system. Space shades are the future of geoengineering.

6. Economic Feasibility

A principal concern of any proposal for a solution to climate change is cost. The following section will examine the economics of building and deploying a solar shade. First there will be a discussion of a government's responsibility for funding certain programs that enhance public well-being. The section will then examine the possibility of a private and public partnership to further decrease costs of a geoengineering project. Next, the section will calculate approximate costs for a solar shade, based on the amount of area shaded. Finally, the section will conclude with a discussion of what other economic benefits are produced by a solar shade project.

6.1 A Government's Responsibility

The power of a government is derived from the governed – a philosophy that dates all the way back to Plato's writing, and is echoed today in multiple foundational documents; the US Declaration of Independence is one of these. It is thus inherent that a government's responsibility is to the betterment of its citizens[24]. In a globe drastically and quickly being altered by climate change, it is the responsibility of governments to limit the risk to their citizens. If it is accepted that a government's responsibility is to protect its

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[24] The power of the government being derived from the consent of the governed is typically applied to democratic regimes. However, the world is not made up of all democratic regimes. Using the Economist Intelligence Unit's Democracy Index 2016, if regimes from fully democratic to hybrid are included, then 69.9% of countries have democratic elements, while 67.3% of the world's population lives in these countries (116 countries total). It can be concluded that for the *majorit*y of the world that government is in some way beholden to its population (*Democracy Index 2016*, 2017, p. 3).

citizens, it then follows that the government's job is to try to mitigate or adapt to climate change, and to contribute funding towards those ends.

Governments from around the world would primarily fund the proposed solar shade. There is strong precedent for governments funding large scientific projects that a private sector would not invest in, due to high barriers to entry and limited immediate returns. The barriers to entry in science are high overhead costs as well as a lack of potential fungible goods; governments initialize large scientific undertakings for the return of intellectual capital. The precedent for this was set largely in the wake of WWII, when it was cemented in the minds of the public and policy makers that technology was the key to the future. This can be seen in the famous report by Vannevar Bush, "Science: The Endless Frontier" (1945). "Science can be effective in the national welfare only as a member of a team, whether the conditions be peace or war. But without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world…It is in keeping also with basic United States policy that the Government should foster the opening of new frontiers and this is the modern way to do it," (Bush, 1945, np.). The advancements seen in technology in, and after, WWII cemented federal contributions for the advancement of science and technology – a trend that continues globally to this day.

The most evident example of federal funding for science is space programs. It is nearly impossible for the private sector to 'break into' the realm of space because of the huge startup costs, all for the possible return of a rover crashing on Mars. Governments were not designed to make money[25], and this is why they are able to fund space, science, and technology research. The production of a solar shade would fall into this category of scientific investment, and hence be eligible for government funding.

Additionally, a solar shade also falls into the category of national safety, as climate change continues to threaten millions. "Without climate-informed development to reduce the impacts of climate change on the poor, climate change could force more than 100 million people into extreme poverty by 2030," (Lyster, 2017, p. 440). It is not a leap to extrapolate that governments would be the primary funders of an effort to combat

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[25] This statement is meant to convey that the government and a business have different end games. A government answers to its citizens, and makes money off taxes – however, it is not answerable to 'investors' and is not designed to generate capital.

climate change, as seen from the pattern of commitment to fighting climate change with federal dollars that already exists. "…the U.S. Government spent more than $32.5 billion on climate studies between 1989 and 2009. This doesn't count about $79 billion more spent for climate change technology research, foreign aid and tax breaks for "green energy","(Larry, 2011, np.). Conclusively, any government interested in technological advancement, public well-being, and national security has strong precedent and motivation for funding a solar shade project.

Another point to be highlighted is that the more actors the cost is shared across, the less the burden on each individually. If the cost of solar shade is shared between the whole world, the burden will seem much lighter. The GDP [gross domestic product] of the world was $75.5 trillion in 2016[26] (*GDP (current US$)*, 2017, np.). A noteworthy example on the potential division of funds (assuming whole world agreement) is the UN's method of contributions. When the UN Committee on Contributions sets the amount for each country, they take into account gross national product, lower per-capita income, as well as the external debts of the country. "The General Assembly has directed that percentage shares range from a minimum of 0.001% to a maximum of 22%, and a maximum of 0.01% for those nations designated as "least developed countries"," (Dubbudu, 2016, np.). If the cost distribution of the solar shade were to follow this method, it would ensure equity as already agreed upon by the 193 members of the UN.

In conclusion, governments would most likely fund the majority of a solar shade project. They have incentive to fund a solar shade because it reduces risks to citizens by climate change. In addition, governments have a precedent to fund science that will benefit humanity, even if the science has no immediate commercial returns. The existing finance agreement within the UN would provide a good basis off of which to construct a financial arrangement to support the production of a solar shade.

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[26] World GDP is constantly growing as the world economy grows. The world GWP was $1.37 trillion in 1960 (*GDP (current US$)*, 2017, np.).

6.2 Private/Public Partnership

Another facet of this proposal that lowers cost of production is the partnership between private and public sectors (public meaning government). Government is operational, but some would argue not the most efficient, when it comes to funding projects. A popular example of this is military spending – it has been documented that at times, the Pentagon paid $285 for a screwdriver, $7,622 for a coffee maker, and $437 for a tape measure (Smith, 1986, np.). The cause of this waste is, primarily, government contracts that were awarded sans competition.

However, there is promise in a model of government contracts awarded after partial competition. This can be seen, applicably, in the space market. NASA has entered a new era of awarding contracts based upon private sector competition: this accomplished the twofold goal of private corporation investment in space, as well as lowering costs for NASA. Contracts are not awarded determinately; rather, they allocated funds only after strict scheduling and milestone benchmarks are met. COTS [Commercial Orbital Transportation Services][27] is the primary example contract. "NASA required that its commercial partners share in the cost of the COTS system development and demonstration. The rationale was to both lower NASA's costs and to give COTS partners incentive to design, build, and demonstrate their systems in a timely manner…The funded SAAs [Space Act Agreements] thus allowed for commercial partners to broadly retain intellectual property rights, another incentive for them," (Kisliuk, 2015, np.) NASA's employment of COTS has successfully demonstrated that government can efficiently distribute funding and contracts to private corporations, reducing costs. It must be highlighted that the backbone of the success of COTS is the milestones of achievement that funds were awarded upon. Additionally, before a contract is award, companies publically bid on the contract, submitting proposals of their technology, timeline, and cost. NASA then selects the companies that will receive funds.

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[27] This contract was born out of a goal to demonstrate commercial partners' capability in space. Primarily, the awards for this program are now used for satellite launches, as well as resupply missions of the International Space Station (Kisliuk, 2015, np.).

There is danger in government contracts. "…when you contract out to a private contractor and take both competition and government oversight mostly out of the picture, you've created a government-sanctioned monopoly – a private company basically does the work of the state but with an eye toward making profit, not through competition but through a parasitic relationship with the state," (Kain, 2011, np.). This danger is averted in the model that NASA has created – there is both competition (in bids) and oversight (in required milestones). Conclusively, for a solar shade production, private-public partnership would increase competition, reduce cost, and encourage innovation.

6.3 Calculation of Cost

It is at this point in the proposal that an estimate of project cost must occur. The following cost estimates are reliant largely upon the cost of transporting materials to space. The idea of a solar shade is only recently realizable due to the huge cost reduction in launching materials to space, thanks to the private sector interest in space. An Atlas V rocket, the rocket used to launch missions to the moon and the largest rocket to date, had a lift capacity of 140,00 kilograms – accompanied by a price tag of $14,000 a kilogram. The rockets newly in design, developed first by Blue Origin and SpaceX, drastically reduce cost by having reusable first stages. The SpaceX Falcon 9 (with reusable 1st stage), can lift 22,800 kilograms, for a price of $62 million - this puts the price at around $2,700 per kilogram (Selding, 2016, np.). Clearly, reusable first stage rockets have drastically changed the price of launching materials to space. This is the technology that has finally made a solar shade proposal actionable instead of laughable.

The following cost estimates are based on freely available information and approximations. Costs have been calculated for different wattage drops – to counter all of anthropogenic forcing to date, a drop of 2.3 W/m^2 is needed. Additionally, options for drops of 0.5, 1, 1.5, and 2 W/ m^2 are also listed. Another variable that cost is contingent upon is the size of the individual shade units. The smallest calculated unit has a radius of 5 meters[28]; the largest unit has a radius of 25 meters. For the exact calculation of cost, please code used for calculations, appendix B.

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[28] All units are assumed to be circles in area calculations.

Possible Radii of solar shades (once deployed) – 5m, 10, 15m, 20m, 25m

Possible Radii each unit	5m	10m	15m	20m	25m
Area covered by one unit	78.5 m^2	314.2 m^2	706.9 m^2	1256.6 m^2	1963.5 m^2
Mass of one unit	7.2 kg	9.8 kg	14.1 kg	20.2 kg	27.9 kg
Possible wattage drop	0.5 W/ m^2	1.0 W/ m^2	1.5 W/ m^2	2.0 W/ m^2	2.3 W/ m^2
Area needed covered @ L1 point	4.55e10 m^2	9.11e10 m^2	1.37e11 m^2	1.82e11 m^2	2.09e11 m^2

Drop of 0.5 W/ m^2

Radius Shade	5 m	10 m	15 m	20 m	25 m
Units needed to shade 4.55e10 m^2	5.97e8	1.45e8	6.44e7	3.62e7	2.32e7
Mass total	4.17e9 kg	1.42e9 kg	9.09e8 kg	7.13e8 kg	6.49e8 kg
Cost with Falcon 9	$11.3 trillion	$3.86 trillion	$2.47 trillion	$1.99 trillion	$1.76 trillion
Cost with Falcon Heavy	$6.90 trillion	$2.35 trillion	$1.50 trillion	$1.21 trillion	$1.07 trillion

Drop of 1.0 W/ m^2

Radius Shade	5 m	10 m	15 m	20 m	25 m
Units needed to shade 9.11e10 m^2	1.16e9	2.89e8	1.29e8	7.25e7	4.64e7
Mass total	8.35e9 kg	2.84e9 kg	1.82e9 kg	1.46e9 kg	1.30e9 kg
Cost with Falcon 9	$22.7 trillion	$7.72 trillion	$4.95 trillion	$3.98 trillion	$3.53 trillion
Cost with Falcon Heavy	$13.8 trillion	$4.70 trillion	$3.01 trillion	$2.42 trillion	$2.15 trillion

Drop of 1.5 W/m^2

Radius Shade	5 m	10 m	15 m	20 m	25 m
Units needed to shade 1.37e11 m^2	1.74e9	4.35e8	1.93e8	1.09e8	6.96e7
Mass total	1.25e10 kg	4.26e9 kg	2.73e9 kg	2.19e9 kg	1.95e9 kg
Cost with Falcon 9	$34.1 trillion	$11.6 trillion	$7.43 trillion	$5.97 trillion	$5.29 trillion
Cost with Falcon Heavy	$20.7 trillion	$7.04 trillion	$4.52 trillion	$3.63 trillion	$3.22 trillion

Drop of 2.0 W/m^2

Radius Shade	5 m	10 m	15 m	20 m	25 m
Units needed to shade 4.55e10 m^2	2.23e9	5.80e8	2.58e8	1.45e8	9.29e7
Mass total	1.67e10 kg	5.68e9 kg	3.64e9 kg	2.93e9 kg	2.59e9 kg
Cost with Falcon 9	$45.4 trillion	$15.5 trillion	$9.90 trillion	$7.96 trillion	$7.06 trillion
Cost with Falcon Heavy	$27.6 trillion	$9.40 trillion	$6.03 trillion	$4.84 trillion	$4.29 trillion

Drop of 2.3 W/m^2

Radius Shade	5 m	10 m	15 m	20 m	25 m
Units needed to shade 4.55e10 m^2	2.67e9	6.68e8	2.97e8	1.67e8	1.07e8
Mass total	1.92e10 kg	6.54e9 kg	4.19e9 kg	3.37e9 kg	2.99e9 kg
Cost with Falcon 9	$52.2 trillion	$17.8 trillion	$11.4 trillion	$9.16 trillion	$8.12 trillion
Cost with Falcon Heavy	$31.8 trillion	$10.8 trillion	$6.93 trillion	$5.57 trillion	$4.94 trillion

From the above calculations, the cheapest way to implement a solar shade to completely reverse anthropogenic forcing is to launch 25 meter-radius solar shade units on a Falcon Heavy rocket. This still comes with a price tag of $4.49 trillion – no small asking price. It is possible to reduce the price further with larger individual shades, or with additional revolutions in launch pricing.

6. 4 Return on Investment

A solar shade would require a very large investment indeed. This would be accompanied by a cooler world, a more habituated world. A solar shade would be worth its price tag, especially because it would negate future costs associated with global warming. Climate change is estimated to cost billions: "…an annual $12 billion increase in electricity bills due to added air conditioning; $66 billion to $106 billion worth of coastal property damage due to rising seas; and billions in lost wages for farmers and construction workers," (Greenstone, 2017, np.). Some cost estimates attach a $2 trillion price tag to lost productivity by 2030, as heat and weather make work unbearable in some places around the globe, especially Asia (Yi, 2016, np.). However, the motivation of cost evasion is not usually enough to prompt investment.

Along with the costs that will be avoided if global warming is suppressed, a solar shade will also provide a moderate amount of returns on investment. The first of these is the creation of jobs. The oversight and assembly required for, at minimum, 23,200,000 solar shade units[29] would create vast new employment opportunities, and expanded job markets.

Additionally, solar shade production will require the engagement of a vast array of technologies. When people are trained in using technology, it correlates to an increase in human capital. Increases in human capital are increases in economic value. Principally, any workforce trained for or employed in solar shade production translates to an increase in economic value through vocational education that these individuals receive. "With the rise of an information-based economy, raw materials have become less important and organizational skills and flexibility more important," (Nye, 1990, p. 164). In a global setting, these returns would be especially attractive to any country that qualifies as a LDC. LDCs are typically lacking in technology, or the human capital to employ

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[29] This number is the amount of solar shade units to reverse 0.5 W/m^2 of forcing, assuming a solar shade unit radius of 25 meters.

technology. Solar shade production involvement would create greater returns for these workforces, as opposed to more educated MDC workforces (returns here would still be apparent, but of a lesser magnitude). Effectively, solar shade production will increase economic value of its workforce, and thus is of economic value.

There is one final possible source of economic return from a solar shade, however it does require more research in order to develop the technology. A solar shade in space has the potential to double as a solar power array in space, continually collecting clean energy. The energy would be transferred from space and back to Earth in the form of microwaves. This technology was first investigated in the 1970s during the oil crisis, but was discontinued due to cost projections (Dickerson, 2016, np.)[30]. The Satellite Power system required no technical breakthrough to implement at its time of conception, and advances in technology now would act to perfect the microwave-energy receiver (Jenkins, 1993, p. 311). "An advantage for the military, as well as civilians, would be that they could build receivers at remote operating bases and locations where it is logistically difficult and incredibly costly to deliver diesel fuel," (Dickerson, 2016, np.). Unlimited space-based power is the most promising return on investment if it was integrated with a solar shade.

If cost aversion were a large enough motivator, it is likely that the production of a solar shade would be inevitable. The world has the funds, as well as the dire need. As it stands, motivation can be found in additional direct returns for investment that a solar shade would offer. There would be rampant job creation due to solar shade production, as well as an increase in human capital for all involved in the project. Finally, there is promise of unlimited power, if solar shade technology is coupled with solar panel technology. The economics of a solar shade are not cheap, but then again, drastically altering the world's climate through rampant carbon emissions is not either. And at least with a solar shade, humanity gets to be proud of its innovation and tangible invention.

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[30] Cost projections for this project were astronomical, once again, due to the cost of launch to low Earth orbit in the 1970s.

6. Economic Feasibility - Conclusion

Developing a solution to slow and reverse the rate of climate change is no easy task, and it is not a cheap one either. It is the responsibility of governments to take a leading role to combat climate change and protect their citizens from the associated risks, especially fiscally. Thanks to advances in technology, the cost of implementing a solar shades solution to climate change is now feasible. A solar shade would not only act as a cost aversion mechanism, but would also contribute to economies by creating jobs, growing human capital, and reinvesting government money into economies. Coupling solar energy technology to a solar shade is a further exciting possibility, which would generate great returns for investment. A solar shade is a tangible, actionable, realizable solution to climate change, and nowadays has a feasible price tag attached.

7. Proposed Oversight Body

If something as world-altering as geoengineering is the next step to combat climate change, it will need an organization of control that is equally globally encompassing. This proposal recognizes that geoengineering should not be undertaken unilaterally, or even with a small coalition of actors. Affecting global systems morally requires global involvement, and transparency at every level. First, this section will examine why governments are assumed and predicted to be the primary actors in a geoengineering proposals. This section will then outline a recommended, informed model for solar shade governance. Finally, the section will conclude with recommendations of how to motivate states to join a geoengineering agreement.

7.1 The Responsibility of Government to Act

One thing that must be analyzed as relevant to the conversation of geoengineering, and scientific investment in general, is the responsibility of governments to act. Specifically, it is the responsibility of governments to act in protection and promotion of their citizens. Science and scientific progress is a worthy pursuit, proven in both intellectual and economic value, thus promoting citizen success. “New manufacturing industries can be started and many older industries greatly strengthened and expanded if we continue to study nature’s laws and apply new knowledge to practical purposes,” (Bush, 1945, np.). If there is a global technological production of a solar shade, it would be a boon to the world overall.

Additionally, it is imperative for good government to foster and fund scientific research, as it serves to better whole populations; the private sector cannot be relied upon to invest in science if it sees no immediate returns[31]. Protecting citizens from the effects of global warming, and attempting to mitigate its effects, is a governmental duty – if this means investing in geoengineering to potentially resolve climate change, it would be the duty of governments to dedicate funds. Public goods, such as the atmosphere, inspire free riders, which is a market failure - if governments did not act with authority and oversee the issue of climate degradation; it is improbable that the world market would be able to solve the problem. Thus, in the interest of protecting citizens, it is necessary that governments sponsor commitments to combating climate change. This introduces the necessity of governments’ inclusion to any body that would be created to research, fund, and oversee a solar shade production and implementation.

7.2 A Model of Control

This section will outline, moderately broadly, a potentially successful design for a global pursuit of geoengineering. Specifically, details of three different functional bodies will be discussed, along with communication channels and responsibilities between bodies. The goal is to construct a governance organization that is responsive to physical risks, has decision making power, takes responsibility for outcomes, as well as a societal understanding of the science taking place – it has been asserted that any truly effective framework will address these concerns (Dilling & Hauser, 2012). This is by no means a cap on the number of facets that an organization concerning geoengineering is composed of. Rather, this proposed structure is an informed place to start.

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[31] This is especially pertinent to basic research. Basic research is pursuit of scientific knowledge solely for the pursuit of basic knowledge of how the universe functions – research into the atom is an example.

7.2.1 3 Bodies: Science, Government, Communication

For a geoengineering project, the three bodies that must be assembled are scientific, oversight, and communication bodies. The scientific body should be assembled from authorities in all pertinent fields[32]. "The most important single factor in scientific and technical work is the quality of the personnel employed," (Bush, 1945, np.). A team of top-tier scientists should be gathered, with support staff, as the authority on the geoengineering project. However, an important lesson of history – these scientists must not be restricted from holding multiple employments or responsibilities. Vannevar Bush in his famous report *Science: The Endless Frontier* (1945) highlighted the fact that, in pursuit of the best, it is important not to disqualify scientists with gainful employment from contributing to research (notwithstanding the provisions of any other laws). The organization should have dedicated investigators, while allowing input from all experts in the field, whether or not their main focus is the solar shade. It shall be the mission of the scientific body to quickly and efficiently investigate and report upon the geoengineering project, communicating technical results publically and recurrently.

There should be an additional, concurrent scientific institute, but this one centered on the 'soft' sciences. Geoengineering will have effects in many realms; international, economic, sociological, etc. It is important that to be effective and accepted, a geoengineering project must understand the way in which it is affecting society. It is important to model and consider different reactions and future reactions, and to have planned for multiple world responses. "Just as additional expertise beyond the physical sciences contributes to proposals to make for meaningful broader impacts, for example, experience in public participation, engagement or other anticipatory governance mechanism could be drawn upon to make these plans meaningful," (Dilling & Hauser, 2012, p. 11). As a geoengineering project is global, it is desirable to have experts in all the scientific realms of the globe to report on the changes accrued from geoengineering.

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[32] Pertinent fields for geoengineering are, but not limited to: atmospheric science, biology, geology, chemistry, agriculture, physics. These are physical sciences, whose direct effects will be modeled and recorded as data.

The next body that is essential to a geoengineering project is an oversight body. This body shall reflect the plurality of nations – modeled after the General Assembly of the UN; each state shall have a representative, a voice[33]. It is possible that an organizational body would evolve beyond a one state one vote representational system, but that would have to be specified as the body evolves. The most important thing is that no nation be silenced, and that no nation or bloc feels as if they have a lesser voice. It is the suggestion of this paper that the oversight body be set up as a new entity of the United Nations. The UN has a history of establishing state coalitions, and a functional organization that would provide a valuable starting point for an organization in oversight of geoengineering.

The main purview of the oversight body will be creation of a plan for geoengineering and political management. The oversight body shall have a mechanism to vote on proposed changes, informed by the scientific bodies. A core responsibility of governance should be interactive links between the new governing body and ongoing scientific research, punctuated by periodic revaluation of the governance structure to ensure it is adaptive to the new needs geoengineering will accrue (Dilling & Hauser, 2012) (Keith et al., 2010). Additionally, the oversight body will control the monies of a geoengineering project. An important duty of the oversight body is to ensure that funds for project advancement are secured for at least three years. This is to ensure that startup costs do not transition to sunk costs – every dime the world invests in a geoengineering solution are valuable, and must be applied to a concrete contribution in the fight against climate change.

One of the most important responsibilities of the government organization would be promoting and ensuring transparency at every stage in the project. "Building and earning trust goes beyond simply providing information, however, and extends to the area of transparency in planning and potentially including stakeholders in decision making – in essence building social capital among interested parties," (Dilling & Hauser, 2012, p. 7). It is imperative that the established technology remains in civil control – there must be no military involvement or regulation. This technology will remain un-weaponized

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[33] This proposal will not dive into the representation of possible nations that are not recognized as states. That issue is beyond the detail of this proposal, but will still affect this part of organizational formation.

and transparently controlled. Control must be vested in a democratic body with peaceful intents, to encourage the vestment of trust in a solar shade and its solely benign intents. The US ‘Shelby Amendment’ is a strong model for this - the Data Access Act of 1999 requires that federal agencies ensure all data produced from federal money will be available to the public through procedures established in the Freedom of Information Act [FOIA] (Fischer, 2013, p. 2). This should be extended to geoengineering – the knowledge of how the Earth reacts to inputs is everyone’s purview. Trust in government, or control organizations, is essential to ensure their efficacy. It is thus imperative and just that a control body for geoengineering function as transparently as possible.

The final body that shall be established is a communications body - essentially a media organization. The purpose of a communication body is to make communication between the geoengineering organization and the global public possible. The body shall have ‘journalists’ to translate new scientific data into layperson articles that can be easily read to obtain project information. Additionally, these reports should be translated to multiple languages. Finally, the communication body shall be responsible for upkeep of a ‘public forum’. The Internet is what will make this possible – a channel for public communiqué shall be established and proliferated through the Internet. Received input should be screened into different subjects – hard science and public suggestions. All received communiqué shall be reviewed for potential applicable information – it is possible that an amateur scientist discovers something valuable for all. The purpose is to keep an open communication channel for substantive public engagement, which has the goal of improving the quality of decision making (Dilling & Hauser, 2012, p. 8). Communications should be kept as a source of public opinion statistics in relation to geoengineering projects, if nothing else.

These three bodies together – scientific, oversight, and communication, represent the minimal, archetypal bodies that this proposal deems necessary to the success of any geoengineering undertaking. It is additionally necessary that these bodies be highly integrated and communicate regularly with one another - one entity with different functioning departments.

7.2.2 Model of Economic Agreement

A necessary decision of a coalition that is formed is the quantity of financial contributions by each participant. This proposal suggests modeling potential financial contributions off of the system for member state contributions to the UN. “The UN is funded by its member countries and the contribution of each member country is determined based on an assessment done every three years. The assessment takes into account the GNP, per capita income & external debt of countries for fixing the quantum of contribution,” (Dubbudu, 2016, np.). In this way, a financial obligation calculated would have a measure of equity that has already proven acceptable to the states of the world. The aforementioned oversight body should be the one in charge of determining details of contractual monetary obligations of signatories to any geoengineering project.

7.2.3 Partnership between Private Business and Government

As mentioned in the ‘Economic Feasibility’ section of this proposal, the partnership of government and private business will decrease the cost of geoengineering. It has been proven time and time again that a free market system results in a product that is the most efficient allocation of resources. An example of this is the competition NASA held for its contract for human-capacity rockets. Free market competition between the Sierra Nevada Corporation, SpaceX, Boeing, and others originally, ensured the cheapest price for NASA, while a contract was only awarded if specific tests were passed by prototype product (Davenport, 2014 np.). Thus, a government body was able to improve return on investment by enabling free market competition, while the market system profited from governmental investment. This should be the aim of any geoengineering organization - the most efficient allocation of investment, while ensuring that monies are recycled back into, and thus growing, the world economy.

7.3 Motivating States to Join

Following the discussion of pertinent issues and how an organization should be structured, it is now important to turn to the question of how to motivate states to invest and proceed with a geoengineering undertaking. The answer to this question will be examined through the lens of power extension, investment, and public-influenced participation.

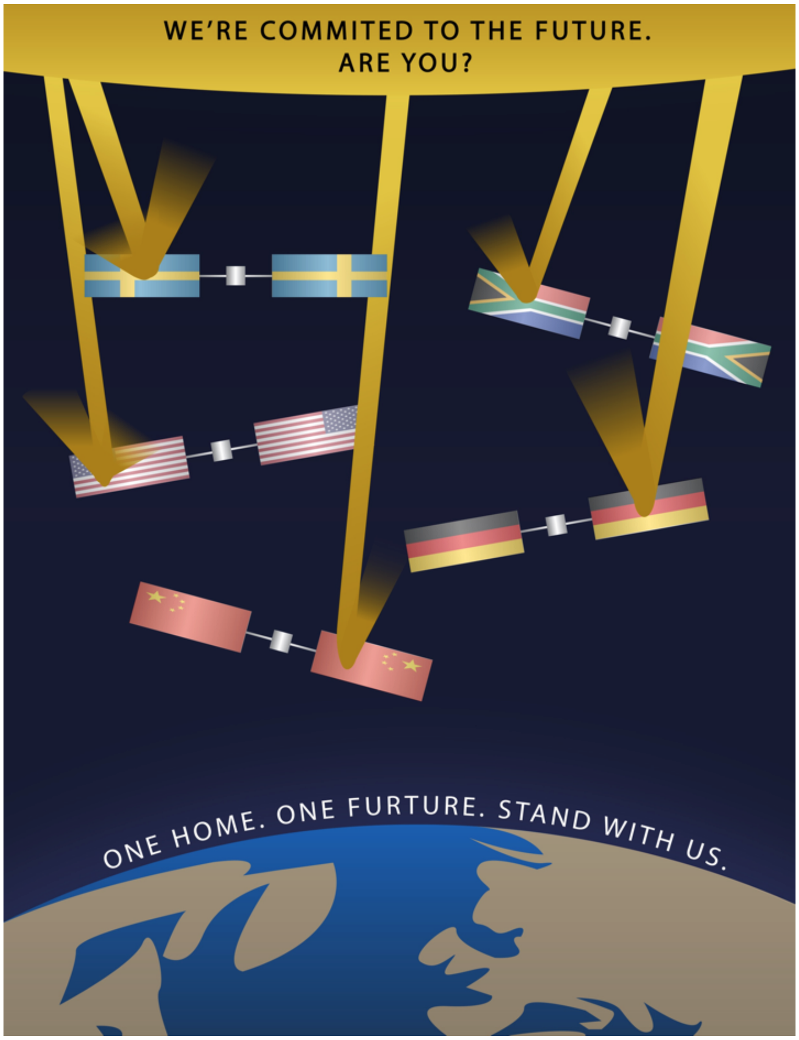
The largest issue in the upkeep of a common good is how to motivate caretaking. This idea is encapsulated by ‘free riders’ in an economic system - when individuals take advantage of a common good without paying their fair share. As Aristotle articulately encapsulated the idea: “What is common to the greatest number gets the least amount of care. Men pay most attention to what is their own: they care less of what is common…When everyone has is own sphere of interest…the amount of interest will increase, because each man will feel that he is applying himself to what is his own,” (Rowlands, 1995, p. 4). Luckily, the historical ratification of the Montreal Protocol as well as the Paris Agreement points to a global concern for climate – the world has already indicated a growing interest in the atmospheric system.

Another powerful way to influence states into joining any climate agreement is to illuminate how joining a geoengineering project could enhance the soft power they project to the world. Soft power is a term coined by Joseph Nye in 1990 to assess the ways that states influence each other and exchange power in the ‘modern’ world. “The dictionary tells us that power means an ability to do things and control others, to get others to do what they otherwise would not. Because the ability to control others is often associated with the possession of certain resources, politicians and diplomats commonly defined power as the possession of population, territory, natural resources, economic size, military forces, and political stability,” (Nye, 1990, p. 153): this type of power is coined ‘hard-power’.

Soft power, on the other hand, is the coercion of states through other realms of influence. “Today, however, the definition of power is losing its emphasis on military force and conquest that marked earlier eras. The factors of technology, education, and economic growth are becoming more significant in international power, while geography, population, and raw materials are becoming somewhat less important,” (Nye, 1990, p. 154). Essentially, the attractiveness of a particular culture contributes to how much power it has. “The ability to affect what other countries want tends to be associated with intangible power resources such as culture, ideology, and institutions…If its culture and ideology are attractive, others will more willingly follow," (Nye, 2009, p. 167). With the transition of power from military to that of influence, this has also given rise to the amount of power that an individual actor has. Coupled with the Internet, individual actor power can proliferate and attract adherents even more readily. All of these facets together mean that through soft power, there are multiple ways in which to attract states and other actors to a geoengineering climate agreement.

Below is a model poster that highlights how soft power can be extended through geoengineering. Essentially, this visual propaganda. States seen as caring about the environment, and investing in its care, are commonly construed as morally just as well as forward-thinking and progressive. This building of correlation in the minds of the public highlights the 'good' a state is participating in as a global actor, and thus increases the states soft power by making their ideals, and participation reflecting those ideals, attractive and positively associated.

(Special thanks and credit to Zack Pyle for the creation of this graphic.)



The first facet of soft power that should be utilized is that of money. It is aspired to attract as many multinational corporations [MNCs] to the project as possible. The benefit of MNCs is that they have ties in multiple countries, and thus economic (and therefore political) influence in most countries. Most of these will be large space industry companies, such as SpaceX. Anything Elon Musk says generates huge amounts of media attention and thus interest – adherents to the plan will follow. However, when working with these corporate actors, it is imperative that the governmental organization for a solar shade is transparent in any funds exchanged, and how the corporations are involved. Publics are wary of private investment in geoengineering, as it opens the door for unilateral or inequitable influence of the technology. This is understandable and must be assuaged as much as possible by the integrated and dedicated transparency at every level of the project.

Another part of accumulating soft power will require idea proliferation through the use of the Internet. As evidenced by the Paris Agreement, the world wants to fix climate change – getting the word out that there may be a solution will generate rapid coverage and many supporters. The strength of individual actors can be shown in the development of a faction that has occurred in the US – while Donald Trump doesn't wish to continue being party to the Paris Agreement, individual states within the US (thanks to the 10th amendment) have declared their individual intent to be party to the agreement.

This prompts the next point about soft power and climate change. The culture and ideology of combatting climate change is attractive and, as Nye says, attractive ideologies lead people to follow. Coupled with this is the fact that the modern world is passionate about advances in technology, the next big venture, the coupling of science and materials to push mankind to do the once unthinkable. The sentiments of Kennedy's Moon speech still echo through the world – "We choose to go to the Moon!...We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone," (*We choose to go*, 1962, np.). Replace 'Moon' with 'fix climate change' and the speech becomes impassioned rhetoric for building a solar shade.

If a proposal for geoengineering is shaped in such a way as to expand a state's or actor's soft power, it will be attractive to those looking to advance their influence of the world. It should be highlighted that those who back a geoengineering proposal first will have the most soft power – "A state may achieve the outcomes it prefers in world politics because other states want to follow it or have agreed to a situation that produces such effects. In this sense, it is just as important to see the agenda and structure the situation in world politics as to get others to change in particular cases," (Nye, 1990, p. 166). Thus, being first to the drawing board means first to the power board. It is highly likely that publics who think geoengineering is the future will push governments, which are inherently reactive, to support a global geoengineering project. To back a geoengineering project is to demonstrate to the world that a government is vehemently concerned about climate change, and dedicated to solving the issue. This extends their soft power, through positive association in the minds of publics. To the supporters goes the notoriety.

The next motivator to join a geoengineering project is that of human capital. Specifically, participation in a massive technologically advanced geoengineering project promises benefits through the positive externality of education. This incentive will be especially strong if LDCs feel they can gain access to education and technology that has been previously inaccessible. As seen with the Montreal Protocol, the draw of technology is a strong motivator for involvement, and should be readily encouraged. The sharing of technological creations across states will motivate LDC participation, as well as having the overall effect of increasing the industrialized level of the world. The building of a solar shade would not technically increase technological development of states, as all of the technology will be deployed to space and originate in design for one purpose. The investment is in human capital; education gains from the training of specified mechanics, to the exposure of scientific knowledge on a global scope, all facilitated by the geoengineering organization. Principally, every participant in a geoengineering project will come away with a measurable increase in knowledge, or human capital, and thus contribute to their states.

The final motivator for state participation in a geoengineering venture may indeed be due to societal pressures. An investigation by Rowlands (1995) concluded that "states were predominantly reactive" (p. 258) – their motivation to be party to climate agreements was not inherent, but influenced by its citizens. “The evidence from the study of the politics of global atmospheric change suggest that states acted as ‘gate-keepers’ between, on the one hand, the desires for an international cooperative arrangement and, on the other hand, the tangible formation of one,” (Rowlands, 1995, p. 259). These lines of evidence lead to the conclusion that a strong societal objective is translated realistically into state action in the realm of climate agreements. Essentially, grass-roots pressure in favor of participation in a geoengineering project is likely to translate into real state involvement.

An additional line of inquiry that may be worth pursuing in further studies is the possibility of motivating LDCs to join a geoengineering project in exchange for debt forgiveness. If the World Bank and International Monetary Fund could be convinced to match geoengineering project contributions and debt forgiveness, it would further incentivize countries to participate. Debt of LDCs to world banks is a hot button issue and is the source of much inequity in the world development system. If debt forgiveness were a condition of geoengineering project participation, it would be an amazingly attractive offer for many countries struggling to develop. However, the exact economics of such a trade-off warrant much further in-depth and lengthy investigation. Still, it is an interesting possible incentive in the pursuit of increasing geoengineering funding and participation globally.

7. Proposed Oversight Body – Conclusion

To reiterate, this proposal advocates for a control organization of a solar shade project that is divided functionally into three parts – scientific, governmental, and communication. It is necessary that these different parts communicate frequently to ensure adaptability as the world’s understanding of geoengineering continues to evolve. It is also imperative that communication occurs with the global public, in accessible forms, and with channels for feedback. Transparency must be a foundation of this control organization. Finally, it is recommended to appeal to the soft power pinning of states to motivate them to join a geoengineering project, as positive image in the minds of the public can be translated into international influence. This proposal is novel in its desire to design a geoengineering structure and an oversight body at the same time. Technologies of predictive analysis, such as those that involve geoengineering, tend to pre-empt political discussion (Jasonoff, 2003, p. 239); this is neither desirable nor easily acted upon. The contributions of this section act to create an informed and encompassing proposal for a solar shade, from the technical to the governmental, as it all lies within the same purview – global alterations and systems interactions.

8. Policy and Geoengineering Proposals

One important aspect of geoengineering and climate change that needs to be addressed and considered is how policy and technology interact. Geoengineering raises brand new policy questions in a field where policy construction is already highly problematic – climate change. This section will first present a recap of the solar shade technical aspects and whether or not they are feasible. The focus will then move to policies that have been enacted in relation to climate change, using history to highlight the difficulties present when working in the field of climate change. This section will then explore the most challenging issues when it comes to creating policy for climate change. Finally, the section will conclude with an examination of what policy issues this proposal for a solar shade assuages, and how it is innovative in those areas.

8.1 Solar Shade Feasibility

Before the policy challenges incurred by a solar shade are addressed, it is important to assess whether or not the proposal is pragmatic, and would ever reach a stage where policy decisions were necessitated. The three areas of feasibility addressed here are technological feasibility, whether the effects of the technology are tolerable, and whether or not the technology’s price tag is acceptable.

The technology for a solar shade is definitely feasible. As this proposal has highlighted, what makes it feasible is that all the technological components required for solar shade production have already been invented and tested. The only remaining thing required is assembly. Thus, a solar shade is entirely technologically feasible with the technological knowledge and goods the world currently possesses.

Second, the effects of a solar shade are also acceptable. It has been shown that a solar shade geoengineering project would have a lesser amount of externalities than other proposed geoengineering models at this time. Unlike other solar radiation management techniques, a solar shade does not contribute any substances directly to the atmospheric system. It will not alter precipitation patterns as greatly as cloud seeding or sulfuric injections, and it will not bolster the amount of cloud condensation nuclei – if it is not possible to correctly model clouds, it is highly undesirable to attempt geoengineering projects that would have direct impact on cloud formation. Finally, this solar shade proposal answers the ethical question of having an ‘undo’ button for geoengineering. There are those who recommend a tiered evaluation system for geoengineering proposals, based upon levels of perturbation (Dilling & Hauser, 2012); this solar shade proposal is the most acceptable in that system, as risks can be essentially undone.

Finally, there is a question of whether or not this method of geoengineering is economically feasible. A weakness of this proposal may be the fact that it has an in-depth cost analysis, which revealed that a solar shade comes with a large economic cost. Geoengineering proposal cost estimates are typically vague and unreliable (Victor et al., 2009, p. 69), enabling them to seem plausible when in reality they are not. This proposal has concluded that to reverse anthropogenic climate forcing, using the largest solar shades possible, the accompanying price would be about $4 trillion. Many will see this number and conclude that the proposal is not economically feasible. However, the reality is that a view of what is economically feasible needs to address scope of economies, as well as considering time. For a unilateral actor, this proposal is not economically feasible; likely it is not feasible for a small coalition of actors either. When the whole world is considered, the economics become much more feasible – the Gross World Product [GWP] in 2016 was $75.64 trillion (*Gross domestic product 2016*, 2017, p. 5). Additionally, if a solar shade is constructed over a stretch of years, the cost will be spread across both actors and time, making the cost more bearable. Finally, the question of economic feasibility inherently includes a question of how to value the world climate as is. The question of valuation of natural goods is beyond the scope of this paper, but there are economic values tied to nature preservation. Additionally, not solving climate change introduces the cost of risk aversion and crisis management – the US alone could be facing a climate change bill of $82 billion (Barrett, 2007, p. 50), and the Northern Hemisphere has an easier projected future than other regions of the globe. Essentially, the question of economic feasibility is multifaceted and warrants its own proper investigation. Nevertheless, there is enough information to conclude that when the world economy is considered, there is enough money to fund a solar shade, which makes it doable. Whether it is probable remains another issue.

In conclusion, it is the assertion of this proposal that a solar shade project is mostly feasible. There is no doubt that it is technologically possible. A solar shade is ethically feasible in comparison to other geoengineering methods – it has less negative externalities, and it can be easily undone or scaled back after implementation. There is a shadow of doubt that the economics of a solar shade would be deemed feasible, but it is undeniably doable.

8.2 A History of Climate Agreements

In preparation for a discussion of climate change policy and the issues that accompany it, this section will now briefly discuss the history of two climate change agreements – the Montreal Protocol and the Paris Agreement. Both are heralded as the landmark successes in climate change policy. The following examination of their history is aimed at highlighting the initial conditions that produced climate change agreements, as well as their strengths and weaknesses.

8.2.1 The Montreal Protocol

It was discovered around the 1980s that there was a decrease in the ozone layer of the stratosphere, making it easy for high-energy ultraviolet light to reach the ground – the energy of these photons are detrimental to the health of most life on Earth. It was shortly shown that the decrease in ozone was due to a chemical reaction with a recent increase in the production of chlorofluorocarbons [CHCs], a common chemical in refrigerant.

The Montreal Protocol was arguably born because of a coalescence of factors that were perfectly timed. The first is that DuPont, the main manufacturer of CHCs, held a patent for CHCs that was about to expire. Additionally, in the time between when alarm was raised about the effect of CHCs on the ozone and the signing of the Montreal Protocol, DuPont was able to manufacture a safer, substitute chemical – hydrofluorocarbons [HFCs][34]. This meant that the main industry driver of CHCs, and their economic condition and contribution, would not be largely affected by a ban. Additionally, a scientific mission in 1984 confirmed that CHCs were maliciously impacting the ozone by discovering an alarming, large ozone hole about the Arctic. On the political front, the EU was the second largest manufacturer of CHCs, but eventually willing to transition, while smaller LDCs were just beginning to incorporate CHCs into industry and did not largely produce them. This meant that with US political weight strongly advocating for transition to the newly produced HFCs, the Montreal Protocol was soon organized.

The Montreal Protocol was ratified in 1987, and is a global treaty to phase out the production and consumption of ozone damaging and depleting substances. "The Montreal Protocol is signed by 197 countries – the first treaty in the history of the United Nations to achieve universal ratification – and is considered by many the most successful environmental global action," (*International Actions – The Montreal Protocol,* 2015, np.). For a bit of perspective, the UN was established in 1945 – this means 42 years went by before the whole world agreed on anything. While this may give some a pessimistic view of the effectiveness of the UN, it should instead inspire hope. Hope because, if nothing else, it proves that the world and its nations have a precedent and a capability to act together in order to preserve the Earth.

How the Montreal Protocol brought all states to the signing table warrants a brief investigation. Probably the most important considerations were the allowances that the North ceded to the South[35]. The first allowance was a five year delay in compliance with Protocol levels of CFC emissions – this was to allow the Southern countries more time to

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[34] Although they sound similar, HFCs do not have a large detrimental impact on the ozone because they do not contain chlorine – a main catalyst for ozone destruction in the stratosphere.

[35] In international affairs, the terms 'North' and 'South' are commonly used to delineate between More Developed Countries [MDCs] and Lesser Developed Countries [LDCs]; this is because the northern hemisphere geographically has a majority of MDCs, while the Southern hemisphere has a majority of LDCs. As always, there are exceptions to the rule (for example, Australia is and MDC).

industrialize, as CFCs were necessary for many industrial processes in the 80s. Additionally, the North included language for facilitation of technology transfer to Southern states (Rowlands, 1995, p. 169). Another factor that enabled a global agreement was a quieting of East-West aggression. Essentially since its formation, the UN had been polarized by the Cold War, as both the US and USSR, with veto powers, searched for ways to antagonize each other. However, in the 80s, there was a temporary cooling of hostilities, creating a window of opportunity for a little bit of global good. From the Montreal Protocol, it appears that recognition of North-South differences (and thus incentives) is required to create climate policy, as well as good political atmosphere timing.

Following, there were a few issues that inhibited the Montreal Protocol and were brought to light after its signing, which are still valuable for informing future climate action. First, it was highlighted that individuals can have a retarding effect on the road to an agreement. "On the climate change issue, one individual probably did more to thwart the effort to achieve an international cooperative agreement than any other did to advance it – namely, John Sununu," (Rowlands, 1995, p. 248). A certain amount of skepticism in the climate field is healthy, "…but do not assume that the leader out front should necessarily be followed," (Rowlands, 1995, p. 248). This highlights the fact that in policy creation, individual actors can sometimes be highly inhibiting.

Another stumbling block for the Protocol was that states used historic information to inform their negotiating position. Essentially, low CFC producers did not want the same punishment that high CFC producers would be subject to. After the Protocol was signed, there was 'buyer's remorse' from Southern states – some began to feel that the North had taken advantage of them. The main reason for this was that the language of the promised technology transfer was vague and non-defined and thus the Northern states had little defined accountability. Finally, the Protocol was seen by some to deepen Southern dependence on the North – it allowed Northern states to exceed CFC production quotas as long as the excess went to Southern states. Any change to the Protocol also required a majority representing at least 50% of consumption – meaning the Northern states had disproportionately large input over their Southern counterparts (Rowlands, 1995, p. 171). This illustrates one of the largest stumbling blocks in policy relations – not every actor has had the same contribution to climate change. Southern states typically want to be recognized as not contributing equally to climate harm (in terms of amount emitted), arguing that they should thus not have to contribute as largely as MDCs to the solution.

Many of the issues that were highlighted in the Montreal Protocol would still be apparent in any contemporary climate agreement. The Montreal Protocol is climate policy on a simplified scale – CHCs were one emission that needed to be curbed, and had a ready and agreeable substitute. It may not be possible to scale the Montreal Protocol into a current climate agreement, but the problems and successes of the Protocol can be extrapolated, and reflect larger trends in climate change policy and the difficulties in enacting it.

8.2.2 The Paris Accords

The most recent example of a climate agreement is the Paris Agreement, which came into force in November 2016. "The multilateral climate change negotiations under the 1992 United Nations Framework on Climate Change (UNFCCC) have been underway now for 24 years, culminating in the 2015 Paris Agreement," (Lyster, 2017, p. 438). 167 of the 197 Parties to the Convention have ratified it thus far. The Agreement is novel in the world of climate agreements, because it is structured off of a 'bottom-up' model, meaning each state produces an individualized action-plan and mitigation/abatement goals, called 'nationally determined contributions' [NDCs].

The main goal of the Paris Agreement is to keep global warming "well" below 2 degrees Celsius of pre-industrial levels. It would be marvelous, but naïve, to think this monumental agreement arose solely due to love of the planet. "Interests play a pivotal role in politics…. A situation in which all key actors, operating as self-interested utility maximizers, calculate the benefits of coordinating their policies to be greater than the costs of necessary for international co-operation," (Rowlands, 1995, p. 151). States are self-interested entities, hankering for preservation, prosperity, and sovereign rights. The Paris Agreement has managed to enable and preserve all three through the employ of a bottoms-up approach to mitigation, and this can be seen as the cornerstone of its success.

The Paris Agreement intrinsically enables states' preservation and prosperity, as its goal is to ensure a continuingly habitable world. "Additionally, the agreement aims to increase the ability of countries to deal with the impacts of climate change, and at making finance flows consistent.... To reach these ambitious goals, appropriate mobilization and provision of financial resources, a new technology framework and enhanced capacity-building is to be put in place, thus supporting action by developing countries and the most vulnerable countries, in line with their own national objects," (Summary of the Paris Agreement, 2016, np.). It can be surmised from this statement that LDCs party to the Paris Agreement are given access to financial aid and technology to developed adaptation and mitigation strategies. As with the Montreal Protocol, it is safe to conclude that the Paris Agreement is attractive to LDCs because it offers, once more, technology transfer.

One of the most pivotal elements of the Paris Agreement is how it preserves sovereignty of signatories. Nationally determined contributions [NDCs] facilitate this by enabling each state to decide how much they wish to combat climate change, based on their own unique circumstances. "There are no legally binding emissions reduction targets under the Paris Agreement…Parties are required to prepare, communicate and implement successive voluntary nationally determined contributions, to be pursued through domestic mitigation measures. Each successive NDC must represent a progression beyond the Party's current NDC and reflect its highest possible ambition," (Lyster, 2017, p. 447). While this creation of an NDC program was an acceptable model for the whole world and allowed for the ratification of the Paris Agreement, it sadly falls short. The European Parliament noted that current pledge contributions still put the world temperature at 3 degrees Celsius over pre-industrial levels. Concrete carbon-mitigation was sacrificed for flexibility.

Another unfortunate failing of the Paris Agreement is ability to fund and ensure implementation of adaptation projects. Many projects have been proposed and approved, but have not yet received promised funding. Additionally, political instability in many regions of the world further disrupts deployment of adaptation activities (Lyster, 2017, p. 449). Finally, something that may begin to be an issue is intra-governmental discord. "Countries may increasingly be starting to undertake similar critiques of each other's pledges, albeit it an informal manner," (Chan, 2016, p. 298). If discord and accusations become commonplace among states, it will breed ill feeling. It is acceptable for civil actors to make critiques, and there is evidence of this motivating higher levels of commitment; nonetheless, states should refrain from critiquing each other, and instead focus on achievement of the common goal.

Nevertheless, the Paris Agreement is a beacon of hope for the Earth's climate system. It exemplifies the world's commitment to a better future, and shows innovation in design. This innovation with an NDC program is admirable, as it has created perceived equity for all states – when a state defines its own contributions, there is no external actor to critique or criticize for unfair restrictions. While this method has produced less mitigation than the declared goal of the Paris Agreement, the bottom-up approach is valuable in its solution to global equity disparity.

8.3 Major Issues in Policy Building

From the previous section, it can be seen that climate agreements to this point have had some shortcomings due to policy issues. The Montreal Protocol illustrates that industry, politics, and science have different motivations and concerns when it comes to policies. Additionally, the Montreal Protocol and the Paris Agreement both illustrate the technology transfer can be a powerful bargaining chip to motivate LDCs to sign policy agreements. Finally, the Paris Agreement facilitated whole-world cooperation by having a bottoms-up approach to policy building, easing the issue of equity between players. Both agreements are hallmarks of their time, and the policy work that had to occur before the enactment of each was enormous.

This section will now examine the major issues that arise when attempting to construct climate change policy. Additionally, these will be further examined through the lens of geoengineering, and the extra complications that it introduces. These are the majority of the major disputes that any geoengineering proposal will have to solve or negotiate answers to if there is any hope of it being enacted on a global stage.

8.3.1 Who makes the decisions?

The first issue in climate change policy, and geoengineering policy, is how to determine who makes the decisions. This essentially equates to the question of ‘who sets the thermostat’. In the Paris Agreement, for example, the answer to this question would be the countries themselves – the bottoms up approach of NDCs allow each sovereign state to make their own decisions. This question involves both power play and representation, and how they will relate to the governance of geoengineering.

To begin, the issue of power. In climate change, there will be both winners and losers. It is predicted that a large portion of Russia, as it warms, will become fertile for crop production; just as a large portion of Africa and Asia will become uninhabitable, dry, and hot. In this case, Russia wins if the climate continues to warm, while other countries lose (Robock, 2008). This illustrates a main problem in policy creation – what temperature is the desired temperature? “One nation’s emergency is can be another’s opportunity and it is unlikely that all countries will have similar assessments of how to balance the ills of unchecked climate change with the risks that geoengineering could do more harm than good,” (Victor et al., 2009, p. 66). Additionally, Russia wields a large amount of power, especially in comparison to smaller LDCs. This can produce disparities in whose voice is heard, and whose wishes are prioritized.

Another issue closely tied to that of power is that of who or whom should be able to research and implement geoengineering projects. “The ‘best shot’ characteristic of geoengineering is simultaneously its most comforting and its most troubling feature – comforting because it means that global warming could be solved without the need for international cooperation; troubling because a single country could conceivably have the capacity to wreak havoc on the entire globe,” (Bodansky, 2013, p. 548). Unlike cutting emissions, geoengineering is not an aggregate good (Bondansky, 2013), and as such even unilateral actors could possibly implement geoengineering schemes. Unilateral action would make any geoengineering design highly questionable and may undermine its legitimacy (Victor et al., 2009).

To further complicate the issue, it is possible for the private sphere to decide to become a unilateral actor in geoengineering – it is not a domain of only public entities. It is argued that a form of governance that applies to both private and public actors is required (Bodansky, 2013). It is true that traditionally private actors are subject to the laws of their state, however, the fact that the areas being affected would be the atmosphere and not private territory complicate this issue of jurisdiction and legal standing (Bodansky, 2013).

Additionally, if a unilateral actor was a state, one must consider the possibility of the use of force and thus inter-state conflict to cease any geoengineering the rest of the world had not agreed to (Bodansky, 2013). "But effective legal norms cannot be imperiously declared. They must be carefully developed by informed consensus in order to avoid encouraging the rogue forms of geoengineering they are intended to prevent," (Victor et al., 2009, p. 75). An international body of organization to create rules and regulations for geoengineering is imperative to the future. It is further recommended that decisions about geoengineering and its governance could be delegated to existing international institutions that are forums for international discussion, such as the UN (Bodansky, 2013). "For SRM [solar radiation management], the main problem will be establishing legitimate collective control over an activity that some might seek to do unilaterally," (Keith et al., 2010, p. 427).

In conclusion, one of the most prominent issues that arise when creating policy for geoengineering is how to decide who is in control. The majority of literature strongly advocates for the formation of an international body to create legislation and oversight of any proposed geoengineering. It is also advocated to avoid unilateral geoengineering, perhaps even going so far as to ban it. A remaining debate is how international a coalition to research and enact geoengineering must be – does the whole world need to be involved? Or just a condensed coalition? Finally, if a worldwide entity is formed, there will be must debate over whether it is truly equitable, or if there are preexisting power disparities built into the system[36].

8.3.2 Is there geoengineering liability?

A common question with the issue of geoengineering is that of liability. The issue of climate change liability policy is complicated even without the added aspect of

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[36] An example of this is the UN, where five states, and only five, have veto power – these five states, coincidently, are those that were 'winners' at the end of WWII: the US, USSR (now Russia), France, England, and China.

geoengineering. In climate agreements to date, LDCs (which are more risk prone) have pushed for mechanisms through which to receive recompense for damages caused by climate change. This has frightened many MDCs, "developed countries felt deeply uncomfortable with the notion of liability and have consistently refused to negotiate any legal responsibility," (*Loss and Damage*, 2016, p. 3). The issue essentially boils down to the fact that MDCs don't want to create the mechanism or legislation for LDCs to persecute them for climate change liability.

Some climate agreements have included a proverbial nod to the issue of liability, without acknowledging it directly. Specifically, the newest language in the Paris Agreement ensures that "…all progress was explicitly focused on facilitative – rather than punitive – approaches," (*Loss and Damage*, 2016, p. 3). This is a tone to be mirrored in any geoengineering project. The history of liability in climate change is a good starting place when determining the liability of geoengineering. It is the unfortunate reality that LDCs are poorer and thus less able to have insurance against the damages of climate change. MDCs are begrudging and don't want to feel persecuted into providing funds to LDCs – instead, the world seems to address the issue by creating institutions for general aid to help recovery and develop risk aversion strategies.

Adding the caveat of climate change liability due to geoengineering further complicates the policy. "…the assignment for blame after a geoengineering disaster would be very different from the current debates over who is responsible for climate change…by contrast, the side effects of geoengineering projects could be readily pinned on the geoengineers themselves," (Victor et al., 2009, p. 71). In a system of geoengineering, it would appear that it would be easier to prosecute people or organizations for liability. However, "Given the difficulty of attributing outcomes in a chaotic system to any one particular action, definitively establishing liability will likely be a challenge," (Dilling & Hauser, 2013, p. 5). Thus, due to the highly variable nature of the climate system, even if a geoengineering project was established, it would be difficult to conclusively show that ill-effects were due to the geoengineering, and would further increase the difficulty of trying to establish liability.

In conclusion, the issue of liability in geoengineering is complicated. It would be hypothetically easy to prosecute a specific project for climate changes. However, the world has a history of avoiding liability clauses in agreements, opting instead for facilitating disaster relief. If a geoengineering project were controlled internationally, there would also be less chance of liability issues arising (particularly if the project were strongly democratically controlled). Overall, liability in geoengineering is a tricky issue, but there is precedent that enables the issue to be addressed in a roundabout manner.

8.3.3 Is enforcement of geoengineering policy possible?

The main purpose of policy, agreements, or collaborations of any kind is that they produce rules to govern the workings of something. In geoengineering, the goal of policy would be to create rules through which to govern the research, implementation, and continuation of any project. However, the question of enforceability remains.

The issue of enforcing intergovernmental policies is a looming one, prevalent even outside the climate policy. The largest example is the UN – UN legislation is theoretically binding. However, as the UN has no direct enforcement or policing agency, there are essentially no direct consequences or measures of enforcement for parties to a treaty. "In the parallel case of the [UN] Security Council, the Security Council lacks the power in most cases to prevent states from suing force unilaterally, so states continue to do so when they have a sufficient national interest. There is no reason to think that an International Geoengineering Authority would be any more successful in curbing unilateral action when countries feel that their vital national interests are at stake," (Bodansky, 2013, p. 549). Just as enforcement is an issue that plagues the majority of international agreements, it is a prevalent issue in the discussion of geoengineering as well.

Further, and slightly more worrying, is that security concerns linked with geoengineering may prompt militaristic response. This applies particularly if a unilateral, or even a small coalition, or actors were to implement geoengineering, If a geoengineering scheme is seen as harmful enough, it is possible that it could be seen as a form of terrorism, and subjected to the same level of militaristic retaliation as current terrorist threats (Bodanksy, 2013).

It can thus be concluded, that if the goal of an organization governing geoengineering was to ensure cooperation, this necessitates the formation of an enforcement body. The chances of this realistically happening are virtually nil, as any such enforcement agency would be seen as a potential threat to the national sovereignty of all states. However, ‘enforcement’ through other means is possible. This is more a form of coercion than that of security enforcement – for example, to encourage compliance with the Montreal Protocol, states would be subjected to trade embargoes and other international backlash if they rescinded on the treaty (Rowlands, 1995). Worldwide, international treaties are no longer strictly concerned with militaristic enforcement, but rather pursue other coercive measures to ensure compliance; it is likely this approach would extend to geoengineering policy as well.

8.3.4 Civil or military control of equipment?

The new issue that often appears in discussion of climate change policy, and especially geoengineering, is how to ensure that the technology does not become weaponized. One of the reasons this issue is highly prevalent is because the majority of technology can be qualified as dual-use technology: what can be used for ordinary purposes can also be weaponized. This is a heightened fear in geoengineering, because geoengineering proposals are able to alter whole climate systems – how can it be ensured that the intention is benign?

Geoengineering can be qualified as an emerging technology; “Such technologies involve forward thinking and planning, and tied to national investments and aspirations, and evoke hopes as well as fears,” (Linner & Wibeck, 2015, p. 9). There is potential to do great good with geoengineering, as well as the potential of weaponization. It is highlighted by Victor et al., (2009), that the management of geoengineering is like the world’s continued storage of the smallpox virus: a potentially dangerous disease should it be released, but also a potential source of a cure if smallpox ever re-emerges in the world. “All of these are potentially dangerous endeavors that governments, with scientific support, have been able to manage for the greater good,” (Victor et al., 2009, p. 76). The fear of weaponization is a rational one, but it is also a limiting one. Sharing technology and working together to overcome paranoia of the dual use of technology is how the Mir space station came to be, how viruses are stored for potential future cures, and how geoengineering should be managed.

It would be imperative that any attempts at geoengineering remain in civilian control, and not a subsidiary of a military entity. This concept, that science and technological advancement thrives off autonomy and civilian control, harkens to Vannevar Bush, who wrote an ideology that the majority of the US scientific system is based upon (Jasonoff, 2003). The main question for geoengineering is not when and how, but rather it is a question of how it should be governed (Barrett, 2007). If there was any hope of geoengineering being seen as a benign attempt to fix climate change, it must originate from a civilian organization, not a military one.

8.3.5 How does the public interact with geoengineering?

A recurrent main issue with attempting to create climate change policy for geoengineering is: how does the public interact with the policy? If a global engineering project impacts everyone, it is only fair that global citizens understand and perhaps have a say in what is going on. Thus, this policy issue can be broken down even more into subsidiary issues: how is information about geoengineering disseminated and accessible to the public, and how can a meaningful dialogue between the public and policy makers be constructed? (Jasonoff, 2003).

One of the first complications with public communication is transparency. Transparency in what is happening, as well as transparency in how easily shared information can be understood. There have already been cases of geoengineering being halted because the public was not thoroughly consulted. The SPICE experiment to test cloud-seeding using just water vapor was halted not on the grounds that dangerous or did not meet regulations. It was halted because it was evaluated that the purpose and future intent of the mission were not communicated to the public, and there was no channel for discussion between the public and the stakeholders (Macnaghten & Owen, 2011). This cessation of a geoengineering project on the grounds of lack of transparency to the public, and not the science itself, highlight how prominent of an issue public inclusion is when creating policy for geoengineering. “The framework [for communication] should have been in place before the project’s conception,” (Macnaghten & Owen, 2011, p. 293). It is clear that a mechanism for communication with the public, and transparency of what is occurring, is a necessity for successful geoengineering policy.

This transparency can be fostered in a number of ways. “Mechanisms to provide information on what is planned and for what purpose can be a first step toward providing transparency such a voluntary, public registries that include information on funding sources, personnel, research plans, project outcome, etc.,” (Dilling & Hauser, 2012, p. 7). A working example of government transparency in science is the US Shelby Amendment. The US ‘Shelby Amendment’, or the Data Access Act of 1999, requires that federal agencies ensure all data produced from federal money will be available to the public through procedures established in the Freedom of Information Act [FOIA] (Fischer, 2013, p. 2). This policy is an example of what could be extended to geoengineering – the knowledge of how the Earth is being altered, and reacting to inputs, is everyone’s purview.

As also mentioned in the preceding quote, transparency is required of funding, and also of what part private corporations play in geoengineering. A fear is the privatization of geoengineering technology. This would mean that systems of engineering were ‘trade secrets’, and as such not necessarily transparent to the world community.

Transparency is necessary for all geoengineering so that research can proceed in a safe and open manner. “Geoengineering raises understandable fears about technological hubris,” and this fear can translate into moratoriums against all geoengineering, as blanket guidelines have an attractiveness of simplicity (Bodanksy, 2013, p. 547). Fear needs to be dissuaded through transparency and a construction of trust between the public and the entity that is controlling geoengineering, lest fear result in suboptimal outcomes. “…a moratorium would likely have the biggest effect on countries that tend to be risk averse and that would have pursued geoengineering research most responsibly, helping to establish sound research norms. A moratorium could thus have the perverse effect of leaving the field of geoengineering research to less responsible countries that ignore the moratorium and engage in riskier activities,” (Bodanksy, 2013, p. 547). Clearly, transparency in every aspect of geoengineering needs to be a foundation of any geoengineering policy.

Additionally, the issue of accessibility accompanies the issue of transparency. Even if information is about a scientific proposal or research is published, it is likely that it would be filled with jargon and specialized knowledge that the public would not be able to grasp (Dilling & Hauser, 2013). If transparency is the goal, accessibility is a necessity; this means papers would potentially need to be rewritten in laymen's terms, and spread through open-access platforms. Also, to be truly global, these papers would need to be translated into other languages.

The final issue is how to create a meaningful discussion between the public and decision-makers. Transparency, as described above, is necessitated in order to hold an informed discussion. Additionally, there needs to be a route for communication between publics and decision-makers – many have suggested using the Internet as such a mechanism. The Internet is not a wholly proliferated communication mechanism, but it is arguably the largest and most easily accessible. The prevailing attitude is that the goal of communication centered on geoengineering should encourage an adaptive governance structure, that responds to the concerns of global constituents.

A policy of transparency and a meaningful means of communication is the ideal for institution with any geoengineering system. Publics may be understandably frightened at such a novel and advanced plan as global systems alterations through means of technology. However, technology has reached a stage where such alterations are now possible, and may provide answers to climate change challenges that are otherwise unsolvable. It is seen as vital that geoengineering policy address the issues of public interaction and public engagement by encouraging them, and designing mechanisms for their facilitation.

8.3.6 The "moral hazard" stumbling block

The final overarching issue with creating policy for geoengineering is that some are against geoengineering from the beginning. They instead argue that society should focus on solving the root of the climate change problem – emissions. "If humans perceive an easy technological fix to global warming that allows for "business as usual" gather the national and international will to change consumption patterns and energy infrastructure will be even more difficult. This is the oldest and most pervasive argument against geoengineering," (Robock, 2008, p. 17). The issue of where should policy regarding climate change focus – emissions, or mitigation, is one that deserves investigation.

Sadly, the history of the world since 1965 points to an inability to address climate change through emissions reduction, with many failed attempts along the way. "Rather than slowing, the growth of emissions has accelerated since the Framework Convention was signed. Emissions have consistently been at the upper end of the formal projections of emissions that are used to predict future climate change," (Keith, 2013, p. 35). Hope springs eternal – the world is noticing it has a problem, and is having more and more discussions about how to combat climate change, how to switch to clean energy. In the US, more people are now employed in solar energy than in coal, gas and oil combined (*U.S. Energy and Employment Report*, 2017, p. 7). Unfortunately, this optimism cannot be convolved with the available data – emissions are increasing, at an increasing rate. "Stabilizing atmospheric concentrations requires a 60-80% cut in CO_2 emissions worldwide. In the years since the Framework Convention on Climate Change was adopted, global emissions have risen about 20%. Even if the Kyoto Protocol is implemented to the letter, global emissions will keep on riding. So will concentrations," (Barrett, 2007, p. 49).

Still, there are those that will ask why monies put towards geoengineering are not better put towards reducing emissions. The answer involves integration, incentives, and time. The consumption of fossil fuels and natural gas is integrated into essentially every aspect of industrialization on which current economies are built. Physical capital[37] has huge startup costs, offset by projected income over time. This means a company cannot profitably stop using factories currently producing goods and build a new climate-conscious factory. Fossil fuels are the foundation of every industrialized economy around the globe. In terms of incentives, the cheaper option, geoengineering or emissions reduction, will win out. But there is hope – new physical capital that is constructed is more and more likely to be constructed with renewables for energy. "Global renewable power generation capacity rose by 9 per cent last year — a fourfold increase from the start of this century — buoyed by the growth of newer sources such as solar power that shot up by more than 30 per cent. For the second year in a row, renewable energy accounted for more than half the new power generation capacity added worldwide,"

---

[37] Physical capital is an economic term for physical objects that are necessary for production. Examples include factories, the machines within the factories, tractors, etc.

(Clark, 2017, np.). Geoengineering is the solution industry needs while it undergoes the process of replacing fossil fuel based physical capital (at the end of its lifetime) with renewables-based physical capital.

There are those that would contend this. Robock (2008) posits: “If global warming is a political problem more than it is a technical problem, it follows that we don’t need geoengineering to solve it,” (p. 18). He highlights that governments give subsidies to fossil fuel industries, annulling state mandates targeted at reducing emissions. Global warming is a political problem. The reason geoengineering is the solution is because a technical solution is one that the current political climate may be able to palate. Recall, one of the reasons that Montreal Protocol was so successful and easy to pass was that industry was supportive of it – DuPont had a patent about to expire, and could make money off CHCs substitute that it had developed. Current industry, which as explained above is still based on fossil-fuel consumption, is highly repellent of any attempts to manage emissions. Global warming is a political problem, but science is the answer, because an attempt at a political solution would never be supported. This can be seen in the Paris Agreement – amazing legislation and political cooperation, but it still falls short of the world goal for emissions levels. The world needs geoengineering policy over emissions policy, because just because something is a political problem, it does not mean it has a solely political solution.

Finally, the most important reason geoengineering should receive monies over mitigation, is time. Climate protocols were signed in 1992. This means it has been 25 years, and emissions are rising, consistently. Another 25 years of the same thing would be disastrous – 25 years to reach a stable emissions level will also have irreversible effects. “Geoengineering is a stopgap measure, a ‘quick fix’ a ‘Band-Aid’…Catastrophic climate change would likely unfold over a number of centuries, but avoiding it will require a technological revolution, and geoengineering might help to ‘buy time’ to develop and diffuse these new technologies,” (Barrett, 2007, p. 47). If carbon scrubbers could just as efficiently cool Earth’s climate for the same funding, this should be advocated. Sorrowfully, this technology is not at hand. “SRM [solar radiation management] could alter the global climate within months… In contrast, because of the carbon cycle’s inertia, even a massive program of emission cuts or CO_2 removal will take many decades to slow global warming discernibly," (Keith et al., 2010, p. 426). There is no doubt that humanity has the propensity for great technological advancements – the problem is the globe needs a solution today, not after 25 years of continued increasing emissions.

Change is a painful process, one that humanity does not undergo quickly. Unfortunately, drastic change in both people's lifestyles and the bedrocks of industry are what would be required in an emissions-focused climate battle. The amount of time this battle would be waged over is longer than it would take to implement a geoengineering solution to climate change, and thus, monies are better put towards addressing the effects, and not the problem. In an idyllic world, carbon emissions would be reduced easily and with enough funding. Sadly, the world at a CO_2 level over 400 PPM, is not the idyllic one. Hope springs eternal, but recurrent patterns demonstrate the world is incapable of being politically resolute enough to solve climate change, leading to the conclusion that geoengineering is laudable, even if it does not address the root problem of climate change.

8.4 How This Proposal Resolves Issues Inherent to Geoengineering Policy

There have only been a handful of geoengineering research attempts at this point in time, and the majority of those have been halted due to their inability to quell fears. However, it is possible to address the majority of issues that arise in the contemplation of climate change and geoengineering policy, given the right organizational institutions. As the experience with the SPICE experiment highlighted, framework for control of geoengineering needs to be initiated and established before any technical work on a geoengineering project begins (Macnaghten & Owen, 2011). The goal of this proposal is to enable a construction such as this, where technical aspects of geoengineering are considered conjointly with policy and organization.

The proposed oversight body offers a solid foundation for an intergovernmental control organization, which would solve the issue of control of geoengineering. Primarily, instituting an intergovernmental organization greatly lessens the likelihood of unilateral actors. Additionally, the proposed one state, one vote representation as in the UN General Assembly creates a more equal legislative field for geoengineering policy. Unfortunately, due to the sometimes back-channeled nature of politics, there would likely still be at least slight power biases. Nevertheless, this proposed international organization would solve many questions of control. For example, international agreements mean there would now be legal guidelines in order to control private and state actors. Finally, "…international institutions could play an important role in helping to remove the taboo against geoengineering prevalent in the scientific community and to legitimate research activities," (Bodansky, 2013, p. 546). Essentially, an international organization would help to ensure that risk-averse states have a seat at the table, and enables science to develop logically, transparently, and judiciously, avoiding scenarios of under-researched geoengineering being implemented in panic by a solo actor.

On the issue of liability, the proposed organization has no direct solution. However, it is likely that the issue of liability would continue to be treated warily, and without legal mechanisms for liability claims. Arguably, an international institution would be a measure against the possibility of the scientists behind geoengineering being liable: "…the credibility of regulatory science ultimately rests upon factors that have more to do with accountability in terms of democratic politics, than with the quality of science as assessed by scientific peers," (Jasanoff, 2003, p. 233). A geoengineering organization that has interplay between scientists and government control means that the science has already passed a regulatory buffer before being instated, and would make it much less likely that scientists would be attacked for the effects of geoengineering. It is predicted that a policy of liability as established by a control organization for geoengineering would mimic that established under the Paris Agreement. Not a mechanism to claim liability, but a fiscal organization created to fund projects for risk aversion, disaster relief, and other possible negative geoengineering externalities. Liability is one of the most difficult subjects to address in climate policy, but it is likely liability measures would follow current trends of principally being support funds.

Another difficult policy issue is enforcement of agreements. International legal norms are more effective if they are in legal form, precise, and implemented through an accredited and trusted international organization; states must have little incentive to violate the agreement, as well as the ability to comply (Bodanksy, 2013, p. 543). The previously proposed organization would have a high degree of effectiveness in control because it meets all of these five factors that encourage and influence behavior. An organization is codified in legal form, and being a subsidiary or partner to the UN would lend organizational legitimacy to the body. Also, precise control and overview of geoengineering through such an organization creates precise rules and precedent in geoengineering, creating meaningful constraints on geoengineering and limiting the possibly of rash actors. Finally, states would have little incentive to violate the rules of an organization because geoengineering preserves many of the faculties that states have self-interests in maintaining, unlike emissions regulation policy.

Cost, if shared among states in the same manner UN membership contributions are determined, are unlikely to make states more likely to defect from the agreement. As long as states are able to make financial contributions, even if they are not a 'full' agreed upon amount, they have the ability to comply. This is a struggle for the Paris Agreement, as a large number of states that have neither the technology nor the experience in adaptation and mitigation are being asked to respond technologically to climate change (Lyster, 2017). If an organization for control and governance of geoengineering is developed presently, and preceding the geoengineering, there is less of a chance that individual actors will panic and attempt geoengineering on their own. The less chance of a 'defector', the less of an issue enforcement becomes, especially military enforcement. Thus, enforcement of geoengineering policy could be peacefully instituted and sustained if the proposed model of organization is instituted.

The next issue of geoengineering policy is that of control. An international organization ensures civilian control, essentially because there is no world military. Additionally, a transparent democratic process under international control means that no one actor would have access to unique technology. This means any technology that could be weaponized would be a global good whose advances do not unfairly bolster military capabilities of any state. An international organization is a peaceful organization.

Following, it has been established that just policy for geoengineering needs to include a high level of interaction between the global public and the geoengineering project. The proposed organization of control has a communications branch for just this purpose. The communications branch enables meaningful public interaction through translation of scientific documents into laymen’s terms, as well as foreign languages. The Internet as a mechanism of communication is largely accessible by all, and resources should be devoted to reviewing communiqués, and processing potentially useful ones. Additionally, algorithms can be introduced to scan communications and track public opinion. This proposal’s communication branch of organization lays the groundwork for effectively addressing policy concerns of enabling meaningful, global conversation about geoengineering.

There has never before been an extensive geoengineering proposal than encompassed both scientific and societal sides. “…three areas of concern to which a governance framework for research needs to be responsive: actual physical risk, decision-making power/responsibility for outcomes, and the societal meaning of the research. We assert that to be truly effective, a framework should provide elements to address all of these concerns. To date, such a comprehensive framework is lacking for geoengineering research,” (Dilling & Hauser, 2013, p. 10). The success of this proposal’s organization of control is vested in its ability to address all three critical areas, as determined above. The scientific body can determine and test actual physical risk, in the breadth of sciences. Employing scientists from atmospheric to economic fields (hard and soft sciences) enables geological, atmospheric, economic, political, and societal research and risk analyses to be undertaken – beyond physical risks, geoengineering governance should understand all risks. The proposed international control organization meets the criterion of having a decision making power, whose democratic process and interplay with the scientific body means it is responsible for the geoengineering project, protecting individuals from litigations. Finally, the communication organization conveys to the world what is happening, in understandable language, and allows the world to respond. Arguably, this proposal puts forth a governance framework that meets the criterion for being truly effective.

8. Policy and Geoengineering Proposals – Conclusion

The creation of policy is never easy, and the difficulty is only exacerbated by the amount of actors privy to the agreement. Nevertheless, the world has historically come together multiple times in order to create policy with the aim of preserving home. In the aim of preserving home, with the technological capabilities at hand, it is now feasible to research and possibly institute geoengineering in order to combat climate change. Geoengineering creates even more policy issues, but they are not unanswerable ones. The governance organization outlined in this proposal mitigates and solves many policy issues. It is a comprehensive and informed baseline structure, and sets the stage for democratic, transparent, and equitable global participation in geoengineering. Conclusively, geoengineering convolves science and policy; this proposal enables the successful and momentous consideration and construction of this duality.

Conclusion

Earth's atmosphere is a collective good, enjoyed by all: it is responsible for the protection of life from harmful radiation as it made a hop, skip and a jump out of the puddle it was born in and onto land, for the green and blue filaments of the Aurora Borealis shimmering in the Arctic night, for the afternoon thunderstorms that roll across the prairie. The global scope of the atmosphere makes it a collective good – and it makes climate change a collective atrocity.

There are many in the world who still live in denial, doubting climate change and its severity, resting complacently on the argument "the climate has changed before, this is nothing new". The beginning of this thesis is for them.

The climate has changed before, it has been warmer on Earth than current average temperatures, and the climate will continue to change. However, nothing on the magnitude and timescale of climate change today has ever been caused by natural Earth systems. The ignorance that facilitates the ability of some to remain calm in the face of anthropogenically caused climate change must be annihilated.

The Earth is warming, ten times faster than it ever has before. Human activity is circumventing the natural carbon cycle, removing and aerating carbon on massive scales. This carbon cannot be recycled back into the carbon cycle as quickly as human industry necessitates its removal. The result has been an atmosphere so enriched in carbon dioxide that it has increased the atmosphere's ability to act as a greenhouse, increasing average temperatures at astounding rates. This anthropogenic climate forcing has acidified oceans, melted ice caps, and altered precipitation patterns. The future, if this pattern of carbon consumption holds, is one humanity could not have imagined creating for itself. Millions will become displaced and economically underprivileged, coastlines will be swallowed as sea levels rise, vast swathes of continents will become essentially uninhabitable during summers, and millions of species will be lost forever as the 6th mass extinction transpires. There is no concrete model to tell when the tipping point will occur, but humanity is rapidly increasing the chances of finding it. There will be no way to refreeze permafrost, to refreeze polar ice caps, to bring back species pushed to extinction, to restore the cityscapes lost to rising tides.

But there is hope.

Politics, to this point in time, have tried and failed to solve climate change. Emissions regulation is admirable, and should be encouraged, but humanity is not forward-thinking enough to regulate emissions on the scale needed. The fear of free riders, of an actor getting ahead from uninhibited emission, while another handicaps themselves by caring for the climate, is so pervasive and overwhelming in a capitalistic global economy that it castrates impactful attempts at emissions regulation. Industry is a huge capital investment, and factories cannot be switched to renewable energy sources overnight. Fossil fuels are the current cornerstone of industry. But this will not always be the case. Renewable energy is growing at constant rates, providing clean and emissions free energy. The missing piece of this equation, the one needed to equate industry and clean energy, is time.

The solution to climate change is one that creates time. A solution that moderates the rate at which climate is changing, easing the rate at which adaptation is necessitated, creating time for industry to switch to renewable energy, for massive carbon scrubbers to be developed. Politics has tried and failed. Luckily, human ingenuity means new technological solutions become feasible every century, every year.

A technological solution to climate change is what the world needs.

Many have disregarded or laughed at the possibility of geoengineering to this point. It seemed impractical, overambitious, unfeasible, and hope was still largely vested in a political solution. The Paris Agreement, a hallmark of 2016, the best climate agreement the political sphere could create, fails to keep global warming beneath the 2 degrees Celsius goal. In order to save the globe and humanity's way of life, as it is known, it is time to think outside the box.

As this proposal has demonstrated, a solar shade is the best possible geoengineering solution that could be implemented to forestall and even reverse the majority of climate change consequences. A solar shade in space does not add to an already pollutant-rich atmosphere, and is the only geoengineering proposal to date that has the ability to be undone. Climate alterations cannot be modeled exactly, as the world has no comprehensive and completely accurate climate model to date. This necessitates an 'undo' button for any geoengineering proposal that wishes to be seriously considered. This proposal meets that criterion.

Additionally, this solar shade proposal includes an in-depth economic analysis, from predicted cost, to returns for investment. A solar shade will not be cheap, but it will be easy. All of the technology required for production is currently viable. And a solar shade will have return for investment – there will be human capital created, monies will be recycled into the global economy, and there is a possibility for integration with space solar power.

This proposal is also innovative in the inclusion of plans for both technological, and political, implementation of geoengineering. To date, there has not been a model of geoengineering that included an effective and overarching model of governance. Geoengineering science and geoengineering policy are two sides of a coin that should not be divorced in literature – it is the duty of world-altering science to understand the societal impacts it will have as well. This proposal, in due diligence, and in recognizing the responsibility that comes with advocating geoengineering, lays the grounds for a three-bodied governmental organization to be initiated along with the proposed solar shade.

Many will argue that geoengineering is not natural, and that is speaks to the technological hubris of man. They are not wrong. But there is nothing natural about aeration of carbon stores from lithospheric rock that took millions of years to bury. Technological hubris has inundated mankind, with machines to create artificial light at the flick of a switch, to aquifers to hold back tides from land that would normally be underwater. It is time to take what many perceive as a weakness, a failing, and turn it into a saving grace. Space has always been a realm of inspiration, a realm to strive for the once impossible, to dream of the virtuousness that mankind can accomplish, together. Technological innovation in space is the answer to forestalling the tide of maliciousness that continued climate change will bring. A solar shade, in space, is the solution that Earth needs.

Appendix A – Details of the Atmosphere

The atmosphere of Earth is typically divided into five layers. The bottommost layer is the troposphere, typically defined to reach to an altitude of 6 – 20 km. The next layer is the stratosphere, extending to 50 kilometers. The mesosphere is next, extending to 85 kilometers. The thermosphere is the next layer, extending to 600 kilometers. Finally, the exosphere is last, and is the upper limit on the atmosphere. It extends to (up to) 10,000 kilometers (Zell, 2015, np.). All of the different layers of the atmosphere are interesting and intriguing in their own right. However, the exosphere, thermosphere, and mesosphere have so little matter (there is a great distance between particles) that they will be discussed briefly, and as one entity – the 'upper atmosphere'. This section will now delve deeper into the photochemistry of each of the lower sections of the atmosphere, where the majority of reactions occur, in order to investigate how a solar shade would impact photochemistry.

Troposphere

First, a concise investigation of the troposphere. The troposphere, being the lowest layer, means that it is where most particles of the atmosphere live – the troposphere contains 75-80% of the mass of the whole atmosphere). This is also the layer were most clouds are found, and where almost all weather occurs (*The Troposphere – overview*, 2011, np.). It is transparent to wavelengths in the visible spectrum, and microwave. The troposphere can have a further defined layer, the boundary layer. This is the bottom most kilometer of the atmosphere, where turbulent mixing due to diurnal temperature variations takes place. During nighttime, temperature inversion occurs as the ground radiates in IR, meaning temperature decreases with altitude. The boundary layer is essentially where matter transition and mixing from ground to atmosphere originates (Kyle, 1991, p. 19).

The troposphere is a complicated system because of the quantity of inputs and outputs. An exact discussion of tropospheric constituents and reactions is a subject for entire papers – recommended is "The Photochemistry of the Troposphere" by T.E. Graedel. This section will highlight broad implications and a few specific important reactions.

The troposphere behaves essentially like a turbulent fluid, moving particles constantly as pressure, temperature, and forces all fluctuate with weather systems [footnote: Strong trade wind interface at the equator results in very limited mixing between the two hemispheres (North and South) at low latitudes. However, mixing becomes more gradual at higher latitudes (Graedel, 1985, p. 47). This means that any aerosol, instead of being confined to one local area, is quickly transported, usually large distances. Gases in the atmosphere also have specific lifetimes, and the result of lifetimes and weather is, "…few gases react rapidly enough for their effects of be confined to the local scale. Most are primarily global in effect…therefore, the effects of local emissions are felt throughout the troposphere," (Graedel, 1985, p.49). This is pertinent to climate change, as it emphasizes that emissions be one entity, are felt by the whole world.
One phenomenon that should be related is smog production; "Smog refers to the mixture of oxidized compounds resulting from the emission of hydrocarbons and oxides of nitrogen into the sunlit atmosphere," (Graedel, 1985, p. 69). The reactions that occur to create oxidized compounds are devoid of photon input, meaning a solar shade would not effectively combat the creation of smog. Interestingly, the ingredients to produce smog also react to form ozone, thus, "Ozone concentrations are often used as indications of the severity of smog," (Graedel, 1985, p.70). These emittants can cause eye irritation and decreased pulmonary function; while a solar shade is a solution to climate change, mitigation efforts for carbon emissions are still desirable.

After ground-based emissions, the other input to consider is the stratosphere. Separating the stratosphere and the troposphere is the tropopause, an isothermal layer that occurs around 20 kilometers at the equator, but occurs essentially at the surface of artic regions, principally in winter (Kyle, 1991, p. 24). The tropopasue is significant because it efficiently inhibits matter transport. This is one of the reasons most clouds occur in the troposphere; the air is so cooled it inhibits convection, minimizing water vapor that makes it into the stratosphere. Transport of other molecules does happen, but at a very slow rate.

Stratosphere

The stratosphere is where the majority of photochemistry happens due to a sufficiently high concentration of molecules coupled with energetic photons that have managed to pierce the upper atmosphere[38]. "The stratosphere is quite important radiatively because the ultraviolet and short wavelength radiation from the sun is absorbed there," (Kyle, 1991, p. 26). Following is a chart to illustrate what chemicals are in the stratosphere, their flux, and where they come from.

Table 1: Chemical Budgets of the Stratosphere (Turco, 1985, p. 84)

Chemical family or species	Photochemical production in stratosphere	Photochemical destruction in stratosphere	Flux from troposphere	Flux from mesosphere
O_x	35,000	35,000	-300	~0
HO_x	14	14	-0.1	~0
H_2O	55	<1	-55	-.03
NO_x	0.9	0.3	-0.5	-0.1
N_2O	0	20	20	<1
CH_4	0	30	30	~0
Cl_x	0.5	0	-0.5	~0
SO_x	0.1	0.2	0.1	~0

The stratosphere is most notable for containing the ozone. Ozone is chemically O_3, and effectively absorbs ultraviolet radiation. "…the small quantity [of ozone] is sufficient to absorb all the ultraviolet radiation between 0.2 micrometers and 0.3

---

[38] This relationship can be clearly observed in a Chapman profile, where a peak appears at optimum occurrence of photons and molecules. The stratosphere has a Chapman peak where there becomes the correct ration of odd-oxygen and UV photons.

micrometers that enters the layer," (Saha, 2008, p. 102). Ozone also effectively absorbed in the Huggins band (0.32 – 0.36 microns), the Chappuis band (0.45-0.65 micrometers), and in the red and IR, at 4.7, 9.6, and 12 micrometers. This information is noteworthy, as it means incoming radiation in these bands is effectively nulled by ozone in the stratosphere, and does not significantly contribute to terrestrial warming. For solar shade construction, if the shade was not reflective to these wavelengths, if would be permissible. UV light is so effectively absorbed by the stratosphere (and upper atmosphere) that a shade would still be effective, even if transparent to these wavelengths.

Ozone is typically concentrated in the range of 25 – 30 kilometers. It is produced through photodissociation of oxygen molecules by UV photons. It is destroyed by certain wavelengths of light (typically UV) as well (Saha, 2008, p.103), but the cycle of ozone construction and destruction is in equilibrium when considered as a self-contained unit[39]. However, ozone destruction[40] [can be facilitated by other molecules, mainly NO, NO_2, H, OH, and Cl. For example, the growing prevalence of chlorine in the atmosphere is having a negative impact on the amount of ozone present; this was especially rampant when hydrofluorocarbons were still used in industry[41]. It can be concluded that the atmosphere strongly attenuates wavelengths smaller than 0.3 micrometers, so it would be permissible if a solar shade is not reflective to wavelengths shorter than that. It is necessary in that

---

[39] The relationships for the construction of ozone is as follows

1: $O_2 + hv \rightarrow O + O$

2: $O + O_2 + M \rightarrow O_3 + M$

(M is a third body that absorbs the extra energy and momentum released during dissociation; acting as catalyst). Also produced this way:

1: $O_2^* + O_2 \rightarrow (O_2 + O) + O \rightarrow O_3 + O$

2: $O + O_2 + M \rightarrow O_3 + M$

(Saha, 2008, p. 102).

[40] Ozone destruction occurs through multiple processes.

1: $O_3 + hv \rightarrow O_2 + O^*$

2: $O_3 + O \rightarrow O_2^*$

3: $Cl + O_3 \rightarrow ClO + O_2$

(Saha, 2008, p. 102)

[41] ClO is a much more effective ozone dissociator per molecule than either OH or NO, reaction cycles to dissociate O_3 can occur hundreds of times before a Cl molecule is made inert (Turco, 1985, p.104).

case to ensure that emissions of molecules that contribute to the dissociation not increase in quantity, for example closely monitoring the amount of chlorine emitted.

Upper Atmosphere

The upper atmosphere includes the exosphere, thermosphere, and mesosphere. The upper atmosphere is the section that most strongly mitigates short wavelengths, less than 0.2 micrometers (the far UV and x-ray). The thermosphere lies above 80 kilometers, and is responsible for absorbing 0.02 – 0.1-micrometer wavelengths, creating ionization (Torr, 1985, p. 167). The thermosphere sometimes has a separate delineation, called the ionosphere. "The ionosphere is defined loosely as the region where free electrons are present in sufficient quantity to affect the propagation of radio waves," (Torr, 1985, p.187). While important in UV absorption, the thermosphere (and ionosphere) is transparent to visible wavelengths. As such, if a solar shade were to not reflect extreme UV and x-ray, they would still be abated by the thermosphere.

The mesosphere, the intermediary layer between the thermosphere and the stratosphere, reaches from about 50-80 kilometers. The composition and chemistry of the mesosphere is more difficult to study than that of other layers because of its height – it is not accessible by weather balloon, and satellites orbit above it, not able to direct measure it. As altitude increases, temperature decreases in this layer, indicating that it does not contain UV absorbers. Additionally, because this is the layer where meteorites and space debris burn up, it has a higher concentration of iron and affiliated metals than do the other layers (*The Mesosphere – overview*, 2008, np.). The mesosphere is also important for turbulence and air currents, and contains strong East to West winds.

Appendix B – Code for Cost Calculations

All programming was done in Python language, in a conda root iPython notebook.

```
get_ipython().magic(u'pylab inline')
import math
import numpy as np
import random
import matplotlib.pyplot as pl
```

This first section will simply list the different possible radii for individual components of a solar shade. The minimum will be 5m, and the largest will be 25 m. These are radii for hypothetical circular shades since it seems that most research into origami shades is radially-opening.

```
#list of possible radii
radii = (5, 10, 15, 20, 25) #units of meters
#find the area covered by each shade of each possible radii
areas = []
for radius in radii:
  area = math.pi * (radius**2)
  areas.append(area)
print areas
```

This next section will calculate how many individual units would be needed to shade the required area, for each radii. First, a calculation of total area will take place. This is to give estimates for area coverage needed, for different total mitigations. It will be calculated for if desired cooling was 0.5 Wm^-2, to the complete 2.3Wm^-2 to mitigate anthropogenic forcing as calculated by the IPCC 2014 report.

```
wattagedrop = (0.5, 1.0, 1.5, 2.0, 2.3) #units of W m^-2
#from 'Measurement-Flux' use average flux received at Earth
fluxE = 1372.9414668

#now subtract the amount we wish to drop flux
newfluxes = []
for drop in wattagedrop:
  new = fluxE - drop
  newfluxes.append(new)

  #now divide fluxE by the new flux and subtract 1 to get percentage change in flux
percentdrop = []
for flux in newfluxes:
  percent = (fluxE/flux) - 1
  percentdrop.append(percent)

#now to figure out how big of an area needs to be shaded to match corresponding drop in flux
#Earth anglar size at L1 is 1.2497e11 km - this would be the area needed to shade whole earth
#but only need to shade a little percentage of Earth: mutliple Earth size at L1 by percent drop
areaEarth = 1.2497e14 #this is in meters^2 because our percentage drop is for W/m^2
areacovered = []
for percent in percentdrop:
  area = areaEarth*percent
  areacovered.append(area)
```

```
#now need to calculate how many of each unit at each radii to shade different areas
unitsneeded = []
for area in areacovered:
  #print area
  for radii in areas:
    #print radii
    number = area/radii
    unitsneeded.append(number)
#print unitsneeded

#that list is a little convoluted
#here, we'll create individual lists for each wattage drop, within the list will be the
#number of units for the desired wattage drop, based on how big initial radius is

#let A = wattage drop of 0.5, B = drop of 1.0, C = 1.5, D = 2.0, G = 2.3
#for list brackets, first variable is inclusionary, second is exclusionary
unitsforA = unitsneeded[0:5]
unitsforB = unitsneeded[5:10]
unitsforC = unitsneeded[10:15]
unitsforD = unitsneeded[15:20]
unitsforG = unitsneeded[20:]
A = pl.scatter(areacovered, unitsforA, color = 'b')
B = pl.scatter(areacovered, unitsforB, color = 'c')
C = pl.scatter(areacovered, unitsforC, color = 'y')
D = pl.scatter(areacovered, unitsforD, color = 'm')
G = pl.scatter(areacovered, unitsforG, color = 'r')
pl.xlabel("Area Covered at L1 [m^2]")
pl.ylabel("Number of Shade Units Needed")
pl.xlim(0.3e11, 2.3e11)
pl.ylim(0, 2.8e9)
pl.legend((A, B, C, D, G), ('Wattage Drop 0.5 Wm^-2', 'Wattage Drop 1.0 Wm^-2','Wattage Drop 1.5 Wm^-2', 'Wattage Drop 2 Wm^-2', 'Wattage Drop 2.3 Wm^-2'), ncol = 1, fontsize = 8 )
```

The following section will calculate approximate mass for each unit, of each radius.

Each unit will include:
-solar shade (of appropriate radius)
  *using the low mass of 1 kg/93 m^2 for 7.6 micrometer Kapton film
  *using density of aluminum to be 2.7g/cm^3 (reflective coating)
-CubeSat, for which aveage mass is 1.33 kg per U [U=unit] (Jackson, 2017, np.)
- +5 kg error range, to include mass of cables, fasteners, etc. and possibility of larger that 1 U sized cubesats (they're launched in 1U, 2U, 3U, 6U, or 12U)

```
#the first step is to find the mass of the shade

#first, we need to convert density of aluminium to a mass
#using James Webb numbers, aluminium coating of ~100 nm (Lynn, 2016, np.) = this is height
Amasspershade = []
for area in areas:
  #area is in meters^2, 100nm = 1e-7 meters, 2.7g/cm^3 = 2700kg/m^3: will all give mass in kg
  massA = area*(1e-7)*2700
  Amasspershade.append(massA)
#print Amasspershade

#next, find mass of Kapton for each area, assuming 1 kg per 93 m^2
Kmasseach = []
```

```
for area in areas:
   massK = area/93
   Kmasseach.append(massK)
#print Kmasseach
#now add the mass of Kapton plus aluminium to get total shade mass
totalmassshade = [Kmasseach[i] + Amasspershade[i] for i in xrange(len(Kmasseach))]
#print totalmassshade #units of kg

#now to get total mass per each unit, add 1.33 kg for Cubesat and +5 for error
totalmassunit = []
for massS in totalmassshade:
   mass = massS + 1.33 + 5
   totalmassunit.append(mass)
print totalmassunit #units of kg
```

Now that we have the total mass per each unit of different radius, we will figure out the total mass of each shade, for each proposed wattage drop.

```
#lets do this one wattage drop at a time so it's easier to keep straight

#for a drop of 0.5 Wm^-2
totalmassA = [unitsforA[i] * totalmassunit[i] for i in xrange(len(unitsforA))]
print totalmassA #units of kg
print unitsforA
pl.scatter(unitsforA, totalmassA)
pl.xlabel('Number of Units to Shade - Radius from 5 - 20m')
pl.ylabel('Total Mass of Shade [kg]')
pl.xlim(0, 6e8)
pl.ylim(0.5e9, 4.3e9)
pl.title('Total Mass to Decrease Flux 0.5 Wm^-2; Radius Shade Increasing')
#so to read graph, the top right is most units = smallest radius = most mass

#for a drop of 1.0 Wm^-2
totalmassB = [unitsforB[i] * totalmassunit[i] for i in xrange(len(unitsforB))]
#print totalmassB #units of kg

#for a drop of 1.5 Wm^-2
totalmassC = [unitsforC[i] * totalmassunit[i] for i in xrange(len(unitsforC))]
#print totalmassC #units of kg

#for a drop of 2.0 Wm^-2
totalmassD = [unitsforD[i] * totalmassunit[i] for i in xrange(len(unitsforD))]
#print totalmassD #units of kg

#for a drop of 2.3 Wm^-2
totalmassG = [unitsforG[i] * totalmassunit[i] for i in xrange(len(unitsforG))]
#print totalmassG #units of kg
```

The final section will be to calculate the cost of deliverance of each total solarshade. From a price graphic, the SpaceX Falcon9 can deliver 22,800 kg to LEO for a cool $62 million. The Falcon Heavy can deliver 54,400 kg to LEO for $90 million. The first flight of the Falcon Heavy is slated for November 2017, after being pushed back due to 'setbacks in development'. Price will be calculated for both rockets.

The company Blue Origin was also considered, as they also have developed reusable primary stage rockets. However, it appears their main focus is human delivery, and do not have the payload/thrust capability of the SpaceX varients.

```
#first calculate cost using the Falcon9 - $62,000,000 for 22,800 kg
#there are cost for geoengineering to block 0.5 W/m^2
costA = []
print totalmassA
for mass in totalmassA:
   #print mass
   cost = mass/22800.0
   cost2 = cost*62000000
   #print cost2
   costA.append(cost2)
print costA

#now calculate cost using the Falcon Heavy - $90,000,000 for 54,400 kg
costAheavy = []
for mass in totalmassA:
   cost = (mass/54400)*90000000
   costAheavy.append(cost)
print costAheavy

#first calculate cost using the Falcon9 - $62,000,000 for 22,800 kg
#there are cost for geoengineering to block 1.0 W/m^2
costB = []
print totalmassB
for mass in totalmassB:
   #print mass
   cost = mass/22800.0
   cost2 = cost*62000000
   #print cost2
   costB.append(cost2)
print costB

#now calculate cost using the Falcon Heavy - $90,000,000 for 54,400 kg
costBheavy = []
for mass in totalmassB:
   cost = (mass/54400)*90000000
   costBheavy.append(cost)
print costBheavy

#first calculate cost using the Falcon9 - $62,000,000 for 22,800 kg
#there are cost for geoengineering to block 1.5 W/m^2
costC = []
print totalmassC
for mass in totalmassC:
   #print mass
   cost = mass/22800.0
   cost2 = cost*62000000
   #print cost2
   costC.append(cost2)
print costC

#now calculate cost using the Falcon Heavy - $90,000,000 for 54,400 kg
```

```
costCheavy = []
for mass in totalmassC:
  cost = (mass/54400)*90000000
  costCheavy.append(cost)
print costCheavy

#first calculate cost using the Falcon9 - $62,000,000 for 22,800 kg
#there are cost for geoengineering to block 2.0 W/m^2
costD = []
print totalmassD
for mass in totalmassD:
  #print mass
  cost = mass/22800.0
  cost2 = cost*62000000
  #print cost2
  costD.append(cost2)
print costD

#now calculate cost using the Falcon Heavy - $90,000,000 for 54,400 kg
costDheavy = []
for mass in totalmassD:
  cost = (mass/54400)*90000000
  costDheavy.append(cost)
print costDheavy

#first calculate cost using the Falcon9 - $62,000,000 for 22,800 kg
#there are cost for geoengineering to block 2.3 W/m^2
costG = []
print totalmassG
for mass in totalmassG:
  #print mass
  cost = mass/22800.0
  cost2 = cost*62000000
  #print cost2
  costG.append(cost2)
print costG

#now calculate cost using the Falcon Heavy - $90,000,000 for 54,400 kg
costGheavy = []
for mass in totalmassG:
  cost = (mass/54400)*90000000
  costGheavy.append(cost)
print costGheavy
```

Appendix C – Code for Average Flux Measurements

```
import math
import numpy as np
import random
import matplotlib.pyplot as pl

'''
This first section of code is in order to calculate the average solar flux over the whole
orbit of the Earth. The Earth has a very close to circular orbit, which means that the distance
from closest sun approach (perihelion) does not differ that much from furthest sun approach
(aphelion).
The error is calculated by through 1. knowing the average change in emissivity with the sun spot
cycle is 0.1 % 2. calculating the standard deviation on the mean of received flux.
At the bottom is a graphical representation of received flux throughout the year.

#We know the emissivity of the sun
#varies by .1% with sunspot cycle - this is our error
E = 3.86e26 #watts
errorE = 3.86e23 #watts

#now we want to calculate average solar flux at a give distance - earth orbit
#create an array of distance between aphelion and perihelion
#aphelion = 1.52097e11 m
#perihelion = 1.47098e11 m
#we'll get a moderate amount of data points is we set our counter equal to 0.001
#you'll notice our aphelion number is different because arange excludes the last parameter
distance = np.arange(1.47098, 1.52197, 0.001)

#we need to add back on the exponential to our distances
Distances = distance*(1e11)

#now we need to calculate solar flux at each distance
fluxs = []
for length in Distances:
    S = E/ (4*math.pi*(length**2))
    fluxs.append(S)

#now we need to get the error on each distance
#the error in E is 0.1%, so that's the only error that should propogate for our distances
disterrors = []
for length in Distances:
    error = length*0.001
    disterrors.append(error)

#now that we have all our fluxes and errors, we need to figure out the average
#make the list into an array so we can sum it
fluxes = np.array(fluxs)
sumflux = sum(fluxes)
averageflux = sumflux*(1.0/51)
print averageflux #this is W m^-2

#now we need the error in our value of average flux, or the standard deviation
difference = []
for flux in fluxs:
```

```
    diff = (flux - averageflux)**2
    difference.append(diff)

Diffs = np.array(difference)
Diffssum = sum(Diffs)
stdflux = ((1.0/50)*Diffssum)**0.5
print stdflux

#however, the uncertainty in our best estimate for the received flux is the standard deviation of the mean
SDOMflux = stdflux/(51**0.5)
print SDOMflux

#so now we have that the average received solar flux is 1372.94 +/- 3.81 W m^-2

pl.scatter(Distances, fluxs)
pl.xlabel('Distance from Sun in Meters')
pl.ylabel('Flux in W m^-2')
pl.title('Plot of Flux Reducation as Distance Increases from Perihelion to Aphelion')
```

The next section will essentially repeat the same methods as above. However, this average flux measurement is to calculate the average flux at the L1 point, which lies 1.5 million km from the Earth, and orbits with Earth.

```
#We know the emissivity of the sun
E = 3.86e26 #watts
errorE = 3.86e23 #watts

#now we want to calculate average solar flux at a give distance - L1 point
#create an array of distance between aphelion and perihelion: L1 occurs at a distance of
#1.5 million km from Earth
#aphelion = 1.52097e11 - 1.5e9 m
#perihelion = 1.47098e11 - 1.5e9 m
#we'll get a moderate amount of data points is we set our counter equal to 0.001
#you'll notice our aphelion number is different because arange excludes the last parameter
apL1 = 1.52097 - 0.015
perL1 = 1.47098 - 0.015 + 0.001
distanceL1 = np.arange(perL1, apL1, 0.001)

#we need to add back on the exponential to our distances
DistancesL1 = distanceL1*(1e11)

#now we need to calculate solar flux at each distance
fluxsL1 = []
for length in DistancesL1:
    S = E/ (4*math.pi*(length**2))
    fluxsL1.append(S)

#now we need to get the error on each distance
#the error in E is 0.1%, so that's the only error that should propogate for our distances
disterrorsL1 = []
for length in DistancesL1:
    error = length*0.001
    disterrorsL1.append(error)

#now that we have all our fluxes and errors, we need to figure out the average
#make the list into an array so we can sum it
```

```
fluxesL1 = np.array(fluxsL1)
sumfluxL1 = sum(fluxesL1)
#print len(fluxesL1)
#need to divide the sum by how many data points there are - in this case, 49
averagefluxL1 = sumfluxL1*(1.0/49)
print averagefluxL1 #this is W m^-2

#now we need the error in our value of average flux, or the standard deviation
differenceL1 = []
for flux in fluxsL1:
  diff = (flux - averagefluxL1)**2
  differenceL1.append(diff)

DiffsL1 = np.array(differenceL1)
DiffssumL1 = sum(DiffsL1)
stdfluxL1 = ((1.0/48)*DiffssumL1)**0.5
print stdfluxL1

#however, the uncertainty in our best estimate for the received flux is the standard deviation of the mean
SDOMfluxL1 = stdfluxL1/(49**0.5)
print SDOMfluxL1

#so now we have that the average received solar flux at L1 is 1400.87 +/- 3.62 W m^-2
```

Appendix D – Insolation Calculations

*Average flux at Earth = 1372.506 W/m^2

*New flux at Earth (to counter 2.3 W/ m^2 anthropogenic forcing) = 1370.206 W/ m^2

*This means there needs to be a 0.00168% decrease in the amount of light Earth receives.

*The flux at L1 will be greater than at Earth, because it lies 1.5 million kilometers closer.

Distance Sun to Earth = 1.496e11 meters
Distance Earth to L1 = 1.5e9 meters
E is solar emissivity, 3.86e26 Watts

$$S_{L1} = \frac{E}{4\pi(1.496e11m - 1.5e9m)^2}$$

$$S_{L1} = 1400.449\ W/m^2$$

* Find the average amount of sunlight the Earth receives on a given day

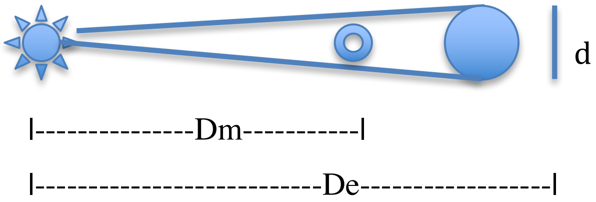
~ Area circle (only one half of Earth receives light at a time)
~ Earth's radius is 6.371e6 meters, this gives A = 1.2752e14 meters squared
~ Multiple this area, by the amount of flux per meter Earth receives
Flux total = (1372.506 W/ m^2) * (1.2752e14 m^2) = 1.75022 Watts
~ Now, we want to decrease total flux by 0.00168% = 2.9404e14 Watts

*Knowing the average flux at L1, and the amount of energy we need to reduce into the Earth system, we can figure out the area that needs to be shaded at L1

$$Area\ Shade = \frac{2.9404\text{e}14 \text{ Watts}}{1400.449\ W/m^2}$$

$$Area\ Shade = 2.0996e11\ meters$$

*Know we need to know the angular size of Earth at L1, so shades stay shadowing Earth, and not just random space. To do this, use the small angle formula. (not to scale)



* First, use known constants and the small angle formula to find the angular size of Earth – the angular size for Earth and L1 will be the same.

$$Tan\theta = d/D$$

* This gives an angular size of 0.2928" ; this means the mirror diameter is 6307134.7 meters – this is the angular diameter that the solar shades can cover at L1 and still shade Earth.

Appendix E – Umbral Calculations

|--------Dsun – Dshade----|----------Dumbra?---------|

* The distance from the Sun to the L1 point is 148.1 million kilometers
* Radius Sun = 6.957e5 km
* Radius Satellite (assuming 10 meters) = 0.01 km

$$\alpha = \arcsin \left(\frac{r_{sun} - r_{shade}}{d_{sun} - d_{shade}}\right)$$

* Plugging in values from above gives you alpha = 0.00469 radians
* Now, to find the umbral shadow length

$$D(umbra) = \frac{r_{sat}}{\sin(\alpha)}$$

* This gives you an umbra length of 2.1287 km for a 10 meter diameter shade, up to an umbra of 6.3863 km for a 30 meter diameter shade. So clearly, there is no danger of the shade umbra hitting Earth.

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