How New International Pollution Regulations on Cargo Ships are Influencing the Debate on Solar Geoengineering

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Anthropogenic climate change is becoming an increasingly severe problem that needs dire attention. Although scientists generally agree with the causes of climate change and how it is affecting us, experts will offer a wide range of different opinions on how to best address climate change and prevent the situation from getting worse. Proposed solutions range from ending our reliance on fossil fuels by adopting renewable or nuclear energy, widespread adoption of electric vehicles (EVs), investing in sustainable public transportation, economic policies such as a carbon tax, reducing domestic consumption particularly with plastic goods, and restoring habitats so they can become effective carbon sinks (Turrentine, 2022).

Perhaps the most contentious of all climate solutions is geoengineering. Geoengineering /does not have a universally agreed upon definition, but in the context of this paper the definition of geoengineering can be "the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming"(Shepherd et al., 2009, p. ix). Geoengineering is not a single solution, but rather an umbrella term for many different types of solutions, from increasing the albedo of landscapes by planting high albedo crops to reflect more sunlight, capturing and storing CO2 directly from the atmosphere, fertilizing the ocean to promote plankton growth which would act as a carbon sink, thinning high altitude cirrus clouds which trap solar energy, and many other proposals(*Proposed Geoengineering Technologies*, n.d.). Many authors divide geoengineering into two main categories: solar geoengineering, also known as solar radiation management (SRM), focuses on different methods of decreasing the total amount of solar energy that is absorbed by the planet, and carbon geoengineering which seeks to remove carbon dioxide from the atmosphere (*Harvard's Solar Geoengineering Research Program*, n.d.). Although there is a lot of interesting debate surrounding carbon geoengineering, the main criticisms are relatively simple and easy to understand: carbon geoengineering is too inefficient and too expensive to be treated as a logical investment when there are cheaper and more effective alternatives yet to be implemented (Harvey, 2023). As a result, this paper will focus primarily on solar geoengineering.

On the other hand, many popular SRM solutions are relatively cheap and could potentially have widespread and incredible results. These solutions are generally theoretically sound and have models demonstrating their effectiveness. Despite this, many climate scientists reject geoengineering solutions outright and some have even discouraged geoengineering from being researched. Geoengineering is a relatively new field of study, and much work still needs to be done on how SRM can be implemented/researched responsibly and ethically. When talking about technology that could affect every area on the planet, is there any situation in which geoengineering can be implemented responsibly, and if so what scientific evidence and circumstances would be required? A recent policy change has unintentionally yielded evidence that marine cloud brightening solutions could have a measurable and substantial impact on the climate, which has agitated the geoengineering debate more than ever before, a debate that will only become more important as the planet continues to surpass unfortunate climate change milestones. While reflecting on new evidence that geoengineering could be an effective tool in our fight against climate change, we must ask if evidence of its efficacy is enough to justify its implementation, or are there still larger environmental and social considerations that illegitimize the idea entirely?

Background

The principle behind geoengineering is to attempt to offset some of the effects of climate change by cooling down the Earth. Solar geoengineering would not reduce the amount of greenhouse gases in the atmosphere, but instead would only reduce the amount of sunlight absorbed by the planet. As a result, SRM would not counteract other effects of pollution such as ocean acidification due to the absorption of carbon dioxide, or decreased air quality due to the abundance of pollutants (Burns et al., 2019). Even the strongest proponents of geoengineering will admit that geoengineering is a supplement, not a replacement, to efforts to reduce greenhouse gas emissions. This leads to the first major critique of geoengineering; some climate scientists argue that geoengineering discussions will make the fight to reduce greenhouse gas emissions appear less dire. Critics argue that eliminating greenhouse gas emissions is the most effective proven solution to addressing climate change and is the only way to achieve the warming limit of 1.5°C above pre-industrial levels, a goal set in the Paris Agreement. Opponents argue that geoengineering is a distraction and will only harm the fight against greenhouse gasses if the public is falsely led to believe that there are other viable alternative options to address climate change, while proponents counterargue that the only way to achieve the ambitious 1.5°C goal is to take every possible opportunity to reduce global warming, which would include geoengineering alongside aggressive reductions of carbon emissions.

SRM techniques tend to be subject to more controversy when their effects are more significant/widespread. Surface albedo techniques are methods of increasing the amount of light reflected from Earth's surface by making the surface brighter. One surface albedo technique that has been implemented for decades with little to no controversy is painting roofs and pavement white. In most cases, painting buildings white is done primarily to reduce energy costs by buildings by reducing the need for AC during summertime, but this does increase the amount of sunlight reflected back into the atmosphere. The cooling effect of the white roof technique is highly localized and minimal and is widely regarded as a very safe though highly ineffective method of cooling the planet, so much so that some climate scientists reject even considering this a form of geoengineering (hankschannel, 2023). Compare this with other surface albedo techniques such as installing reflective panels across broad ranges of deserts. Although this method would be significantly more effective as deserts experience some of the highest levels of incident solar radiation, the potential ecological consequences and unknown effects on atmospheric processes makes this proposal subject to extensive objections from environmental scientists. (Shepherd et al., 2009)

The most popular and probably most controversial geoengineering proposal is stratospheric aerosol injection (SAI). SAI is effectively a way of simulating the global cooling effect that occurs after large volcanic eruptions. Major volcanic eruptions inject considerable quantities of sulfate aerosols into the stratosphere, which persist for years and increase the amount of sunlight reflected into space. This effect could be replicated without requiring a volcano by using aircraft to release hydrogen sulfide (H_2S) or sulfur dioxide (SO_2) as gases in the stratosphere which would then oxidize into sulfate particles. Although cost estimates vary based on the estimated amount of material required by different models that researchers have developed, but there seems to be a consensus among advocates that SAI could nearly completely offset the warming caused by CO2 while being incredibly affordable. The annual budget of SAI programs is generally estimated to be on the order of 10s of billions of dollars annually or less which is comparable to the budget of the US Environmental Protection Agency (EPA). Although some scientists propose that a custom-built fleet of aircraft would be required to efficiently disperse the aerosols, no new technologies would need to be developed and there are no real concerns on whether SAI can be physically implemented. (Burns et al., 2019; Shepherd et al., 2009)

Critics of SAI point out that there are numerous potential unintended negative consequences. Following volcanic eruptions, biological productivity decreases because plants that rely on photosynthesis have less access to sunlight. SAI could not only cause widespread damage to ecosystems, but it could also damage the global food supply chain. There are also concerns that the ozone layer could be impacted by these aerosols, as sulfate would cause the ozone layer to deplete. Other aerosols such as calcium carbonate might cause the ozone layer to inflate, but more research needs to be done on aerosols as most of the current research on SAI focuses on sulfate. The effects on other processes like the hydrological cycle are also uncertain. (Burns et al., 2019; Shepherd et al., 2009)

Thus far, most experiments on SRM have been primarily restricted to computer models and in some rare cases isolated ecosystems (Cho, 2024). Major questions still exist on whether these ideas truly scale to the large and incredibly complex system that is the Earth's climate. At the same time, there are some climate scientists who not only argue against geoengineering, but also argue that geoengineering should not even be researched. Not only is there the concern of harming the fight against greenhouse gas emissions, but some argue that geoengineering is a slippery slope and funding research into the topic will only justify its future use. Others argue that anything except real world data is insufficient until climate models significantly improve, but performing a real-world geoengineering experiment without understanding its consequences would be wildly irresponsible. Although calls for research are growing, funding for geoengineering research has been difficult to obtain and has been a significant hurdle for proponents. Without the ability to research and promote their ideas, advocates for SRM have largely been at an impasse with their opponents.

IMO 2020: An Unintended Experiment on Marine Cloud Brightening

Heavy Fuel Oil (HFO), also known as bunker fuel, is a category of fuel oil that is a made from the substances left behind during petroleum refining after the higher quality hydrocarbons have been removed (McKee et al., 2014). Due to its low cost compared to cleaner fuel options, HFO is the primary fuel source used for marine shipping vessels, an industry that accounts for roughly 3% of global carbon emissions ("Climate Impact of Shipping," 2023). Historically, regulations on HFOs have not been strict especially regarding emissions of sulfur oxides (SOx) and nitrogen oxides (NOx), which are harmful pollutants that are contributing to both ocean acidification and climate change.

This changed in 2020 when the United Nations International Maritime Organization (IMO) established new restrictions on fuel used by shipping vessels that required the use of fuel with a sulfur content of no more than 0.50%, down from the previous limit of 3.50%. These new restrictions, nicknamed IMO 2020, is projected to reduce the amount of sulfur pollution by 8.5 million metric tons per year, which has led to significantly less pollution over oceans and will also improve human health as sulfur oxides are known to increase risk of several conditions such as asthma, lung cancer, stroke, and cardiovascular disease. (*IMO 2020 - Cleaner Shipping for Cleaner Air*, 2019).

However, IMO 2020 had an unintended side effect. Sulfur oxides have been a target for environmentalists because they react with water vapor to form sulfuric acid, which eventually forms acid rain and is destroying many ecosystems, particularly in the ocean. This reaction also catalyzes the formation of clouds in a process called cloud seeding. Ships that burn high sulfur fuel form clouds in their wake called ship tracks which can be visible from outer space. These reflective clouds reduce the amount of sunlight absorbed by the Earth's surface, and so sulfur dioxide has a temporary but measurable cooling effect.

Following the implementation of IMO 2020, the number of ship tracks has significantly decreased due to the decline of ships burning high sulfur fuel. The decreased cloud cover, particularly over the North Atlantic Ocean where most shipping lines run, is believed to be one of the primary factors that has led to the increased ocean surface temperatures shown in Figure 1 (Manshausen et al., 2023; Voosen, 2023). This effect is not a complete surprise to scientists, as the cooling effects of sulfur pollution is well known and some scientists even predict that temperatures may increase as a result of IMO 2020, but the magnitude of change shown in Figure 1 was a shock to many scientists.

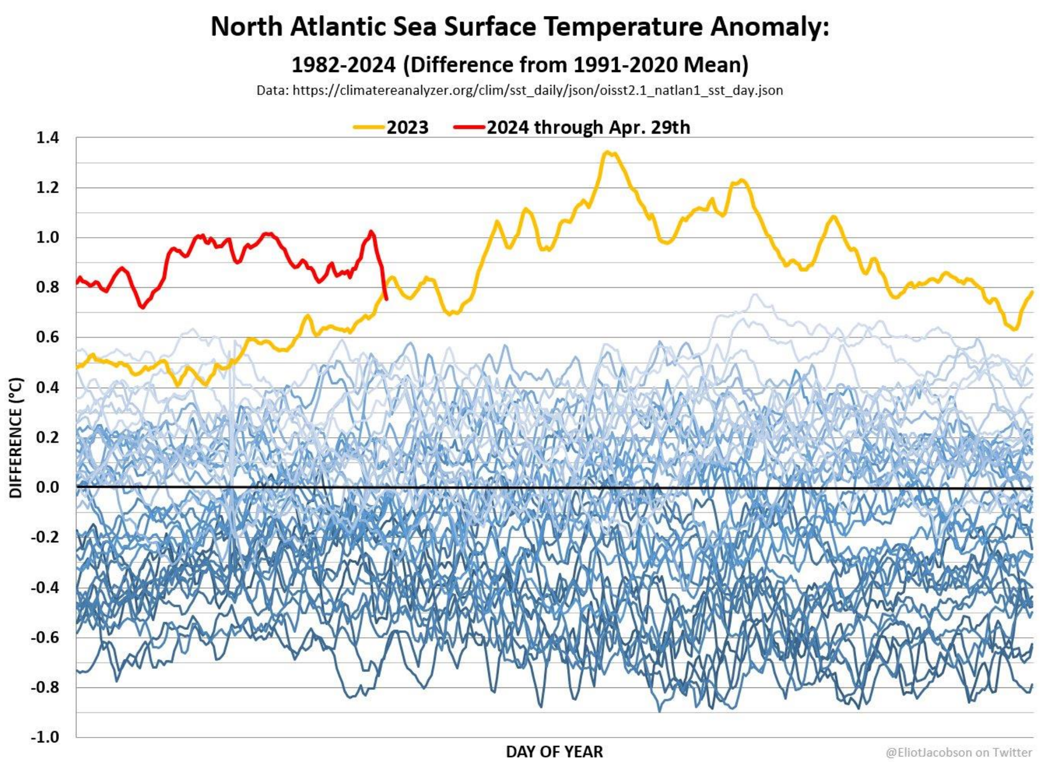

Figure 1 North Atlantic Sea surface temperature anomaly plotted through April 29, 2024. (Prof. Eliot Jacobson [@EliotJacobson])

Although the implications of the rapid increase in ocean temperatures does not bode well for the climate crisis, and likely contributed to the fact that 2023 was the hottest year on record (Voosen, 2024), some saw these findings as evidence that geoengineering could be implemented successfully. Marine cloud brightening is a geoengineering strategy that involves increasing the amount of sunlight reflected by clouds over the oceans, either by making clouds more reflective or more abundant. Humans were effectively accidentally doing geoengineering for decades before IMO 2020 by injecting cloud seeding sulfur oxides into the atmosphere. The significant warming we are now experiencing is evidence that the previous sulfur emissions were performing marine cloud brightening and causing an unintended but meaningful cooling effect. The most promising part is that other, less harmful options exist besides sulfur dioxide that are comparably effective cloud seeders. The most common suggestion is to use salt water directly from the ocean. The sea salt attracts moisture and enables cloud seeding as water vapor condensates around the crystal, and additionally this is a very low-cost solution (Hill & Ming, 2012). By equipping cargo ships with devices that spray sea water into the sky, we can restart this cloud brightening and cool the planet again.

For geoengineering proponents, the IMO 2020 rule change was a great accident. Experiments on geoengineering at this scale are exceedingly difficult to accomplish. Many climate scientists oppose geoengineering, so an experiment at this scale would have impossible to receive approval. Much smaller experiments with localized effects are struggling to receive approval, so a broad experiment that could impact the entire planet would be completely off the table and completely irresponsible. Additionally, even if an experiment on this scale was approved, the cost of injecting aerosols continuously throughout the Atlantic Ocean would have cost a fortune. Funding a project like this would have been impossible. Because of this, it is possible that stronger evidence on geoengineering may never be created again.

Why Many Critics Remain Unimpressed

In spite of the effects of IMO 2020, many climate scientists remain steadfast in their opposition to geoengineering. Knowing that a solution works is not the same as knowing that there are no negative consequences. The climate is an incredibly complicated system, and we will need collect more data over the next several years before we can make substantial conclusions on the effects of marine cloud seeding solutions.

We have very little idea how cloud seeding solutions can affect precipitation patterns. Some models predict that these cloud seeding solutions can increase the probability of droughts in some areas, some models predict that the probability of severe tropical storms can increase, and some models predict both results can happen simultaneously. (Shepherd et al., 2009)

Additionally, there is no such thing as accidental geoengineering. Geoengineering is defined as an intentional act, and accidentally altering the climate is not the same as engineering the climate even if the effects are the same. Consider the possibility that a person, group, or nation state unilaterally begins cloud seeding, and the following year a drought occurs in a different part of the world, and the year after that a category 5 hurricane occurs in another different part of the world. If there is any uncertainty in how cloud seeding can affect various climate systems, this hypothetical situation could become disastrous. Even if it turns out that these disasters occurred due to unrelated reasons, the possibility that they were a result of actions that intentionally altered the climate could potentially start a war.

Imagine a similar situation, where a single group unilaterally performs this cloud seeding for some prolonged duration, but then suddenly stops overnight for whatever reason, perhaps due to political pressure. The effects of cloud seeding are relatively short lived, and if the effects of this cloud seeding were significant until they abruptly stopped entirely, that could cause significant levels of climate change on a timescale of weeks or even days. The current climate crisis is destroying ecosystems because the climate is changing on a timescale of decades/years, the potential disaster that could result from this type of climate shock would be a catastrophe. This phenomenon, known as termination shock, is especially worrisome to many climate scientists and some fear that it could even be weaponized. (Burns et al., 2019; hankschannel, 2023; Pamplany et al., 2020; Shepherd et al., 2009)

Conclusion

The IMO 2020 change has generated invaluable evidence that a particular form of SRM, marine cloud brightening, could be a viable option for combating the effects of climate change. However, geoengineering is a potentially very dangerous idea, and a lot of care needs to be taken to ensure geoengineering is implemented responsibly if at all.

It cannot be stressed enough that geoengineering is not a replacement to combating greenhouse gas emissions and ending our reliance on fossil fuels. Eliminating CO2 emissions as soon as possible is the single most effective and important step to addressing climate change, and that is not likely to change soon. However, our opportunity to keep the planet's warming below the 1.5°C threshold is disappearing fast, and many models are already predicting that we will not be able to achieve that goal. But as temperatures continue to rise, we may need to begin to seriously consider taking additional actions to combat climate in order to protect ecosystems. The record breaking warm waters in 2023 caused 100% coral mortality in the Sombrero Reef in

Florida, fueled fires in the Mediterranean and Canada, and strengthened Typhoon Doksuri which made landfall in China (Tim Meko & Dan Stillman, 2023). These problems will only get worse.

Although the consequences of IMO 2020 is not enough evidence that we should begin geoengineering at large scales, it is evidence that the idea should be taken seriously and more money should be invested in geoengineering research and especially SRM research. It is time to move past false dilemma and slippery slope fallacious arguments and recognize that geoengineering could prove to be an incredibly important tool alongside emission reductions, particularly if/when we reach dangerous levels of warming above 1.5°C. Care should be taken by scientists to not misrepresent geoengineering, but with responsible education and marketing the public can be properly informed about the risks and shortcomings of geoengineering and understand that the fight to eliminate greenhouse gas emissions is still of primary concern. Additionally, it is hard to imagine there is any circumstance in which society will return to fossil fuels when renewable energy sources are already the cheapest option for 85% of global power generation as of March 2021, along with the many other environmental, economic, and health benefits of not burning fossil fuels (Moore & Bullard, 2021).

For geoengineering to be implemented responsibly and ethically, it must first be studied extensively to ensure that we have a good understanding of the effects of geoengineering. Additionally, it must be done multilaterally, and all effected countries must agree on how the geoengineering should be achieved and implemented. The current climate crisis has largely been caused by unilateral decision making with little to no regard for other nations, and that is a mistake we can't repeat again. 196 states signed the Paris Agreement, so there is hope that climate change diplomacy will advance to the point of being able to create such a treaty. If a well understood geoengineering solution were to be implemented alongside greenhouse gas reductions, with the consent and endorsement of all relevant nations, then it could be an invaluable tool to assist the fight against climate change which is looking more dire every day.

References

Burns, L., Keith, D., Irvine, P., & Horton, J. (2019). *Technology Factsheet: Solar Geoengineering* (B. Belei, Ed.). Belfer Center for Science and International Affairs, Harvard Kennedy School. https://www.belfercenter.org/sites/default/files/2019-06/TechFactSheet/solargeoengineering%20-%205.pdf

Cho, R. (2024, April 24). Solar Geoengineering To Cool the Planet: Is It Worth the Risks? – State of the Planet. *State of The Planet*. https://news.climate.columbia.edu/2024/04/24/solar-geoengineering-to-cool-the-planet-is-it-worth-the-risks/

Climate impact of shipping. (2023, July 21). *Transport & Environment*. https://www.transportenvironment.org/challenges/ships/greenhouse-gases/

hankschannel. (2023, October 4). *Is Geo-Engineering Going to Save (or Destroy) Us?* https://www.youtube.com/watch?v=Gs-ed1CEokc

Harvard's Solar Geoengineering Research Program. (n.d.). Harvard University. Retrieved April 30, 2024, from https://geoengineering.environment.harvard.edu/geoengineering

Harvey, F. (2023, April 25). Carbon dioxide removal: The tech that is polarising climate science. *The Guardian*. https://www.theguardian.com/environment/2023/apr/25/carbon-dioxide-removal-tech-polarising-climate-science

Hill, S., & Ming, Y. (2012). Nonlinear climate response to regional brightening of tropical marine stratocumulus. *Geophysical Research Letters*, *39*(15). https://doi.org/10.1029/2012GL052064

IMO 2020—Cleaner shipping for cleaner air. (2019, December 20). International Marine Orangization. https://www.imo.org/en/MediaCentre/PressBriefings/pages/34-IMO-2020-sulphur-limit-.aspx

Manshausen, P., Watson-Parris, D., Christensen, M. W., Jalkanen, J.-P., & Stier, P. (2023). Rapid saturation of cloud water adjustments to shipping emissions. *Atmospheric Chemistry and Physics*, *23*(19), 12545–12555. https://doi.org/10.5194/acp-23-12545-2023

McKee, R. H., Reitman, F., Schreiner, C., White, R., Charlap, J. H., O'Neill, T. P., & Goyak, K. O. (2014). The Toxicological Effects of Heavy Fuel Oil Category Substances. *International Journal of Toxicology*, *33*(1_suppl), 95S-109S. https://doi.org/10.1177/1091581813504230

Moore, J., & Bullard, N. (2021). BloombergNEF's Executive Factbook. *BloombergNEF*.

Pamplany, A., Gordijn, B., & Brereton, P. (2020). The Ethics of Geoengineering: A Literature Review. *Science and Engineering Ethics*, *26*(6), 3069–3119. https://doi.org/10.1007/s11948-020-00258-6

Proposed Geoengineering Technologies. (n.d.). Geoengineering Monitor. Retrieved April 30, 2024, from https://www.geoengineeringmonitor.org/technologies/

Shepherd, J., Caldeira, K., Cox, P., Haigh, J., Keith, D., & Launder, B. (2009). *Geoengineering the climate: Science, governance and uncertainty*. Royal Society.

Tim Meko & Dan Stillman. (2023, July 28). Ocean temperatures are off the charts. Here's where they're highest. *Washington Post*. https://www.washingtonpost.com/weather/2023/07/28/ocean-temperature-maps-heat-records/

Turrentine, J. (2022, December 13). *What Are the Solutions to Climate Change?* NRDC. https://www.nrdc.org/stories/what-are-solutions-climate-change

Voosen, P. (2023, August 2). *'We're changing the clouds.' An unintended test of geoengineering is fueling record ocean warmth*. https://www.science.org/content/article/changing-clouds-unforeseen-test-geoengineering-fueling-record-ocean-warmth

Voosen, P. (2024, January 9). *2023 was the hottest year on record—And even hotter than expected*. Science. https://www.science.org/content/article/even-warmer-expected-2023-was-hottest-year-record