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# Geoengineering Risks in the Arctic

## Abstract

The Arctic, a region emblematic of climate change's profound impacts, stands at the nexus of potential geoengineering interventions. This paper delves into various geoengineering methodologies, including Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR), assessing their feasibility and implications for the Arctic environment. Highlighting advanced detection techniques, from satellite monitoring to computer-based modeling, this paper discusses the challenges posed by the Arctic's unique climatic conditions and geopolitical intricacies. Furthermore, with the Arctic's strategic significance encompassing vital shipping lanes and rich natural resources, the potential socio-political ramifications of geoengineering are explored. Emphasizing the necessity for international collaboration and transparency, the study concludes that while geoengineering presents promising avenues, a balanced, cooperative, and informed approach is crucial to ensure the sustainability of both the Arctic and global ecosystems.

*Key words:* Geoengineering, Arctic ecosystems, climate change

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## Geoengineering Risks in the Arctic

The Arctic, with its vast expanse and profound significance to global climate systems, has emerged as a critical frontier for innovative approaches to combat climate change. Within this context, one term increasingly garners attention: geoengineering. As defined by the Intergovernmental Panel on Climate Change (IPCC), geoengineering refers to "the intentional large-scale manipulation of the Earth's physical processes to counteract climate change (IPCC, 2013)." But for defense and security planners, this is not merely a scientific endeavor. The ability to detect, monitor, and understand geoengineering activities in the Arctic is paramount. The region holds not only strategic geopolitical value but is also where the interplay between geoengineering measures and their potential risks could directly impact patterns of resource extraction, maritime navigation, and military operations. As the global population grapples with a changing climate, ensuring a clear understanding and vigilant oversight of interventions in the Arctic becomes indispensable.

## Standard Geoengineering Methods

Geoengineering represents a spectrum of interventions aimed at intentionally manipulating the Earth's physical processes to counteract the impacts of climate change. Within this domain, two primary methodologies emerge: solar radiation management (SRM) and carbon dioxide removal (CDR).

Solar Radiation Management (SRM) is a suite of techniques designed to diminish the amount of sunlight that reaches and is absorbed by the Earth, thereby acting as a countermeasure to global warming. The urgency of employing these techniques is palpable in areas like the Arctic, a region bearing the brunt of accelerated warming, marked by extensive ice melt and subsequent ecosystem disturbances. One prominent SRM approach is Stratospheric Aerosol Injection (SAI), also known as “volcanic forcing,” which entails the introduction of reflective particles, such as sulfate aerosols, into the stratosphere.

Volcanic forcing refers to the impact of volcanic eruptions on the Earth's climate. When volcanoes erupt, they can spew vast amounts of ash and various gases into the atmosphere, with sulfur dioxide ($SO_2$) being one of the most significant in terms of climatic impact. Upon reaching the stratosphere, sulfur dioxide reacts with water vapor to form sulfate aerosols. These tiny aerosol particles spread out and form a thin, reflective layer around the Earth. This layer acts like a shield, reflecting a portion of the incoming solar radiation back into space, which can lead to a cooling effect on the Earth's surface. The cooling effect can be substantial and prolonged, depending on the magnitude of the eruption and the amount of sulfur dioxide released. For instance, the 1991 eruption of Mount Pinatubo in the Philippines, one of the largest eruptions of the 20th century, resulted in a global temperature drop of about 0.5°C for over a year (McCormick et al., 1995).

While natural volcanic eruptions serve as a periodic source of volcanic forcing, there have been theoretical discussions about artificially replicating this process as a geoengineering method to counteract global warming. This idea, often termed "stratospheric aerosol injection," involves intentionally releasing sulfur-containing compounds into the stratosphere to mimic the cooling effect seen after major volcanic eruptions. Authors in Chen et al (2020) assessed the controllability of Arctic sea ice extent through sulfate aerosol geoengineering by simulating the injection of SO2 into the Arctic stratosphere and making annual adjustments to injection rates. The simulation showed that Arctic sea ice cover could be remediated by 2043 and maintained until solar geoengineering was terminated. However, such interventions come with significant uncertainties and potential risks, ranging from changes in precipitation patterns to stratospheric ozone depletion. Arctic SO2 injection would not only cool the Arctic but also disrupt the Asian and African summer monsoons, which could have significant impacts on the food supply for billions of people (Nalam et al., 2018; Robock et al., 2008).

Another SRM technique is Marine Cloud Brightening (MCB). By seeding marine clouds with fine seawater droplets, MCB seeks to bolster their reflectivity, ensuring that they send back more sunlight into space (Ahlm et al., 2017). Applied in the Arctic context, increasing the albedo of marine clouds, especially during periods of sunlight, might yield localized cooling effects, potentially curbing the pace of sea ice melt. Additionally, even though the creation and dispersal of artificial snow or ice in the Arctic may not fit the conventional global SRM mold, it holds potential. Elevating the region's albedo through this approach could be instrumental in mitigating some of the adverse warming effects uniquely observed in the Arctic.

Carbon Dioxide Removal (CDR) techniques, central to geoengineering strategies, focus on the direct extraction of CO2 from the atmosphere. Prominent among these methods is Carbon Capture and Storage (CCS), wherein $CO_2$ is captured at emission sources, such as power plants, and subsequently stored in geological formations to prevent atmospheric release. Bioenergy with Carbon Capture and Storage (BECCS) combines biomass utilization with CCS, allowing for net-negative emissions. Ocean-based strategies, like ocean fertilization, promote the uptake of $CO_2$ by phytoplankton through the addition of nutrients to marine ecosystems. Another approach, enhanced weathering, involves accelerating the Earth's natural weathering process by disseminating specific minerals that, when broken down, absorb $CO_2$ and convert it into stable carbonates.

Beyond CCS, enhanced weathering is gaining traction as a CDR technique with potential relevance for the Arctic. At its core, enhanced weathering involves introducing minerals, notably olivine, basalt, and serpentine, into the soil to expedite the natural carbon absorption process (Taylor et al., 2016). These specific minerals are chosen due to their rich content of elements like magnesium and calcium. As they degrade, they undergo reactions with carbon dioxide to produce stable carbonates, sequestering the $CO_2$ in the process.

However, a potential drawback is the energy and resources required for mining, grinding, and distributing these minerals on a large scale, which could offset some of the benefits. With the Arctic's expansive permafrost territories, currently under threat from global warming, there emerges an intriguing proposition to employ enhanced weathering. Introducing these minerals into regions where permafrost is thawing could serve the dual purpose of stabilizing these zones while enhancing their carbon sequestration capacity. This approach emphasizes the need for geoengineering methods that resonate with the distinct features and hurdles inherent to regions like the Arctic.

## Alternative Geoengineering Methods

In the preceding section, standard mechanisms of Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) are presented. While these methods are at the forefront of geoengineering discussions, they are by no means exhaustive. Alternative methods that, although not as widely discussed in literature, hold significant potential in the context of climate mitigation. This section includes a series of these alternative strategies: the deployment of space mirrors, the nuances of cloud thinning and seeding, the marine approach of ocean fertilization, and the surface-level interventions of albedo modification.

### Space Mirrors

The concept of space mirrors, a futuristic proposition within the geoengineering realm, offers a vision where massive reflective structures are stationed in space to deflect a portion of the Sun's rays (United

Nations Environment Programme, 2023). The primary objective of this idea is to diminish the amount of solar radiation reaching our planet, aiming to mitigate the effects of global warming. To visualize the functioning of this system, one would imagine the deployment of either numerous small mirrors or a few vast reflective shields into space. A strategic positioning, often considered at the Lagrange Point L1— a point where gravitational forces between the Earth and Sun balance perfectly— would allow these mirrors to effectively "hover," maintaining a consistent orientation relative to our planet and the Sun (McInnes, 2010).

Upon their optimal positioning, these mirrors would work to bounce back a fraction of the Sun's light. Even a slight dip in solar radiation, theoretically, could usher in a cooling effect robust enough to counterbalance some of the escalating global temperatures. An intriguing advantage of such a system is its adjustability: if it's deemed that the mirrors are reflecting either too much or too little sunlight, their orientation could be fine-tuned for desired outcomes.

Yet, like many ambitious endeavors, this concept doesn't come without its share of hurdles and apprehensions. Foremost among these are the sheer technical and logistical challenges. Crafting, launching, and sustaining such an expansive array of mirrors presents complexities that, in many ways, exceed our current technological capabilities. Moreover, the financial toll of such a mammoth undertaking could be staggering, given the inherently high costs associated with space missions. Beyond the tangible challenges, the theoretical realm of space mirrors introduces potential pitfalls too. Tweaking the delicate balance of solar radiation could inadvertently trigger disruptions in global weather patterns or jeopardize delicate ecosystems. Furthermore, there's the looming "termination effect." Should the mirror system malfunction or necessitate decommissioning, a rapid reintroduction of previously deflected sunlight could exacerbate global warming, especially if our atmosphere remains laden with greenhouse gases.

## Cloud Thinning & Seeding

Another approach, cloud thinning, which employs methods to reduce cloud density, could allow more sunlight to penetrate, with potential cooling implications (Duffey et al., 2023). Cloud thinning, an intriguing facet of geoengineering, encompasses techniques designed to diminish cloud cover, thereby allowing an enhanced influx of sunlight to reach Earth's surface. This concept posits that by decreasing the density or extent of certain cloud types, especially those at lower altitudes, intervention activities might usher in more solar radiation, leading to localized warming effects. One method garnering attention in this domain is "laser distrail" (Matthews et al., 2016). This technique envisions the use of targeted lasers to interfere with the microphysical processes within clouds, ultimately causing their dispersion. However, such a method's feasibility, along with the energy it demands and potential unforeseen ramifications, are all subjects of ongoing scrutiny.

Shifting from high-tech lasers, we find a more conventional method in cloud seeding. While historically employed to augment rainfall, when tweaked with specific seeding agents or methodologies, cloud seeding could very well thin out clouds or deter their formation. Another avenue under exploration involves the dispersion of specific aerosols into the atmosphere. Theoretically, these aerosols could either catalyze the formation of thinner clouds or prevent certain cloud types from materializing in the first place.

Yet, as society delves deeper into the potential of cloud thinning, it's paramount to exercise caution. The idea, still largely in the realm of theory, carries its share of controversy. While the intentional reduction of cloud cover may warm certain locales, the cascade of potential impacts on global weather patterns, water cycles, and ecosystems cannot be ignored. It's also noteworthy that many geoengineering strategies primarily aim to cool, rather than warm, the planet. As such, any leap towards widespread adoption of cloud-thinning techniques would necessitate rigorous research, meticulous modeling, and judicious testing.

### Ocean Fertilization

Ocean fertilization emerges as another promising geoengineering technique with the potential to combat climate change by enhancing the ocean's natural carbon sequestration processes (Lampitt et al., 2008). At the heart of this approach are phytoplankton, microscopic marine plants. Similar to their terrestrial counterparts, phytoplankton perform photosynthesis, capturing sunlight and atmospheric carbon dioxide to produce food and release oxygen. Yet, vast regions of the ocean, known as 'high-nutrient, low-chlorophyll' (HNLC) zones, possess ample macronutrients but show limited phytoplankton growth due to a deficiency in essential nutrients like iron. In the western Arctic Ocean, nearest the Bering Strait, surface nutrients like nitrates are deplete due to the suppression of ocean upwelling caused by freshwater input from the surrounding landmasses (Clark et al., 2020). This is where ocean fertilization steps in.

By strategically adding iron or other nutrients to these HNLC regions, we can trigger a bloom in phytoplankton. As these organisms flourish, they're expected to absorb significant amounts of $CO_2$ from surface waters, inducing further $CO_2$ uptake from the atmosphere to maintain equilibrium. Furthermore, as phytoplankton die off or become part of the marine food chain, the carbon they've absorbed sink as organic matter to the deep ocean, effectively locking it away for centuries.

Yet, while the principle behind ocean fertilization appears sound, the technique is not without its challenges and concerns. Large-scale phytoplankton blooms have the potential to disrupt marine ecosystems, potentially even leading to oxygen-deprived zones detrimental to marine life. For example, salmon are highly migratory and adaptive, but sudden or drastic changes in their environment could impact their migration patterns, behavior, and survival rates. Questions also arise about the efficiency of this method; specifically, how much of the sequestered carbon remains in the deep ocean versus what's recycled back into the atmosphere. Additionally, although it offers a solution to atmospheric $CO_2$ buildup, ocean fertilization doesn't address another pressing concern: ocean acidification, a result of excessive $CO_2$ absorption by the seas. Lastly, the regulatory, monitoring, and verification aspects of such large-scale interventions present significant hurdles.

### Albedo Modification

Albedo modification is another geoengineering concept aimed at increasing the reflectivity (albedo) of surfaces to counteract some of the effects of global warming by reflecting more sunlight back into space. One such approach is the production and distribution of artificial snow or ice during the warmer months, aiming to bolster the region's albedo and mitigate warming (Zampieri & Goessling, 2019). Another strategy involves the application of reflective materials, like thin sheets, especially over ice areas susceptible to melting. While this might be a feasible solution for smaller regions like glaciers, it presents challenges when considering the vastness of the Arctic Ocean.

An alternative albedo modification method is the distribution of microscopic, hollow glass spheres on ice surfaces (Field et al., 2018). These spheres have the potential to scatter incoming sunlight, effectively enhancing the ice's natural albedo. Glass spheres on ice present some obvious drawbacks and are unlikely to be adopted by most Arctic nations. One final modification technique is introducing specially designed algae or microorganisms to the ice. These organisms could either naturally possess a high reflectivity or produce compounds that increase the ice surface's albedo, presenting a biological solution to the albedo modification challenge.

## Geoengineering Detection in the Arctic

The Arctic, vulnerable to climate change and potential geoengineering solutions, requires careful and informed intervention. The risks of unforeseen outcomes from these actions are significant, with the reversibility of negative impacts still unclear. Detecting geoengineering activities, whether under the Solar Radiation Management (SRM) or Carbon Dioxide Removal (CDR) umbrella, is paramount for gauging their efficacy and understanding their broad implications. The methods employed are diverse, tapping into advanced technologies and refined scientific techniques.

## Methods of Detection

In the pursuit of identifying geoengineering activities in the Arctic, an array of sophisticated instruments and methodologies has been employed. Satellite monitoring remains paramount among these strategies. These orbital satellites conduct thorough assessments of the Earth's atmosphere and terrestrial surfaces, seeking anomalies indicative of geoengineering measures, notably the dispersion of reflective particles associated with stratospheric aerosol injection (SAI) methodologies (Lo et al., 2018; McLinden et al., 2016). Nonetheless, the efficacy of satellites is constrained in the Arctic due to persistent periods of darkness, prevalent cloud cover, and a discernible absence of polar-orbiting satellites. Such limitations hinder consistent imagery, leading to significant observational lacunae. The resultant gaps in holistic surveillance pose challenges for the continuous monitoring of geoengineering indicators within the polar regions.

Supplementing satellite efforts, atmospheric measurements, leveraging both ground-based and airborne instruments, enable scientists to discern changes in atmospheric composition indicative of geoengineering (Thalman et al., 2022). The detection of increased sulfur dioxide concentrations, pivotal in SAI, stands as a testament to their utility. Yet, the inherent challenges of the Arctic – its vast remoteness, limited infrastructure, and volatile weather – pose significant barriers. Establishing extensive ground stations becomes an uphill task, and airborne measurements, given the region's climatic unpredictability, risk becoming hazardous endeavors.

Computer-based modeling further augments our detection prowess (Kravitz et al., 2017). Through simulations of the Earth's responses to diverse geoengineering methodologies, these models unveil potential markers of intervention, such as temperature deviations, precipitation changes, or cloud cover fluctuations. But the Arctic's climatic complexity and its myriad interactions with broader global systems introduce ambiguities. Many models, while adept at large-scale predictions, grapple with nuances on smaller scales. The Arctic's diverse microclimates and terrains necessitate high-resolution data, which some models might inadvertently miss, undermining detection precision in specific Arctic areas.

Statistical analysis then refines the data mosaic formed by satellites, instruments, and models. By identifying patterns and outliers, statistical tools differentiate between natural shifts and potential geoengineering-induced changes (Lo et al., 2016). However, the Arctic's dynamic nature and the scarcity of consistent, long-term data pose challenges. Sifting through the 'noise' of natural variability to detect a definitive geoengineering signal is no minor feat.

Transitioning to CDR, the methods become more intricate, tailored to the nature of carbon capture. Seismic monitoring, for instance, plays a role in ensuring $CO_2$ remains ensnared when stored in geological formations. This is juxtaposed against direct atmospheric measurements which look for changes in $CO_2$ concentrations, acting as a barometer for CDR efficacy. The oceans, integral to many geoengineering strategies, demand their own set of monitoring tools. A sudden alteration in oceanic pH levels could suggest extensive ocean fertilization, for example. And it's not just about large ecosystems; even our drinking water becomes a detection medium. Techniques like fecal indicator monitoring can be harnessed to detect geoengineering impacts on water quality. Moreover, certain CDR strategies release specific elements to facilitate carbon capture. Directly spotting these, whether they are inorganic particles or sustained-release matrices, can shed light on geoengineering's scope and localization. On the biological front, tracking specially engineered organisms offers additional insights.

## Geopolitical Challenges to Detection

Amidst these technical challenges, geopolitical tensions cast an overbearing shadow, complicating collaborative initiatives within the Arctic. Detecting geoengineering activities requires more than just individual methods; a holistic approach that integrates various techniques is crucial. As the Arctic undergoes significant climatic shifts affecting ice patterns, marine ecosystems, and resource availability, timely and accurate data becomes indispensable. Yet, the pressing need for international collaboration and data-sharing is often obstructed by geopolitical tensions both within and outside the Arctic. External political disputes, such as the recent tensions ignited by Russian aggression towards Ukraine, hinder crucial data sharing among Arctic nations. Such geopolitical standoffs not only disrupt the free flow of pivotal information but also breed an environment of mistrust, further entangling efforts to collaboratively oversee and address geoengineering in this delicate region. To harness the potential of geoengineering safely and optimally, transparent, and open communication between nations is essential.

## Current Geoengineering Examples

CDR techniques target the removal of carbon dioxide from the atmosphere. A prominent example of such an endeavor is the work of Reykjavik-based Carbfix. Their innovative solution, termed CCM (Carbon Capture & Mineralization), is strategically located alongside the Hellisheidi Geothermal Power Plant. At this site, $CO_2$ is captured directly from its emission source and amalgamated with water. This carbonated water concoction is then injected into the basalt layers beneath the Earth's surface. There the carbonated water mixes with elements like calcium, magnesium, and iron present in the ground, eventually filling voids in the underground volcanic rock. This solution solidifies into stone within approximately two years, resulting in a permanent sequestration of the $CO_2$. As of March 5, 2021, Carbfix has impressively transformed 100,000 tones of emissions, comprising 65% $CO_2$ and 35% $H_2S$, into rock, marking a significant milestone in climate mitigation efforts. (Eggertsson, 2021)

Another example is the Northern Lights CCS Project in Norway. As part of the Norwegian government's ambition to foster a Carbon Capture & Storage value chain by 2024, this full-scale initiative captures $CO_2$ from industrial locations in the Oslo region. This includes significant contributors such as HeidelbergCement’s cement plant and Fortum Oslo Varme’s waste-to-energy facility. Once captured, the $CO_2$ undergoes liquefaction and pressurization, after which it is shipped to Naturgassparken, an onshore terminal situated on Norway's west coast. From there, the $CO_2$ is temporarily stored in tanks before being conveyed through pipelines to a subsea well in the North Sea. At this last stage the liquified $CO_2$ is injected into a geological storage complex, providing a secure and long-term storage solution.

## Discussion

Detecting geoengineering activities, especially in regions as vast and intricate as the Arctic, is fraught with complications. One primary issue in this endeavor is the spatial and temporal scale of detection. Geoengineering, in theory, aims to effect change on a global scale, producing discernible shifts in atmospheric or environmental conditions that can offset some of the impacts of global warming. When looking at its consequences on broader scales, such as across large regions or the entire planet, certain indicators like surface cooling effects become more noticeable. In fact, it is relatively easier to detect these large-scale shifts. However, the challenge amplifies when attempting to pinpoint the specific effects of geoengineering on sub-continental or localized scales. Given the vast heterogeneity of ecosystems, terrains, and climates within continents, identifying the subtle nuances of geoengineering interventions becomes particularly intricate.

Further adding to the complexity is the selection of appropriate detection methods and filtering techniques. Different detection methodologies, whether they are trend-based filters or multi-variate methods, can yield varying results and levels of sensitivity. For instance, while trend-based filters might successfully highlight long-term alterations in atmospheric conditions or temperatures, they might not be adept at catching transient, yet significant, anomalies. Multi-variate methods, on the other hand, consider multiple variables simultaneously and could be more holistic but might also introduce more complexity and potential areas for error.

Scientific uncertainty poses another challenge. While scientists can, to a degree, detect changes in environmental conditions, pinpointing specific harmful impacts and conclusively attributing them to geoengineering interventions is a much more convoluted process. The Arctic ecosystem, with its myriad interdependencies and sensitivities, could exhibit changes due to a plethora of reasons. Disentangling the specific contributions of geoengineering from other anthropogenic or natural influences is no mean feat.

Ethical concerns further complicate the matter. Once harmful effects are detected and, with some level of confidence, attributed to geoengineering, questions of responsibility arise. Who is accountable for these interventions, especially if they lead to unforeseen negative consequences? And in such scenarios, how does one determine eligibility for compensation? Moreover, quantifying the precise amount of compensation, especially in contexts as invaluable and irreplaceable as Arctic ecosystems, poses significant dilemmas.

## Conclusion

In the ever-evolving tableau of climate change, the Arctic stands as a sentinel, its delicate balance teetering on the precipice of human intervention. As humanity turns to geoengineering as a potential panacea for environmental challenges, these options are filled with profound uncertainties. The plethora of detection methods, from satellites to seismic monitoring, showcase society's technological prowess. However, they also highlight the inherent challenges and nuances of understanding a region as complex and dynamic as the Arctic. Beyond the scientific intricacies, geopolitical tensions further complicate matters, emphasizing the importance of international cooperation and transparency. While geoengineering presents a promising avenue to combat the adverse effects of climate change, it is imperative that any steps taken are well-informed, collaborative, and cognizant of the Arctic's unique vulnerabilities. Only with collective commitment and vigilance can we strike a balance between innovation and preservation, ensuring a sustainable future for the Arctic and the planet at large.

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