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Comparing Arctic Surface Albedo Modification Geoengineering Solutions

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ABSTRACT

As global warming continues, the trend of rapidly declining arctic sea ice is expected to increase. The albedo effect, a regulatory process in earth's climate, has become a positive feedback loop under climate change conditions. Sea ice has a high albedo, reflecting the sun's energy. As sea ice continuously melts, more energy is absorbed, reducing albedo and leading to increasing temperatures that continue to propel the cycle. With increasing concerns regarding the effects of climate change, focus has turned towards geoengineering solutions, which employ human intervention to slow or stop the effects of global warming. Regarding the decline in arctic sea ice, specific solutions that lower global albedo are examined. One of the first solutions was Arctic Ice Management (AIM), which proposed the use of wind-driven pumps to restore the thickness of melting sea ice. A more recent proposal was Glass Microsphere (GM) geoengineering, which involved the addition of reflective glass spheres to ice, increasing the albedo of the surface. Few studies have compared geoengineering solutions; a crucial step towards implementation. Using a mixed methodology of statistical and content analyses, GM and AIM surface albedo modification solutions were compared in terms of sea ice volume and risk factors. Results suggest that GM geoengineering displays a significantly higher capacity to preserve or increase sea ice volume, but is also associated with a higher number of risks compared to AIM. Further comparison of the two solutions is suggested, along with the implementation of climate solutions that combine both mitigation and geoengineering strategies.

Introduction and Literature Review

Earth's climate is warming, and the trend of rapidly declining arctic sea ice extent is expected to continue (IPCC, 2007). National and international organizations must make policy decisions regarding climate change as the steady increase of global warming becomes more apparent. Mitigation efforts, which attempt to limit the harm climate change causes without any direct intervention (IPCC, 2014), are becoming less beneficial as the effects of climate change increase. This trend is partially due to a positive feedback loop involving the albedo effect. As global temperatures increase, mainly due to anthropogenic greenhouse gas emissions, ice melts and Earth's surface experiences a decrease in albedo (Notz & Stroeve, 2016), or the proportion of light that is reflected by a surface. Decreased albedo leads to a greater absorption of the sun's energy into Earth's atmosphere, which leads to a warmer climate, resulting in one of the most severe positive feedback loops in Earth's systems (Manabe & Stouffer, 1980). Combined with the fact that ice sheets have become thinner over time (Comiso, 2012), arctic sea ice is declining rapidly. This phenomenon is the main reason that recent focus in the area of geoengineering, an engineering science that employs human modification of a natural system to combat climate change (Desch et. al., 2017), has turned towards arctic Surface Albedo Modification (SAM) geoengineering strategies. These strategies attempt to combat climate change by altering Earth's surface to lower global albedo and increase sea ice thickness (Stroeve et al., 2012).

This recent focus of climate geoengineering led to the release of the Arctic Ice Management (AIM) geoengineering strategy in 2017 (Desch et. al., 2017). The AIM paper introduced a novel form of arctic geoengineering, which employed clean-energy systems to optimize existing arctic sea ice fluctuations. This solution proposed using wind-turbine powered pumps to pull water up from beneath an ice sheet and spread that water over the ice sheet during winter months. This aimed to increase the volume, lifespan, and albedo of existing ice without chemically altering ice sheets. The paper's research and data collection presented AIM as a possibility to reverse climate change, employing many existing equations regarding climate data in order to create a new equation that optimized AIM. The data collected evaluated the best values for the thickness of the added layer of water and the amount of added ice needed to prevent ice from fully melting in summer. The summer sea ice minimum, or the time of maximum ice melt, is considered September. Using various calculations, the paper concluded that if the water pumped onto the ice sheet reached a thickness of 0.68m and was allowed to fully freeze before the process was repeated, just one additional meter of ice would help set climate change back by about 17 years. The paper also explained a basic design for the AIM device. This solution was the first in a wave of new climate data regarding SAM geoengineering, and how global systems would respond to the changes those geoengineering solutions create.

The proposal of the AIM solution led to a review and further evaluation of the effects of the AIM strategy. Published in 2019, two researchers at the Hemholtz Centre for Polar and Marine research in Germany collected data on the short- and long-term effects of AIM through use of the Alfred Wegener Institute Climate Model (AWI-CM) (Zampieri & Goessling, 2019). The study also determined how AIM would affect Earth's climate as a whole, rather than just looking at regional impacts, which allowed for greater conclusions to be drawn on the effectiveness of AIM geoengineering. Data collected from this study suggested that although the solution would increase sea ice lifespan and albedo, as predicted by Desch et. al., AIM would not have a great enough effect on temperature to significantly cool Earth's climate outside of the arctic; however, the source did prove that AIM postponed an ice-free arctic ocean by 66 (±6) years by increasing sea ice volume. Last, the source confirmed that AIM was an entirely reversible solution, meaning that if, after implementation, a disastrous issue appeared with this solution, AIM could be turned off and the effects could be completely reversed after about ten years. The possibility of using a SAM geoengineering solution, such as AIM, to postpone the catastrophic effects of climate change until a more permanent solution is established is an idea that has been heavily built upon in multiple reviews of geoengineering strategies.

A year after the proposal of AIM, many new targeted arctic geoengineering solutions were presented, including the Glass Microsphere (GM) geoengineering strategy. This strategy, published in 2018, discussed chemically altering sea ice to increase albedo, lifespan, and coverage (Field et. al., 2018). This alteration would be conducted through the application of "snow-like" K1 microspheres, a type of tiny, bright white silica bubble. A materials study within the paper and within the additional materials determined that K1 microspheres also mimic many of the properties of ice, such as density, color, non-toxicity, and others. Additional testing also determined the radius of these microspheres that had the greatest effect in increasing albedo. The proposed application of the solution is to spread the spheres over the surface of an ice sheet in late fall, where the microspheres will then be frozen into the ice sheet and prevent the sheet from melting in summer months. GM geoengineering was tested through both climate models and field tests, attributing a greater credibility to the information gathered in this source. The data gathered showed that temperature decreased by about 1.5 °C in a global model displaying effects of the treated ice, along with a multitude of other positive effects. This solution provided footing for further experimentation regarding geoengineering that physically alters components of an existing system, while other types of SAM geoengineering, such as AIM, had focused on optimizing an existing system.

A few years after publication, a review of the GM geoengineering solution was published within a larger paper. This study was created with the purpose of reviewing different types of geoengineering for implementation in the Canadian arctic by the Canadian government (Barclay, 2021). One of the sections of this paper focused on the GM geoengineering solution as a form of SAM geoengineering. The paper described this solution as a small-scale, reversible form of geoengineering compared to the much larger solutions in other types of geoengineering. The paper concluded that the use of the GM strategy, coupled with mitigation efforts, could act as a temporary solution for climate change by protecting the delicate balance of the arctic while a more permanent solution was being developed. This study cast doubt on the ability of any albedo-modifying solution to fully change the global climate, but it concluded that the GM solution could help stall arctic sea ice melt and thus slow down the warming of the climate, which would decrease the urgency of the situation and allow for research on a more permanent, holistic solution for climate change. This paper also suggested that since GM is fully reversible, it would be easier to implement than other, more permanent geoengineering solutions, where GM could act as a test for the implementation of geoengineering with the option of fully reversing the effects if needed.

The type of review used in Barclay has been replicated by several other authors for different purposes. In the last year, a comparative study was published that examined the political effects of different types of geoengineering (Moore et. al, 2021). This paper is much broader than previous reviews of individual solutions, and the types considered were entire fields of geoengineering. The "targeted arctic sea ice management" section considered SAM geoengineering, including both the GM and AIM strategies, and drew conclusions based upon scientific and economic feasibility, which were determined from existing research. The employed methodology, a combination of descriptive and analytical methods, is common in geoengineering review papers. In this case, it was specifically focused on how geoengineering solutions could be considered by governments and other policymakers. The study determined that SAM geoengineering solutions would have some positive effects, but there is considerable doubt about the global implications and lasting consequences of these types of geoengineering. By comparing fields of geoengineering rather than individual solutions within a field, this paper concluded that SAM geoengineering solutions are some of the lowest-risk strategies, as solutions within larger fields like solar geoengineering are often irreversible and difficult to test.

The surrounding research all leads up to the following question: using data gathered on sea ice volume and ethical factors, which of the AIM or GM arctic geoengineering solutions is more feasible for future implementation? The purpose of this research is to evaluate GM and AIM geoengineering in terms of sea ice volume and risk based on an analysis of existing research, with the goal of drawing conclusions that will aid in future policy-making decisions. Other sources have explained each of these solutions, but no source directly compares them in terms of scientific and ethical feasibility, specifically sea ice volume and risk factors. Based on conclusions from existing data, it can be predicted that since GM geoengineering involves the direct intervention of a new component to an existing environmental system, this solution will have greater effects but more severe consequences. Since the AIM strategy involves optimizing an existing system, it can be predicted that this solution will likely have less helpful effects, but also less environmental risks. This research is crucial because it provides a specific comparison between two types of arctic SAM geoengineering, and as the climate crisis is rapidly worsening, it is important to compare different possible solutions in order to make informed policy decisions. The scope of this project eliminates the possibility of gathering new data through an experimental method or modeling system, but by comparing existing data, new conclusions can be drawn about certain factors of AIM and GM. As AIM modifies the existing system while GM adds something new to the system, the conclusions from this research may also be applicable for other geoengineering solutions. It is also a common conclusion in this field that reversible geoengineering, if otherwise feasible, could be used to delay climate change while a better solution is reached.

Note. The extent of research on the GM and AIM strategies discussed, while very thorough, is limited by a small number of researchers and reviewers. This has resulted in a limited sampling of data sources for analysis. This paper attempts to maximize existing data and include all identified limitations to construct a credible perspective.

Methodology

In order to draw an accurate conclusion on the implementation of AIM and GM geoengineering, a mixed methodology data collection was used. This method consisted of two main components: a statistical analysis to compare the effectiveness of each solution on sea ice volume data, and a content analysis to determine and compare the risks of each solution. This method was used to provide the most accurate data and analysis possible from a limited amount of published research. The combination of a risk assessment and determination of sea ice volume effectiveness together provide a limited evaluation of the feasibility of each solution.

Statistical Analysis

The first portion of the method involved finding original, public-access raw data sets from climate models for both geoengineering solutions. For GM geoengineering, the reference section of the proposal paper (Field et. Al., 2018) contained available raw data. There was no accessible data within the proposal paper for AIM (Desch et. Al., 2017), so raw data was used from the paper that reviewed AIM using a climate modeling simulation (Zampieri & Goessling, 2019). Although these data sets were obtained from different climate models, there was enough overlap to allow for a comparison. The data set for AIM used the AWI-CM to model its results, while the data set for GM employed the more widely used National Center of Atmospheric Research Community Earth System Model (CESM). However, both research groups compared sea ice volume data gathered from their individual models to the widely accepted Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS). As both papers deemed that the data gathered was significant in accordance with PIOMAS, it was possible to make a comparison between these data sets.

After collecting data sets, the next step was deciding which values could be used to compare the solutions, as multiple factors are measured in climate modeling programs. Although comparing multiple variables would provide a conclusion with greater scope, the constraints of this study prevented the analysis of multiple variables. It was determined that the sea ice volume values in each of the datasets could be converted from three-dimensional climate data to two-dimensional, manipulable data. The units for each set were also feasible for conversions, so sea ice volume data was compared. The sets were compiled into a computerized spreadsheet program. For the purpose of statistical analysis, Microsoft Excel was used. Separate sheets were used for different data sets initially, all within the same file for organization. After conversions were complete and time-value labels were added, the two sets were combined into a single sheet. Conversions were completed through Excel, with both sets using the units km^3. Next, a comparable time period had to be found, as GM datasets measured the years 2000 to 2040, and AIM datasets measured the years 2020 to 2100. To maintain a comparison, the overlapping data from the years 2020 to 2040 was used.

Inferential statistics were used for this statistical comparison. Within Excel, the *t*-test formula was used to automatically statistically evaluate the selected arrays. This test measured the statistical difference between the datasets to determine if there was significant difference between the two. If the value was significant, average calculations were made for each set, and the set with the larger value was considered to have the greater impact on preserving or increasing arctic sea ice over time. If the difference was not statistically significant, it was concluded that each solution had the same feasibility for sea ice volume, or that neither solution had a great impact on preserving arctic sea ice in terms of volume. These values and considerations were compiled to draw conclusions on the feasibility of each solution in terms of sea ice volume.

Content Analysis

The second portion of the method involved a risk analysis, specifically, a conceptual content analysis, which determined the existence and frequency of concepts within a set of texts ("Content Analysis", 2022). This portion was used to determine the existence of possible risks surrounding each of the solutions with the goal of determining which has a higher overall risk. For the purpose of this research, "risk" is defined as the possibility of hazard or danger, specifically those risks that are directly caused by either AIM or GM geoengineering. Based on this definition, it was determined that certain language normally surrounds the discussion of risks in a paper that presents data, however, each paper was fully and thoroughly read through to avoid missing any outliers. For sample phrases, see Appendix A. This definition did not include risks discussed that were not caused by the solutions themselves. Multiple samples discussed the hazard of climate change going unsolved, but as this risk does not directly stem from either geoengineering solution, it was disregarded for the purpose of this study.

Samples for the content analysis were chosen from a limited number of existing sources based upon proximity to the discussion of AIM and GM geoengineering and credibility. Thus, papers that did not include the discussion of either AIM or GM were excluded, papers that were not peer-reviewed or cited by others were excluded, and papers with a main discussion of another type of geoengineering, such as solar geoengineering, were excluded, so as to avoid the inclusion of risks involved in types of geoengineering other than AIM and GM. Next, rules were set for the process of encoding each sample. To start, it was decided that the categories of the content analysis would be based around themes within the text, as basing this type of analysis around specific words or phrases may have led to some of the discussion of risks being coded incorrectly or being left out of the encoding process entirely. Thus, it was also decided that the categories had to be broad enough to avoid missing any of the risks listed by researchers, but specific enough to be differentiable. Because of the sheer spectrum of possible risks for each solution, it was decided that the categories would be flexible, allowing for the addition of categories after the initial list and throughout the coding process in an open encoding system.

The procedure of encoding was defined next. First, baseline categories were created based on initial research and the literature review. This process included referencing risk analyses for solar geoengineering (Robock, 2008) but excluded risks that were only applicable to solar geoengineering, such as risks involving irreversibility or scale. Next, these categories were defined and added into a new spreadsheet. Short names for each category were featured in the first column and definitions were placed in the second column. Sample names were listed in the topmost row.

Table 1. Initial Risk Categories and Definitions for Content Analysis.

Risk Category	Definition of Category
Weather/Climate Systems	This category will deal with the risk of a geoengineering solution having effects on the climate that are not just those of atmospheric cooling. This category may involve changes in storm patterns, increasing numbers and intensity of storms, changes in pressure systems, and changes in temperature.
Unexpected Consequences	This category will deal with the risk of a geoengineering solution having effects on the climate that are not predictable. This includes specific examples or a general statement that unexpected side effects may occur.
Wildlife/Biological	This category will deal with the risk of a geoengineering solution having effects on the environment that harm or may harm local wildlife. This category may involve the mention of a specific species, or a blanket statement that the introduction of a solution could have adverse effects on wildlife.
Change in Ice Properties	This category will deal with the risk of a geoengineering solution having effects on arctic ice itself that could cause harm to the environment or cause some unexpected event. This category includes chemical or physical changes to the properties of ice.

Development/Manufacturing	This category will deal with the risk of a geoengineering solution's development, manufacturing, or implementation process having worse effects on the environment than the solution itself could counter.
Breakage/Materials Malfunction	This category will deal with the risk of a geoengineering solution's physical materials breaking or malfunctioning in a way that could cause harm to the environment. This could be any part of the intervention itself breaking and resulting in adverse effects.

Description: A table containing the initial list of risk categories and definitions, defined before the encoding process.

The process of encoding each sample then began. A logical progression of encoding each sample was maintained in order to be as accurate as possible. The language surrounding different types of risks was varied, but general discussions of ongoing investigation or uncertainty, as well as key words such as “adverse”, “ill”, “consequences”, “damage”, “collateral”, and “unexpected”, were used to locate risks. However, not every risk contained any of these key words, and it was important to fully read and interpret every sample to avoid missing any outliers. Appendix A includes multiple examples of signal phrases for each risk type. If a risk was listed, it was marked with a “√” in the spreadsheet. If a risk was not listed, it was marked with a “.”. If a risk was described that did not fit into one of the existing categories, a new category was created. This procedure was repeated for the rest of the samples.

Upon completion of the encoding process, a frequency analysis was completed. Each sample was sorted into categories, either AIM or GM. If a paper contained discussion of both AIM and GM, it was separated into two different samples that were evaluated separately, and thus fit into one category or the other. Within each category, the number of sources that mentioned a certain type of risk was recorded, providing a frequency analysis for each type of risk within that category of geoengineering solution. A frequency analysis was also performed independent of category, with the goal of determining an overall risk factor. From these analyses, comparison and discussion were possible.

Results

Statistical Analysis

Data sets were gathered from public-access libraries. The process of downloading and converting these sets into a two-dimensional format is described in Appendix B. Values for sea ice volume, once converted, were described in km^3. The full process of converting data after formatting for sea ice volume is summarized in Appendix B.

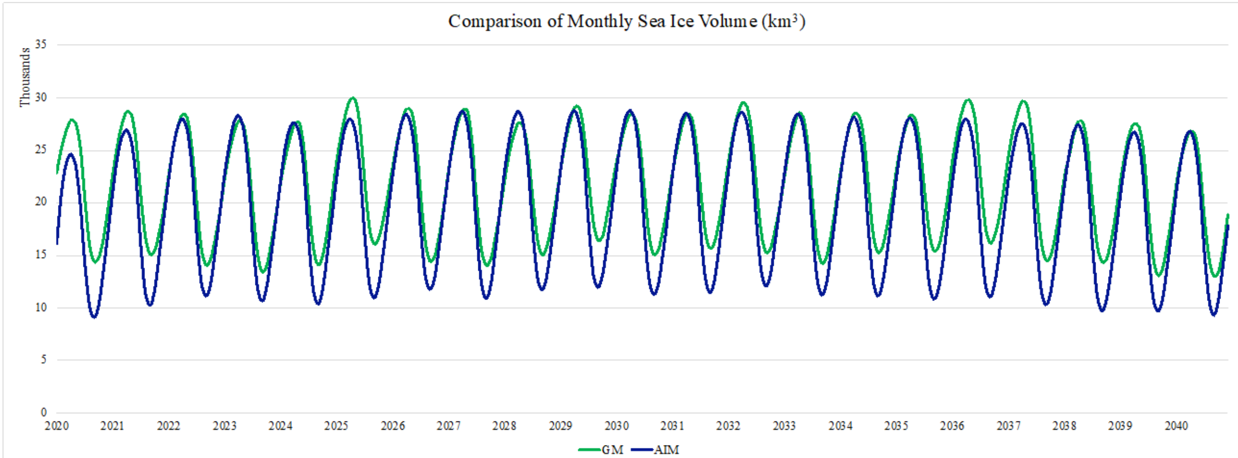

Figure 1. Sea Ice Volume in km^3 from 2020-2040. A graphical representation of sea ice volume (km^3) measured monthly from 2020 to 2040. The blue line shows data for AIM geoengineering; the green line shows data for GM geoengineering. Yearly fluctuations are shown as the valleys in the graph depict annual sea ice minimums (September) and the peaks depict annual sea ice maximums (March). As seen, AIM has consistently lower minimums when compared to GM.

Table 2. Statistical Analysis of Sea Ice Volume Datasets.

t-test *p* value	1.14625×10^{-48}
Average AIM sea ice volume (km^3)	19815.38
Average GM sea ice volume (km^3)	21863.55
Difference between averages	2048.17

Description: A tabular summary of the statistical analysis of the sea ice volume datasets shown in Figure 1. This table shows, the *t*-test value, average values of sea ice volume for AIM and GM, and the difference between the two averages.

First, it should be noted that the goal of this study is not to determine the magnitude of the difference between GM and AIM geoengineering for either risks or sea ice volume effects. Rather, this study seeks to determine if there is a significant difference between the two approaches in order to aid in future policy decision making and research surrounding the topic. The average values of each solution are taken for the sole purpose of demonstrating which study had the larger value and was thus more effective.

Table 2 shows the *t*-test value for sea ice volume data. As shown, $p < 0.05$, proving that there is a significant difference between the two datasets. This *p* value may seem extreme, but due to the conversion of three-dimensional data into two-dimensional data, a more extreme value is accounted for, and the conclusion drawn is still valid. Average values for GM and AIM in terms of sea ice volume and the difference between these averages show that GM maintains significantly larger sea ice volume over time, aligning with the higher sea ice minimums seen in Figure 1. This suggests that GM is more effective than AIM in preserving or increasing sea ice volume over time.

Content Analysis

A combined total of ten samples were collected for analysis, five for each solution. Although this number was limited by the novelty of the field of arctic geoengineering, especially in terms of altering surface-albedo properties, the depth and credibility of each sample upheld the validity of this study. For full tables of the encoding process, see Appendix C.

During the encoding process, two new categories were added. These categories are described in Table 4. Additional signal phrases for new categories are also listed within Appendix A.

Table 4. Final Risk Categories and Definitions for Content Analysis.

Risk Category	Definition of Category
Weather/Climate Systems	This category will deal with the risk of a geoengineering solution having effects on the climate that are not necessarily those of atmospheric cooling. This category may involve changes in storm patterns, increasing numbers and intensity of storms, changes in pressure systems, and changes in temperature.
Unexpected Consequences	This category will deal with the risk of a geoengineering solution having effects on the climate that are not predictable. This includes specific examples or a general statement that unexpected side effects may occur.
Wildlife/Biological	This category will deal with the risk of a geoengineering solution having effects on the environment that harm or may harm local wildlife. This category may involve the mention of a specific species, or a blanket statement that the introduction of a solution could have adverse effects on wildlife.
Change in Ice Properties	This category will deal with the risk of a geoengineering solution having effects on arctic ice itself that could cause harm to the environment or cause some unexpected event. This category includes chemical or physical changes to the properties of ice.
Development/Manufacturing	This category will deal with the risk of a geoengineering solution's development, manufacturing, or implementation process having worse effects on the environment than the solution itself could counter.
Breakage/Materials Malfunction	This category will deal with the risk of a geoengineering solution's physical materials breaking or malfunctioning in a way that could cause harm to the environment. This could be any part of the intervention itself breaking and resulting in adverse effects.
Timing/Overuse- Added by Sample 5	This category will deal with the risk of a geoengineering solution having adverse effects on the climate because of overuse of a solution or improper timing of the solution. This may be that the solution could be detrimental if applied at the wrong time, or that overuse of a solution creates adverse effects. This does not include solutions having a preferable time of implementation, the sample must state that adverse effects would occur if the solution was not implemented at a specific time.
Atmospheric Changes- Added by Sample 9	This category will deal with the risk of a geoengineering solution having adverse effects on the atmosphere at the place of implication. This could be the release of gas due to the geoengineering solution or other atmospheric effects.

Description: A table containing the full list of risk categories after the encoding process and definitions of each.

Table 5. Statistical Analysis of Risks Identified by Category.

Categories	AIM	GM

Weather/Climate systems	3	4
Unexpected Consequences	5	4
Wildlife/Biological	0	5
Change in Ice Properties	4	3
Development/Manufacturing	2	1
Breakage/Materials Malfunction	0	3
Timing/Overuse- added by sample 5	2	0
Atmospheric Changes- added by sample 9	2	2
Total Risk per solution	18	22
Average Risk frequency per category	2.25	2.75
t-test *p* value	0.28635758	

Description: Statistical analysis of risk factors when sorted by category. The table shows the number of risks listed in each category for the two different solutions, the total number of risks, the average number of risks per category, and the *t*-test value.

As shown in row 12 of Table 5, a *t*-test of the risk analysis after being sorted based on category reveals that there is no significant difference in the category distribution of risks for each solution, $p > 0.05$. This means that there is no significant difference in the amount of risk each solution has for each category. This does not verify any conclusion surrounding the risks of AIM and GM; however, because it is highly unlikely that each of the listed risks would be equally impactful, a further examination of each individual category led to more specific information for use in future research. For example, every sample for GM geoengineering mentioned some sort of environmental risk relating to wildlife and the arctic ecosystem, whereas none of the AIM samples brought up that risk. Over half of the GM samples also considered the risk of a malfunction with the implemented solution, but, once again, no risk was brought up in that category for AIM. A further inspection of geoengineering solutions in terms of specific risks could provide better insights on the consequences of geoengineering in the future.

Table 3. Statistical Analysis of Risks Identified by Sample.

Number of risks identified per sample	AIM	GM
Sample 1	4	4
Sample 2	4	5
Sample 3	3	4
Sample 4	4	4
Sample 5	3	5
Total	18	22
Mean	3.6	4.4
t-test *p* value	0.00806504	

Description. A tabular representation of the risk factor statistical analysis. This shows the number of risks identified for each sample, the total number of risks for AIM and GM, and the *t*-test value.

Note. Samples, for the sake of simplicity, are labeled as 1-5 for each category in Table 3. These numbers correlate to the samples in the full table, featured in Appendix C, so Sample 1 in this table would equate to the first sample of both AIM and GM in the full table, Samples 1 and 2.

The number of risks identified per sample, independent of category, is displayed in Table 3. Since $p < 0.05$, there is a significant difference between the total risk for each solution when examined independent of category. This verifies the alternative hypothesis, suggesting that GM geoengineering has a higher overall risk factor than AIM, although there is no significant risk in the category distribution of each.

Discussion

Based on the analysis of collected data, the following conclusions can be drawn:

1. GM Geoengineering displays significantly higher sea ice volume from the years 2020-2040. This suggests that GM geoengineering is more effective than AIM in preserving or increasing sea ice volume.
2. GM geoengineering has, on average, a higher number of identified risks than AIM when examining risks mentioned by existing researchers. This points towards the conclusion that GM geoengineering has a higher risk factor than AIM.

Limitations

The sheer extent of the topic at hand has led to several drawbacks in the employed methodology. It should be noted that there are many factors involved in decisions regarding geoengineering, even on the smaller and more reversible scale of SAM geoengineering solutions like GM and AIM.

When examining numerical data, there are many variables outside of sea ice volume that are used to measure the effectiveness of a geoengineering solution. This study attempts to simplify existing data on these two solutions in terms of sea ice volume and overall risk factors, but it does not attempt to provide an all-encompassing feasibility measure or discuss economic and political factors. This study also does not aim to predict any of the outcomes of either solution, just suggests general conclusions based on existing research.

As previously mentioned, there are a limited number of sources available for the scope of this study, but the extensive detail of each researcher and data set maintains the validity of this study.

For the analysis of sea ice volume, raw data was converted from two different sources. The data was manipulated to be comparable; however, the GM solution was at the end of its implementation while the AIM solution was at the beginning of implementation for the time period measured. Because of the yearly fluctuations in climate, it was determined that the results would not be valid unless a comparable time frame was created, but the differences in the level of implementation for the two solutions is a limitation of this study.

Future Research

To make future decisions surrounding the field of arctic SAM geoengineering, the magnitude of factors involved must be evaluated. Future statistical comparisons of AIM and GM in terms of different variables, such as change in surface temperature, average albedo, change in precipitation, and sea ice area could provide a more well-rounded determination of the feasibility of each study.

Another reason that these two solutions are important is because both have been determined to be, in past studies, fully reversible. A comparison of reversibility in terms of the same factors measured for feasibility could also be helpful in future policy decisions.

Future work on risk factor analysis should determine the magnitude of risk for each solution, either overall or in terms of specific variables. It is also likely that there are risk factors not discussed in this study, which should be examined in future research or testing.

Conclusion

In an ideal world, geoengineering would never have to be considered to combat climate change. Mitigation efforts should be made before turning to human modification, but with the alarming increase in the rate of climate change, lack of governmental response, and the determined "tipping point" (IPCC, 2021) moving closer, it may be necessary to resort to geoengineering. Previous research has determined that a localized, reversible form of geoengineering would be best in terms of ethical responsibility (Moore et.al., 2021), so comparisons of relatively small-scale solutions, such as the one performed in this study, are necessary to make informed policy decisions in the future.

Neither AIM nor GM geoengineering should be considered as sole solutions to climate change. This study does not advocate the implementation of either of the discussed solutions, but it does concur with the conclusions of years of research: the best approach to the urgency of climate change would be a coupled mitigation and geoengineering solution. Climate change is a large-scale problem that cannot be solved by a single solution, so by coupling efforts, the likelihood of slowing or reversing climate change increases, and negative effects are limited.

Ultimately, this study suggests two broad conclusions regarding AIM and GM geoengineering when compared with each other: that GM geoengineering maintains a higher level of sea ice over a 20-year period compared to AIM geoengineering, and that GM geoengineering has a greater overall risk factor than AIM. By converting large sets of numerical and descriptive data into general statements, this study attempts to aid in policy making decisions and future research in the field of geoengineering.

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