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Does Solar Geoengineering have any Scope in a Climate Emergency?

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Abstract

Geoengineering, also called climate engineering, has been considered as one of the major responses to avert the dangerous climate change along with adaptation and mitigation since 2006. Geoengineering, especially solar radiation management (SRM), is a technological approach to combat global warming by managing the incoming solar radiation. The claim behind the coinage of geoengineering as an option to avert dangerous climate change is that it can serve as an emergency mechanism if the earth crosses the dangerous tipping points due to the anthropogenic climate changes. However, this claim of the proponents is rigorously opposed by many scientists and ethicists. This paper tries to give an objective presentation of the current debate over SRM geoengineering as a policy option in a climate emergency. The paper is developed around the research question, does geoengineering carry any potential to avert a climate emergency scenario? This is answered by analysing the main streams of arguments made by the proponents and opponents with regard to the desirability or non- desirability of SRM in a climate emergency caused by the anthropogenic climate change? This question is tried to be answered primarily by a review of literature presenting and analysing the challenges and opportunities at stake in geoengineering as an emergency option. The literature exhibits a sharp divide between the proponents and opponents of the geoengineering technologies. A definitive judgement over its desirability or non-desirability is rendered ambivalent by the prevalent scientific uncertainties, inadequate data, insufficient field tests and the unprecedented scale and range of consequences of deploying such a technology with a global outreach in the open system of the earth. The literature presents an unsettled debate in this regard. Most of the second generation of ethical deliberation over geoengineering is inclined to reject the scope of SRM geoengineering as a policy option in an emergency scenario. The discussion argues that an informed decision on the scope of solar geoengineering in an emergency scenario demands geoengineering framings specific to emergency and the greater presence of emergency scientists on the debate is recommended.

Keywords: *Geoengineering, Solar Radiation Management, Sulphate Aerosol Geoengineering, Climate Emergency, Anthropogenic Climate Change.*

1. Introduction

The dynamic interplay between the opposite principles of *yin* and *yang* in the Chinese symmetry of the absolute - where when of the principles reaches its climate naturally retrieves to give way to the other opposite - offers an analogical model for representing the history of the human technological interaction with the earth. The industrial revolution and subsequent technological revolutions triggered the onset of the dangerous climate change and brought nature to the verge of the ecological imbroglio. On the other hand, the same science and technology that is blamed for the climate change is invited to explore a technological response to the climate change. The negative ambits of technology are now poised to retrieve in favour of the positive gamut of the technology. Geoengineering is to be conceived within such a dialectic of the historical interaction between technology and nature.

Though there were several artificial measures attempted over the history to control whether and natural environment, a full-fledged technological proposal to combat climate change has its beginning in the various proposals branded under geoengineering. It all began with the paper by Nobel laureate Paul Crutzen [17] in 2006 proposing geoengineering as a technological option to combat climate change, though he was keen to present it as a choice of lesser evil. Crutzen referred to solar radiation management by deploying sulphate aerosol particles in the stratosphere to reflect the incoming sunlight back to the space. Crutzen's proposal generated a lot of heat among the scientific and ethical communities and it triggered an acrimonious debate on the scientific feasibility and ethical desirability geoengineering. Though the prospects of any consensus among scientists, ethicists and policy makers still seem very dim, it has helped geoengineering to move from a fringe discipline to one of the mainstream proposals to combat climate change. Accordingly, it found inroads into the climate assessment reports of the IPCC (*Intergovernmental Panel on Climate Change)* in 2014 [33]. The potential prospects and perils in geoengineering as an emergency response makes it an unprecedented technology that deliberately and foundationally manipulates the earth. Of late in 2023, Climate Overshoot Commission which was launched in 2022 to propose comprehensive strategy to reduce climate risk recommended researches in carbon dioxide removal from the atmosphere and solar radiation modification as potential policy portfolios to avert dangerous climate change. Once deployed it is likely to drag the anthropogenic impact on earth to completely unprecedented levels [15].

A 'magic bullet' [73] against climate change, and 'emergency brake,' [74] are some of the metaphors that betray the technological hype accompanying geoengineering. Whereas the opponents have the other extreme coinages like a 'brute force' [32] and the 'geoengineering taboo'. [45] The focus of this essay is on the scientific feasibility and ethical desirability of geoengineering as an emergency response to combat climate change. Although geoengineering refers to a broad range of technologies, solar radiation management is the most relevant form of technology from the emergency point of view. Accordingly, this paper is focused mostly on compiling the merits and demerits of solar radiation management as an emergency response, as claimed by the proponents and opponents. However, an overview of the various geoengineering technologies is offered in the beginning to give a general picture about geoengineering to the beginners on the topic.

It needs to be clarified at the outset that the very emergency-framing of geoengineering is questioned by several scholars. However, upon scrutiny of the arguments it could be noticed that this questioning is a negation of the emergency merit of geoengineering rather than the negation of the element of emergency in geoengineering debates. The emergency framing of the SRM was dormant in the in the trend-setting paper by Nobel laureate Paul Crutzen in 2006 where he presented SRM as a lesser evil or as a last resort option. Although the merit of SRM as a last resort option is refuted by many scholars including the Royal Society, most proponents are inclined to find a greater ethical force pushing ahead geoengineering in an emergency scenario only. SRM was not conceived in the first place for an emergency scenario. However, many proponents find the desirability of SRM only in a climate emergency. As such, the emergency framing underlies the dominant streams of argument for geoengineering. It needs to be distinguished between the questionable merits of SRM as an emergency policy portfolio in the debate and the presence of SRM as an emergency option in the literature.

Accordingly, the first part of the paper explains what is geoengineering. The second part explains the review methodology of choosing the relevant references on geoengineering and climate emergency. The third part presents the results of the review and the final part highlights some findings and observations on considering geoengineering as an emergency tool for combating dangerous climate change.

What is Geoengineering?

The term geoengineering conventionally refers to geological practices such as making of artificial islands, making of dams, etc. However, in the modern sense it refers to climate engineering by means of Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) scheme of technologies. As the literature popularly coins the term geoengineering, this essay also uses the term geoengineering in the sense of climate engineering. This section dwells briefly on the definition, history and various schemes of geoengineering.

Geoengineering or climate engineering refers to a set of pioneering technological proposals to combat climate change through different approaches and techniques. Though the term geoengineering was in use for long, it entered the Oxford dictionary in 2010. [5] The following table presents the leading definitions of geoengineering. The table lists the different definitions given by leading international bodies who have conducted researches on geoengineering.

Table 1: Geoengineering Definitions

Year	Source	Definition
1992	The US National Academy of Sciences Panel on Policy Implications of Greenhouse Warming	(L)arge-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry [56].
2009	American Meteorological Society (AMS)	“Deliberately manipulating physical, chemical, or biological aspects of the Earth system.” [2]
2009	Royal Society	“The deliberate large-scale intervention in the Earth’s climate system, in order to moderate global warming.” [64]
2010	IPCC	Endorsed Royal Society’s Definition

It could be noted here that the individual definition of the renowned geoengineering scientist David Keith has been influential in shaping the organisational definitions. Keith defined geoengineering as, intentional large-scale manipulation of the environment. [39] Among these various definitions, the one given by Royal Society is more commonly accepted as a standard definition of geoengineering. In order that a technical intervention be considered as geoengineering, it must meet the conditions of being intentional, large-scale and must be directed to combat global warming. In that regard climate change due to fossil fuel burning or ornamental gardening cannot be treated as geoengineering.[39] In contrast to mitigation and adaptation that warrant change of life-styles, geoengineering is a pure high-technology approach. [54]

Making a precise formulation of geoengineering is rendered difficult by various factors. Owing to the differences in the emphasis on a set of technological schemes, geoengineering especially in the initial years of its emergence was also called planetary engineering,[29] climate engineering,[9] climate modification, and earth systems engineering.[53] The variations in emphasis and focus do not allow an easy framing of a uniform definition of geoengineering. Yet another ambiguity prevalent in defining geoengineering pertains to the subset of technologies of geoengineering. It is commonly agreed that the geoengineering schemes can be broadly classified under two categories, viz., SRM and CDR. Although the definition of geoengineering assumes certain parameters, there is no consensus among the scholars as to which all techniques fall under the two major schemes of geoengineering mentioned above. Another semantic ambiguity in this regard is the coinage of geoengineering referring exclusively to SRM. A review conducted in 2019[58] showed that there is a sheer imbalance in the ethical analysis of the SRM and CDR technologies as nearly 70% of the papers focused on the ethics of SRM alone. It can be seen that leading definitions of geoengineering also assumes a conceptual preference for SRM techniques.

History of Geoengineering

Although geoengineering as a proposed scientific response is a recent contender, the history of similar attempts for controlling and regulating the weather could be traced several centuries down the line. The first coinage of the term geoengineering is attributed to Cesare Marchetti, an Italian physicist, who in 1977 used it in the climatic context referring to a proposed method of removing CO_2 in the atmosphere by sinking the same into ocean currents. [48] In the 1970s, Mikhail Budyko, a Russian climatologist, proposed the ideas of modifying the climate by increasing the concentration of aerosol particles in the stratosphere. [11]

Geoengineering proposals received a major shot in the arm in in 1991 when Mount Pinatubo in Philippines erupted in 1991. The eruption of the volcano diffused millions of tons of ashes across the atmosphere acting as a sort of aerosol cloud. Studies showed that it led to significant reduction in the solar radiation absorbed by the earth. [27,76] It gave the scientists a natural model as to how the increase of earth's albedo can result in the reduction of global warming. Geoengineering scientists found a confirmation of the effectiveness of the SRM schemes in the Mount Pinatubo effect. Followingly, there was a proposal for stratospheric burning of Sulfur by the Russian scientist Yuri Izrael in 2005. [21] The momentum for geoengineering was further accelerated by the predictions of environmental scientists like Lovelock [46] and James Hansen [26] that earth has been crossing the tipping point or it has already crossed. Thus, the stage was already well-set for the publication Crutzen's paper in 2006. International conferences on geoengineering by reputed science and research bodies became a regular trend. In 2009, a special report on geoengineering was brought out by the Royal Society of London. [64] 2020 saw the US Congress approving $4M to David Fahey, senior scientist at the US National Oceanic and Atmospheric Administration, for researches on sulphate aerosol geoengineering and cloud whitening techniques. [20]

The following table offers a chronological summary of the major events and factors related to control of weather and climate change that led to the present debate over geoengineering.

Table 2: Milestones in the History of Geoengineering

Year	***Agent***	***Description***
1841	James Pollard Epsy	Proposes connections between volcanic eruptions and rain and suggests great fire can make rain.
1896	Svante Arrhenius	Proposes the link between the rise in temperature and CO_2
1901	Ekholm	More researches on CO_2 and temperature rise
1932	USSR Rainmaking Institute	Solid CO_2 used for cloud seeding
1938	Stewart Callendar	Advancements in CO_2 Theory
1946	General Electric Research Laboratory	Cloud Seeding Researches
1950	Langmuri	Cloud seeding and 'atom bomb' analogy
1956	General Electric Research Laboratory	Experiments with Ice-crystal formation
1960-1961	Leningrad's Institute of Rainmaking	Cloud seeding proposal in in USSR
1960	M. Gorodsky and V. Cherenkov	Space based aerosol injection proposals
1967-72	US Military	Project Popeye and Operation Motorpool
1970	Cesare Marchetti	"geoengineering" coined informally
1978	UN	ENMOD
1980s	L. Francis Warren	Universal System of Weather Control
1983	Thomas Schelling	Proposal for SAI
1984	Stanford Solomon Penner	Proposal for albedo enhancement of the earth
1988	John Martin	Proposals for ocean fertilization
1988	Klaus Lackner	Proposal of 'artificial trees'
1989	James Early	Concept of Solar shield
1991		Mount Pinatubo eruption
1992	US National Academy of Sciences	Recommends climate engineering
2003	Pentagon	Recommends climate engineering
2003	Tyndall Centre for Climate Change Research	Various climate engineering designs
2005	Yuri Izrael	Plans for stratosphere sulphur burning
2006	Paul Crutzen	Editorial in *Climatic Change*
2007	American Academy of Arts and Science	Climate engineering conference
2008	China	Cloud firing before Olympics
2009	MIT	Climate engineering conference
2009	Izrael	Climate engineering field test
2009	Royal Society	Report on climate engineering
2013	IPCC	Mention of climate engineering in the Fifth Assessment Report
2015	US National Academies	Major report on Solar Geoengineering
2018	Harvard University)	SRM research initiatives by leading research institutions including Harvard University
2019-22	NOAA	$22 million investment for SRM researches.

2021	US National Academy of Sciences	Recommendation of \$100–\$200 million over five years for SRM researches
2022	Climate Overshoot Commission	The commission could consider policy portfolio of certain forms of SRM in its various recommendations for reducing climate risk
2023	Climate Overshoot Commission	Proposes that Carbon dioxide removal from the atmosphere and Solar radiation modification should be researched.
2024	UN Environmental Assembly in Nairobi	African countries call for the non-use of solar geoengineering

Geoengineering Schemes

The application of the proposed geoengineering technologies ranges from the planting of trees at the bottom to the giant shields placed in space. All technologies collectively taken can be said to have a global range of application covering the regions of land, ocean and the space. These technologies have designs for deserts, rooftops, polar ice, seas, deep oceans, underwater, clouds, stratosphere and space.

As mentioned above, the most conventional division of geoengineering technologies is into SRM and CDR. What is common to both SRM and CDR is that they operate with a reduction goal. SRM reduction plan targets the reduction of the intake of the sunlight by the earth, whereas CDR aims at the reduction of the concentration of the CO_2 in the atmosphere. They are also respectively called short-wave and long wave geoengineering where short wave refers to solar radiation and long wave to thermal radiation. Interestingly, SRM is said to be endowing the sun with a dimmer switch! [72]

SRM schemes are founded on the central principle that global warming can be confronted by increasing earth's reflexivity. This is achieved by managing various radiations. The surface based schemes for managing radiation and thereby increasing albedo include painting the roof-tops white, brightening the urban settlements, placing mirrors in the deserts, and brightening croplands, pavements and roads. [1] Modified plants or artificial trees can also increase the albedo of the land. Cloud albedo enhancement schemes proposes to disperse sea salt into clouds over the oceans to increase their brightness. The science is that as the salt crystals grow bigger by sucking moisture they reflect more sunlight. [64]

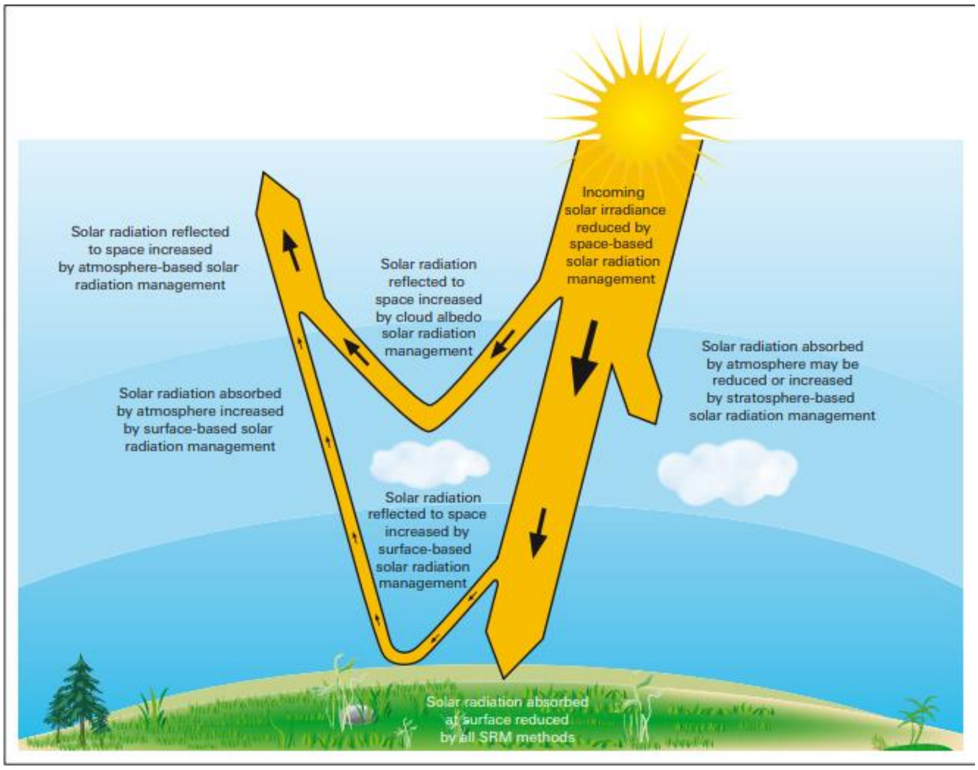

Figure 1: Impact of Different SRM schemes on solar radiation fluxes. Adapted from Royal Society 2009, p. 23.

However, the most contentious technique under the SRM scheme is the stratospheric sulphate aerosol geoengineering (SAG). After the model of the Pinatubo effect, this scheme envisages releasing huge amount of aerosols in the stratosphere. [17] It is proposed to create a Saturn-like ring with aerosol particles. This can be achieved by specially designed aeroplanes. The artificial aerosol cloud reflects more sunlight and thus limits the intake of the sunlight by the earth. There are also more hypothetical proposals like placing huge space mirrors in a low orbit. The objective is the same to divert the incoming sunlight. Satellites will be taking guard of these space mirrors. Understandably, Royal Society does not find a realistic prospect for this proposal and does not consider it to potentially contributing anything realistically. [64]

Table 3: CDR Methods[64] (Adapted with modification from Royal Society 2009)

	Biological	Physical	Chemical
Land Based Techniques	Afforestation and land use	Atmospheric CO_2 scrubbers ('air capture')	*In-situ* carbonation of silicates Basic minerals (incl. olivine) on soil
	Biomass/fuels with carbon sequestration	*In-situ* carbonation of silicates	
		Basic minerals (incl. olivine) on soil	
Ocean Based Techniques	Iron fertilization	Changing overturning circulation	Alkalinity enhancement (grinding, dispersing and dissolving limestone, silicates, or calcium hydroxide)
	Phosphorus/nitrogen Fertilisation		
	Enhanced upwelling		

There are CDR techniques that are land based and ocean based. Depending the on the type of their intervention, they may be further classified as biological, physical and chemical schemes. In the land based scheme scrubbers are proposed to capture CO_2 from air and CO_2 can be absorbed on solids or into alkaline solutions. [64] In another method known as 'bioenergy carbon sequestration,' biomass is used as fuel and the CO_2 produced in the process in sequestered. [64] In the 'enhanced weathering' scheme, the natural reaction process of silicates with CO_2 is accelerated by adding, for example, olivine to agricultural soil. It increases the formation of the carbonates in which carbon is consumed. This is a chemical approach to reduce the measure of carbon concentration in the atmosphere. [64]

In the ocean based CDR scheme, nutrients like iron or nitrogen are added to the ocean to enhance the growth of phytoplankton which can store carbon in their cells. The carbon in their cells is sequestered at the bottom of the ocean as they die. [64] Upwelling and downwelling of the ocean, another ocean based CDR approach, is based on the same principle that overturning the ocean currents can increase the amount of nutrients in the ocean to facilitate the growth of phytoplankton. [64]

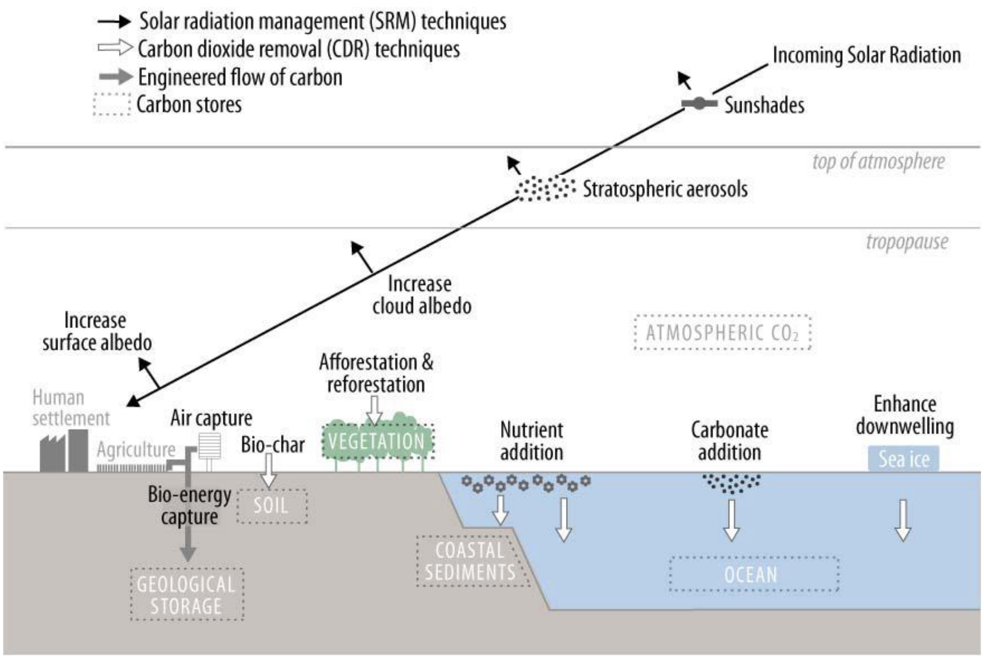

Figure 2: Schematic picturing of various SRM and CDR techniques. Adapted from T. M. Lenton and N.E. Vaughan, "The Radiative Forcing Potential of Different Climate Geoengineering Options," *Atmospheric Chemistry and Physics*, vol. 9:15 (2009).

2. Methodology of Review of Literature

The main approach of this paper is to approach the research question on the desirability of geoengineering in a climatic emergency through a review of literature. Accordingly, search was conducted on the Google Scholar with a set of primary and secondary search words on March 25 and 26, 2023. Primary search words were geoengineering, climate engineering, solar radiation management, carbon dioxide removal and solar geoengineering. Geoengineering and climate engineering were chosen as they are synonymously used in the literature. The choice of solar radiation management and carbon dioxide removal as primary search words is justified as they are the two major subdivisions of geoengineering schemes. Solar radiation management is also coined briefly as solar geoengineering or as SRM in the titles of the papers especially in recent literature and accordingly they also were listed under the primary search words.

The secondary search words were chosen with the precise objective of choosing those papers that deal with the debate on geoengineering as a potential response to avert a climatic emergency. Accordingly, 'emergency' and its variants such as catastrophe and disaster were used as the secondary search words. The semantic variants of catastrophe and disaster such as 'catastrophic' and 'disastrous' were also used as secondary search words. The primary and secondary search words were used in combination as they appear in the title of the article. A paper is qualified for selection if only both primary and secondary search words are figured in the title of the article.

The search produced 50 hits from all combinations. Some combinations of the searches did not produce any hits. 17 citations, and 5 overlapping papers were pruned out in the first round of the selection process reducing the number of papers to 28. The abstract of the chosen 28 papers were skimmed through to ensure that they dealt with geoengineering in the sense of climate engineering. Thus 5 papers were found to be not related to geoengineering and climatic emergency and eliminating them, the number of papers came down to 23.

A second round of search was conducted on the database ScienceResearch.com on April 4, 2023 using the same combination of primary and secondary search words. It returned 48 hits. The overlapping entries with the first search were eliminated and it resulted in the addition of 3 more papers to the selections from the first search. It took the tally of papers now to 26.

Table 4: Search Words

Primary Search Words	Secondary Search Words
Geoengineering Climate Engineering Solar Radiation Management Carbon Dioxide Removal Solar Geoengineering. SRM	Emergency Disaster Catastrophe

Table 5: Results per Combinations of Search Words.

Primary Search Words	Secondary Search words				
	Emergency	Disaster	Catastrophe	Disastrous	Catastrophic
Geoengineering	13	6	5	0	0
Climate Engineering	9	9	2	0	0
Solar Radiation Management	0	0	0	0	0
Carbon Dioxide Removal	0	0	0	0	0
Solar Geoengineering	4	1	1	0	0
SRM	3	0	1	0	0

As clear from the above table, the first and second searches on google scholar and ScienceResearch.com did not yield a comprehensive list of references for a systematic review of the emergency merit of geoengineering. This is understandable as geoengineering is an emerging field of academic research and all the more due to the specific focus on the emergency merit of geoengineering in the search.

Upon examination of the selected papers and skimming through the references listed in the list of selected papers, it was found that several important papers dealing with the emergency value of geoengineering in combating dangerous climate change were missing from the list of selections. There the snowballing methodology was retorted to in adding a number of additional references to the selected list. The papers that are frequently referred to by the leading authors in the discussions on geoengineering were selected through snowballing method. The reports and studies on geoengineering by international bodies such as IPCC and Royal Society were also selected through this method. Thus, an addition 40 papers were added through the snowballing method. This took the total tally of references to 66.

In summary, 23 sources were selected from the first search on Google Scholar, 3 from the second search on ScienceResearch.com and an additional 40 sources were added through the snowballing method taking the total tally of papers to 66.

3. Results

The form of geoengineering that is most relevant from the emergency point of view is the stratospheric aerosol injection. As proven in the natural model of the Pinatubo effect, it has the immediate result of reducing the amount of incoming solar radiation and thereby of containing global warming. This possibility has led some proponents to consider aerosol injection as a reliable emergency response. The following section will present the debate over SRM through SAG as an option for confronting a climate emergency. The arguments for SRM geoengineering as a response to climate emergency is presented first followed by the arguments against it. The listing of the references under an argument does not reflect the opinion of the individual authors on the topic under discussion, rather it only suggests that the listed paper engages with this argument in some depth. It may be noted that some authors engage with an article only to criticise it.

SRM as Desirable in Emergency

Crossing the Threshold: The proponents argue that the recourse to a rigorous technological scheme like aerosol injection in the stratosphere is warranted by the alarming state of affairs that that the earth has crossed several tipping points. [16, 18, 25, 72]

Conversely, a crucial phase transition for the earth is in the offing. It is crossing the climate threshold of the earth. Crossing the climate threshold could be a point of no return. In this scenario, what would be a reasonable scientific response? The returns from the various mitigation policies and the non-compliance with the international climatic protocols including the Kyoto and Paris protocols do not offer a promising scenario of averting the climate change through orthodox means. In that regard, a commitment to the earth and the future of the life on earth is to have recourse to unprecedented measures of technological interventions that can yield immediate results. Hence the need for deploying a stratospheric geoengineering scheme such as sulphate aerosol injection. [29, 30, 41, 42] Accordingly researching and developing geoengineering is necessary. [7]

Imbalance in the Radiation Budget: The sub-variants of the arguments related to climate emergency revolve around various scientific factors. The carbon concentration in the atmosphere need to be contained below 350 ppm. If the anthropogenic emission of greenhouse gases results in excess of 350 ppm CO_2 concentration, it adversely affects the climate sensitivity of the earth by shooting it up over 4 K. The natural corollary of CO_2 concentration above 350 ppm and climate sensitivity being over 4 K is that the it causes imbalances in the radiation budget of the earth. It is feared that current concentration of CO_2 is 400 ppm. [47] Conversely, imbalances in the radiation budget of the earth makes global warming over 2^0C from the pre-industrial revolution phase. The final fiasco awaiting this scenario is a series of catastrophes including the extinctions of several specie including the human. It is hoped that SAG can restore the climate system to pre-industrial states within years after its deployment. [40, 44, 49, 51, 66]

Failure of Conservative Solutions: It might occur here that in this scenario what is important is to reduce the CO_2 concentration instead of controlling the solar radiation. This would seemingly suggest a recourse to CDR schemes over SRM. However, history is testimony that conservative solutions that require change of life-style are not feasible at an international level. Mitigation implies a cruel irony[61] of the prisoner's dilemma – a moral dilemma of obtaining group benefits by individual cooperation or non-cooperation.[61, 75] The pragmatism of the current global culture fixed on immediate and proximate benefits and results is unprepared for radical and authentic solutions. Climate problem remaining an absent problem [52] – where the impacts are not immediately visible – further aggravates the non-committal attitudes of the masses. The resistance from individual nations to reach at a consensus and the failure of the Kyoto and Paris protocols to achieve their target does not assure the effectiveness of such single handed solutions though they are real imperatives. Hence what is required is the balancing of the radiation budget of the earth. Radiation budget can be balanced by manipulating the short wave radiation through stratospheric interventions through aerosol injections. [55]

Imminent Emergency: That climate emergency is not a remote danger, rather an imminent problem is argued to be substantiated by scientific findings. There are reports suggesting that the current CO_2 concentration in the atmosphere is about 380 ppm and it is still mounting up. Hence there is urgency to balance the radiation budget within a decade or so. This cannot be achieved by CDR schemes which are slow in yielding the results and it wold take a long term to bring down the CO2 concentration below 350ppm. [3, 6, 9, 13, 25, 52, 61, 64, 65] If the radiation budget is not well-balanced within a short term environmental consequences such as the acceleration of the melting ice sheets, consequent sea-level rise and the loss of cities in coastal belts are sure to follow.[3, 25, 39] Studies in climate history have shown that even a slight increase in global temperature can lead to massive loss of continental ice sheets.[3] There is a justifiable fear that climate sensitivity is exceeding 4 K.[2] Unlike the absent nature of the climate change in the past decades, this is now becoming a tangible danger. [3,25,61] Extinction of even human species due to climate change is not a wild imagination. [4, 67] Some studies suggest that 15-37% of the present might go extinct by 2050. [67] Hence the urgency of countering the effects of excess CO2 concentration through balancing the radiation budget. [6]

Window-Period for Averting an Emergency: Given the slow rate of the impact of mitigation strategies, SRM can buy time for mitigation to take effect. [3, 25, 64] As SRM can delay the unabated sudden consequences of a sudden climate change and it allows sufficient time for being prepared for combating the dangerous consequences of an emergency. Thus, SRM can be a band-aid to avert the sudden climate change. [3] SRM is a smart way of being ready in anticipation of a climate emergency. Thus, it is described as a contingency plan to be readily kept ready [9] for deploying in an emergency. This argument is in consonance with the other metaphors used for SRM such as insurance policy for climate dangers and Plan B.[30] One author describes it as an emergency tool to avert massive biotic disruption.[52] Contrary to the moral hazard critique of geoengineering that it might water down the efforts at mitigation, it is argued that a technical intervention like stratospheric injection would generate greater awareness about the gravity of the climate change and thus it would trigger a sense of emergency about climate change in the public to combat it.[35, 36, 52, 68]

Self-defence in Climate Emergency: SRM in its most crucial scheme of stratospheric radiation management is invoked in the debate as defending the causes of the nation's most vulnerable to climate change, especially the small and the island nations. [43] Termed as the desperation argument, it holds that in the desperate circumstance of a climatic catastrophe, the small island nations who will be made immediate victims could save themselves if they have researched and developed SRM. The technological feasibility that SRM can be deployed unilaterally by any individual nation seems to further endorse this case. This is also called Tuvalu syndrome in the literature, where the small nations like Tuvalu or Maldives might unilaterally start researching and developing SRM given the gravity of the climatic risks they are exposed to. [34] The self-defence rhetoric of the argument coupled with the easiness of unilateral deployment with no need for an informed consent from various parties is argued to be making SRM a natural choice in a climate emergency. Parametric insurance is proposed as a mechanism to reduce the risks to facilitate cooperative decision making. [31] International cooperation in governance and regulation can be achieved by developing proper mechanisms under the UN with necessary pooling of funds. [50]

Analogy of Emergency Medicine: The example of administering severe dosages of medicine to a seriously sick patient is used in the debate as justification for recourse to SRM. One of the influential metaphors identified in geoengineering discourses is that our planet is a patient.[57] Considering earth and many organisms on it to be on the verge of extinction, one has to break the rules of convention and go for extreme measures to save the planet.[9] The proponents argue that earth would be akin to a terminally sick patient by 2050 and it calls for setting aside the conventional precautions and standard practices taking recourse to extraordinary measures. In such a scenario of earth-emergency, SRM will be justified as a lesser evil.

Emergency and Feasibility: A justificatory rhetoric that is recurrently appearing in the debate for SRM is the feasibility of developing and deploying it in an emergency. There are several angles to the feasibility argument in geoengineering in general, but here we focus only on those feasibilities relevant in the scenario of a climatic emergency. Unilateral research and development, and deployment by individual nations or a small group of nations without the hurdles of international consensus and extensive consultation is projected to be making SRM a feasible option in case of an emergency. It is branded as the do-it-alone argument.[9] Decision making is simple from the administrative point of view avoiding complex institutional and international parameters.[52] The effectiveness of SRM is confirmed in that it is cheap, fast and efficient and modelled after the natural phenomenon of volcanic eruptions.[60] One study claims SAG would cause only less harm than mitigation.[71] There are also extreme claims that cost-benefit ratio in SRM is 1000 to 1[70] and it is cheap and quick to be invoked in an emergency.

Why SRM is not Desirable in an Emergency?

Sudden Termination and Double Catastrophe: One of the most crucial challenges involved in SAG is the termination problem that a sudden stoppage of SRM will lead to the temperature bouncing back at a higher pace. This would imply pushing onto future generations the burden of carrying on with the SAG. It would imply subjecting the future generations to the burdens of the luxurious ways of life of the present generation. [13,70] The scientific estimation is such that if SRM is launched, it will have to be sustained for 500 to 1000 years. It is possible that several unforeseen factors can lead to a sudden ttermination of SRM. Policy issues or ethical reasons also could lead to the discontinuation of SRM. [[70,71] It can lead to a worse-case scenario of climate change. [4,6] The scenario of a double catastrophe such as a natural calamity might halt SAG first and the resultant rise in temperature might bring in a series of other calamities. [4] Such scenarios could lead to the extinction of the species itself. This leads to the argument that the worst state of affairs without SRM might be better than the worst state of affairs with SRM. [6, 22]

Dangerous Side-effects: The known and unknown side-effects of SRM through SAG is a major factor challenging the efficacy of this technological scheme as an emergency response. Predicted side-effects of SRM include reduced global precipitation, monsoon irregularity, problems of acid deposition, and the death of the Amazon forests.[62, 63] These side-effects conversely causes scarcity of food and water in some parts of Asia and Saharan Africa.[3] Southeast Asia will invite drought and the flow of Ganges and Amazon will be significantly slowed down.[10, 13] The reduction of sunlight from SRM through SAG can adversely affect solar power production, and optical astronomy, apart from the issues resulting from implementation impact such as pollution, debris, etc. The sulphate particles deployed could be falling back on earth and the highly concentrated wash-out sulphate particles, [13] can be expected in polar regions which will have serious consequences for the ecosystems there. The net productivity of North America could go down by 50-100%. [13] SRM using space mirrors can cause tracking problems replacement issues, going out of orbit, huge orbital debris, etc. [13]

Irreducible Uncertainties: The debate over the emergency desirability of SRM is loaded with huge scientific uncertainty, some of which are irreducible in nature. Basic parameters for policy making like the duration of deployment, its harms, benefits, outreach, impact, etc., are permeated with uncertainties.[3, 4, 19, 39, 62, 63] As regards space-based schemes Royal Society was not hesitant to conclude that due to uncertainties of time scales and effectiveness, space-based approach cannot be considered to be anything beneficial for combating climate change in a short term.51 Cascades of uncertainties and the risk-proneness in SRM do not qualify SRM to be a reliable scientific technique.[8, 34]

The Complexity of the Earth-system: The earth-system is so complex that tampering with or intentional manipulation as in SRM may invoke unknown harms at a global level for this is a technology with a global outreach given its open-ended exercise. There could be consequences that are irreversible especially because of the non-linear nature of ecological systems. [19] This is related to presumptive argument against SRM. Presumptive argument recognizes the earth's complexity and is deeply sceptical about the ability of scientists in managing it. [59]

Only Partial Offset: Yet another criticism that delegitimises SRM as a viable method to confront a climate emergency is that it only offsets the danger quite partially and temporarily. It lacks a comprehensive approach to control the thermostat. [6, 12, 23, 70] In albedo enhancement, vital issues such as the CO_2 concentration in the atmosphere are ignored. As a technological intervention, geoengineering is only biopolitical paradigm of technology.[38] Critics argue that it is not to be researched as it is not a sustainable solution.[14, 69] Further, the cost-benefit claims are not founded on adequate researches and it does not take into account the indirect cost such as compensation.[24, 28] Hence instead of going for quantitative consumerist parameters in policy making, what is needed is a qualitative move towards simplicity for the sustenance of human existence on earth.[37]

4. Discussion

In this section we will return to the research question, *does geoengineering carry any potential to avert a climate emergency scenario?* The challenges and opportunities at stake in solar geoengineering as available from the results of this review form the data with which we answer the research question. However, it needs to be acknowledged that a straightforward answer at this point is not a definitive yes or no. Although an amateur reading of SRM promises may give an intuitive yes to the exclusively flowery rhetoric of the claims of solar geoengineering as an emergency mechanism, it does not withstand the test of a scholarly critical scrutiny. As one is also introduced to the potential risks and harms of this technology, the excitement gives way to a cautious scepticism. However, as the literature also warns about the chasm between the ideal plans like mitigation and adaptation and the plain ground reality of the poor yield from such measures, pragmatic rationality seems to carry the suggestion that the counter-rhetoric must outstretch the cautious scepticism to an outright negation of this technological scheme. For, the observations of the earth having crossed the dangerous thresholds or about to cross further tipping points - though the details of these claims are still matters of contention - there is a consensus among the scientific community that the dangers of climate change are now vivid and imminent.

As the results from the searches using the keywords related to emergency have shown, there is very little research done on the merits or demerits or SRM in the context of an imminent climate emergency. Although the emergency rhetoric is apparent in the debate, the mainstream debate has dwelt less on the emergency and is focused more on the issues of justice, lesser evil, moral hazard, etc. In a climate emergency scenario, the likelihood of science having to confront the dire reality of unforeseen ecological consequences leading to the extinction of various species, perhaps including humans too, is not a wild fantasy. A predictable, but unprecedented and imminent catastrophic scenario will warrant unprecedented modes of reasoning and strange levels of preparedness to counter it. The foreknowledge about the unlikely scenario of the earth being hit by a giant asteroid may justify the making of massive nuclear weapons to save the earth from the impact of the asteroid. Going by this analogy, perhaps the intuitions against SRM in a normal scenario may become the normal in an emergency scenario. Although emergency-specific analysis of SRM is underdeveloped in the literature, it is the emergency scenario that renders the counter-intuitive justification SRM. If the scientific warnings on earth crossing several thresholds are taken seriously, unpreparedness for such a situation is neither responsible nor rational an approach appealing to the survival instincts of the humanity. A cautious nod for major field tests of geoengineering gains some currency in this context. As vivid from the results section, much of the debate is operating against the backdrop of major scientific uncertainties. Alleviating the uncertainties is an essential prelude for any reasonable response to the research question.

Argument for solar geoengineering from an ethical and social point of view gains maximum weightage when it is viewed against the backdrop of a climatic emergency. Most criticisms against geoengineering are meritorious when viewed against the long-term causative factors of climate change and the wide range of solutions. However, the force of such merits do not hold against the pragmatic, proximate and immediate intuitions and actions warranted by an emergency. It is here that the potential desirability of SRM geoengineering deserves a sympathetic appropriation within the framework of a climatic emergency.

Although the very recommendation for solar geoengineering by Crutzen in 2006[17] which triggered the present momentum of the debate envisaged a lesser evil option for handling an emergency scenario, the review suggests that the emergency analysis has not obtained the due attention of the policy makers, ethicists and other stakeholders. For, the search on the database returned just 23 papers spanning over a period over two decades which directly debate the emergency nuances of geoengineering, though there are over 3400 papers available for geoengineering in general. This hugely disproportionate ratio is no indication that the emergency framing is irrelevant in geoengineering. Rather it suggests the failure of the society to take the scientific warnings seriously as vivified by the failure of the mitigation strategies towards combating dangerous climate change. It means that emergency science and emergency scientist have to engage themselves more with the geoengineering debate. Despite the strong analysis of geoengineering by social and environmental scientists, emergency ethics has not occupied the legitimate space that it deserves on the debate scene. This recommendation does not imply that emergency framing will give greater desirability to geoengineering in an emergency. Call for a more substantive engagement with geoengineering on its benefits and harms in a climatic emergency seems to be one of the pronounced recommendations from this review. This recommendation is all the more significant as there are only two papers [16, 75] dealing with emergency in the recent two years although the emergency rhetoric in climate change gains more and more currency in recent times. This is a research gap that needs to be readily filled up for a reliable answer regarding the potentials of solar geoengineering in a climatic emergency.

In seeking a response to the research question, a progressive strand that is positively identifiable in the debate is the change of the status of geoengineering as a magic bullet solution [73] to a more realistic lesser evil [23] option. The initial hype about geoengineering tended to pile up a junk of crude and fictitious claims lacking in scientific support or critical appropriation. It is to the credit of the cautious scientists and the responsible ethicists that the shallowness of such technological hype has been exposed and the debate has evolved itself to engage seriously both ends of the spectrum of arguments. If the papers published on the ethics of geoengineering in the last one decade are classified as the second generation of arguments, they reflect a more technology-specific and theme-specific argument spectrum. In the complex spectrum of arguments even in the second generation, the emergency dimension has moved to the back burner. While such a change was necessary to undo the false hype and rhetoric in the first generation of arguments, it is time to restore the balance by revisiting the emergency credentials and potentials of solar geoengineering.

Renowned ethicist Gardiner had opined in 2013 that the question of supporting or rejecting geoengineering is an unhelpful distraction in the then phase of the debate. However, the progress of the debate in the second generation of the debate, though far from maturation, legitimizes a serious consideration of this question today from the perspective of climate emergency. The critics had attacked the emergency rhetoric for its use as a cover up for evading several foundational moral issues. However, the inadequate engagement with the emergency nuances of geoengineering as highlighted by the is review suggests that such a critique was not procedurally justified as the due homework on the topic still remains undone.

On the one hand, the review highlights the scope of the unilateral deployment of solar geoengineering by nations most vulnerable be to climate change, especially the small and island nations.[67] On the other, the plight of the poor nations especially those on the global South is highlighted by the opponents as the most challenging issue of distributive justice in solar geoengineering.[58] This dialectic of the asymmetric imbalance between potential harms and benefits among nations is exacerbated by the missing representation of due number of parties from the global South. The authors who contribute to the debate mostly hail from the affluent West though there are a nominal number of scholars from the East, especially form China, participating in the debate. No direct voice of nations which are said to be most in need of geoengineering in an emergency or nations which are destined to be the worst victims of geoengineering is heard in the debate, let alone representation in the policy making forums. We do not fail to recognize the solitary contributions of the Western authors in highlighting the cases of the small island states. This is primarily a procedural impropriety that needs to be rectified towards serious homework prior to any major nod for research and development of solar geoengineering.

Conclusion

The first part of this paper introduced the concept of geoengineering in its historical setting and various technological proposals under geoengineering. As the paper primarily followed the method of review of literature to assess the arguments for and against the desirability of geoengineering in a climate emergency, the second part explained the method of the review. The third part presented the results on the arguments for and against SRM geoengineering as a mechanism for confronting a climate emergency. The final part revisited the research question based on the results. It has been the assessment that the given the present technological of state of affairs with solar geoengineering, the odds are very much against the feasibility of geoengineering to avert a climate emergency. It has been found that the emergency-specific researches are inadequate for any definitive judgement in this regard. The prevalent scientific uncertainties in the field makes the decision making all the more ambivalent. Recommendations were made for the future trajectories of the debate to give special consideration emergency spectrum of the debate and to initiate the measures towards alleviating uncertainties and regional imbalances of the debating parties for an informed and procedurally proper decision making.

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