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Climate Intervention Techniques: Pros and Cons

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A B S T R A C T

Climate intervention (CI) techniques are strategies proposed to modify the Earth's climate system, aiming to mitigate the adverse effects of climate change. In the current scenario of increasing concern about global warming, these techniques emerge as potential complements to traditional mitigation and adaptation measures. This study aims to review the main CI techniques, such as stratospheric aerosol injection, marine cloud brightening, and carbon dioxide (CO_2) removal. The adopted methodology includes a comprehensive review of the state of the art and reference works on the topic, evaluating the effectiveness, risks, and challenges associated with each technique. The results show that stratospheric aerosol injection can reduce global temperature by increasing the Earth's albedo, but it may cause adverse effects such as changes in precipitation regimes, depletion of stratospheric ozone, impacts on radiative balance, and ocean acidification. Similarly, marine cloud brightening causes an increase in albedo. On the other hand, CO_2 removal techniques are seen as potential solutions for decarbonization, although they face challenges related to cost and large-scale efficiency. It is concluded that, despite the feasibility of CI techniques, their long-term impacts present significant uncertainties. Furthermore, the need for a global governance structure is highlighted to avoid unilateral actions that may bring disproportionate risks, especially to more vulnerable countries, such as those in the Global South. Therefore, more interdisciplinary studies are recommended to ensure that these technologies are applied in a safe and just manner.

Keywords: geoengineering, climate intervention, solar radiation modification, climate change, emission scenarios.

Técnicas de Intervenção Climática: Prós e Contras

R E S U M O

As técnicas de intervenção climática (IC) são estratégias propostas para modificar o sistema climático da Terra, visando mitigar os efeitos adversos das mudanças climáticas. No cenário atual de crescente preocupação com o aquecimento global, essas técnicas surgem como potenciais complementos às medidas tradicionais de mitigação e adaptação. Este estudo tem como objetivo revisar as principais técnicas de IC, como a injeção de aerossóis estratosféricos, o branqueamento de nuvens marinhas e a remoção de dióxido de carbono (CO_2). A metodologia adotada inclui uma revisão abrangente do estado da arte e de trabalhos de referência sobre o tema, avaliando a eficácia, os riscos e os desafios associados a cada técnica. Os resultados mostram que a injeção de aerossóis estratosféricos pode reduzir a temperatura global por meio do aumento do albedo terrestre, mas pode causar efeitos adversos, como mudanças nos regimes de precipitação, depleção de ozônio estratosférico, impactos no balanço radiativo e acidificação dos oceanos. Na mesma linha, o branqueamento de nuvens marinhas causa aumento do albedo. Por outro lado, as técnicas de remoção de CO_2 são vistas como soluções potenciais para a descarbonização, embora enfrentem desafios relacionados ao custo e à eficiência em larga escala. Conclui-se que, apesar da viabilidade das técnicas de IC, seus impactos de longo prazo apresentam incertezas significativas. Além disso, destaca-se a necessidade de uma estrutura de governança global para evitar ações unilaterais que possam trazer riscos desproporcionais, especialmente para países mais vulneráveis, como os do Sul Global. Assim, recomendam-se mais estudos interdisciplinares para garantir que essas tecnologias sejam aplicadas de maneira segura e justa.

Palavras-chave: geoengenharia, intervenção climática, modificação da radiação solar, mudanças climáticas, cenários de emissão.

Introduction

Climate change and its impacts are an increasingly recurring and relevant issue (Schaltegger et al., 2011; Princiotta, 2007). Evidence of these impacts includes intense extreme events in various parts of the globe, such as rising sea levels (Moore et al., 2011; Moore et al., 2013; Vousdoukas et al., 2018; Griggs & Reguero, 2021; Nienhuis et al., 2023), droughts (Strauss et al., 2013; Salvador et al., 2020; Gómez-Gómez et al., 2022; Yuan et al., 2023), increased risk of hurricanes (Grinsted et al., 2013; Mannshardt & Gilleland, 2013; Camelo et al., 2020; Rayner et al., 2022; Reed et al., 2022; Balaguru et al. 2023), and degradation of permafrost (Gao et al., 2013; Burke et al., 2020; Murton, 2021; Schuur et al., 2022). As the climate system warms, it is possible to see that points of no return may occur (McKay et al., 2022), and despite government measures to reduce emissions, such as the Paris Agreement (Rogelj et al., 2016), it is tough to achieve these goals and mitigate the effects conventionally (Rogelj et al., 2016; Millar et al., 2017; Tollefson, 2018; IPCC, 2018).

One of the proposals studied for tackling climate change is the so-called Climate Intervention (CI). This proposal consists of geoengineering techniques that aim, through human action, to intervene directly in the climate system to offset human-induced warming partially (Royal Society, 2009; Lawrence et al., 2018; Haywood et al., 2022a; UNEP, 2023). Although the definition seems simple, the strategies are socially sensitive, and the approaches depend on political action (Corner & Pidgeon, 2010; Sovacool, 2021).

The techniques explored by CI mainly consist of (i) stratospheric aerosol injection (Kravitz et al., 2011, 2013a, 2021; Visioni et al., 2021, 2023); (ii) marine cloud brightening (Rasch et al., 2008; Jones et al., 2009, 2011; Mahfouz et al., 2023) and; (iii) carbon dioxide removal (Minx et al., 2018; Buck et al., 2020; Morrow et al., 2020). The following sections describe these techniques in more detail.

Initially called geoengineering or climate engineering, CI can be defined as the deliberate large-scale manipulation of the planetary environment to combat anthropogenic climate change (Robock, 2020). Despite being a relatively recent topic, the beginnings of geoengineering date back to the 1940s, when the possibility of seeding clouds with silver iodide was discovered to produce precipitation (Bruintjes, 1999).

Measures to deal with the adverse effects of climate change comprise a broad umbrella that includes different approaches such as mitigation, adaptation, and climate intervention (Brown, 2010). Mitigation targets the anthropogenic causes of climate change through actions to reduce greenhouse gas emissions or enhance carbon sinks (including transitioning to renewable energy, reducing deforestation, and promoting sustainable land use), while adaptation focuses on initiatives to reduce the vulnerability of natural and human systems to climate change impacts (IPCC, 2022). These actions include different types of adaptation, such as anticipatory, reactive, private, public, autonomous, and planned (Boucher et al., 2014). It seeks to increase the resilience of communities and ecosystems, and examples of this approach include building infrastructure resistant to extreme weather events, implementing early warning systems, diversifying crops, and developing water resource management plans (Forsyth, 2023).

On the other hand, CI comprises technological interventions that aim to alter natural systems to reduce climate change's effects (Baker, 2024). Generally, the technologies composing CI are divided into solar radiation modification (SRM) and removing carbon dioxide (American Meteorological Society, 2022).

SRM aims to reduce the amount of sunlight reaching the earth's surface or increase its reflective capacity. Among the technologies proposed for modifying solar radiation are the injection of aerosols into the stratosphere, the brightening of clouds, the placement of mirrors and space umbrellas, covering the desert with reflective panels, covering glaciers in the Arctic with insulating material or reflective film, the use of white roofs etc. (Zhang et al., 2014). It is worth noting that these techniques do not seek to reduce the level of greenhouse gases in the atmosphere but to cool the earth's average temperature with greater solar reflection, so they can also alter global atmospheric circulation, with potential effects such as changing weather patterns and reducing rainfall (American Meteorological Society, 2022).

Carbon dioxide (CO_2) removal aims to sequester CO_2 from the atmosphere and store it safely. Examples of this approach include: ocean fertilization (stimulating phytoplankton growth with iron, nitrogen or phosphorus to promote carbon removal in large marine quantities); deep carbon burial (technologies that use physical, biological or chemical processes to bury carbon in geological formations such as depleted oil reserves, coal mines or the deep seafloor); biochar (a product obtained by burning biomass through pyrolysis or carbonization, which is then buried in the ground); synthetic trees ("vacuum cleaners" of atmospheric CO_2 by converting sodium hydroxide into sodium carbonate, and then buried in the soil the extracted CO_2 in solid form); upwelling of ocean waters to cool surface waters and increase CO_2 absorption; adding calcium carbonate to the ocean to increase the alkalinity of the water and CO_2 removal; genetically modified algae and microbes to sequester high levels of CO_2 (Zhang et al., 2014).

Although these techniques directly reduce the concentration of greenhouse gases, they are only effective at removing a small amount of atmospheric CO_2 compared to cumulative anthropogenic emissions and may cause potential imbalances in food chains and marine ecosystems (Keller et al., 2014).

One of the biggest challenges facing CI is scientific uncertainty. Although computer simulations and preliminary studies suggest possible benefits (Figure 1), these models cannot capture the full complexity of the climate system and its long-term effects. It is not known, for example, how the injection of particles into the atmosphere could impact precipitation patterns, biodiversity, and entire ecosystems in different parts of the world (Tilmes et al., 2008; Pitari et al., 2014; Fasullo et al., 2018; Visioni et al., 2018; Trisos et al., 2018).

In addition to environmental risks, using CI without a proper understanding of its long-term effects can lead to severe socio-economic consequences. Regional climate change could affect agriculture and water resources (Xia et al., 2014; Proctor et al., 2018). Developing countries, often more vulnerable to climate change, could be disproportionately affected, exacerbating global inequality (Abatayo et al., 2020). In this context, employing CI (especially without clear international agreements and the participation of the countries that could be most affected) could intensify geopolitical conflicts. Moreover, scientists, public policy experts, and environmentalists differ on the ethics and safety of these technologies (Reynolds, 2019; Schubert, 2024; Sovacool et al., 2024).

International regulation of CI faces major gaps, as current environmental treaties do not yet include specific norms for the field. Although conventions such as the Convention on Biological Diversity (CBD) (Du, 2017) and the London Convention and Protocol (Verlaan, 2013; Gailhofer et al., 2023) provide some guidance on activities such as ocean fertilization and encourage a precautionary approach, these documents do not present a cohesive and legally binding regulatory framework. The Paris Agreement, for example, promotes the use of preventive strategies and the consideration of geoengineering impacts but does not directly mention CI. In addition, the IPCC has already outlined these technologies' ethical and social aspects, reinforcing the need for transparent governance and assessing the risks to ecosystems and biodiversity (Reynolds, 2020).

This lack of regulatory uniformity creates geopolitical challenges since, without a clear legal framework, there is a risk of unilateral climate interventions that could affect vulnerable communities and ecosystems in different regions of the globe (Usman et al., 2022). The absence of guidelines on liability and compensation for the possible environmental and social damage caused by CI contributes to increased tensions and international disputes (Pezzoli et al., 2023; Sovacool et al., 2024). Implementing these techniques without consensus can affect the global climate balance, benefiting some countries and harming others (Reynolds, 2019; Abatayo et al., 2020).

CI remains little known and debated in scientific circles and the general public. Unlike widely accepted strategies, CI techniques still lack conclusive studies on long-term risks and impacts. In this context, the Degrees Initiative, formerly known as the Solar Radiation Modification Governance Initiative (SRMGI), emerged in 2010 as a response to discussions about the governance of solar geoengineering, primarily aimed at including scientists and communities from the Global South (Geoengineering Monitor, 2023; Degrees Initiative, 2024). The initiative expanded its focus and, in 2021, reformulated itself to support research into SRM in developing countries. This support includes the Degrees Modelling Fund, which seeks to understand the effects of SRM on the climate of the Global South, and the Degrees Socio-Political Fund, launched to explore the social and political implications of these technologies in the region (Degrees Initiative, 2023).

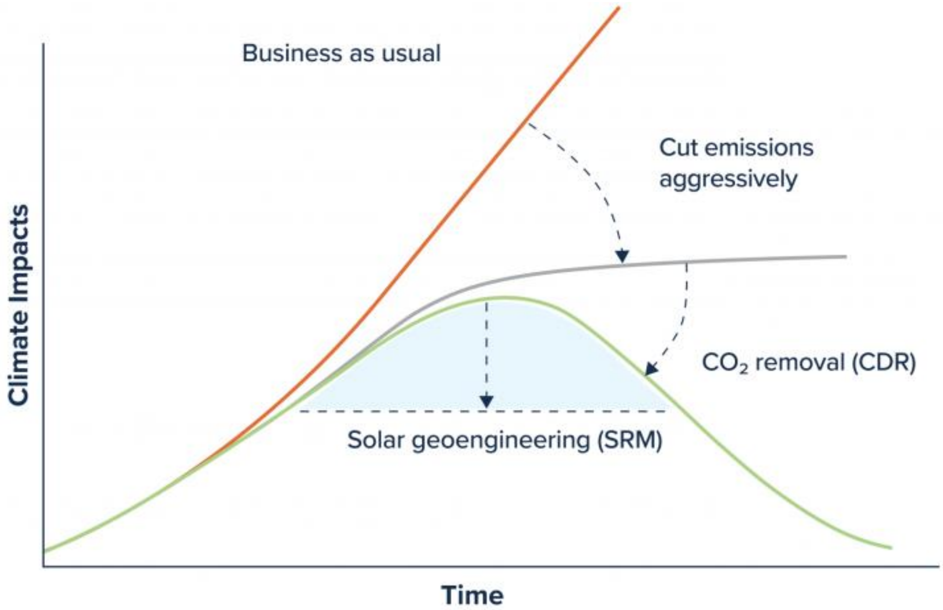

Figure 1. Napkin diagram showing approximately the role of Climate Intervention (CI) with the use of Solar Radiation Management (SRM) and CO_2 Removal (CDR) in climate risk management. Source: Degrees Initiative (2022).

This paper is part of the Brazilian team's contribution to the Degrees Initiative research project, aiming to provide a review of the leading CI techniques, including stratospheric aerosol injection, marine cloud brightening, and carbon dioxide removal. The objective is to assess foundational studies that serve as references in the field and recent research highlighting the state-of-the-art advancements in these technologies. Its focus lies on solar radiation modification and carbon removal, examining their environmental and social impacts. Additionally, the study delves into governance challenges, emphasizing the need for a deeper understanding of the potential consequences of CI techniques, particularly for countries in the Global South.

Material and Methods

This review assessed the scientific literature on CI techniques, focusing on stratospheric aerosol injection, marine cloud brightening, and carbon dioxide removal. The chosen papers were selected through various scientific research platforms, including Google Scholar, Web of Science, SciELO, Scopus, and Science.gov. The primary objective was to evaluate well-established works on the subject and recent studies highlighting state-of-the-art climate intervention techniques. Approximately 200 papers were analyzed, half published in the last five years, ensuring a balanced perspective between foundational research and contemporary advancements.

The analysis involved extracting key information from each selected study, covering the efficacy of each technique, the most significant application results, and the associated challenges. Particular attention was given to climate modeling limitations, uncertainties regarding climate and biodiversity impacts, and political difficulties stemming from the lack of ethical and legal frameworks that include all countries potentially affected by CI techniques. This approach enabled a synthesis of current knowledge and the identification of critical areas needing further research and policy development.

Types of Climate Intervention

Solar Radiation Modification (SRM)

Stratospheric Aerosol Injection (SAI)

According to the Intergovernmental Panel on Climate Change (IPCC), the natural component that can help cool the planet, albeit with uncertainties (Myhre et al., 2013), is the injection of sulfate aerosols into the stratosphere, as it contributes to increase the albedo (Figure 2, Dickinson, 1996; Robock et al., 2010; MacMartin et al., 2016; Kravitz et al., 2016). This technique arose from the knowledge that the global average air temperature decreases by around 0.5 °C between two and three years after volcanic eruptions (Hansen et al., 1996; Parker et al., 1996; Pesquisa Fapesp, 2024). These eruptions can increase the global albedo by between 5 and 10% (Minnis et al., 1993). Thus, SRM (Solar Radiation Management) aims to reduce the incident solar radiation to compensate for the increase in temperature due to greenhouse gas emissions.

In this regard, simulations like the GeoMIP6, from the Coupled Model Intercomparison Project (CMIP6), provide different projections, such as G6solar, which simulates the attenuation of the amount of incident solar radiation artificially reduced, and G6sulfur, which simulates the reduction of the average radiative forcing with stratospheric sulfate aerosols (Kravitz et al., 2015). In addition, Marine Cloud Brightening (MCB) experiments such as G4Sea-Salt evaluate the impact of the technique by injecting sea salt between the latitudes of 30°S and 30°N, noting that the direct effect of aerosols can contribute significantly to the modeled cooling (Kravitz et al., 2013b; Ahlm et al., 2017).

Moreover, the Geoengineering Large Ensemble (GLENS; Tilmes et al., 2018) project simulates sulfur dioxide (SO_2) injections at an altitude of ~25 km at four different latitudes (30°S, 15°S, 15°N and 30°N) at 180°E to maintain the global average surface temperature, the inter-hemispheric surface temperature gradient and the surface temperature gradient from the equator to the pole at 2020 values, under the Representative Concentration Pathway 8.5 (RCP8.5) scenario. Similarly, the Assessing Responses and Impacts of Solar Climate Intervention on the Earth System with Stratospheric Aerosol Injection (ARISE) project simulates SO_2 injections at the exact locations as GLENS (at around ~21.6 km altitude) but keeps the global average temperature close to 1.5 °C above pre-industrial times at the end of the century.

SAI research encompasses both indoor studies which focus on climate modeling (and the analysis of natural analogs like volcanic eruptions) and outdoor experiments that involve injecting particles into the atmosphere to modify the Earth's albedo (Robock et al., 2012).

Climate models suggest that SAI can disperse around 1% of incident solar radiation, which would complement other climate risk reduction measures such as cutting emissions, CO_2 removal, and adaptation (Irvine et al., 2016, 2019; MacMartin & Kravitz, 2016; Parson et al., 2024). Modeling-based studies indicate that SAI can mitigate climate change impacts by offsetting different effects such as the acceleration of the hydrological cycle (Kravitz et al., 2013a; Tilmes et al., 2013), the melting of glaciers (Moore et al., 2014; Zhao et al., 2017), the intensity or frequency of extreme events (Curry et al., 2014; Dagon & Schrag, 2017) and the intensity of tropical cyclones (Moore et al., 2015; Irvine et al., 2019).

However, despite its low cost (Barrett, 2008; Moriyama et al., 2017) and studies suggesting that SAI can promote a climate close to the reference period in almost all regions (Matthews & Caldeira, 2007; Ban-Weiss & Caldeira, 2010; Kravitz et al., 2011, 2014; Tilmes et al, 2014; MacMartin et al., 2018; Irvine et al., 2019; Kravitz & MacMartin, 2020), its use still does not guarantee to offset for changes in temperature and precipitation patterns across the globe (Moreno-Cruz et al., 2012; MacMartin et al., 2014; Kravitz et al., 2014; Kravitz & MacMartin, 2020). For example, SAI can alter precipitation patterns, intensifying negative impacts resulting from El Niño events (Saxler et al., 2015), as well as affecting the monsoon cycle (Robock, 2008; Saxler et al., 2015; Proelss & Steenkamp, 2023).

Furthermore, different SAI applications produce different regional effects, so while SAI in high latitudes cools the polar regions and impacts glaciers (Kravitz et al., 2017; Zhao et al., 2017; Kravitz & MacMartin, 2020), its use in only one hemisphere cools the region and can promote changes in tropical precipitation (Haywood et al., 2013; Kravitz & MacMartin, 2020). Additionally, potential adverse effects of SAI include ecosystem changes (Trisos et al., 2018; Dagon & Schrag, 2019; McDonald, 2022); stratospheric ozone depletion and changes in ultraviolet radiation (Tilmes et al., 2008; Pitari et al., 2014; Robrecht et al., 2021; Tilmes et al., 2022; Moch et al., 2023); interactions with cirrus clouds and effects on the radiative balance (Visioni et al., 2018); ocean acidification (Fasullo et al., 2018); intensification of acid rain (Visioni et al., 2018); effects on agriculture (Xia et al., 2014; Proctor et al., 2018) and health (Robock et al., 2009; Heckendorn et al., 2009; Irvine et al., 2017). Other lesser-known possible effects include rapid warming with the abrupt cessation of SAI application, reduced solar electricity generation, and effects on the electrical properties of the stratosphere and remote sensing (Robock, 2020). A more comprehensive overview of the positive and negative impacts of SAI (as well as other SRM techniques) can be found in Sovacool et al. (2023).

International projects have provided comparative projections with and without SRM. In general, these simulations project a reduction in global warming and fewer extreme events (Barnes et al., 2022; Richter et al., 2022; Tye et al., 2022;

Haywood et al., 2022b; Hueholt et al., 2024) in temperature (Ricke et al., 2010) and precipitation (Bala et al., 2008; Robock et al., 2009; Tilmes et al., 2013). At the regional level, some studies have assessed the impacts of implementing SRM in Africa (Karami et al., 2020: storm trajectory; Pinto et al., 2020: mean and extreme values of temperature and precipitation; Obahoundje et al., 2023: dry and wet extremes), North and Central America (Shields et al., 2022: impacts on atmospheric rivers) and Asia (Kuswanto et al., 2021: extreme temperature indices; Tan et al., 2023: hydroclimatic extremes). Despite this, studies for South America are still scarce. The few studies include, for example, that by Camilloni et al. (2022), which evaluated the impacts of SRM on the hydroclimate of the La Plata Basin, where the intervention can decrease temperature extremes in the basin.

Recently, the first study led by the Brazilian Degrees Initiative team (Degrees Initiative, 2023; Reboita et al., 2024), in collaboration with researchers from South Africa, investigated how SAI and climate change affect extratropical cyclones in the Southern Hemisphere. The results indicate that SAI could mitigate change effects on cyclone intensity, keeping it close to current levels. However, SAI also complicates the systems' behavior. For example, although both scenarios (with and without SAI) suggest a change in the spatial pattern of cyclones, the scenario with SAI indicates a minor reduction in the frequency of systems (Reboita et al., 2024). Thus, the authors highlight the need for further research to understand the implications of SAI on cyclone behavior.

SAI research and implementation raise complex ethical and political dilemmas. Several international treaties and conventions touch on aspects of SRM but do not provide a specific and comprehensive regulatory framework (Bodansky, 2013; Dupuy et al., 2021; Parson & Reynolds, 2021; Felgenhauer et al., 2022). The Convention on Biological Diversity recommended that, without global control mechanisms, no geoengineering activity that could affect biodiversity should be carried out without a sound scientific basis (UNEP, 2010).

The London Protocol banned marine geoengineering activities, but its applicability to SRM remains uncertain (Parson & Keith, 2024). The Climate Overshoot Commission has suggested a moratorium on large-scale interventions until there is greater clarity on the risks (Climate Overshoot Commission, 2023), while the IPCC has highlighted ethical and political implications of SRM, including concerns about climate justice and governance (IPCC, 2018). Organizations such as UNESCO and the United Nations Environment Programme (UNEP) have also promoted discussions but have yet to adopt concrete guidelines (Parson and Keith, 2024). Thus, although SRM remains an area of growing interest, the absence of an effective international governance regime makes it difficult to make informed and secure decisions about its research and possible implementation.

Marine Cloud Brightening (MCB)

Similar to SAI, marine cloud brightening (MCB), also known as "cloud albedo enhancement", is a SRM technique that aims to partially increase atmospheric albedo by reflecting sunlight into space to compensate for atmospheric warming (Latham et al., 2012). The overall cost of MCB is estimated to be similar to that of SAI and is relatively low compared to the costs of mitigating emissions and climate damages (NAS, 2021; Duffey et al., 2023).

The MCB technique consists of injecting sea salt particles into the atmosphere to increase the number of water droplets in low clouds over the oceans, especially in regions with stratocumulus clouds (Figure 2, Latham et al., 2008; Caldeira et al., 2013). Low clouds are excellent means of increasing albedo, as they reflect part of the incident radiation. The more droplets in a cloud, the greater the reflectivity, helping to cool the planet.

MCB increases reflectivity by applying aerosol's first and second indirect effects on clouds (Minnuno et al., 2023). The first indirect effect involves increasing the concentration of droplets in the cloud to increase its optical thickness and ability to reflect more shortwave radiation (Ahlm et al., 2017). The second indirect effect of aerosol is to increase the lifetime of cloud cover, according to the hypothesis that smaller droplets take longer to coalesce into droplets larger enough to precipitate out of clouds (Jones & Haywood, 2012; Horowitz et al., 2020). Thus, understanding the MCB is intrinsically linked to addressing the uncertainties of aerosol-cloud interactions (Parson & Keith, 2024).

MCB could be used more regionally due to the short half-life of tropospheric aerosols (Bala et al., 2011; Haywood et al., 2023) and the area of cloud cover. In addition, studies indicate that there is dependence on the region applied, which can affect different climate regions due to teleconnection effects (Bala et al., 2011; Stjern et al., 2018; Ahlm et al., 2017; Diamond et al., 2022; Odoulami et al., 2024). Potential regions for MCB application include colder areas of the subtropical and mid-latitude oceans (Ahlm et al., 2017).

Global climate models (GCMs) simulations indicate that increasing the concentration of droplets in marine clouds by a few hundred per cubic centimeter could generate a negative radiative forcing capable of offsetting the warming caused by CO_2 doubling (Latham et al., 2012; Minnuno et al., 2023).

However, the effectiveness of MCB is controversial, mainly due to its limited scalability. Studies suggest this technique is only viable in regions with marine stratocumulus cloud formation, covering only around 10% of the Earth's surface (Partanen et al., 2016). Even so, simulations of GCMs show that the MCB application, even in such a restricted area, can have significant climate impacts (Kim et al., 2020; Zhao et al., 2021; Minnuno et al., 2023).

Increasing the number of cloud condensation nuclei (CCN) in marine clouds while keeping the water content constant tends to increase the cloud's albedo, i.e., its ability to reflect solar radiation (Parson & Keith, 2024). However, the net effect of MCB can vary significantly depending on local meteorological conditions, increasing albedo in some situations but having little impact or even reducing albedo in others (Feingold et al., 2024; Parson & Keith, 2024).

Parkes et al. (2012) used a GCM to assess the effects of MCB in three areas with persistent marine stratocumulus clouds located in mid-latitudes over the North Pacific, South Pacific, and South Atlantic. The results showed an average reduction of 0.8 °C in the polar regions' global temperature, which helps mitigate polar amplification by decreasing ice loss at the South Pole and increasing ice cover at the North Pole. These findings show that applying negative radiative forcing exclusively over limited ocean regions can significantly reduce polar ice melt and preserve sea ice.

In addition, MCB can reduce temperature anomalies, slow polar ice loss, and reduce coral bleaching (Latham et al., 2014). Still, it can also increase evaporation, cloud formation, and precipitation in low-latitude land regions (Zhang et al., 2014).

A study has shown that reducing cloud droplet size uniformly over all oceans to counteract warming due to CO_2 doubling results in a 1.3% reduction in global precipitation but increases runoff by 7.5%, especially in tropical areas (Bala et al., 2011). In contrast, increasing the albedo in terrestrial regions causes a more significant decrease in precipitation (13.4%) and runoff (22.3%). Therefore, changing the albedo in the oceans affects the global hydrological cycle less than similar changes over land (Bala et al., 2011; Zhang et al., 2014).

Regarding the Arctic polar region, the MCB can generate a negative local radiative forcing of up to 11 W/m², although the presence of ice particles reduces its effectiveness (Kravitz et al., 2014). However, to preserve sea ice under the RCP8.5 high emissions scenario, a much larger forcing would be required, especially north of 60°N, due to compensatory heat fluxes towards the poles (Tilmes et al., 2014; Duffey et al., 2023).

A recent study concluded that MCB can reduce the risk of heat waves by up to 55% in the remote mid-latitudes and 16% in the near subtropics (Wan et al., 2024). However, under projected warming conditions for the middle of the century, this technique has reduced effectiveness or even increased heat stress in the western United States and globally. These results indicate that interventions that work under current scenarios may not be equally effective as those under climate change.

Additionally, other less understood possible adverse effects of the MCB include stratospheric ozone depletion, negative impacts on marine ecosystems, and uneven cooling effects, potentially exacerbating climate inequalities between regions (Haywood et al., 2023; Ricke et al., 2023; Sovacool et al., 2023).

In this context of scientific uncertainty, GeoMIP has implemented different phases of MCB experiments (Kravitz et al., 2013b): the first phase simulates a uniform increase in ocean albedo to compensate for the effect of a quadrupling of CO_2 compared to pre-industrial levels; the second raises the concentration of droplets in all low-altitude marine clouds to reduce part of the radiative forcing in an RCP4.5 scenario; the third phase injects sea salt aerosols into the boundary layer between 30°S and 30°N to neutralize 2 W/m² of radiative forcing. These tests, particularly in Phase 2 of GeoMIP, seek to understand how the increased concentration of CCN affects cloud albedo, using multiple climate models to ensure greater comprehensiveness in the results (Stjern et al., 2018).

Conducting MCB experiments raises complex political and ethical issues, mainly due to the absence of a transparent system of international governance to regulate such interventions. Morgan and Ricke (2010) suggest creating a "permitted zone" for such experiments, which should be carefully defined to ensure no lasting climate effects. However, this definition is still vague, especially regarding complex impacts such as changes in sea surface temperature and potential consequences for marine ecosystems.

The central argument is that experiments should be conducted cautiously, considering the potential risks and recognizing that failure to act could lead to even more severe consequences due to global warming (Preston, 2013; Rayner et al., 2013). Therefore, this research must be carried out transparently to increase our understanding of climate change and its possible mitigators.

Carbon Dioxide Removal (CDR)

Climate intervention through the removal of carbon dioxide (CO_2), known as Carbon Dioxide Removal (CDR), involves the permanent removal of carbon dioxide from the atmosphere to reduce the concentration of greenhouse gases and thus mitigate the effects of climate change (Climeworks, 2023; Parry, 2022; Mistry et al., 2023). CDR techniques include methods such as removing greenhouse gas from the atmosphere and storing them in natural "carbon sinks" such as forests and soils or through technological approaches like reforestation, bioenergy with carbon capture and storage, and direct air capture (Figure 2, IPCC, 2022; Carbon Market Watch, 2024). Although these approaches could bring global benefits by directly tackling the cause of global warming, there are still uncertainties about their feasibility on a large scale and the possible environmental and social impacts that could arise.

Among the various CDR techniques, each has its peculiarities, benefits, and challenges. Among the primary methods are reforestation and afforestation, which promote planting trees in deforested areas or regions with no forest cover (Denton et al., 2022). Trees absorb CO_2 from the atmosphere during their growth, storing it in their biomass for decades or more (Sovacool et al., 2023). Although effective, these practices can compete for land and water with agricultural activities, and the release of stored carbon can occur in cases of improper burning or harvesting (García-Quijano et al., 2007; Wani et al., 2012; Shi et al., 2013; Sovacool et al., 2023).

Ocean fertilization is a technique that adds nutrients such as iron or urea to the ocean's euphotic zone to stimulate phytoplankton growth. This practice aims to increase the absorption of atmospheric and marine CO_2, reducing environmental and ocean temperatures (Minnuno et al., 2023). Studies indicate that fertilization can promote carbon sequestration by encouraging the formation of organic detritus that sinks into deep waters (Williamson et al., 2012; McGee et al., 2018). However, only a tiny fraction of this carbon reaches the ocean floor, most of which is re-emitted to the atmosphere due to biomass degradation (Keith, 2000; Macreadie et al., 2019). Challenges such as carbon leakage and the lack of reliable models still limit its application on a large scale (Lampitt et al., 2008).

Complementary initiatives, such as increasing ocean alkalinity and restoring coastal ecosystems (such as mangroves, salt marshes, and seagrass beds), known as blue carbon, have also gained prominence (Zhang et al., 2014; Bach et al., 2019; Sovacool et al., 2023). These methods intensify CO_2 absorption and act as important carbon sinks (Sabine et al., 2004). However, ocean fertilization and these strategies require further research to assess their effectiveness and long-term impacts (Minnuno et al., 2023).

Direct air capture with carbon storage (DACCS) uses large fans to remove CO_2 directly from the atmosphere and store it safely in underground geological formations (Jonge et al., 2019; Deutz & Bardow, 2021; Terlouw et al., 2021). Although this technology does not require large land areas, it is energy-intensive and still has high implementation costs (Bui et al., 2018; Fasihi et al., 2019). Bioenergy technologies with carbon capture and storage (BECCS) combine biomass cultivation to generate energy by capturing CO_2 emitted during burning and storing it underground (Kemper, 2015; Fajardy & Dowell, 2017). However, both approaches face similar challenges, such as the need for suitable geological formations and competition for resources such as land and water (Terlouw et al., 2021).

Chemical weathering is a technique that seeks to accelerate natural processes of CO_2 absorption by rocks by crushing them and scattering the fragments on agricultural land or coastal areas (Hartmann et al., 2013; Bach et al., 2019). This method offers long-term storage in the oceans, but there are uncertainties about its feasibility on a large scale and the potential environmental impacts of rock mining (Hartmann et al., 2013; Taylor et al., 2016; Bach et al., 2019).

Agricultural practices that promote soil carbon sequestration, such as crop rotation and increased vegetation cover, also represent a viable option (Sovacool et al., 2023). These practices can improve soil quality while storing carbon for decades, but their efficiency depends on consistent adherence by farmers and land managers.

Finally, the production of biochar involves converting organic material into a type of charcoal by heating it in low oxygen (Lehmann et al., 2011; Wang et al., 2020). This material can be mixed into the soil, storing carbon for long periods and improving fertility (Sun Cha et al., 2016). Although promising, biochar competes with other uses for biomass, such as energy or fuels (Sovacool et al., 2023).

In summary, CDR technologies have great potential to complement climate mitigation efforts, but each approach has specific limitations and challenges. Their large-scale adoption will depend on technological innovations, financial investments, and a global commitment to sustainable solutions to the climate crisis. However, the assessment by Mistry et al. (2023) provides further evidence that CDR is crucial to decarbonizing the global economy and achieving the net-zero targets set by the Paris Agreement.

Despite carbon capture machines, significant challenges exist, such as high implementation and operating costs and low efficiency when dealing with the large amounts of CO_2 dispersed in the atmosphere due to their immense vertical size. These challenges make capturing large quantities a costly process and difficult to scale up, limiting the effectiveness of this technology in large-scale climate mitigation (Budinis et al., 2018).

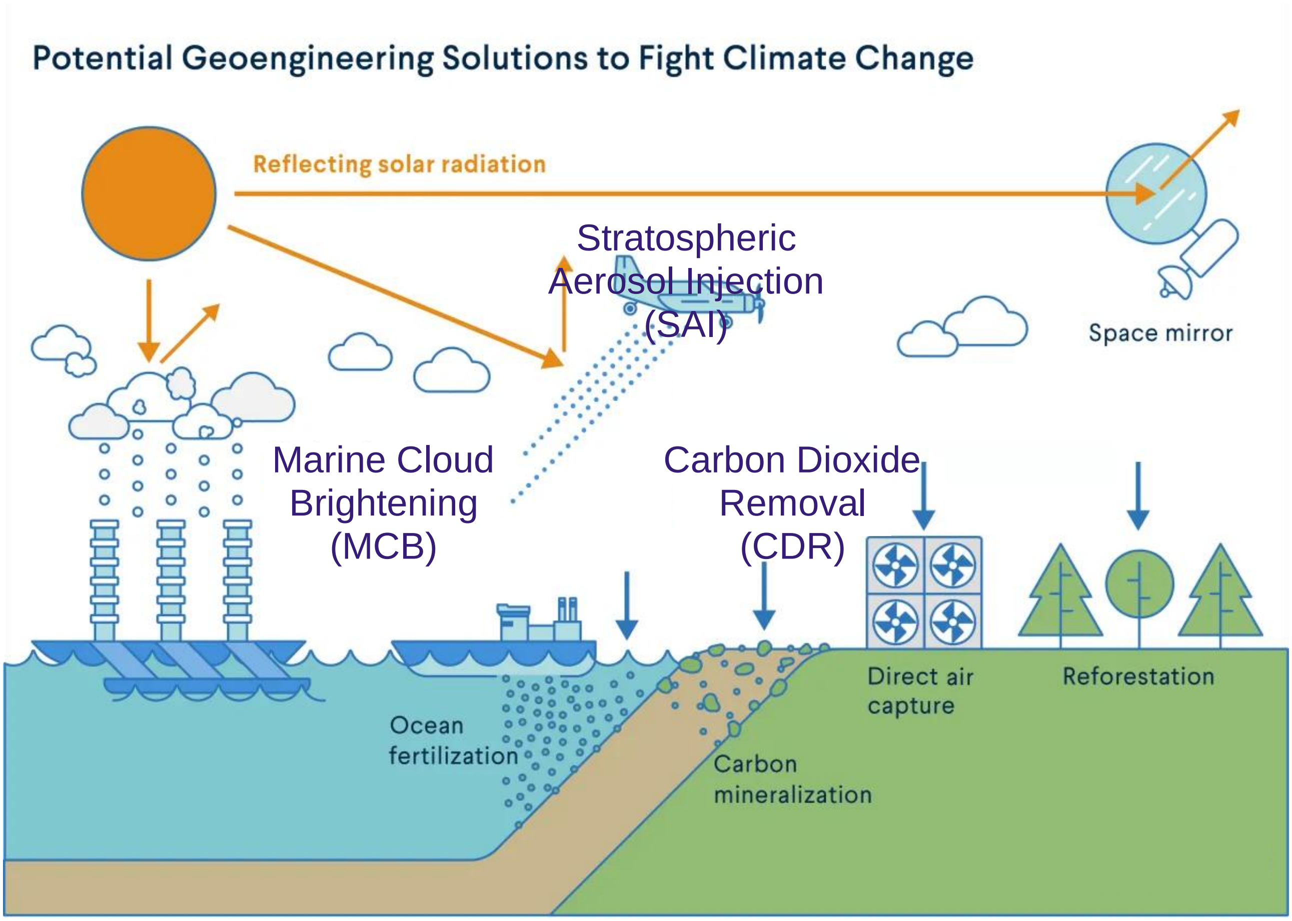

Figure 2: Overview of the main Climate Intervention (CI) techniques. These include Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB) and different forms of CO2 Removal (CDR). Source: EcoEngineer (2024).

Modeling Climate Intervention

Although outdoor research is also deemed necessary, climate models are essential for simulating the effects of CI techniques like SAI and MCB, requiring large-scale, long-term implementations due to the climate system's complexity, with research relying on sophisticated computer models and supercomputers to reproduce Earth's system behavior and assess future climate impacts (Robock et al., 2020).

The techniques are incorporated through parameterized representations based on observations and experiments using advanced technologies and international collaborative programs (Kravitz et al., 2021). GeoMIP (GeoMIP, 2024) was created to standardize geoengineering experiments and resolve inconsistencies between initial studies. Initially, its research involved climate simulations by reducing the solar constant and applying SAI later expanded to other techniques such as MCB (Visioni et al., 2023). Since its creation, GeoMIP has produced more than 100 studies that analyze the impacts of these experiments on climate, ecosystems, and human societies (Visioni et al., 2023; GeoMIP, 2024).

In the United States, institutions such as NCAR, NOAA, and NASA contribute resources and expertise in climate modeling and land surface impacts (Robock et al., 2020). Despite advances, funding for geoengineering research is limited, with a prevalence of studies carried out in developed countries (Brown, 2010) and increasing dependence on private sources (Necheles et al., 2018).

Climate simulations face significant limitations, particularly concerning the accuracy and predictability of the results (Kravitz et al., 2021). Due to the limitations of climate models and the scarcity of observations, reducing uncertainties related to radiative forcing and climate response is challenging (Kravitz et al., 2016). Climate feedbacks, including cloud-aerosol interactions and changes in the hydrological cycle, introduce complexity and uncertainty to projections, while the models' spatial and temporal resolutions remain insufficient to fully capture local phenomena and long-term impacts (Kravitz et al., 2016, 2021).

A recent approach is integrating explicit feedback into climate models to adjust geoengineering techniques in real-time (Kravitz et al., 2016). Based on control theory, this approach makes it possible to monitor the state of the climate and adjust interventions according to the observed climate response, minimizing uncertainties (MacMartin et al., 2013; Kravitz et al., 2016).

Recent advances in the field of CI include using high-resolution models to capture detailed patterns of atmospheric circulation and aerosol-cloud interactions and integrated studies on ecological and social impacts (Kravitz et al., 2021). Despite advances, interdisciplinary research is urgently needed to address knowledge gaps, such as environmental effects at local scales and the ethical risks associated with implementing these techniques.

Conclusion

This article reviewed the leading climate intervention techniques, including stratospheric aerosol injection, marine cloud brightening, and CO_2 removal, and highlighted the essential role of climate modeling in understanding their effects. It discussed how these approaches seek to mitigate climate change impacts, such as global warming and alterations in the hydrological cycle, while facing significant challenges, such as uncertainties in climate feedback, limitations in modeling complex processes, and ethical and social concerns.

Recent advances in climate modeling, driven by initiatives such as GeoMIP, have provided valuable insights into these interventions' regional and global impacts. These contributions include improvements in model resolution, greater integration between climate and ecological studies, and exploring combinations between climate mitigation and adaptation techniques, representing a promising field for the future.

However, geoengineering techniques still involve many uncertainties in various spheres, including scientific, ethical, political, economic, and social. These uncertainties reinforce the need for more interdisciplinary research and global discussions to ensure that, if implemented, these solutions are applied responsibly, minimizing risks and maximizing benefits.

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