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Climate intervention research in the World Climate Research Programme: a perspective

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The 2023 World Climate Research Programme (WCRP) Open Science Conference underscored the critical need for increased climate change mitigation and adaptation efforts, along with enhanced climate knowledge and decision-making systems. This Perspective discusses climate intervention (CI) within WCRP's research framework, emphasizing three main approaches: terrestrial carbon dioxide removal (CDR), marine CDR, and solar radiation modification (SRM). As global anthropogenic greenhouse gas emissions continue to rise, CI strategies are increasingly recognized as potentially critical supplements to traditional mitigation methods. We call for WCRP to take a leadership role in CI research, highlighting the need for inclusivity and collaboration, especially with researchers from the Global South, to establish a firm scientific foundation for an equitable and comprehensive assessment of the benefits and risks of CI approaches relative to the risks of anthropogenic climate change.

KEYWORDS

geoengineering, carbon dioxide removal, solar radiation modification, climate intervention, solar geoengineering

1 Introduction

The World Climate Research Programme (WCRP) Open Science Conference (OSC) in Kigali, Rwanda (October 23–27, 2023) brought together over 1,400 participants representing diverse climate research communities worldwide as well as practitioners, planners, and policymakers. A major theme of the OSC was the urgent need to address climate change through increased ambition for climate mitigation and adaptation, as well as by improving climate knowledge and developing climate decision support systems at both global and regional levels (World Climate Research Programme (WCRP), 2024). The purpose of this Perspective is to share our thoughts on another topic of discussion at the OSC: the role of climate intervention in the WCRP research portfolio. In doing so, we highlight three Research Articles on three climate intervention approaches: terrestrial carbon dioxide removal (Lawrence et al., 2024), marine carbon dioxide removal (Oschlies et al., 2024) and solar radiation modification (Haywood et al., 2024) that are part of this special WCRP issue of *Frontiers in Climate.*

2 Are climate goals within reach?

Society's expanding consumption of fossil fuels and extensive alteration of the terrestrial biosphere has led to a dramatic and ongoing rise in atmospheric levels of carbon dioxide

(CO_2) and other greenhouse gases (GHG) since preindustrial times. Other climate forcing agents like aerosols and surface reflectivity have also changed significantly over time because of human activities. The resulting climate change, with escalating impacts on humans, infrastructure, and natural and managed ecosystems, is affecting every region across the globe, and the consequences of past and continued GHG emissions will be severe and long-lasting, primarily due to the longevity of atmospheric CO_2 (IPCC, 2021).

It is therefore an imperative that anthropogenic CO_2 emissions be immediately reduced (United Nations Environment Programme (UNEP), 2023a). Such reductions are the only way to avoid levels of climate disruption that will be difficult or impossible to address through adaptation. While technically possible, slowing anthropogenic CO_2 emissions is particularly challenging because fossil fuel use is embedded widely in modern economies, including energy and heat production, industry, and modes of transport. Even though progress towards a decoupling of economic growth and emissions has been made in recent years, the speed and magnitude of this transition is falling well short of what is necessary to limit global mean warming to the Paris Agreement target of 1.5°C above the pre-industrial level, and warming levels of 2.5–3°C could be reached by 2,100 even for ambitious emissions reduction (IPCC, 2018; United Nations Environment Programme (UNEP), 2023a). Any warming, even with reduced emissions, will further exacerbate observed increases in the frequency and intensity of extreme weather, the melting of polar and glacial ice, and sea level rise, among other potentially catastrophic changes in the Earth system such as tipping points associated with Amazon dieback, loss of permafrost, and a shutdown of the Atlantic Meridional Ocean Circulation (IPCC, 2021).

3 Climate intervention

It is within this context that the concept of climate intervention (CI) was discussed at the OSC. Climate intervention refers to deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change (Royal Society, 2009). Its primary goal is to modify the Earth's climate system to reduce the adverse impacts of global warming or to reverse some of its effects. There are two main categories of CI: large-scale carbon dioxide removal technologies as well as solar radiation modification (National Research Council (NRC), 2015a, 2015b; American Geophysical Union (AGU), 2024).

Carbon dioxide removal (CDR) approaches are aimed at intervening in the Earth's carbon cycle to durably remove CO_2 from the atmosphere, thereby reducing atmospheric concentrations and addressing the root cause of anthropogenic climate change. Recent scientific assessments indicate that holding climate warming to below 1.5°C is implausible without significant deployment of CDR, and in ambitious mitigation scenarios, net-negative emissions are reached by mid-century (IPCC, 2023). However, there are substantial environmental, technical, societal and economic challenges in using CDR at the scale needed to reach the net zero GHG emissions necessary to achieve the Paris Agreement climate goals. These challenges, and the slow response of the climate system, make it doubtful that CDR could be implemented rapidly enough or at sufficient scale to avoid dangerous levels of climate warming in the near term.

As a complement to long-term emissions reductions, adaptation, and CDR, solar radiation modification (SRM) is being considered as an approach that could rapidly halt, slow down, or reverse climate warming (National Academies of Sciences, Engineering, and Medicine (NASEM), 2021a). SRM approaches are aimed at directly influencing the Earth's radiation budget, such as by reflecting a small percentage (1–2%) of incoming solar radiation back to space. These approaches are based on observations; for example, after large volcanic eruptions that have shown a measurable reduction in solar radiation at the surface and a net cooling of the planet, as well as observed effects of aerosols on clouds (e.g., Lawrence et al., 2018). While SRM may rapidly counter some GHG warming impacts, the extent to which SRM can reduce climate change hazards has not been robustly established, nor has the extent to which SRM may introduce new risks to people and ecosystems (United Nations Environment Programme (UNEP), 2023b). Also, since SRM does not reduce atmospheric CO_2 and other GHG concentrations, it does not address the root causes of anthropogenic climate change. Furthermore, some other environmental harms from increased concentrations of CO_2 and other GHGs would continue, such as ocean acidification. Any potential SRM deployment would therefore be at best a temporary measure that could operate in parallel with mitigation measures, including CDR, with SRM deployment declining as radiative forcing by anthropogenic GHGs decline globally. However, overshoot scenarios suggest that the decline in GHG concentrations will be relatively slow in the future, so the 'temporary' nature of SRM may be several decades or even several centuries. Some scientists strongly oppose even basic SRM research, in part because of the risk that such efforts may delay or deter commitments to reduce emissions, in addition to significant concerns over the current lack of governance (Biermann et al., 2022).

Before we share our perspectives on the role of WCRP in CI research, we first provide very general overviews of CDR and SRM approaches.

3.1 Carbon dioxide removal

The systemic effect of CDR is threefold and is likely to change with time, if ambitious mitigation pathways are followed: (1) during periods of net-positive emissions, CDR will be needed to bolster emissions reductions to lower atmospheric CO_2 concentrations; (2) CDR will be needed to compensate remaining difficult-to-avoid emissions in order to reach net-zero goals (Belaia et al., 2021); and (3) in the likely situation of at least a temporary overshoot of the carbon budget necessary to reach end-of-century temperature targets (IPCC, 2018), CDR will be needed to exceed any remaining emissions so that atmospheric CO_2 concentrations decline.

3.1.1 Land-based approaches

To meet the Paris Agreement climate goals, current scenarios estimate that CDR will need to remove roughly 5–9 Gt CO_2 $yr.^{-1}$ by mid-century and 10–17 Gt CO_2 $yr.^{-1}$ by the end of the century (IPCC, 2023). Possible land-based CDR approaches to help meet that goal include the management and expansion of existing land-based carbon sinks, such as afforestation and reforestation, changes in forest management, changes in agricultural practices to increase and maintain top-soil carbon content, and carbon mineralization (accelerated weathering). Technological approaches include bioenergy combined with carbon capture and geological storage, and direct air capture of CO_2 combined with geological storage. While such land-based CDR approaches are expected to be an essential component of future climate mitigation strategies, governance is needed, and significant scientific gaps and environmental concerns remain, although they vary among the different approaches.

In Lawrence et al. (2024), we explore a range of different land-based CDR approaches, identify research gaps that must be closed to assess their carbon removal potentials, and address challenges scaling from current land-based activities of around 2 Gt CO_2 yr.$^{-1}$ to the possible 10–17 Gt CO_2 yr.$^{-1}$ by the end of the century. We also explore the competing issues of land management and sustainable development, as well as possible co-benefits of ecosystem conservation. Nature-based solutions, technological approaches and modified agricultural practices are all discussed. Finally, we describe some of the implementation and ongoing management constraints of these approaches, issues of carbon permanence once CO_2 is removed from the atmosphere, requirements for monitoring, reporting and verification, and the need to understand governance and societal responses to implementation and maintenance of different land-based CDR approaches.

3.1.2 Ocean-based approaches

Natural ocean processes currently take up about a quarter of anthropogenic CO_2 emissions from fossil fuel consumption and deforestation from the atmosphere and absorb more than 90% of the additional heat trapped in the system. The ocean, therefore, already provides an invaluable service slowing the atmospheric growth of CO_2 and associated climate change, though at the high cost of ocean warming, rising sea levels, ocean deoxygenation and ocean acidification. Numerous approaches for deliberate ocean CDR, ranging across biotic and geochemical methods to more industrial techniques, have been proposed by scientists, engineers, and technologists to complement CO_2 emission reductions and contribute to the portfolio of climate response strategies. However, there remain crucial unresolved questions regarding many aspects of ocean CDR, including effects on the ocean ecosystem and available food, and how it can be monitored, reported, and verified. Detection and attribution of CDR signals is particularly challenging in the globally connected and moving ocean due to the large natural marine carbon pool with its considerable spatial gradients that are continuously modulated by time-varying ocean currents, mixing and biological source and sink terms. Moreover, the baseline against which the impact of CDR activities will have to be quantified includes the ongoing uptake of anthropogenic carbon dioxide at a current rate of about 10 Gt CO_2 yr.$^{-1}$, i.e., a temporal change larger than the signal of any individual marine CDR deployment envisaged so far.

In Oschlies et al. (2024) we investigate a wide range of marine CDR approaches with respect to their potential, risks and side effects, as well as the challenges associated with technical feasibility, governance and social acceptance. Biotic approaches examined range from the enhancement of coastal vegetated ecosystems to open-ocean methods such as microalgae ocean fertilization and macroalgae sinking and harvesting, sometimes proposed in combination with artificial upwelling. Biotic marine CDR methods that, by definition, impact marine ecosystems and also nutrient and oxygen cycles are compared with geochemical approaches such as ocean alkalinity enhancement and direct ocean CO_2 removal that aim at modifying the carbonate chemistry of the surface ocean without directly impacting marine ecosystems.

3.2 Solar radiation modification

While CDR approaches address the root cause of climate change, and thus are widely viewed as an important component of climate mitigation, SRM applications would not significantly reduce atmospheric CO_2 concentrations. There is strong agreement in recent literature that potential SRM deployment would therefore be best applied as more of a temporary measure that could plausibly operate in parallel with mitigation strategies designed to achieve sustained net zero or net negative CO_2 emissions globally. Hence, SRM should never be viewed as the main policy response to climate change.

SRM is, however, the only known approach by which climate warming could be reduced quickly. This means that, while decarbonization efforts continue, SRM could be used to either limit how far global temperatures overshoot a desired limit or to slow the rate of warming while world transitions to a higher temperature level. Earth system model simulations consistently show that a well-designed SRM strategy could counteract some of the adverse effects of increasing GHGs on global and regional climate, including reduced extreme heat and rainfall events and reduced loss of land ice and sea ice. The possibility that SRM may be able to reduce climate damage and alleviate some negative climate change impacts underscores the need for research and assessments to establish whether SRM deployment could be a viable and complementary option to climate mitigation and adaptation (Rahman et al., 2018; National Academies of Sciences, Engineering, and Medicine (NASEM), 2021a; United Nations Environment Programme (UNEP), 2023b; European Union (EU), 2023; American Geophysical Union (AGU), 2024; Environmental Defense Fund (EDF), 2024).

In most SRM approaches, a small amount (1–2%) of sunlight is reflected to space through, for instance, stratospheric aerosol injection, marine cloud brightening, or increasing the albedo of the surface (land, oceans, and cryosphere). Cirrus cloud thinning is often categorized as an SRM method, although instead of altering the amount of sunlight that enters the Earth system, it would allow more infrared radiation from Earth to escape into space. It is worth noting that some SRM approaches are more uncertain than others; for instance, the plethora of uncertainties associated with aerosol-cloud interactions mean that the degree of potential cooling offered by marine cloud brightening strategies is highly uncertain. The extent to which SRM can reduce climate change hazards and alleviate ecological damage and human suffering has not been robustly established. Other concerns include the governance of potential field tests and eventual potential deployment; whether deployment decisions would be made in an inclusive, equitable and transparent manner; whether SRM discussions might shift financial, political, and intellectual resources from mitigation and adaptation efforts (the "moral hazard" problem); and how SRM deployment could lead to societal risks, including international conflicts (United Nations Environment Programme (UNEP), 2023b). Many, if not all, of these concerns have likely contributed to a reluctance among researchers and decisionmakers to advance SRM research and discussions around its governance. In this regard, more transparency in SRM research and improved access to syntheses of the science could be helpful.

In Haywood et al. (2024), we describe the most prominent SRM scenarios and strategies, including stratospheric aerosol injection, marine cloud brightening, cirrus cloud thinning, mixed-cloud thinning, and surface albedo modification, and assess the major research gaps associated with them. Other less prominent SRM proposals such as space mirrors, and marine sky brightening are also briefly discussed.

4 Discussion

4.1 A role for WCRP

As described in more detail by Haywood et al. (2024), Lawrence et al. (2024), and Oschlies et al. (2024) in this issue, many CI approaches have been proposed and are being studied. While CI has been discussed for decades (e.g., Lamb, 1971), its prominence is increasing because emissions reductions are evolving slowly and the adverse impacts of climate change are becoming more frequent, increasing the chances that various CI approaches will be attempted by international consensus or by individual nations or actors, especially in the context of reaching net-zero emissions, of temperature overshoot reversal, and of possibly "shaving the peak" of a temperature overshoot. Moreover, professional societies (e.g., American Meteorological Society (AMS), 2022), National Academies (e.g., National Academies of Sciences, Engineering, and Medicine (NASEM), 2019, 2021a, 2021b), intergovernmental organizations (e.g., United Nations Environment Programme (UNEP), 2023b), non-governmental organizations (e.g., Environmental Defense Fund (EDF), 2024) and others have recently called out the importance of research on CI to understand its benefits and risks relative to the risks posed by climate change, while being careful to not advocate for pathways to deployment at this time.

With CI approaches beginning to proliferate as potential pathways to reduce, remove, or counteract some of the effects of climate change, international research efforts are urgently needed to determine the effectiveness, risks, and opportunities of CI relative to the risks of climate change and inform societal decisions about possible implementation. It is in this context that it is important for WCRP, as a world leading climate research programme, to engage in the topic of CI. Already, WCRP plays a significant role by advancing and coordinating much of the international climate science research that the Intergovernmental Panel on Climate Change (IPCC) assesses. In our view, it should play a similar role for CI research. We are thus supportive of the launch, in February 2024, of a WCRP Lighthouse Activity (LHA) on Climate Intervention Research. Lighthouse activities are designed to be ambitious and transdisciplinary research efforts that integrate across other WCRP programs to rapidly advance the science and institutional frameworks needed to better manage climate risk and meet society's urgent need for robust and actionable climate information.

We see several clear roles WCRP could play in advancing CI research, with an emphasis on WCRP core strengths in observing, understanding, and modelling relevant physical science processes, as well as evaluating feedbacks and impacts across physical and biogeochemical systems. Moreover, aspects of CI research are already taking place across the various WCRP core projects and other LHAs, but they are not well coordinated across communities even within the WCRP family. As such, WCRP could establish an inventory of existing and planned efforts, as well as research and knowledge gaps, and it could help coordinate activities and plans across its core teams, including identifying and prioritizing CI research questions and approaches. WCRP could also proactively develop targeted meetings and workshops, or commissioned papers, in collaboration with external groups. Our expectation is that those directly involved in the CI LHA have already begun such deliberations.

More generally, we feel it is critical for WCRP to leverage its role as an honest broker and a respected community voice to build trust and transparency in CI research, for instance by creating a registry or repository of information on CI research. An international registry could serve as a centralized platform where scientists could share detailed aspects of their research, including research designs, hypotheses, assumptions, models, data and resulting publications, as well as sources of funding. This could not only foster collaboration but also enhance the reproducibility and reliability of scientific findings, building trust in CI research and empowering decisionmakers and the public to form well-informed views and positions on CDR and SRM approaches.

By assembling strong, global expertise in CI approaches, WCRP could also facilitate the provision of accessible syntheses of the benefits and risks of proposed CDR and SRM approaches relative to climate change impacts. Such syntheses could lay the scientific groundwork for an international assessment of CI, for instance by the IPCC or the United Nations Environment Programme (UNEP), as has recently been called for (United Nations Environment Programme (UNEP), 2023b; Tilmes et al., 2024). The aim of CI syntheses, from a WCRP perspective, would be to establish the natural science basis of CDR and SRM to guide the research required to serve as a foundation for governance and decision making. A regular synthesis process would ensure an ongoing review of evolving CI literature and identification of key scenarios, environmental consequences, uncertainties, and knowledge gaps.

WCRP needs to emphasize that there are many ethical, moral, socio-economic, and philosophical issues of concern, and that support for research does not equal endorsement or suggest deployment of CI technologies. WCRP should also recognize the transdisciplinary nature of CI research and seek opportunities for partnerships. Broadly speaking, there are several relevant national programs and efforts, but they are not well coordinated and communication across them is lacking. Coordination and communication with Future Earth and other international research programs, like the World Weather Research and the Global Atmosphere Watch Programmes within the WMO, are also needed. WCRP should thus assume a leadership role, in not only coordinating internally, but across this broader array of efforts. This could include a role for WCRP in bridging science (physical and social), politics and governance, and facilitate the entrainment of developing nations and the Young Earth System Scientists community, who are currently underrepresented in CI research, as is discussed more below.

4.2 WCRP and global inclusivity

Most countries in the Global South (GS) are vulnerable to climate change despite their low historical GHG emissions (Trisos et al., 2022). Similarly, risks from CI approaches would have regional impacts, likely felt more significantly by the most vulnerable countries. As most CI research occurs in Global North (GN) research institutions, largely because most funding is derived from GN funders, the CI research agenda has been set by GN researchers and results interpreted through a GN lens. It is well understood that GN-driven research (1) cannot adequately address the research concerns of the GS; (2) reinforces inequitable power relationships and asymmetries in knowledge, expertise and technical capacity; (3) does not foster a two-way learning process;

and (4) does not build relationships on which sustained, equitable research can be conducted (Steynor et al., 2020; Vincent et al., 2020; Trisos et al., 2022). GS researchers face many barriers to inclusivity in CI research including access to funding (Overland et al., 2021), infrastructure (Meque et al., 2021), knowledge (Bohannon, 2016) and inequitable power relationships (Vincent et al., 2020).

There is, therefore, an ethical imperative for the GS to be at the forefront of CI research, discussion and evaluation with GN colleagues (e.g., Horton and Keith, 2016; Rahman et al., 2018), which may be facilitated by the WCRP. Regarding SRM research, for instance, a recent survey suggested that GS participants viewed specific SRM technologies favorably in terms of potential benefits, but they expressed concerns that this could undermine climate-mitigation efforts and promote an unequal distribution of risks between poor and rich countries (Baum et al., 2024). GS communities add value to these discussions as they have different value systems to those of the GN, and they bring different perspectives on climate change impacts, ecosystems, loss and damage and adaptation and mitigation (Bala and Gupta, 2019).

To facilitate GS research in SRM, the Degrees Initiative (DEveloping country Governance REsearch and Evaluation for SRM) has funded 25 CI projects in GS countries involving over 150 researchers since 2018. Those researchers have addressed SRM impacts on the physical climate (Pinto et al., 2020; Clarke et al., 2021; Camilloni et al., 2022; Kuswanto et al., 2022), oceans (Ayissi et al., 2023), extremes (Odoulami et al., 2020; Patel et al., 2023) and agriculture (Egbebiyi et al., 2023). Several researchers who were capacitated through the Degrees programme now participate in WCRP structures and have assisted in framing an inclusive research agenda and narrative developed for the WCRP CI lighthouse as well as the WCRP endorsed Geoengineering Model Intercomparison Project (Visioni et al., 2023).

While the initiatives noted above are an encouraging start to global inclusivity, the WCRP recognizes that the GS has a critical contribution to make in the CDR and SRM research arena and that a significant, sustained effort is needed to improve inclusivity and support truly global CI research. A WCRP registry or repository on CI research could also empower researchers in the GS through a centralized sharing of research resources.

5 Final thoughts

As a respected global research programme, WCRP can facilitate comprehensive and globally inclusive research into the benefits and risks of proposed CDR and SRM approaches relative to climate change impacts. One outcome of this could be the provision of periodic, accessible syntheses to lay the scientific groundwork for international assessments of CI, perhaps by the IPCC or UNEP. Also, WCRP activities in CI research could benefit from partnerships with a range of international organizations since the issues surrounding CI (scientific, social, economic, governance, and intergenerational) are complex and extend well beyond its traditional expertise. By advancing and coordinating truly international research, WCRP has an important role to play by enhancing accountability and building trust in CI research. In so doing, it would help address the demand for a more robust knowledge base over the next decade, so that decisionmakers and stakeholders could make well-informed decisions on the role of CI as part of a comprehensive strategy to address climate change.

We are very supportive of WCRP usefully stepping into the global leadership void that currently exists around coordinating, promoting, evaluating and advancing CI research internationally. WCRP could become the leading scientific voice on matters of deliberate human interventions into the climate system.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JHu: Conceptualization, Writing – original draft. JHa: Conceptualization, Writing – original draft. PL: Conceptualization, Writing – original draft. CL: Conceptualization, Writing – original draft. AO: Conceptualization, Writing – original draft.

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Conflict of interest

The authors declare that this perspective was written in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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