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"Cooling credits" are not a viable climate solution

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Abstract

As the world struggles to limit warming to 1.5 or 2 °C below pre-industrial temperatures, research into solar climate interventions that could temporarily offset some amount of greenhouse gas-driven global warming by reflecting more sunlight back out to space has gained prominence. These solar climate intervention techniques would aim to cool the Earth by injecting aerosols (tiny liquid or solid particles suspended in the atmosphere) into the upper atmosphere or into low-altitude marine clouds. In a new development, "cooling credits" are now being marketed that claim to offset a certain amount of greenhouse gas warming with aerosol-based cooling. The science of solar climate intervention is currently too uncertain and the quantification of effects insufficient for any such claims to be credible in the near term. More fundamentally, however, the environmental impacts of greenhouse gases and aerosols are too different for such credits to be an appropriate instrument for reducing climate risk even if scientific uncertainties were narrowed and robust monitoring systems put in place. While some form of commercial mechanism for solar climate intervention implementation, in the event it is used, is likely, "cooling credits" are unlikely to be a viable climate solution, either now or in the future.

Keywords Climate risk · Climate intervention · Solar radiation modification · Stratospheric aerosol injection · Marine cloud brightening · Geoengineering

1 Introduction

Despite substantial progress in clean technology and increasing policy ambition, the world remains off track to hold warming to the Paris Agreement targets of well below 2 °C and, aspirationally, no greater than 1.5 °C above pre-industrial temperatures (United Nations Environment Programme 2022). In light of this, a growing number of scientists and advocates—including the authors (Diamond et al. 2022; Wanser et al. 2022)—have called for expanding research into solar climate interventions that would utilize tiny solid or liquid

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particles suspended in the atmosphere (aerosols) to reflect more sunlight away from Earth and thus offset some of the effects of global warming due to greenhouse gas emissions from fossil fuel burning and deforestation (Crutzen 2006; NASEM 2021; United Nations Environment Programme 2023).

Notwithstanding the relatively early state of solar climate intervention research, at least one company has already been founded to market "cooling credits" that purport to offset a given quantity of greenhouse gas emissions with the emission of aerosols or their precursor gases (Temple 2022). In the near term, the science of solar climate intervention is simply too uncertain for such credits to be meaningful market instruments. More fundamentally, however, many of the climatic and environmental effects of greenhouse gas emissions are incommensurate with those from aerosol injections. If solar climate interventions are to be part of society's portfolio of responses to climate change, they must be complements to, not substitutes for, mitigation.[1] A market approach to solar climate intervention based on uncoordinated "cooling credits" is not a viable climate solution now and is unlikely to ever be in the future.

2 Uncertain efficacy and inadequate monitoring

A conceit behind "cooling credits" is that they can serve as suitable substitutes for carbon credits and offsets that, at least in theory [and accounting for carbon cycle responses (Zickfeld et al. 2021)], reverse the harms that would have occurred due to some quantity of emitted greenhouse gases by compensating additional mitigation efforts elsewhere or procuring a drawdown and secure long-term storage of CO_2. Despite their promise, in practice, the widespread use of carbon offsets has thus far been inhibited by challenges to quantifying carbon drawdown and storage permanence supported by monitoring, reporting, and verification (Babiker et al. 2022). The uncertainties associated with quantifying the cooling from the emission of some mass of aerosol (or precursor gas) and translating this to the warming from some mass of carbon are substantially larger. Indeed, estimating how much greenhouse gas warming has been masked by present-day aerosol pollution (largely via its effects on clouds) is one of the greatest uncertainties in climate science (Forster et al. 2021). Very similar physics and chemistry challenges apply to both understanding the effect of aerosol pollution today and predicting what would happen under a hypothetical future solar climate intervention deployment.

Stratospheric aerosol injection (SAI), in which aerosols or precursor gases would be added to the upper atmosphere (Budyko 1974; Crutzen 2006), would almost certainly be able to produce a cooling effect like that observed after large explosive volcanic eruptions (Hansen et al. 1992; Robock et al. 2013). However, how much material would be necessary to produce the desired level of global mean cooling and how this would vary by injection altitude, latitude, and timing remains highly uncertain (MacMartin et al. 2017; Rasch et al. 2008; Visioni et al. 2017, 2020, 2021). The type and amount of material injected in addition to its seasonality and location would also affect potential side effects.

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[1] While our argument in support of this statement primarily relies on physical science aspects, we acknowledge that there exist important political, socioeconomic, and ethical considerations that would lead to the same conclusion. Our goal in this essay is to outline the physical science case against "cooling credits" in a manner that is broadly compatible with different value systems. Our avoidance of some more normative arguments as out of scope should not therefore be taken as indifference or irrelevance.

The cooling ability of marine cloud brightening (MCB), in which sea salt would be sprayed into low-lying clouds to make them more reflective and potentially longer lasting (Conover 1966; Latham 1990; Latham et al. 2012), is less certain than for SAI. Aerosol-driven cloud enhancements have been clearly observed in effusive volcanic eruptions (Chen et al. 2022; Gassó 2008; Malavelle et al. 2017; McCoy and Hartmann 2015; Toll et al. 2017; Yuan et al. 2011) and other "natural experiments" (Christensen et al. 2022) like pollution tracks from international shipping (Conover 1966; Diamond et al. 2020; Durkee et al. 2000; Manshausen et al. 2022; Radke et al. 1989; Russell et al. 2013) and large industrial centers (Hobbs et al. 1980; Toll et al. 2019; Trofimov et al. 2020). Statistically significant detection of regional radiation changes (Seidel et al. 2014) has been more challenging, however, except in ideal conditions for the particularly susceptible stratocumulus cloud regime (Diamond et al. 2020). Whether substantial cooling can be routinely and predictably achieved in other cloud regimes and regions is a major uncertainty for assessing the technical feasibility of MCB (Diamond et al. 2022; Feingold et al. 2022). Questions about the proper size of injected particles also have major implications for the mass of aerosol required for a given cooling (Hoffmann and Feingold 2021; Wood 2021), and the answers will likely vary for clouds under different weather states. Seeding in unfavorable meteorology can even lead to counterproductive cloud evaporation and darkening (Y.-C. Chen et al. 2012; Coakley and Walsh 2002; Zhang and Feingold 2023).

For both SAI and MCB, major investments in monitoring would be necessary to confidently detect that an intervention was working as intended (Feingold et al. 2022; NASEM 2021). This would involve a sustained commitment to maintaining and improving the capabilities of a global observing and monitoring system for Earth's radiation budget and atmospheric composition including, among other initiatives, expanded balloon and aircraft measurements of stratospheric properties and advances in retrieving cloud and aerosol properties from space- and ground-based sensors.

3 Incommensurate impacts of greenhouse gases and aerosols

Even if these (and many other) uncertainties are narrowed in the coming years (Wanser et al. 2022), the different natures of environmental effects from increasing greenhouse gases and the impacts of reflecting sunlight complicate direct comparisons. Solar climate interventions like SAI and MCB[2] work by reducing the amount of shortwave radiation from the sun that the Earth absorbs, whereas the greenhouse effect warms by preventing Earth's longwave ("heat") radiation from escaping out to space. As a result of this difference, cooling by reflecting sunlight decreases precipitation more than the same cooling from avoided greenhouse gas emissions (Bala et al. 2008) [see illustrative climate model results (Boucher et al. 2019a, b, 2020a, b; Visioni et al. 2021) in Fig. 1a, b]. A well-designed solar climate intervention could plausibly reduce both temperature and precipitation impacts of

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[2] Although this essay focuses on SAI and MCB as the most well-studied solar climate intervention techniques, other proposals exist like shading the Earth with a space-borne sunshade or increasing the reflectivity of Earth's surface. Proposals to use aerosol injections to thin high-altitude cirrus clouds (Mitchell and Finnegan 2009) or polar mixed-phase clouds (Villanueva et al. 2022) are also sometimes included in discussions of solar climate intervention. However, those interventions work by allowing more longwave radiation to escape Earth (and indeed may allow more sunlight to be absorbed, not reflected) and thus have somewhat different considerations than are discussed here.

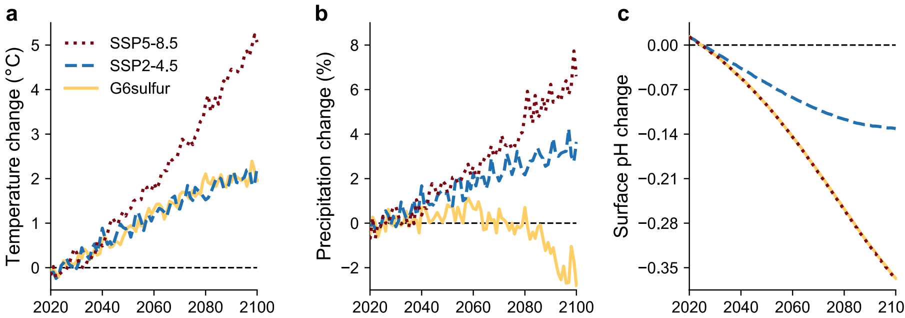

Fig. 1 Example climate changes under a high greenhouse gas emissions scenario (SSP5-8.5), a lower greenhouse gas emissions scenario (SSP2-4.5), and a scenario in which the warming from the high greenhouse gas emissions scenario is reduced to that from the lower greenhouse gas emissions scenario via stratospheric aerosol injection (G6sulfur). Global mean surface temperature (**a**), precipitation (**b**), and surface ocean pH (**c**) results are shown from simulations of the Institute Pierre-Simon Laplace's IPSL-CM6A-LR climate model (Boucher et al. 2019a, b, 2020a, b) for G6sulfur (solid yellow lines), in which sulfur dioxide is injected into the stratosphere such that global mean surface temperature is maintained at the level of those in SSP2-4.5 (dashed blue lines) despite actual emissions from SSP5-8.5 (dotted red lines). Changes are shown as departures from the SSP5-8.5 2020–2030 mean values. Even though both SAI and mitigation from SSP5-8.5 to SSP2-4.5 greenhouse gas emissions result in similar temperature evolutions (**a**), SAI overcorrects the precipitation change (**b**) and does not ameliorate ocean acidification (**c**). See Visioni et al. (2021) for details. Although the values shown are for only one model and scenario, any solar climate intervention would produce qualitatively similar results

climate change simultaneously, but only by explicitly aiming not to fully offset greenhouse gas warming (Irvine et al. 2019; Irvine and Keith 2020). The mismatch between changing shortwave and longwave radiation could also alter the distribution of temperature change, for example, between day and night, between seasons, and between the tropics and the poles (Bala and Caldeira 2000; Jiang et al. 2019; Kravitz et al. 2013). The distribution of risks and benefits will therefore differ between mitigation and a solar climate intervention even for the same amount of avoided global mean warming.

Because solar climate interventions do not directly decrease the amount of CO_2 in the atmosphere, they are unable to substantially ameliorate ocean acidification (Fig. 1c). On the bright side, solar climate intervention would reduce the stressor of warming, potentially increasing resiliency in the face of continued acidification. But by breaking the historic link between global temperatures, radiation, and atmospheric CO_2, ecological systems may find themselves in environmental conditions for which there is no recent analogue, with as-yet unknown consequences (Zarnetske et al. 2021).

There is also a timescale mismatch between the cooling produced by aerosol interventions and warming from CO_2, which can linger in the atmosphere for hundreds to many thousands of years after emission. Aerosol from an SAI deployment would remain in the stratosphere for months to years unless replenished; sea salt from an MCB deployment would leave the lower atmosphere on a timescale of days. Although it is possible, on paper, to use accounting metrics like the "global warming potential" (Forster et al. 2021) over some time period to equate long-term CO_2 warming and shorter-term aerosol cooling, their effects will differ in reality and there is no obvious choice for the proper metric.

In addition to the issues above that pertain to all solar climate intervention methods, there are also risks specific to each technique. As examples, chemical and circulation effects of SAI may delay recovery of the ozone hole (Haywood et al. 2022; Tilmes et al. 2008; Tilmes et al. 2022) and the patchiness of MCB (which can only be performed where the right kinds of clouds occur) could cause circulation responses with deleterious consequences for precipitation in some regions (Bala et al. 2010; Hill and Ming 2012; Jones et al. 2009). These uncertain negative side effects, likely to vary nonlinearly with the nature of delivery and volume of material, mean that the risks and benefits of a solar climate intervention cannot be calculated simply as the sum of individual inputs. Highly coordinated or centralized activity may therefore be required to minimize risks and maximize benefits under continually evolving environmental conditions. This would run counter to the idea of a marketplace of uncoordinated individual actors with incentives primarily (or only) tied to scale.

Thus, even if a solar climate intervention were to work exactly as its deployer intends, reducing sunlight will not provide a one-to-one offset of greenhouse-gas-driven climate change. Mainstream proposals therefore tend to conceptualize solar climate intervention as a temporary measure to be wound down as mitigation and carbon dioxide removal scale up (MacMartin et al. 2018), which would be inconsistent with the widespread adoption of “cooling credits” that are not tied to the drawdown of atmospheric CO_2 and may instead contribute to its continued rise. Although it is possible that some form of market mechanism may be appropriate as part of an overall coordinated strategy—for example by linking shorter-term solar climate interventions and longer-term carbon dioxide removal (Lockley et al. 2019)—it would be imperative that the solar climate interventions complement mitigation and carbon dioxide removal, not substitute for them.

4 Conclusion

Solar climate interventions may one day be critical components of the broader portfolio of climate policies to limit damages from greenhouse gas warming. If they are, however, it should not be through a “cooling credit” mechanism that is unquantifiable in the medium-term and, due to the differences between the environmental consequences of greenhouse gases and aerosols, fundamentally incompatible with the imperative to maximize safety and minimize harm. Although at least one startup has already launched (Temple 2022), policymakers, businesses, and individuals can deter such initiatives by sending a clear signal that there will be no business opportunity for such unsubstantiated “cooling credits” within carbon markets or voluntary offset initiatives now or in the future.

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Data availability Model output for the G6sulfur, SSP2-4.5, and SSP5-8.5 experiments is publicly available from the Earth System Grid Federation (https://esgf-node.llnl.gov/search/cmip6/).

Declarations

Competing interests The authors declare no competing interests.

References

Babiker M, Berndes G, Blok K, Cohen B, Cowie A, Geden O, Yamba F (2022) Cross-sectoral perspectives. In: Shukla PR, Skea J, Slade R, Khourdajie AA, Diemen Rv, McCollum D, Pathak M, Some S, Vyas P, Fradera R, Belkacemi M, Hasija A, Lisboa G, Luz S, Malley J (eds) Climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Bala G, Caldeira K (2000) Geoengineering Earth's radiation balance to mitigate CO2-induced climate change. Geophys Res Lett 27(14):2141–2144. https://doi.org/10.1029/1999gl006086

Bala G, Duffy PB, Taylor KE (2008) Impact of geoengineering schemes on the global hydrological cycle. Proc Natl Acad Sci USA 105(22):7664–7669. https://doi.org/10.1073/pnas.0711648105

Bala G, Caldeira K, Nemani R, Cao L, Ban-Weiss G, Shin H-J (2010) Albedo enhancement of marine clouds to counteract global warming: impacts on the hydrological cycle. Clim Dyn 37(5–6):915–931. https://doi.org/10.1007/s00382-010-0868-1

Boucher O, Denvil S, Levavasseur G, Cozic A, Caubel A, Foujols M-A, Lurton T (2019a) IPSL IPSL-CM6A-LR model output prepared for CMIP6 ScenarioMIP ssp245. Retrieved from: https://doi.org/10.22033/ESGF/CMIP6.5264

Boucher O, Denvil S, Levavasseur G, Cozic A, Caubel A, Foujols M-A, Lurton T (2019b) IPSL IPSL-CM6A-LR model output prepared for CMIP6 ScenarioMIP ssp585. Retrieved from: https://doi.org/10.22033/ESGF/CMIP6.5271

Boucher O, Denvil S, Levavasseur G, Cozic A, Caubel A, Foujols M-A, Lurton T (2020a) IPSL IPSL-CM6A-LR model output prepared for CMIP6 GeoMIP G6sulfur. Retrieved from: https://doi.org/10.22033/ESGF/CMIP6.5059

Boucher O, Servonnat J, Albright AL, Aumont O, Balkanski Y, Bastrikov V, Vuichard N (2020b) Presentation and evaluation of the IPSL-CM6A-LR climate model. J Adv Model Earth Syst 12(7). https://doi.org/10.1029/2019ms002010

Budyko MI (1974) Miller Ed. Climate and life, English. Academic, New York

Chen Y-C, Christensen MW, Xue L, Sorooshian A, Stephens GL, Rasmussen RM, Seinfeld JH (2012) Occurrence of lower cloud albedo in ship tracks. Atmos Chem Phys 12(17):8223–8235. https://doi.org/10.5194/acp-12-8223-2012

Chen Y, Haywood J, Wang Y, Malavelle F, Jordan G, Partridge D, Lohmann U (2022) Machine learning reveals climate forcing from aerosols is dominated by increased cloud cover. Nat Geosci 15:609–614. https://doi.org/10.1038/s41561-022-00991-6

Christensen MW, Gettelman A, Cermak J, Dagan G, Diamond M, Douglas A, Yuan T (2022) Opportunistic experiments to constrain aerosol effective radiative forcing. Atmos Chem Phys 22(1):641–674. https://doi.org/10.5194/acp-22-641-2022

Coakley JA, Walsh CD (2002) Limits to the aerosol indirect radiative effect derived from observations of ship tracks. J Atmos Sci 59(3):668–680. https://doi.org/10.1175/1520-0469(2002)059<0668:Lttair>2.0.Co;2

Conover JH (1966) Anomalous cloud lines. J Atmos Sci 23(6):778–785. https://doi.org/10.1175/1520-0469(1966)023<0778:Acl>2.0.Co;2

Crutzen PJ (2006) Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? Clim Change 77(3–4):211–220. https://doi.org/10.1007/s10584-006-9101-y

Diamond MS, Director HM, Eastman R, Possner A, Wood R (2020) Substantial cloud brightening from shipping in subtropical low clouds. AGU Adv 1(1):e2019AV000111. https://doi.org/10.1029/2019av000111

Diamond MS, Gettelman A, Lebsock MD, McComiskey A, Russell LM, Wood R, Feingold G (2022) Opinion: to assess marine cloud brightening's technical feasibility, we need to know what to study—and when to stop. Proc Natl Acad Sci USA 119(4):e2118379119. https://doi.org/10.1073/pnas.2118379119

Durkee PA, Noone KJ, Bluth RT (2000) The Monterey Area Ship Track experiment. J Atmos Sci 57(16):2523–2541. https://doi.org/10.1175/1520-0469(2000)057<2523:Tmaste>2.0.Co;2

Feingold G, Ghate V, Russell LM, Blossey P, Cantrell W, Christensen MW, Zheng X (2022) DOE-NOAA marine cloud brightening workshop. U.S. Department of Energy and U.S. Department of Commerce NOAA; DOE/SC-0207; NOAA Technical Report OAR ESRL/CSL-1

Forster P, Storelvmo T, Armour K, Collins W, Dufresne J-L, Frame D, Zhang H (2021) The earth's energy budget, climate feedbacks, and climate sensitivity. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 923–1054

Gassó S (2008) Satellite observations of the impact of weak volcanic activity on marine clouds. J Geophys Res 113:D14S19. https://doi.org/10.1029/2007jd009106

Hansen J, Lacis A, Ruedy R, Sato M (1992) Potential climate impact of Mount Pinatubo eruption. Geophys Res Lett 19(2):215–218. https://doi.org/10.1029/91gl02788

Haywood J, Tilmes S, Keutsch FN, Niemeier U, Visioni D, Yu P, Wilka CA (2022) Chapter 6. Stratospheric aerosol injection and its potential effect on the stratospheric ozone layer. In: Aquila V, Rosenlof KH (eds) Scientific assessment of ozone depletion: 2022. World Meterological Organization, Geneva, p 509

Hill S, Ming Y (2012) Nonlinear climate response to regional brightening of tropical marine stratocumulus. Geophys Res Lett 39(15):L15707. https://doi.org/10.1029/2012gl052064

Hobbs PV, Stith JL, Radke LF (1980) Cloud-active nuclei from coal-fired electric power plants and their interactions with clouds. J Appl Meteorol 19(4):439–451. https://doi.org/10.1175/1520-0450(1980)019<0439:Canfcf>2.0.Co;2

Hoffmann F, Feingold G (2021) Cloud microphysical implications for marine cloud brightening: the importance of the seeded particle size distribution. J Atmos Sci 78:3247–3262. https://doi.org/10.1175/jas-d-21-0077.1

Irvine PJ, Keith DW (2020) Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards. Environ Res Lett 15(4). https://doi.org/10.1088/1748-9326/ab76de

Irvine PJ, Emanuel K, He J, Horowitz LW, Vecchi G, Keith D (2019) Halving warming with idealized solar geoengineering moderates key climate hazards. Nat Clim Change 9(4):295–299. https://doi.org/10.1038/s41558-019-0398-8

Jiang J, Cao L, MacMartin DG, Simpson IR, Kravitz B, Cheng W, Mills MJ (2019) Stratospheric sulfate aerosol geoengineering could alter the high-latitude seasonal cycle. Geophys Res Lett 46(23):14153–14163. https://doi.org/10.1029/2019gl085758

Jones A, Haywood J, Boucher O (2009) Climate impacts of geoengineering marine stratocumulus clouds. J Geophys Res: Atmos 114(D10):D10106. https://doi.org/10.1029/2008jd011450

Kravitz B, Caldeira K, Boucher O, Robock A, Rasch PJ, Alterskjaer K, Yoon J-H (2013) Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). J Geophys Res: Atmos 118(15):8320–8332. https://doi.org/10.1002/jgrd.50646

Latham J (1990) Control of global warming? Nature 347(6291):339–340. https://doi.org/10.1038/347339b0

Latham J, Bower K, Choularton T, Coe H, Connolly P, Cooper G, Wood R (2012) Marine cloud brightening. Philos Trans Royal Soc A: Math Phys Eng Sci 370(1974):4217–4262. https://doi.org/10.1098/rsta.2012.0086

Lockley A, Mi Z, Coffman DM (2019) Geoengineering and the blockchain: Coordinating carbon dioxide removal and solar radiation management to tackle future emissions. Front Eng Manag 6(1):38–51. https://doi.org/10.1007/s42524-019-0010-y

MacMartin DG, Kravitz B, Tilmes S, Richter JH, Mills MJ, Lamarque J-F, Vitt F (2017) The Climate response to Stratospheric Aerosol Geoengineering can be tailored using multiple injection locations. J Geophys Research: Atmos 122(23):512,574–512,590. https://doi.org/10.1002/2017JD026868

MacMartin DG, Ricke KL, Keith DW (2018) Solar geoengineering as part of an overall strategy for meeting the 1.5 degrees C Paris target. Philos Trans Royal Soc A: Math Phys Eng Sci 376(2119):20160454. https://doi.org/10.1098/rsta.2016.0454

Malavelle FF, Haywood JM, Jones A, Gettelman A, Clarisse L, Bauduin S, Thordarson T (2017) Strong constraints on aerosol-cloud interactions from volcanic eruptions. Nature 546(7659):485–491. https://doi.org/10.1038/nature22974

Manshausen P, Watson-Parris D, Christensen MW, Jalkanen J-P, Stier P (2022) Invisible ship tracks show large cloud sensitivity to aerosol. Nature 610(7930):101–106. https://doi.org/10.1038/s41586-022-05122-0

McCoy DT, Hartmann DL (2015) Observations of a substantial cloud-aerosol indirect effect during the 2014–2015 Bárðarbunga-Veiðivötn fissure eruption in Iceland. Geophys Res Lett 42(23):10409–10414. https://doi.org/10.1002/2015gl067070

Mitchell DL, Finnegan W (2009) Modification of cirrus clouds to reduce global warming. Environ Res Lett 4(4):045102. https://doi.org/10.1088/1748-9326/4/4/045102

NASEM (2021) Reflecting sunlight: recommendations for Solar Geoengineering Research and Research Governance. The National Academies Press, Washington, DC

Radke LF, Coakley JA, King MD (1989) Direct and remote sensing observations of the effects of ships on clouds. Science 246(4934):1146–1149

Rasch PJ, Tilmes S, Turco RP, Robock A, Oman L, Chen CC, Garcia RR (2008) An overview of geoengineering of climate using stratospheric sulphate aerosols. Philos Trans A Math Phys Eng Sci 366(1882):4007–4037. https://doi.org/10.1098/rsta.2008.0131

Robock A, MacMartin DG, Duren R, Christensen MW (2013) Studying geoengineering with natural and anthropogenic analogs. Clim Change 121(3):445–458. https://doi.org/10.1007/s10584-013-0777-5

Russell LM, Sorooshian A, Seinfeld JH, Albrecht BA, Nenes A, Ahlm L, Wonaschütz A (2013) Eastern Pacific Emitted Aerosol Cloud experiment. Bull Am Meteorol Soc 94(5):709–729. https://doi.org/10.1175/bams-d-12-00015.1

Seidel DJ, Feingold G, Jacobson AR, Loeb N (2014) Detection limits of albedo changes induced by climate engineering. Nat Clim Change 4(2):93–98. https://doi.org/10.1038/nclimate2076

Temple J (2022) A startup says it's begun releasing particles into the atmosphere, in an effort to tweak the climate. MIT Technology Review, Cambridge, MA

Tilmes S, Müller R, Salawitch R (2008) The sensitivity of polar ozone depletion to proposed geoengineering schemes. Science 320(5880):1201–1204. https://doi.org/10.1126/science.1153966

Tilmes S, Visioni D, Jones A, Haywood J, Séférian R, Nabat P, Niemeier U (2022) Stratospheric ozone response to sulfate aerosol and solar dimming climate interventions based on the G6 Geoengineering Model Intercomparison Project (GeoMIP) simulations. Atmos Chem Phys 22(7):4557–4579. https://doi.org/10.5194/acp-22-4557-2022

Toll V, Christensen M, Gassó S, Bellouin N (2017) Volcano and ship tracks indicate excessive aerosol-induced cloud water increases in a climate model. Geophys Res Lett 44:12492–12500. https://doi.org/10.1002/2017gl075280

Toll V, Christensen M, Quaas J, Bellouin N (2019) Weak average liquid-cloud-water response to anthropogenic aerosols. Nature 572(7767):51–55. https://doi.org/10.1038/s41586-019-1423-9

Trofimov H, Bellouin N, Toll V (2020) Large-scale industrial cloud perturbations confirm bidirectional cloud water responses to anthropogenic aerosols. J Geophys Res Atmos 125(14):e2020JD032575

United Nations Environment Programme (2022) Emissions gap report 2022: the closing window — climate crisis calls for rapid transformation of societies. Nairobi, Kenya

United Nations Environment Programme (2023) One atmosphere: an independent expert review on solar radiation modification research and deployment. Nairobi, Kenya

Villanueva D, Possner A, Neubauer D, Gasparini B, Lohmann U, Tesche M (2022) Mixed-phase regime cloud thinning could help restore sea ice. Environ Res Lett 17(11):114057. https://doi.org/10.1088/1748-9326/aca16d

Visioni D, Pitari G, Aquila V (2017) Sulfate geoengineering: a review of the factors controlling the needed injection of sulfur dioxide. Atmos Chem Phys 17(6):3879–3889. https://doi.org/10.5194/acp-17-3879-2017

Visioni D, MacMartin DG, Kravitz B, Richter JH, Tilmes S, Mills MJ (2020) Seasonally modulated stratospheric aerosol geoengineering alters the climate outcomes. Geophys Res Lett 47(12):e2020GL088337. https://doi.org/10.1029/2020gl088337

Visioni D, MacMartin DG, Kravitz B, Boucher O, Jones A, Lurton T, Tilmes S (2021) Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations. Atmos Chem Phys 21(13):10039–10063. https://doi.org/10.5194/acp-21-10039-2021

Wanser K, Doherty SJ, Hurrell JW, Wong A (2022) Near-term climate risks and solar radiation modification: a roadmap approach for physical sciences research. Clim Change 174(3–4):23. https://doi.org/10.1007/s10584-022-03446-4

Wood R (2021) Assessing the potential efficacy of marine cloud brightening for cooling Earth using a simple heuristic model. Atmos Chem Phys 21(19):14507–14533. https://doi.org/10.5194/acp-21-14507-2021

Yuan T, Remer LA, Yu H (2011) Microphysical, macrophysical and radiative signatures of volcanic aerosols in trade wind cumulus observed by the A-Train. Atmos Chem Phys 11(14):7119–7132. https://doi.org/10.5194/acp-11-7119-2011

Zarnetske PL, Gurevitch J, Franklin J, Groffman PM, Harrison CS, Hellmann JJ, Yang C-E (2021) Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth. Proc Natl Acad Sci 118(15):e1921854118. https://doi.org/10.1073/pnas.1921854118

Zhang J, Feingold G (2023) Distinct regional meteorological influences on low-cloud albedo susceptibility over global marine stratocumulus regions. Atmos Chem Phys 23(2):1073–1090. https://doi.org/10.5194/acp-23-1073-2023

Zickfeld K, Azevedo D, Mathesius S, Matthews HD (2021) Asymmetry in the climate–carbon cycle response to positive and negative CO2 emissions. Nat Clim Change 11(7):613–617. https://doi.org/10.1038/s41558-021-01061-2