Understanding the Urgent Need for Direct Climate Cooling

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Abstract

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The long-term average global temperature increase inadequately predicts the harm from regional or local extreme precipitation and heat events. Climate change, especially polar amplification, has already caused enormous damage and is likely to abruptly accelerate the risk of further catastrophic harm to humans and other species in the absence of urgent direct climate cooling efforts to slow or reverse it. At least eighteen potential direct climate cooling methods have been identified with the potential to address such climate disruptions. A precautionary approach would be to evaluate such direct climate cooling methods for their capacity to return our planetary trajectory towards known and healthy climate conditions. An evaluation framework could test and monitor small scale deployments under constrained conditions. This paper includes short summaries of eighteen of these methods, almost all written or reviewed by climate cooling experts from among those cited in the footnotes. The methods listed in alphabetical order comprise:

- Bright Water
- Buoyant Flakes
- Cirrus cloud thinning (CCT)
- Extremely diluted Aqua Regia Aerosol (EDARA)
- Fizz Tops (Fiztops)
- Ice shields to thicken polar ice
- Iron Salt Aerosol (ISA)Marine algal bloom stimulation
- Marine Cloud Brightening (MCB)
- Mirrors for Earth's Energy Rebalancing (MEER)
- Ocean Thermal Energy Conversion (OTEC)
- Restoring natural upwelling from tropical to temperate latitudes
- Restoring soil and vegetation
- Seawater atomization (Seatomizers)
- Stratospheric Aerosol Injection (SAI)
- Surface Albedo Modification (SAM)
- Titanium Oxide Aerosol (TOA)
- Tree planting and reflective materials in urban areas

Given multiple potential methods to directly cool the climate, relying exclusively on GHG emissions reductions and removal seems incompatible with responsible stewardship of the planet. With direct cooling of the Earth having the potential to dramatically reduce harm, preserve ecosystems and save lives, including it as a policy opportunity in the development of a climate restoration plan that would return global warming to well below 1° C would seem to be an urgent imperative for world leaders. The tragic example of Pakistani floods this year induced by excessive Himalayan melt and extreme monsoon events underscores the compelling evidence that even 1° C of warming is too much. With such increasing impacts from human-induced global warming, an effective restoration plan would then seem to focus on three key components: a) deploying a direct cooling influence, at least initially particularly focused on cooling the polar regions and the Himalayas, b) reducing GHG emissions, including an early focus on methane and other short-lived warming agents, and c) removing legacy CO_2, methane and other GHGs from the atmosphere and oceans. With indications that the rate of warming is accelerating, it will be vital over the next few decades to keep the climate from spiraling out of control. Only the application of emergency cooling "tourniquets", applied immediately or as soon as is reasonably advisable, has the potential to slow or reverse ongoing climate disruption and worsening climate impacts. While reducing emissions of GHGs and removing GHGs from the atmosphere and ocean are both essential for limiting warming, both approaches will require decades to be effective and neither seems capable of returning global warming to below 1° C during this century. And with polar warming leading to accelerating sea level rise, only direct climate cooling can potentially slow or reverse loss of Arctic sea ice that may lead ultimately to the total loss of the Greenland Ice Sheet, with its potential for up to 7 meters of sea level rise.

These are the imperatives, challenges and opportunities of our epoch to which we must immediately and urgently respond. Humanity has never faced an existential threat so critical for the survival of human civilization and our fellow living species on this planet.

1. Introduction

The greenhouse gas (GHG) emissions reduction strategy that has been pursued over the last three decades by the Conference of the Parties (COP) to the UN Framework Convention on Climate Change (UNFCCC) has not yet even stopped the growth in emissions, much less halted ongoing climate change, which will require, at the very least, getting to net zero emissions. Indeed, Greenland sea level fingerprints and Himalayan melt rates are strong indicators of accelerated warming, which will accelerate further climate calamities. Loss of glacial ice in all three poles including the Himalayas is accelerating, prompting an acceleration in the rate of sea level rise; polar warming is also triggering a change in atmospheric circulation leading to an increasing incidence of extreme weather that is overstressing ecosystems and pushing planetary climate toward tipping points that will eliminate the potential to return to healthy climate conditions .[15]

However, such an irreversible outcome is not inevitable. Employing one or more direct climate cooling influences has the potential to reduce the likelihood of destructive climate calamities over the next few decades while providing the time that appears will be needed to achieve net-zero emissions and scale up approaches to pulling the atmospheric concentrations of CO2 and other greenhouse gasses toward their pre-industrial values. Limiting global warming, especially peak global warming, in this way would create time for ecosystems to come back into equilibrium, thus helping to reinvigorate the natural environment over the longer term.[16]

The argument that any direct climate cooling method, whether localized or global, co-developed or not, should not be researched or implemented because it is a "moral hazard" that would slow GHG mitigation efforts has been put forth for several decades and with varied reasoning. But this argument as well as others about unanticipated consequences, "termination shock" or harmful climate destabilization if abruptly ended, and equitable governance, are concerns that in general, could be applied to many other efforts to reduce climate and environmental harm.[17] Climate adaptation, for example, was initially opposed as a potential moral hazard that could reduce pressure to cut emissions.[18,19] Regulations to reduce harmful

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[15] Lenton, Timothy M., Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen and Hans Joachim Schellnhuber. 2019. Climate tipping points - too risky to bet against. Nature 575, Nov. 28.

[16] Baiman, Ron. 2022 forthcoming. Our Two Climate Crises Challenge: Short-Run Emergency Direct Cooling and Long-Run GHG Removal and Ecological Regeneration. *Review of Radical Political Economics.* Unedited pre-print: https://www.cpegonline.org/post/our-two-climate-crises-challenge

[17] Biermann, Frank, Jeroen Oomen, Aarti Gupta, Saleem H. Ali, Ken Conca, Maarten A. Hajer, Prakash Kashwan, Louis J. Kotzé, Melissa Leach, Dirk Messner, Chukwumerije Okereke, Åsa Persson, Janez Potocˇnik, David Chlosberg, Michelle Scobie Stacy D. VanDeveer. 2021. Copernicus Solar geoengineering: The case for an international non-use agreement. *Wires Climate Change.* November.

[18] Jebari, Joseph, Olúfẹ́mi O. Taiwo, Talbot M. Andrews, Valentina Aquila, Brian Beckage, Mariia Belaia, Maggie Clifford, Jay Fuhrman, David P. Keller,Katharine J. Mach, David R. Morrow, Kaitlin T. Raimi, Daniele Visioni. 2021. From moral hazard to risk-response feedback. *Climate Risk Management* 33.

[19] Manshausen, Peter, Duncan Watson-Parris, Matthew W. Christensen, Jukka-Pekka Jalkanen, Philip Stier. 2022. Invisible ship tracks show large cloud sensitivity to aerosol. *Nature* 610: 101–106 (2022): https://www.nature.com/articles/s41586-022-05122-0

sulfur emissions from cargo ship bunker fuel have reportedly had the unintended consequence of causing a global warming termination shock.[20] Equitable world governance is proving to be a challenge in achieving rapid, and at scale, global emissions reductions.[21]

While important considerations, the increasing pace of harmful climate impacts has so far not been sufficient to get a significant reduction in the share of global energy coming from fossil fuels, and meanwhile, the extent of impacts from extreme weather, for example, has consistently increased. Delaying direct cooling has instead led to greater harmful climate impacts, some now irreversible. There is little indication that this situation will change. Intervention related moral-hazard arguments cannot be settled *a priori* and do not properly compare the possible risks of some climate cooling methods against the convincingly projected impacts and risks that lie ahead if directly cooling the climate is not undertaken.[22] Several climate cooling methods are local and low-tech and have few if any potential risks.

The long-term average global temperature increase is an inadequate metric for assessing the harm from regional or local extreme precipitation and heat events. Climate change and especially polar amplification have already caused enormous damage, and further loss of sea ice and glacial ice are likely to abruptly accelerate the risk of further catastrophic harm to humans and other species in the absence of urgent direct climate cooling efforts to slow or reverse it.

There are at least eighteen potential direct climate cooling methods that merit early consideration, responsible investigation, and possible implementation and evaluation. This paper includes short summaries of these methods written by climate cooling experts. The methods listed in alphabetical order are:

- Bright Water
- Buoyant Flakes
- Cirrus cloud thinning (CCT)
- Extremely diluted Aqua Regia Aerosol (EDARA)
- Fizz Tops (Fiztops)
- Ice shields to thicken polar ice
- Iron Salt Aerosol (ISA)
- Making building and paving material more reflective and planting trees in urban areas
- Marine algal bloom stimulation
- Marine Cloud Brightening (MCB)
- Mirrors for Earth's Energy Rebalancing (MEER)
- Ocean Thermal Energy Conversion (OTEC)
- Restoring natural upwelling and kelp forest ecosystem services offshore

[20] Simmons, Leon, James E. Hansen, Yann Dufour. 2021. Climate Impact of Decreasing Atmospheric Sulphate Aerosols and the Risk of a Termination Shock, Annual Aerosol Science Conference, November: https://www.researchgate.net/publication/356378673_Climate_Impact_of_Decreasing_Atmospheric_Sulphate_Aerosols_and_the_Risk_of_a_Termination_Shock?channel=doi&linkId=619775253068c54fa50008bb&showFulltext=true

[21] Baiman 2022 op. cit.

[22] Jabari et al op. cit

- Restoring soil and vegetation
- Seawater atomization (Seatomizers)
- Stratospheric Aerosol Injection (SAI)
- Surface Albedo Modification (SAM)
- Titanium Oxide Aerosol (TOA)

With the availability of multiple potential methods to directly cool the climate, relying just on GHG emissions reductions and removals restricts consideration of options to how much further warming will occur rather than also including potential options for actually reducing current warming, which seems incompatible with responsible stewardship of the planet, especially because returning to the lower level of warming of the 20th century would be expected to reduce harm, preserve ecosystems, and save lives. International adoption of an encompassing climate restoration plan utilizing all policy options would offer the potential for pulling back to below 1° C. Such a plan would include: a) direct actions to exert a cooling influence on the planet, particularly aimed at limiting warming in the polar regions and the Himalayas; b) reducing GHG emissions, including especially an early focus on reducing the atmospheric levels of methane and other short-lived warming agents; and c) sequestering, using, or chemically destroying legacy concentrations of CO_2, methane and other GHGs pulled back from the atmosphere and oceans.

Over at least the next several decades, and possibly much longer, the primary role of direct cooling influences would be mainly directed at keeping the climate from spiraling out of control as a result of ongoing emissions. Only the application of emergency cooling "tourniquets", applied immediately or as soon as is reasonably advisable, has the potential to slow or reverse ongoing climate disruption and worsening climate impacts. Only direct climate cooling has the potential to slow and then reverse Arctic sea ice melting. Moderation of intensifying extremes, the likelihood of which are increasing markedly, must be immediately and urgently taken on so that presently inhabited lands do not have to be abandoned.[23] Humanity has never faced an existential threat so critical for the survival of human civilization and our fellow living species on this planet.

The following sections will address four key issues. Section 2 describes the need for relevant climate change metrics and goals; Section 3 will address the risk of not immediately slowing or reversing polar amplification; Section 4 will summarize methods for direct climate cooling; and Section 5 describes the need for an urgent call for direct climate cooling in addition to the traditional approaches of reducing emissions and enhanced removal of GHG from the atmosphere. Section 6 then presents the paper's conclusions.

2. The Need for Relevant Climate Change Metrics and Goals

[23] Hansen, James, Makiko Satoa, and Reto Ruedy. 2012. Perception of Climate Change. *PNAS*: https://www.pnas.org/doi/full/10.1073/pnas.1205276109

The ten-year moving average of global surface temperature that is used as the primary climate change metric is a lagging and inadequate measure of harm being experienced from climate change.[24] The IPCC and COP's use of the time-averaged increase in global-average temperature change as their metric, a metric developed early on by scientists to get a strong signal-to-noise ratio, downplays the change being experienced by peoples and countries and fails to portray the seriousness of the changes in extreme weather that are being experienced. With respect to observations, averaging over time rather than calculating the present value from, say, a linear (or nonlinear) trend analysis significantly understates the amount of present warming and proximity to the Paris Agreement's warming goals. Averaging over time also fails to account for the year-to-year (and shorter-term) temperature excursions due to variability. Many types of impacts are most dependent on short-term excursions rather than decadal-averaged departures. Recent events are making clear that the worst impacts are from short-term weather extremes, such as flooding precipitation, prolonged heat waves, etc.[25]

The increase in the global-averaged temperature is also a metric that virtually no one experiences. Warming is greater over land than over the ocean, especially in mid- and high latitudes (and very especially in the Arctic), so most people are experiencing (and in the future will be experiencing) warming that is greater than the global average.[26] And for those living in low-latitude regions that experience warming that is less than the global average, changes in precipitation are generally the most important impact, either as a result of prolonged heat waves and much drier conditions as the subtropics expand, or much wetter conditions because the trapped heat in low latitudes increases ocean evaporation and leads to more intense and prolonged precipitation.[27]

Also, neither the globally averaged temperature metric nor the focus on projections out to 2100 provides useful insight into the likely and ongoing amounts of sea level rise. Paleoclimatic analyses suggest an equilibrium sea level sensitivity exceeding 12 meters per degree change in global average temperature.[28] The present rate of warming is at least 10 times greater than the average rate of warming during the deglaciation phase from the Last Glacial Maximum during which the average rate of sea level rise was 1.2 meters/century for 100 centuries while the global average temperature was rising at an average rate of one degree every 10 centuries.[29] The recent IPCC assessment giving assurances that the rise in sea level by 2100 would be less than a meter is far from convincing given the increasing rate of flow of glacial streams coming off the Greenland and Antarctica and geological evidence that ice sheet decay occurs much

[24] In the IPCC AR6 (2022) average global warming is measured using decadal averages, as explained in Figure SPM.1: "Panel (a) Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, years 1–2000) and from direct observations (solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged."

[25] Bhutto, Fatima. 2022. *What is Owed to Pakistan, Now One-Third Underwater*. Sep. 3. New York Times

[26] https://climate.mit.edu/ask-mit/which-parts-planet-are-warming-fastest-and-why

[27] https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/

[28] https://phys.org/news/2011-12-paleoclimate-potential-rapid-climate.html

[29] Jouzel J et. al. 2007. Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years. *Science* 317 (5839). Plots here: https://en.wikipedia.org/wiki/Deglaciation .

more rapidly than ice sheet formation and would be very hard to stop once initiated.[30] A 2022 NOAA technical report estimates that even if net-zero GHG emissions were reached now, existing levels of GHGs in the atmosphere and oceans will (in the absence of direct climate cooling or other countermeasures) lead to about 0.6 meters of sea level rise along the US coast by 2100.[31]

The internationally proposed goal of reaching net-zero emissions as a way of halting climate change also fails to recognize changes in the global carbon cycle being caused by past and present emissions. As defined by the IPCC, the net-zero calculation refers only to direct human-induced emissions (i.e., emissions in national inventories).[32] This would be fine were the natural emission and uptake of greenhouse gasses to stay constant, but this is not the case, and will not be in the future. Already, the Arctic and Amazon basins have shifted from being natural sinks of CO_2 to natural sources, and the thawing of permafrost, warming of coastal sediments, ongoing forest conversion to farmland, occurrence of wildfires, and more, are reducing natural carbon uptake and storage and increasing natural emissions. By the time human-induced emissions reach net-zero, net natural emissions will be strongly positive and so global warming and climate disruption will continue. Counterbalancing these emissions with human-induced negative emissions will be very challenging given the magnitudes involved. NOAA has reported a super-linear increase in methane year over year that has a biogenic origin based on the stable isotope studies, a profound realization of a potential tipping point.[33] Methane levels are now almost three times higher than they were pre-industrially.[34,35]

In many of the model simulations of the potential for direct cooling, studies have tended to focus on offsetting warming from two or even four times the preindustrial CO_2 concentration to

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[30] Box, J.E., Hubbard, A., Bahr, D.B. *et al.* Greenland ice sheet climate disequilibrium and committed sea-level rise. *Nat. Clim. Chang.* (2022). https://doi.org/10.1038/s41558-022-01441-2

[31] Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

[32] https://www.ipcc.ch/sr15/chapter/glossary/ "Net zero emissions: Net zero emissions are achieved when *anthropogenic emissions* of *greenhouse gases* to the *atmosphere* are balanced by *anthropogenic removals* over a specified period. Where multiple greenhouse gases are involved, the quantification of net zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon). See also *Net zero CO_2 emissions*, *Negative emissions* and *Net negative emissions*."

[33] https://research.noaa.gov/article/ArtMID/587/ArticleID/2769/New-analysis-shows-microbial-sources-fueling-rise-of-atmospheric-methane

[34] https://gml.noaa.gov/ccgg/trends_ch4/

[35] Ming, Tingzhen, Wei Li, Qingchun Yuan, Philip Davies, Renaud De Richter, Chong Peng, Yanping Yuan, Sylvain Caillo, Nan Zhour. 2022. Perspectives on removal of atmospheric methane. *Advances in Applied Energy*: https://www.sciencedirect.com/science/article/pii/S2666792422000038

achieve high signal-to-noise in their results.[36] While interesting sensitivity analyses, these simulations have been unrealistic in any practical or political sense. Much more relevant have been initial studies aimed at incrementally counterbalancing future warming, so first stabilizing the climate at the present level of warming, and then slowly bringing the global average temperature, inadequate metric that it is, back down toward its mid-20th century value.[37,]

As an overall goal, a reasonable policy approach in deployment of direct cooling would be to not let the situation get worse and only then take actions to moderate these calamity-inducing alterations to the climate that have occurred. In doing the research to evaluate how best to proceed, three points need to be considered:

a) Not everything needs to be learned and researched to its ultimate degree before starting intervention, as there should be learning along the way that is used to tune the intervention as it is ramped up. Perfection in understanding through modeling and analysis will be impossible and cannot be allowed to stop getting field research started. Basically, implementation and research must be tightly coupled.
b) The relative benefit-detriment evaluation needs to be primarily with respect to the catastrophic conditions that are being avoided. In comparing the degree of return toward mid-20th century conditions, the comparison needs to determine how the envelopes of variability compare rather than just focus on differences in the time-averaged conditions. The better question is, will conditions with direct climate cooling interventions be more or less bearable than without intervention?
c) A range of possible interventions exists in terms of season and location, and the patterns and intensities may well need to change over time. Deployment of options that permit adjustment would seem preferable to ones that cannot be readily adjusted.

3. The Risk of Not Immediately Slowing or Reversing Polar Amplification

Based on current trends the planet is poised to begin crossing a critical climate tipping point, Arctic summer sea ice melting. Within two decades, in addition to year around thinning, the Arctic is projected to be ice-free during the entire month of September, see figure 1.[38]

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[36] See for example: Zhou, Chen, Mark D. Zelinka, Andrew E. Dressler, and Minghuai Wang. 2021. Greater committed warming after accounting for the pattern effect. Nature Climate Change Vol. 11 February.

[37]Irvine, Peter J., Ben Kravitz, Mark G. Lawrence, Dieter Gerten, Cyril Camminade, Simon N. Gosling, Erica J. Hendy, Belay T. Kassie, W. Daniel Kissling, Helene Muri, Andreas Oschlies, Steven J. Smith. 2017. Towards a comprehensive climate impacts assessment of solar geoengineering. *Earth's Future*: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000389

[38] Lenton, Timothy M et al 2020, op. cit.

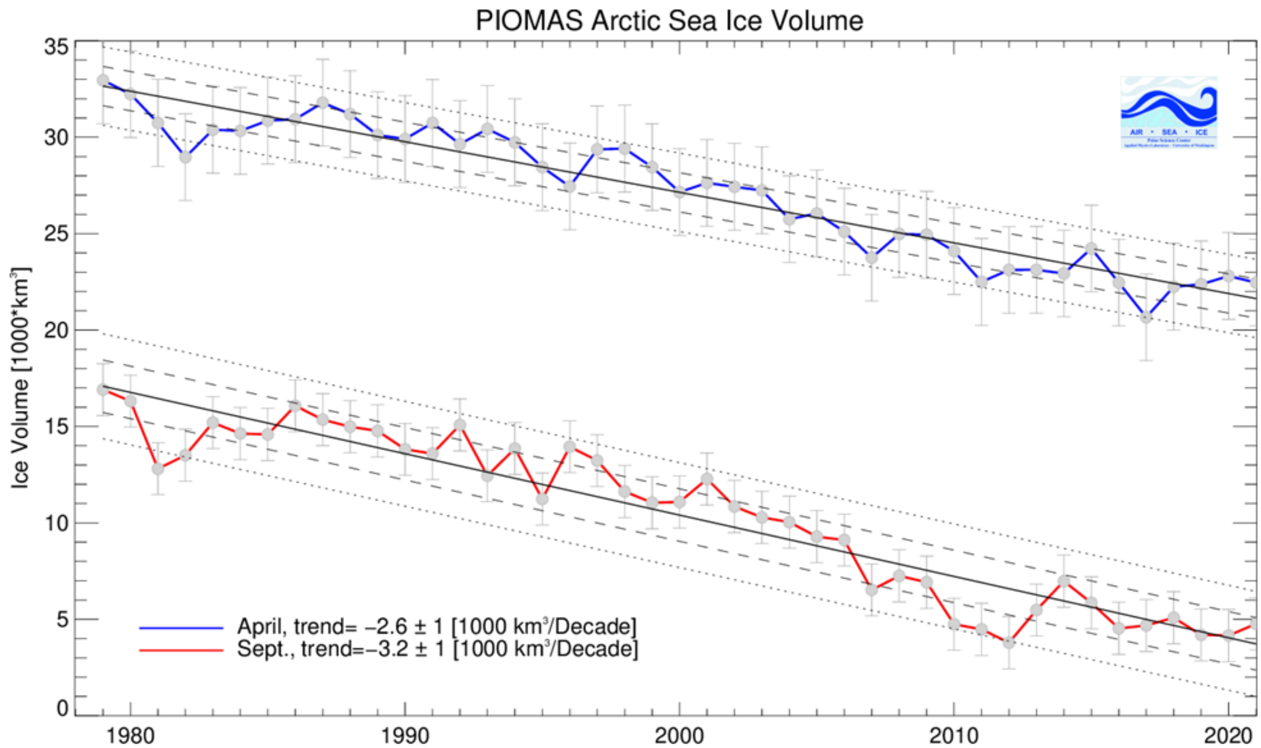

Figure 1: 1979-2021 Monthly Sea Ice Volume from PIOMAS for April and Sep.
Source:
http://psc.apl.uw.edu/wordpress/wp-content/uploads/schweiger/ice_volume/BPIOMASIceVolumeAprSepCurrent.png. Downloaded 12/26/2021 from the Polar Science Center, Applied Physics Laboratory, University of Washington, USA.

Estimates included in Pistone et al. (2019) and corroborated by multiple other studies using different data and methodologies, suggest that lower albedo due to earlier surface melting and ice thinning and loss would lead to a global forcing impact increase from 1979 to the present equivalent to the warming effect of more than 20 years of GHG emissions at current rates.[39,40]

There has been a tendency over the past few decades for climate models to simulate less thinning and loss of Arctic sea ice than has been observed. Pistone et al (2019) report that observed Arctic sea ice retreat per degree of global warming was 2.1 times larger than the mean of a large suite of models, with no model simulating as much reduction in sea ice cover as

[39] Pistone, Kristina, Ian Eisenman and Veerabhadran Ramanathan. 2019. Radiative Heating of an Ice-Free Arctic Ocean. *Geophysical Research Letters* 46(13): 7474–7480.
[40] Baiman, Ron. 2021. In Support of a Renewable Energy and Materials Economy: A Global Green New Deal That Includes Arctic Sea Ice Triage and Carbon Cycle Restoration. Review of Radical Political Economics 53 (4): 557-573, footnote 6.

the observations.[41] A recent (2021) study found that from 2002 to 2018 Arctic ice has thinned 60% more than climate models have projected.[42]

From 1971 to 2019, the Arctic warmed three times, and from 1979 to 2021 nearly four times, faster than the rate of increase in the global average surface temperature anomaly.[43,44,45,46] Disproportionate warming has affected all three poles (i.e., including the Himalayan 'pole' at the top of the world, which is a critical source of water for 2 billion people [47,48,49]). This "polar amplification" is contributing to the acceleration of losses of ice-sheet mass in Greenland, the Himalayas and Antarctica.

Current levels of global warming are already causing calamitous consequences. A 2021 report by Christian Aid found that the six years with the costliest (over $100 billion) climate disasters have occurred since 2011, and a recent *Wall Street Journal* article noted that bad weather is a major factor in the 2021 run-up in regional and global energy and commodity prices, including for wheat, tin, coffee beans, natural gas, fertilizer, cement, steel; and plastic, including resins, additives, and solvents.[50,51] If nothing is done to try to prevent or slow the loss of Arctic sea ice, and reverse global warming, these impacts will continue to get worse and the risk of crossing other even more catastrophic tipping points will increase.[52]

Failure to begin deployment of direct cooling influence in the very near-term necessarily will lead to greater harm and increased risk, at least until net-zero global GHG emissions are

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[41] Pistone et al 2019, op cite. p. 7475. Simulations were from a suite of models included in the Coupled Model Intercomparison Project Phase 5.

[42] Mallett, R.D.C.; Stroeve, J.C.; Tsamados, M.; Landy, J.C.; Willatt, R.; Nandan, V.; Liston, G.E. 2021. Faster decline and higher variability in the sea ice thickness of the marginal Arctic seas when accounting for dynamic snow cover. *Cryosphere* 15: 2429–2450.

[43] Arctic Monitoring and Assessment Program. Arctic Climate Change Update 2021: Key Trends and Impacts, May 20, 2021: https://www.amap.no/documents/doc/arctic-climate-change-update-2021-key-trends-and-impacts.-summary-for-policy-makers/3508

[44] "The observed Arctic sea ice retreat per degree of global warming is 2.1 times larger than the CMIP5 ensemble-mean result, with no model simulating a value as extreme as the observations. This suggests that there may be substantial systematic biases in the model projections of the level of global warming at which the Arctic becomes annually ice free." Pistone et al 2019: 7475, op cit.

[45] McSweeney, Robert. 2019. Q&A: How is Arctic warming linked to the 'polar vortex' and other extreme weather? *Carbon Brief*. January 31.

[46] Rantanen, Mika, Alexey Yu. Karpechko , Antti Lipponen , Kalle Nordling , Otto Hyvärinen, Kimmo Ruosteenoja, Timo Vihma, and Ari Laaksonen. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*: https://doi.org/10.1038/s43247-022-00498-3

[47] https://climate.nasa.gov/vital-signs/ice-sheets/

[48] https://www.cnbc.com/2021/12/20/himalayan-glaciers-melting-at-extraordinary-rate-research-finds-.html

[49] https://www.nationalacademies.org/our-work/himalayan-glaciers-hydrology-climate-change-and-implications-for-water-security

[50] Christian Aid. 2021. Counting the cost 2021: A year of climate breakdown. December 27.

[51] Dezember, Ryan. 2021. Blame Bad Weather for Your Bigger Bills. *Wall Street Journal* Dec. 28.

[52] Lenton et al 2019, op cit.

achieved and legacy concentrations of GHGs are pulled back out of the atmosphere and oceans. Recent modeling suggests that, in the absence of direct climate cooling, if (anthropogenic and natural) net-zero emissions were to be achieved after 3667 Gigatons of CO2eq GHG (or 1000 Gigatons of carbon estimated to result in global warming of about 2.0° C) were accumulated in the atmosphere, global warming would remain at roughly 2.0° C for at least another 50 years due to continued thermal rebalancing from legacy ocean warming, even with continued ocean uptake of legacy CO2 from the atmosphere.[53,54] This suggests that after net-zero is achieved additional trillions of tons of legacy GHG would have to be directly removed from the atmosphere to reach atmospheric levels of CO_2 well below 350 ppm in order to cool the planet, remove carbon from the ocean, and restore the climate and ecosystem.[55,56]

Assertions that the risks of trying to cool the climate, regardless of method attempted, will always be greater than the risk of not attempting to do so, seem hard to justify *a priori*. Many of the approaches to offset climate warming mimic natural influences on the climate, or the impact of everyday human activity and can be quickly terminated if unanticipated adverse impacts arise. Delay in accelerating research, and then beginning to intervene to offset at least some of the global warming, as emissions continue at high levels, will lead to further warming, climate disruption and likely avoidable increases in human suffering and ecosystem disruption. These points have recently been recognized by many prominent national and international scientific and policy associations and think tanks, but unfortunately not yet by national or international climate decision-making bodies.[57]

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[53]Andrew H. MacDougall, Thomas L. Frölicher, Chris D. Jones, Joeri Rogelj, H. Damon Matthews, Kirsten Zickfeld, Vivek K. Arora, Noah J. Barrett, Victor Brovkin, Friedrich A. Burger Micheal Eby, Alexey V. Eliseev, Tomohiro Hajima, Philip B. Holden, Aurich Jeltsch-Thömmes, Charles Koven, Nadine ,Mengis, Laurie Menviel, Martine Michou, Igor I. Mokhov, Akira Oka, Jörg Schwinger, Roland Séférian, Gary Shaffer, Andrei Sokolov, Kaoru Tachiiri, Jerry Tjiputra, Andrew Wiltshire, and Tilo Ziehn. 2020. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosciences*, 17, 2987–3016: https://doi.org/10.5194/bg-17-2987-202 .

[54] Hausfather, Zeke. 2021.Explainer: Will global warming 'stop' as soon as net-zero emissions are reached? April 29: https://www.carbonbrief.org/explainer-will-global-warming-stop-as-soon-as-net-zero-emissions-are-reached/

[55] Schuckmann, Katrina von, Lijing Cheng, Matthew D. Palmer, James Hansen, Caterina Tassone, Valentin Aich, Susheel Adusumilli, Hugo Beltrami, Tim Boyer, Francisco José Cuesta-Valero, Damien Desbruyères, Catia Domingues, Almudena García-García, Pierre Gentine, John Gilson, Maximilian Gorfer, Leopold Haimberger, Masayoshi Ishii, Gregory C. Johnson, Rachel Killick, Brian A. King, Gottfried Kirchengast, Nicolas Kolodziejczyk, John Lyman, Ben Marzeion, Michael Mayer, Maeva Monier, Didier Paolo Monselesan, Sarah Purkey, Dean Roemmich, Axel Schweiger, Sonia I. Seneviratne, Andrew Shepherd, Donald A. Slater, Andrea K. Steiner, Fiammetta Straneo, Mary-Louise Timmermans, and Susan E. Wijffels. 2020. Heat Stored in the Earth System. *Earth System Science Data* 12 2013–2041. Data in Schuckmann et al (2020) suggests that about 1,710 Gigatons of CO_2 would need to be removed from the atmosphere to get from the 2018 level of 410 ppm to a 1989 level of 353 ppm CO_2 in the atmosphere, see Baiman 2021 footnote 9, op. cit.

[56] Baiman, Ron 2021 op. cit. footnote 9.

[57] See for example: 1) National Academy of Sciences. 2021. *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance.* Washington, D.C.: The National Academies Press, 2) A Policy Statement of the American Meteorological Society Adopted by the AMS Council on 2 February 2022: https://www.ametsoc.org/index.cfm/ams/about-ams/ams-statements/statements-of-the-ams-in-force/climate-intervention/ , 3) Reflecting Sunlight to Reduce Climate Risk Priorities for Research and International Cooperation. Stewart M. Patrick. April 2022. Council on Foreign Relations: https://www.cfr.org/report/reflecting-sunlight-reduce-climate-risk , 4) The Cambridge Center for Climate Repair:

4. **Potential Methods for Direct Climate Cooling**

The following is a menu of eighteen proposed direct climate cooling approaches that we suggest merit early consideration and responsible investigation with actions that can be monitored and reported on. They are listed in alphabetical order with short summaries that are written or reviewed by climate cooling experts. It is our recommendation that many of these methodologies be researched and evaluated for simultaneous, complementary implementation. We do not, however, wish to imply that all of the methods listed below are needed in every case. Indeed, further research will no doubt provide insight into which methods show the most promise and the least risk, and are best suited for achieving their goals with the lowest costs in financial, material, and energy terms, and with regard to other important economic, or social and environmental objectives, in particular situations.

- **Bright Water:** Micron-radius hydrosols could be used to substantially brighten surface waters at very low volume fractions of parts per million and energy costs of J m^{-2} to initiate and milliwatts m^{-2} to sustain.[58]
- **Buoyant Flakes** are buoyant rice husks coated with waste mineral powders rich in the phytoplankton nutrients of iron, phosphate, silica and trace elements that are typically deficient in warming surface waters. The minerals' ultra-slow release is intended to provide a sustainable basis for an enhanced, marine food web. The flakes would contribute in four ways to planetary cooling. First, because the phytoplankton fed by the flakes are of lighter color than the dark blue of the deep ocean more sunlight would be reflected. The phytoplankton will transform some of the sunlight into biomass from dissolved carbon dioxide. Krill and other diel vertically migrating (DVM) species would carry much of that biomass to the ocean depths. Finally, many species of phytoplankton produce DMS (dimethyl sulfide) which creates highly-reflective marine clouds.[59]
- **Cirrus Cloud Thinning (CCT)** would seed high-altitude tropospheric cirrus clouds with ice nuclei, seeking to cool the planet by allowing increased long-wave radiation to escape to space.[60] Research on cirrus cloud thinning or CCT has been entirely based on cloud modeling at global and regional scales with mixed results due to the many poorly constrained variables governing the partitioning of homogeneous and heterogeneous ice nucleation (i.e., hom and het). CCT can only be effective when cirrus clouds form

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https://www.climaterepair.cam.ac.uk/restoring-broken-climate-systems , 5) The Climate Overshoot Commission: https://www.overshootcommission.org/

[58] Sietz, Russell. 2011. Bright water: hydrosols, water conservation, and climate change. *Climate Change* 105:365-381: https://link.springer.com/article/10.1007/s10584-010-9965-8

[59] Clarke, William S. 2022. More Climate Solutions. May. Accessed at: https://drive.google.com/file/d/1TNYF1HtCx0nWk2MeYarQm64EsgZAN3xH/view?usp=sharing

[60] Mitchell, D. L., and W. Finnegan. 2009. Modification of cirrus clouds to reduce global warming. Environmental Research Letters 4(4).

substantially through hom (i.e., hom cirrus). A critical need in CCT research is to establish measurement-based constraints on the global spatial and temporal distribution of hom cirrus. Fortunately, recent progress in cirrus cloud property remote sensing is providing such constraints. This satellite remote sensing shows that hom cirrus are common at high- and mid-latitudes during non-summer months, being mostly over mountainous terrain in the midlatitudes. This is fortuitous since CCT is most effective when sunlight is minimal (i.e., during winter). These findings need to be assimilated into climate models to determine the potential efficacy of CCT.[61]

- **Extremely Diluted Aqua Regia Aerosol (EDARA)** is a naturally occurring acidic aerosol in the oceanic boundary layer, formed from volcanoes and sea-salt sources. Produced naturally by the ocean, in the atmosphere and by ship exhausts and other NOx pollution, EDARA sets up a photo-catalytic cycle in which up to 1000 methane molecules are oxidized to CO_2 and water by each chlorine atom in aerosol particles. EDARA converts several bands of the sun's radiation energy spectrum into chemical energy, thus enabling powerful methane depletion chemistry. The average lifetime of methane in the air might be halved by a global EDARA-mimicking intervention in as little as five years. Natural ecosystems would benefit from the cooling influence. A second strong cooling influence could be provided by EDARA's natural brightening of clouds to reflect solar radiation. EDARA could be inexpensively and safely made from ship pollution.[62]
- **Fizz Tops (Fiztops)** are table sized, floating, lightweight, solar-powered units that are designed to inject nanobubbles into the sea surface microlayer (SSML). They may either be anchored to cool a specific area of ocean, coral reef or aquaculture operation, or else be free-floating. Small bubbles are highly reflective of incoming solar energy. Hence, they can shade and cool underlying water. Unlike larger bubbles, nanobubbles have 'neutral' buoyancy and can live for months in the SSML. They may also increase overall planetary cooling by warming the SSML, releasing ocean heat to the troposphere by evaporation where it may then be better radiated to space.[63]
- **Ice shields to thicken polar ice** could be made by pumping polar sea water to the surface to thicken Arctic sea ice in the winter. Heat released by freezing would be emitted to space during winter, while in the warmer months the increased surface albedo would cool the ocean and slow the melting of sea ice. Power from offshore wind turbines could pump seawater onto the surface sea ice to form a disc, to thicken the ice by up to an estimated 80 meters each year. Each wind turbine might power several pumping stations. Arrays of ice lenses would freeze solidly together, creating open ocean polynyas in warmer seasons to provide ideal habitat for wildlife. Ice arrays might be grown from the shore outwards or configured in deeper water up to several hundred meters depth. Increasing the presence of sea ice, which would start to restore arctic

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[61] Mitchell, D. L., Garnier, A., Pelon, J., and Erfani, E.: CALIPSO (IIR-CALIOP) retrievals of cirrus cloud ice particle concentrations. Atmos. Chem. Phys., 18, 17325–17354, https://doi.org/10.5194/acp-18-17325-2018, 2018.
[62] Oeste, Franz and Clive Elsworth. Sep 2022. Essentials of the rich EDARA photochemistry, its albedo enhancement and its impact on the ocean's photic zone and the status of its development: https://drive.google.com/file/d/1o6i7xqH49O6H4Z2iQtY0mkUWibzQSltO/view?usp=sharing

[63] Clarke 2022 op cit.

albedo, stabilize the jet stream and help restore a livable climate. Dense, frigid brine made by ice formation would concentrate salt, CO2 and oxygen in the pumped seawater, sending this dense water deep into the ocean. There, the oxygen would be expected to benefit benthic life, whilst the CO2 would react with seabed carbonates (shells, bones and limestone) to form benign, dissolved and slightly alkaline bicarbonate that has a residence time of up to millennia. Hence, we could achieve planetary cooling, biosphere restoration, and safe carbon sequestration at scale with a single, nature-based technology.[64,65,66]

- **Iron Salt Aerosol (ISA)[67]** is based on dust-driven chemistry that has occurred naturally over the ocean in the troposphere for millions of years. It depletes tropospheric greenhouse gases, and makes smoke particles more easily washed out by rain. It mimics natural dust deposition by very diffusely fertilizing large ocean areas, drawing down CO_2 and increasing ocean biomass. This increases the 'smell of the sea' (dimethyl sulfide or DMS), an aerosol from marine algae that makes clouds, which cool the ocean beneath them. ISA could be dispersed from offshore wind turbines and/or purpose built 'Seatomizers' into winds that blow out to sea.[68]
- **Marine algal bloom stimulation** would cool the climate by stimulating algal bloom to increase ocean albedo. A two-stage amplified blooming of *Emiliana Huxleyi* (EHUX) is proposed. In the first stage, seed EHUX is cultured in sealed, ocean-based photobioreactors filled with water from below the thermocline, into which starter algae and supplemental nutrients are dosed. CO_2 concentration in the bioreactor headspace is controlled to stimulate maximal algae growth rate. Seed EHUX is harvested semi-continuously to maintain nursery growth at its exponential threshold. In the second stage, the harvested EHUX is dispersed with additional nutrients into selected ocean spaces. Open ocean blooms start in their exponential phase, outpacing yield-limiting growth of competing species. Bloom expansion slows and ceases as nutrients are consumed and virus-induced lysis kills the algae. Albedo of the bloom area increases during the growth phase from continual shedding of coccoliths and reaches a peak during lysis. The bloom area is left fallow for a period sufficient for grazers, viruses and competing species to return to pre-bloom concentrations. EHUX is nature's primary source of dimethyl sulfide, which on decomposition condenses water vapor that seeds the production of highly reflective marine clouds.[50] Ocean surface albedo and the rate of temperature fall can be modulated. Bloom locations and seasons can be varied as

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[64] Steven J. Desch, Nathan Smith, Christopher Groppi, Perry Vargas, Rebecca Jackson, Anusha Kalyaan, Peter Nguyen, Luke Probst, Mark E. Rubin, Heather Singleton, Alexander Spacek, Amanda Truitt, Pye Pye Zaw, Hilairy E. Hartnett. 2017. Arctic ice management, Earth's Future 5(1): 107–127.
[65] Clarke, William S. 2021. Ice Shield Strategies. Winwick Business Solutions. September 9. Available upon request from the author: sevclarke@icloud.com
[66] Clarke 2022 op cit.
[67] Ming, T., de Richter, R., Oeste, F. D., Tulip, R., & Caillol, S. (2021). A nature-based negative emissions technology able to remove atmospheric methane and other greenhouse gases. Atmospheric Pollution Research, 12(5), 101035.
[68] Oeste, Franz Dietrich, Renaud de Richter, Tingzhen Ming, and Sylvian Caillol. 2017. Climate Engineering by Mimicking Natural Dust Climate Control. Earth System Dynamics 8(1):1–54.

required to create maximized impact of surface and cloud cover, and blooms can be quickly shut down by stopping seed dispersion or by introducing viruses into a bloom.[69]

- **Marine Cloud Brightening (MCB)** is a climate cooling approach that turns saltwater into mist to make marine clouds reflect more sunlight. If MCB could increase the reflectivity of the Earth by 0.5%, it would be enough to reverse the present amount of global warming. Calculations indicate this is feasible at low cost and low risk. Suitable low-level clouds cover about 18% of the oceans. Research has shown that cloud reflectivity depends on both saltiness and the size of cloud drops. Smaller drops of water reflect more sunlight than larger drops.[70] MCB requires a mist that produces equal-sized small drops of salt water to form cloud condensation nuclei. To increase cloud formation in clean mid-ocean air, Latham et al. suggested that salt from a submicron spray of filtered sea water would provide the required extra nuclei to brighten clouds.[71] Calculations indicate surprisingly little spray would be needed to return the planet to preindustrial temperatures. MCB nuclei are short lived, washed out by the next rain. Forecasts of humidity and wind speed and direction a few days ahead might enable highly targeted MCB deployment by region and season, with the potential to moderate storms, droughts and floods, and cooling of ocean currents such as those flowing into the Arctic. Design of wind-driven MCB vessels is advanced. The Australian government is presently supporting MCB to prevent coral bleaching on the Great Barrier Reef.[72,73]

- **Mirrors for Earth's Energy Rebalancing (MEER)** involves deploying mirror arrays on the Earth's surface to reflect excess downwelling solar radiation as a means of decreasing local, regional, and global temperatures.[74] Implementation is proposed in the contexts of agricultural adaptation,[75,76,77] urban heat island alleviation,[78,79] freshwater

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[69] Fry, Robert, Sambhudas Chaudhuri, Grant Gower, Steven Fry, Steven Hughes, Barry Wroobel, Michael Routh, Kenneth Klabunde, Madeline Ison, Jeramy Hughes, Steve Traylor, and Jerry Shkolnik. 2022. Ocean-Amplified Carbon Capture with Maximal Export to Seafloor. Carbon Restoration Technologies Inc : https://drive.google.com/file/d/1L02o6b1g8iT9GmbPcdwjoUUdqnbGJq8x/view?usp=sharing

[70] Twomey, S., The influence of pollution on the shortwave albedo of clouds, *J. Atmos. Sci.*, 34, 1149– 1152, 1977.

[71] Latham, John, Keith Bower, Tom Choularton, Hugh Coe, Paul Connally, Gary Cooper, Tim Crafts, Jack Foster, Alan Gadian, Lee Galbraith, Hector Iacovidess, David Johnston, Brian Launers, Brian Leslie, John Meyer, Armand Neukermans, Bob Ormond, Ben Parkes, Phillip Racsh, John Rush, Stephen Salter, Tom Stevenson, Hailong Wang, Qin Wang, and Rob Wood. 2012. Marine Cloud Brightening. *Phil. Trans. R. Soc* 370(1974): 4217–4262.

[72] Mims, Christopher. 2009."Albedo Yachts" and Marine Clouds: A Cure for Climate Change? *Scientific American* Oct. 21: https://www.scientificamerican.com/article/albedo-yachts-and-marine-clouds/ For global MCB cost estimates see "Sea Level Rise and Ice Recovery" by Stephen Salter, August 14, 2020, available upon request to S.Salter@ed.ac.uk.

[73] Salter, Stephen. 2022. MCB Field Trial Simulation Proposal. Accessed at: https://drive.google.com/file/d/1wiE-QIxgkV9UcoBjSH9KgD9DVUptMYaR/view?usp=sharing

[74] Cooling the planet with surface reflectors: https://www.meer.org/

[75] Environ. Res. Lett. 14, 064003 (2019)

[76] Front Nutr. 9, 786421 (2022)

[77] Ongoing MEER field experiment in Plymouth and Concord NH, USA.

[78] Environ. Sci. Technol. 49, 14672–14679 (2015)

[79] Ongoing MEER field experiment near San Francisco CA, USA.

conservation,[80,81] and renewable energy generation, as well as ecosystem protection.[82,83] Stationary surface mirrors, optimally oriented, are estimated to have the potential, on average, to reduce the net top of the atmosphere flux by 70 watts per square meter.[84,85] Complete neutralization of warming from annual global GHG emissions is estimated to cost in the range of 200-500 billion USD per year, with payback through water saving and crop yield improvements within ten years. To stabilize the climate at 2022 levels against further warming until 2100 would require installing a mirror surface area of order ten million square kilometers on arable and non-arable land, assuming continued emissions produce 4.5 watts per square meter of radiative forcing (RCP4.5). This coverage would be likely to improve total agricultural output due to the water savings, drought protection, and thermal alleviation provided by the solar collectors. MEER's solar reflector devices are upcycled from glass bottles, aluminum cans, and PET packaging. Devices for the most scalable application in agriculture use a hybrid bamboo-glass material system for structural support.[86] Mirrored roofing tiles would reduce heat wave mortality and energy system overload exacerbated by the urban heat island effect.[87,88] Replacing colored nets in agriculture with mirrors could improve productivity by reducing heat stress and agricultural water usage.[89,90] Preliminary experimental data suggest agricultural soil cooling by up to 4°C at a depth of 10 cm at mid-latitude (43°N),[54] with cooler soil storing more carbon.[91] Mirrors over freshwater bodies can reduce evaporation from reservoirs, rivers, and aqueducts. Compared to floating photovoltaic systems,[57] floating mirrors would do more to cool the water and reduce evaporation by cooling the air-water interface.[92] Mirror deployment on a 10-100 km^2 range could produce regional climate oases by lowering ground and air temperatures by several degrees Celsius, without significant change in rainfall.[93] MEER's albedo enhancement would be energy-efficient and spatially confined. Implementation would bring significant benefits to highly engineered environments of built urban environments, agricultural fields, freshwater reservoirs and aqueducts. MEER thus has the potential to moderate global warming as part of democratic efforts to locally preserve human habitat.

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[80] Nature Sustainability 4, 609–617 (2021).
[81] Ongoing MEER field experiment near San Francisco CA, USA.
[82] Nature 543, 373–377 (2017).
[83] Marine Biology Research 16,643-655 (2020).
[84] Climate Dynamics 44, 3393–3429 (2015).
[85] Unpublished analyses based on CERES 2018 data.
[86] Unpublished prototyping and engineering data (MEER).
[87] Environ. Res. Lett. 9 104014 (2014).
[88] Earth's Future,5, 1084–1101 (2017).
[89] Hort. Technol. 32, 22-27 (2022).
[90] James Ngelenzi Munywoki, Master's Thesis.
[91] Nature Communications 12: 6713 (2021).
[92] Sci. Rep. 6: 35070 (2016).
[93] White-roofed greenhouses in Almeria have cooled the regional climate.

- **Ocean Thermal Energy Conversion (OTEC)** would utilize the temperature difference between surface and deeper ocean waters, and a low boiling point working fluid, to cool the planet while generating baseload energy and removing CO_2 from the atmosphere.[94,95]

- **Restoring natural Ocean upwelling from tropical to temperate latitudes.** Upwelling of deep ocean water can bring cooler, nutrient rich water to the surface. Systems have been designed to power such upwelling devices using renewable energy such as solar, wind or wave energy and even ocean thermal energy conversion. One modeling study by Oschlies et al (2010) has shown that conducting upwelling at large scale can reduce air global surface air temperatures by up to 1 degree over decades of implementation. An additional benefit at large scale could be to reduce the severity of severe ocean storms, such as hurricanes, cyclones and typhoons. Such ocean upwelling can also increase the earth's carbon sequestration potential through the ocean's biological pump and also through terrestrial vegetation, as lower land surface temperatures can stimulate greater terrestrial biomass growth and carbon fixation. At a smaller scale, upwelling can be combined with seaweed mariculture by providing cooler nutrients required to sustain seaweed growth. Cultivated seaweeds can be harvested for large food, feed and fertilizer markets while sequestering seaweed biomass in the deep ocean by either measuring the flux falling off naturally during growth or through approaches that bale and sink harvested seaweeds.

- **Restoring soil and vegetation:** This will increase evapotranspiration from the soil and vegetation to cool the planet.[96,97,98] Recent research suggests that reforestation can increase evapotranspiration which in turn increases cloud formation and climate cooling. The interaction of temperature, wind, vegetation species, and soil water retention capacity are critical factors in determining where and how this solution is applied. Additional co-benefits of improved soil health, reforestation, and wetland restoration, include flood protection, carbon removal and sequestration, and increased

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[94] Rau, Greg and Jim R. Baird. 2018. Negative-CO_2-emissions ocean thermal energy conversion. *Renewable and Sustainable Energy Reviews* 95:265-272.

[95] Gleckler PJ, Durack RJ, Stouffer RJ, Johnson GC, Forest CE. Industrial-era global ocean heat uptake doubles in recent decades.2016. Nature Climate Change: https://doi.org/10.1038/nclimate2915

[96] Jehne, Walter. 2021. The importance of vegetation for the water cycle and climate. Dec. 8. UNEP and German Scientific Forum: https://www.youtube.com/watch?v=aZDkwWA8iB8

[97] Piao, S., X. Wang, T. Park, C. Chen, X. Lian, Y. He, J. W. Bierke, A. Chen, P. Ciais, H Tommervik, R. R. Nemani, and R. B. Myneni. 2020. Characteristics, drivers and feedbacks of global greening. *Nature Reviews Earth and Environment* 1: 14–27.

[98] https://www.aweimagazine.com/article/saving-our-soils-for-future-generations/

biodiversity.[99,100] The application of Biochar can increase soil water retention and thus evapotranspiration potential.[101]

- **Seawater atomization (Seatomizers)**: Anchored wind turbines would spray sea water droplets into the lower atmosphere to increase evaporation and cooling. The turbine would force water through high-flow spray nozzles to generate mists from seawater. Effects could include: increased evaporation, oceanic brine return, marine cloud brightening, ocean surface cooling, coral reef shading, and controllable downwind precipitation. Addition of sublimated ferric chloride pellets to produce iron salt aerosols would increase albedo, destroy methane and smog, increase ocean biomass and increase cloud cover and rainfall in targeted areas downwind.[102]
- **Stratospheric Aerosol Injection (SAI)** is a well-known global climate cooling proposal that mimics the cooling effects of sulfate aerosols from volcanic eruptions. For example, the 1991 Mount Pinatubo eruption reduced the global average surface temperature by an estimated 0.6°C for 15 months.[103] SAI is the most studied direct cooling method. Research suggests that adverse effects of SAI would be minimal if applied at low levels or aerosol injection. Climate model simulations indicate that SAI might be able to reduce the global mean temperature increase by up to 2° C.[104] The optimal deployment would likely involve building up from low to higher injection amounts, monitoring the response carefully over time to adjust the timing, pattern and volume of any injection. Influences on temperature and precipitation patterns over time require careful study as they would be different than if comparable cooling were a result of lowering the excess GHG concentrations. A leading study has estimated a start-up capital cost of $3.5 billion over 15 years and an operational cost of $2.25 billion a year for 15 years after that to reduce anthropogenic radiative forcing per decade by a half.[105] While significant reductions of the warming could likely be accomplished, the actual climate would not return to exactly what it was in the past (a qualification also applying to many of the other approaches as well), and so it would be important to continuously monitor the results and adjust as the effort proceeded, in order to minimize regional risks that might develop. Gradual, regionally and seasonally targeted, SAI applied during the spring in polar regions with conventional aircraft, has been proposed as potentially more effective in restoring polar sea ice cover, and less risky in some aspects as the aerosol would fall out of the

[99] https://engineering.princeton.edu/news/2021/08/09/planting-forests-may-cool-planet-more-thought
[100] https://www.sciencedaily.com/releases/2011/09/110914161729.htm
[101] Tongtong Wang, Catherine E. Stewart, Cengceng Sun, Ying Wang, Jiyong Zheng. 2017. Effects of biochar addition on evaporation in the five typical Loess Plateau soils, *Centena* 162: 29-39: https://www.sciencedirect.com/science/article/abs/pii/S0341816217303818
Author links open overlay panel
[102] Clarke 2022 op cit.
[103] NASA. 2011. Global Effects of Mount Pinatubo. Earth Observatory. June 15. Accessed at: https://earthobservatory.nasa.gov/images/1510/global-effects-of-mount-pinatubo
[104] D. G. MacMartin, D. Visioni, B. Kravitz, J.H. Richter, T. Felgenhauer, W. R. Lee, D. R. Morrow, E. A. Parson, M. Sugiyama, Scenarios for modeling solar radiation modification, PNAS 2022 https://doi.org/10.1073/pnas.2202230119
[105] Smith, Wake and Gernot Wagner. 2018. Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. Environmental Research Letters 13 (12): https://iopscience.iop.org/article/10.1088/1748-9326/aae98d/pdf

stratosphere more quickly, if injection needed to be quickly terminated due to unintended adverse consequences.[106,107] However, the non-uniformity of the cooling would make it infeasible as a single strategy to offset low-latitude climate change. It might also be possible to release carbonyl sulfide gas that would mix up to the stratosphere from the Earth's surface or troposphere, although the biological impacts of this approach need to be further researched.[108]

- **Surface Albedo Modification (SAM)** would brighten ice and snow in selected regions of benefit, to slow melting, thereby potentially restoring the overall reflectivity of ice cover to that of preindustrial times, which would likely contribute to moderating a range of climate impacts.[109] [110] Putting a thin layer of ecologically benign material on the surface of glacial or sea ice, snow, or a melt pond, would be expected to enhance the ability of the icy surface on land or sea to reflect incoming solar radiation, keeping temperatures cooler. Research on pond ice in Minnesota has shown this approach to work. Climate modeling has demonstrated that preserving high-albedo reflectivity would have the potential to reverse the accelerating feedback loop of melting that is increasing temperatures. Small-scale field research tests, carefully monitored for effectiveness and safety, could be conducted with permissions from and in transparent partnerships with local and Indigenous partners, using safe materials in small regions under local control. Safety and acceptability of such tests require that any unexpected negative effects be contained and remediated promptly. Global climate modeling can be used to indicate potential test areas of greatest benefit or risk.[111]
- **Titanium Oxide Aerosol (TOA)** is a method to reduce the rate of polar and mountain ice melt during summer months by shielding melting ice fields and open polar ocean surfaces from direct sunlight by creating white fog and cloud cover. Melting ice could also potentially be preserved by whitening it with TiO_2 rich marble powder, which is non-toxic. TOA could also be used to reduce the intensity of wildfires, both with a pre-fire season intervention of cooling cloud cover to keep the ground moist, and during fires. The most scalable application of the TOA method is to form a haze that would brighten clouds through condensation on sub-micron particles of TiO_2, SiO_2 and $AlCl_3$. When these particles get rained out, they would coagulate to form gel-like flakes that eventually become clay. A multi-decadal TOA intervention carried out annually during the summer melting season might have the potential to reduce melting rates sufficiently

[106] Lee, Walker, Douglas MacMartin, Daniele Visioni, and Ben Kravitz 2020. Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs". *Earth System Dynam*ics 11(4):1051–1072.
[107] MacCracken, Michael. 2010. SAI Restoring Arctic Ice Field Trial Proposal for 2015. Accessed at: https://drive.google.com/file/d/1cziCp2wZDHDvrLVAgO04I2dZ9qmfzQgp/view?usp=sharing
[108] Quaglia, Ilaria, Daniele Visioni, Giovanni Pitari, and Ben Kravitz**.** 2021. An approach to sulfate geoengineering with surface emissions of carbonyl sulfide. *Atmospheric Chemistry and Physics* 22(9): https://acp.copernicus.org/articles/22/5757/2022/
[109] Field, L., D. Ivanova, S. Bhattachartyya, V. Mlaker, A. Sholtz, R. Decca, A. Manzara, D. Johnson, E. Christodoulou, P. 2018. Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering. *Earth's Future* 6(6): 882–889.
[110] Field, Leslie. 2021. Restoring Arctic Ice: A New Way to Stabilize the Climate. *Arctic Circle*, March 9: https://www.arcticcircle.org/journal/restoring-arctic-ice-a-new-way-to-stabilize-the-climate
[111] https://www.brighticeinitiative.org

to restore mountain and polar glaciers, ice sheets and ice shelves to their pre-industrial ice mass.[112]

- **Tree planting and reflective materials in urban areas:** Certain pavement materials can reflect three to five times more sunlight than asphalt. The more highly reflective materials include light-colored aggregate, higher slag or limestone content concrete, and reflective coatings. White or light colored roofs also increase albedo compared to dark roofing materials such as asphalt that are typically used. In urban settings with their high pavement and roof surface areas, using reflective materials can lower temperatures and moderate urban heat islands. However, in certain contexts and seasons, the benefits can be negated. Increased reflection onto nearby buildings can heat their facades and raise building energy demand for air conditioning. Also, the cooling effects of reflective surfaces may be welcome in summer but may result in higher heating costs in the winter. Increasing a city's tree canopy can also lower urban temperatures. Strategically applied in the proper settings, integrating reflective pavement and roofs with urban tree planting can be an effective strategy for reducing heat island effect locally. If implemented on a world scale, this strategy could, over time, contribute to global climate cooling.[113,114,115,116,117]

5. The Necessity for Direct Climate Cooling in addition to GHG Reduction and Removal

While perhaps theoretically possible, insufficient and unfulfilled government commitments, economic realities and the sheer magnitude of the task make it unrealistic to think global GHG emissions can be cut in half, or even a third, by 2030. A 2021 United Nations Environmental Program report noted that such cutbacks would be necessary to have a greater than 66 percent chance of keeping global warming below 1.5 °C, or "well below 2.0 °C" (1.8 °C), through the 21st century.[118] The World Meteorological Organization estimates that there is a 50 percent chance that the annual average global temperature increase will exceed 1.5 °C in at least one year by

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[112] Elsworth, Clive and Franz Oeste. Aug 2022. Climate cooling, ice preservation and wildfire suppression by dispersal of Titanium Oxide Aerosol (TOA): https://drive.google.com/file/d/1ruCGWm3vN0mrDSq-CuNLVmv_T4K_VBtA/view?usp=sharing

[113] Debbage, N. and Shepherd, J.M. (2015) The Urban Heat Island Effect and City Contiguity. Computers, Environment and Urban Systems, 54, 181-194.

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[117] "Effects of white roofs on urban temperature in a global climate model",K. W. Oleson,G. B. Bonan,J. Feddema, First published: 03 February 2010 https://doi.org/10.1029/2009GL042194

[118] "To keep global warming below 1.5°C this century, the aspirational goal of the Paris Agreement, the world needs to halve annual greenhouse gas emissions in the next eight years." For a 66% chance of 1.4-1.5°C warming in 2100 total GHG would have to be reduced to 25 (22-31) GT CO_2eq in 2030 (See Table ES.1 of the United Nations Environmental Program Emissions Gap Report, Oct. 26, 2021: https://www.unep.org/resources/emissions-gap-report-2021). This would require cutting emissions in half by 2030 based on 2022 estimated world GHG emissions of 50 GT CO_2eq (see Ritchie et al 2021 op cit., footnote 12).

2026.[119] Recent research suggests that even if emissions were stopped immediately in 2022, long term thermal equilibrium will produce above 2.0 °C warming before 2100.[120] In addition, Fossil-fuel generated aerosols, notably sulfur from combustion of coal and use of bunker fuel by ships, exert an estimated 0.5° - 1.1° C cooling impact.[121] As such emissions are reduced over time to reduce other environmental and health concerns, the warming influence of existing legacy GHG loadings in the atmosphere and oceans would very likely cause the decadal-average increase in global average temperature to exceed 1.5° C, and possibly 2.0° C, until the stock of short-lived warming agents in the atmosphere declines.[122, 123]

Extreme heat waves, polar ice melting in all three 'poles', disastrous weather events and impacts, tell us that the consequences resulting from the increase in the Earth's temperature are already putting the United Nations Sustainable Development Goals out of reach. The only way to prevent ever more frequent and severe catastrophic impacts is to apply direct cooling tourniquets to our bleeding planet in the near-term, as nations work to cut their emissions and remove sufficient GHGs to cool and stabilize the climate in the long-term.

To moderate global warming before key impacts become irreversible, a climate restoration plan with a goal of limiting global warming to well below 1° C in the near-term needs to be adopted and then promptly implemented. Such a plan would need to have three complementary components:

1. Deployment of near-term direct cooling influences, particularly focused at first on reducing amplified warming in the polar regions and the Himalayas,
2. Accelerated reductions of GHG emissions, including especially an early focus on methane and other short-lived warming agents, and
3. Building up capabilities for reducing the legacy concentration increases of CO_2, methane, and other GHGs by pulling down their loading in the atmosphere and oceans.

In the absence of a committed effort to directly cool the planet, the accumulation of GHGs in the atmosphere is projected with high confidence to cause very severe damage and suffering for generations to come while disproportionately impacting the world's poorest and most vulnerable populations. Achieving the international goal of halving emissions by 2030 to keep average warming below 1.5 °C, or even the slightly less stringent Paris agreement goal aimed at achieving a 66 percent chance of keeping warming "well below" 2.0 °C or below 1.8 °C, would

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[119] World Meteorological Organization. May 9, 2022: https://public.wmo.int/en/media/press-release/wmo-update-5050-chance-of-global-temperature-temporarily-reaching-15%C2%B0c-threshold

[120] Zhou, Chen, Mark D. Zelinka, Andrew E. Dressler, and Minghuai Wang. 2021. Greater committed warming after accounting for the pattern effect. Nature Climate Change Vol. 11 February.

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[122] Lindsey, Rebecca and LuAnn Dahlman 2021. Climate Change: Global Temperature. NOAA March 15: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

[123] Dvorak, M.T.,K.C. Armour, D.M.W. Frierson, C. Proistosescu, M.B. Baker and C. J. Smith. 2022. Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming. *Nature Climate Change:* 547–552

require the equivalent of 8 rounds of five percent reductions in global CO_2 emissions year over year from 2022 to 2030.[124,125] Deep cuts in GHG emissions, and drawdown of GHG from the atmosphere and oceans, are certainly necessary for long-term climate stability, but these steps will likely require a fundamental transformation of the global economy that will take many decades, during which the Earth's ecosystems will be fundamentally disrupted.[126] Any decision to rely on emissions reductions alone precludes the possibility of directly cooling the Earth as a step in reducing climate disruption, preserving ecosystems and, most importantly, saving lives.

6. Conclusion

Direct climate cooling is an essential and timely approach for preventing further warming and its devastating consequences. Most of these direct climate cooling approaches are fast enough to address near-term climate emergencies, complementing essential emissions reduction, GHG removal, and ecological regeneration. With climate disasters increasing, it would seem that establishing agreement on governance mechanisms for direct cooling might well be more feasible than the rapid and deep emission cuts necessary to avoiding further warming, because a complete transformation of global industrial civilization is not required to implement these approaches. If wisely implemented, direct climate cooling would be expected to moderate and even partly reverse ecosystem disruption, and protect and enhance biodiversity by allowing many areas that are becoming too hot to live to become habitable again. By immediately reducing the likelihood of extreme weather, direct cooling would also be expected to reduce loss of life. In addition, acceleration of sea level rise would be made less likely, thereby leading to reduced need for coastal residents to emigrate, thus helping to reduce the risks of conflict.

Although some fossil fuel interests have played an extraordinarily contrarian role in addressing the climate crisis (a role for which many think that they should be held accountable), fossil fuel use in general was not an "original sin," but was rather the basis for modern industrial development. Addressing the climate crisis is, at least in the short-term, primarily a practical environmental and technological problem that must be addressed within existing social and economic systems. Addressing the immediate aspects of the crisis by use of cooling approaches that can moderate global warming would allow for a more realistically feasible pace of emissions reductions while limiting further damage to many ecosystem resources, and perhaps providing a window for some degree of recovery.

Limiting further warming would thus provide an opportunity for societies to evolve from a fossil fuel and mineral mining based economy that is dependent on discovering and mining fossil fuels

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[124] Ritchie, Hannah, Max Roser and Pablo Rosado 2021. CO_2 and Greenhouse Gas Emissions: https://ourworldindata.org/greenhouse-gas-emissions#annual-greenhouse-gas-emissions-how-much-do-we-emit This reference estimates 2022 GHG emissions of 50 GT CO_2eq.

[125] United Nations Environmental Program Emissions Gap Report, 2021, op. cit. Five percent year over year GHG reductions are necessary to cut emissions from 50 GT CO_2eq in 2022 to 33 GT CO_2eq in 2030. This is estimated to be necessary for a 66% chance of staying below 1.8°C in 2100 (Table ES.1). .

[126] See for example the timetable proposed in HPAC. Oct. 2022. "Vision for a Healthy Planet": https://drive.google.com/file/d/1RO0PXjcqP3B6BbNBPQppXVkD-oQXWYJX/view?usp=sharing

and minerals in particular locations, to a potentially more equitable, prosperous and ecologically sustainable civilization based on use of renewable energy and materials, able to harvest energy, and use minerals from the ocean and carbon from the air to synthesize needed materials, almost everywhere on the planet.[127,128] Such a shift would replace today's wasteful and destructive practices with a circular economy where all waste is recycled as a resource. However the world proceeds, equity and environmental justice issues will need to be addressed to meet the Sustainable Development Goals that provide opportunity and a safety net for all.

Gaining global approval for researching and where appropriate implementing cooling influences and GHG emissions reduction and removal will also require attention to issues such as: providing a safe harbor for climate refugees, assisting in overcoming loss and damage from climate disruption, and transferal of technology for climate restoration and ecological regeneration from rich to poor countries and individuals. Doing this rapidly (within decades) and at scale will likely require significant funding. Over the 13 years from 2006 -2018 the Clean Development Mechanism that was part of the mandatory Kyoto accord transferred $303.8 billion from rich countries to poor countries for mitigation and adaptation.[129,130] In contrast the Paris agreement voluntary Green Climate Fund (GCF) had over the 8 years from 2014-2021 raised only $18.2 billion.[131] Equitable reductions in GHG emissions would for example need to support economic development to offset the estimated $4 trillion in foreign exchange from oil and related products that countries comprising 1.1 billion people, or 14.2 percent of world population, depended on in 2019 for over 10% of their total export revenue.[132]
Quite clearly, the GCF will not be adequate for assisting in both recovery from disasters and aggressive efforts to reduce GHG emissions, which will be essential if direct cooling influences are to be sustained until human-induced warming is returned to no more than mid-20th century levels.

During at least the next several decades (and possibly much longer), direct cooling seems likely to be essential to limiting further warming and preventing human-induced climate change from spiraling out of control. Only the application of emergency cooling "tourniquets", applied immediately or as soon as is reasonably advisable, has the potential to slow and even start to reverse ongoing climate disruption. Only direct climate cooling can slow or reverse Arctic sea ice loss, which seems near to flipping the Arctic Ocean into a summertime regime of very little, if any, sea ice. The very serious challenges imposed by increasing climate disruption and the economic opportunity of transforming the global energy system, must be urgently addressed

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[127] Eisenberger, Peter. 2020. REME -- Renewable Energy and Materials Economy -- The Path to Energy Security, Prosperity and Climate Stability. *Physics and Society*: https://arxiv.org/abs/2012.14976
[128] Baiman, Ron 2021 op cit.
[129] "United Nations Framework Convention on Climate Change". *cdm.unfccc.int*.

[130] United Nations Climate Change. 2018. *Achievements of the Clean Development Mechanism*. Accessed at: https://unfccc.int/sites/default/files/resource/UNFCCC_CDM_report_2018.pdf

[131] Green Climate Fund. 2022. *Status of pledges (IRF and GCF-1).* April. Accessed at: https://www.greenclimate.fund/document/status-pledges-all-cycles
[132] Op. cit. Baiman 2022 using World Bank data.

together if unacceptable risks to society are to be minimized. Humanity has never faced an existential threat so critical for the long-term survival of human civilization and the ecosystems of the Earth on which society depends.