Understanding the Urgent Need for Direct Climate Cooling

Ron Baiman[1], Sev Clarke[2], Clive Elsworth[3], Leslie Field[4], Achim Hoffmann[5] Michael MacCracken[6], John Macdonald[7], David Mitchell[8], Franz Dietrich Oeste[9], Suzanne Reed[10], Stephen Salter[11], Herb Simmens[12], Ye Tao[13], Robert Tulip[14]

[1] Benedictine University, Lisle, IL, USA

[2] Winwick Business Solutions P/L, Australia

[3] Citizens Climate Lobby, UK

[4] Bright Ice Initiative, USA

[5] WOXON, The Ocean Enabled Climate Repair Company, UK

[6] Climate Institute, USA

[7] Climate Foundation, Australia 9 Desert Research Institute, USA

[8] Desert Research Institute, USA

[9] gM-Ingenieurbüro, Germany

[10] The Collaboration Connection, USA

[11] University of Edinburgh, UK

[12] Planetphilia, USA

[13] MEER Framework, USA

[14] Iron Salt Aerosol Australia Pty Ltd, Australia

Corresponding author: Ron Baiman (rbaiman@ben.edu)

Key Points:

- Climate change and impacts will continue to accelerate until the warming influences are reduced or offset by direct cooling approaches.
- Direct climate cooling approaches have the potential to reduce local to global portions of human-induced warming influences.
- GHG emission reduction and removal policies alone will take at least decades to halt warming, much less restore 20th century conditions.

Abstract

The intensifying impacts of climate change are exceeding projections and amplifying the risk of catastrophic harm to the environment and society throughout the 21st century. Planned and proposed rates of emissions reduction and removal are not proceeding at a pace or magnitude to meet either the 1.5°C or 2.0°C targets of the Paris Agreement. Moreover, the impacts, damage and loss occurring at today's 1.2°C of global warming are already significantly disrupting the environment and society. Relying exclusively on greenhouse gas (GHG) emissions reduction and removal without including climate cooling options is thus proving incompatible with responsible planetary stewardship. Multiple approaches to exerting a cooling influence have the potential to contribute to offset at least some of the projected climate disruption if deployed in the near term. Employed thoughtfully, such approaches could be used to limit global warming to well below 1° C, a level that has led to large reductions in sea ice, destabilization of ice sheets, loss of biodiversity, and transformation of ecosystems. An effective plan for avoiding "dangerous anthropogenic interference with the climate system," would include: a) early deployment of one or more direct cooling influence(s), initially focused on offsetting amplified polar warming; b) accelerated reductions in emissions of CO_2, methane and other short-lived warming agents; and c) building capacity to remove legacy GHG loadings from the atmosphere. Only the application of emergency cooling "tourniquets," researched and applied reasonably soon to a "bleeding" Earth, have the potential to slow or reverse ongoing and increasingly severe climate disruption.

Plain Language Summary

Climate change, especially polar amplification, has already caused enormous damage and elevated the risk of catastrophic harm to humans, ecosystems, the global economy, and national security worldwide. At least sixteen potential direct climate cooling methods have the potential to moderate at least some of the projected global disruption. Without deployment of at least some of the cited cooling approaches, global warming will soon exceed the 1.5°C or 2.0°C targets proposed in the Paris Agreement. Restoring the relatively beneficial climatic conditions of the mid-to late-20th century will require a restoration plan that would return global warming to well below 1° C. To be effective, such a plan would need to include: a) deploying a major direct cooling influence, perhaps initially focused on cooling the polar regions and the Himalayas; b) accelerating the pace of reduction of GHG emissions, including an early focus on methane and other short-lived warming agents; and c) building up the capability to reduce the loadings of legacy CO_2, methane and other GHGs from the atmosphere and oceans. Only by including the application of emergency cooling "tourniquets" will there be a near-term possibility to reverse the worsening potential for climate disruption.

1 Introduction

The greenhouse gas (GHG) emissions reduction strategy promoted over the last three decades by the Conference of the Parties (COP) to the UN Framework Convention on Climate Change (UNFCCC) has yet to stop the growth in emissions. There has been no progress toward reducing global emissions 43% from 2022 to 2030 to achieve net zero emissions by 2050 as would be required to limit global warming to 1.5°C, or even by just 23% to achieve net zero emissions by 2070 and limit global warming to 2.0°C as stipulated in the Paris Agreement (IPCC, 2022, Table SPM.2; Kharas et al., 2022).

Indeed, Greenland Sea level fingerprints and Himalayan melt rates are strong indicators of accelerated warming leading to more frequent and severe climate calamities. More rapid loss of glacial ice in all three poles including the Himalayas is accelerating 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 (McCay et al., 2022; Lenton et al., 2019). 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 needed to achieve net-zero emissions and scale up approaches to removing CO2 and other greenhouse gasses and lowering their atmospheric concentrations to pre-industrial values. Limiting global warming, especially peak global warming, in this way would provide time for ecosystems to come back into equilibrium, thus helping to reinvigorate the natural environment over the longer term (Baiman 2022).

The argument that research and deployment of any direct climate cooling method, whether localized or global, co-developed or not, constitutes a “moral hazard” because the effect would be to slow GHG mitigation efforts has been put forth for several decades based on speculative reasoning. But this argument as well as others about unanticipated consequences, “termination shock” or harmful climate destabilization if abruptly ended, and the lack of equitable governance, are concerns that in general, could be applied to many other efforts to reduce climate and environmental harm (Biermann et al., 2022). Climate adaptation, for example, was initially opposed as a potential moral hazard that could reduce pressure to cut emissions (Jebari et al., 2021). Regulations to reduce harmful sulfur emissions from cargo ship bunker fuel have reportedly had the unintended consequence of causing a global warming termination shock (Manshausen et al., 2022; Simons et al., 2021). Equitable world governance is proving to be a challenge to achieving rapid, and at scale, global emissions reductions (Baiman, 2022).

Concerns represented in these arguments need to be addressed in any program advancing direct climate cooling. However, the reality of accelerated warming, more catastrophic events and ever-increasing damage and loss has yet to translate into sufficiently urgent GHG emissions reduction and removal or reduced fossil fuel use and development. The moral hazard lies in not pursuing all feasible options to cool the Earth.

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 (Hansen et al., 2022). Many 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 catastrophes.

At this writing, at least sixteen potential direct climate cooling methods merit early consideration, responsible investigation, and possible, closely monitored implementation. and evaluation. The short summaries of these methods that follow are written by climate cooling experts. The methods listed in alphabetical order are:

- Bright Water
- Buoyant Flakes
- Cirrus cloud thinning (CCT)
- Fizz Tops (Fiztops)
- Ice shields to thicken polar ice
- Making building and paving material more reflective and planting trees in urban areas

- Marine Cloud Brightening (MCB)
- Mirrors for Earth’s Energy Rebalancing (MEER)
- Ocean Thermal Energy Conversion (OTEC)
- Restoring soil and vegetation
- Seawater atomization (Seatomizers)
- Stratospheric Aerosol Injection (SAI)
- Surface Albedo Modification (SAM)
- Tropospheric photosensitive aerosols for climate cooling (Climate catalysts)
- WOXON Ocean Heat Conversion (WOHC)

It is abundantly clear that GHG emission reduction and removal is not proceeding at sufficient pace or scale to effectively achieve the Paris agreement temperature rise limitation targets of 1.5°C or 2.0°C in the 21st Century. World leaders must accept this reality and commit to international development and adoption of an encompassing climate restoration plan incorporating all feasible options and a target of limiting global warming to below 1°C. An effective restoration plan would include: a) deploying a direct cooling influence initially focused on cooling the polar regions and the Himalayas; b) reducing GHG emissions, with 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.

Humanity has never faced an existential threat so critical for the survival of human civilization and our fellow living species on this planet. Over at least the next several decades, and possibly much longer, the primary role of direct cooling influences would be to keep the climate from spiraling out of control as a result of ongoing and accumulating GHG emissions. Only the application of emergency cooling “tourniquets,” applied as soon as is reasonably advisable, has the potential to slow or reverse ongoing climate disruption and worsening climate impacts, and polar ice melting. Moderation of intensifying extremes must be immediately and urgently undertaken so presently inhabited lands do not have to be abandoned (Hansen et al., 2012).

The following sections address four key issues: Section 2, the need for relevant climate change metrics and goals; Section 3, the risk of not immediately slowing or reversing polar amplification; Section 4, methods for direct climate cooling; and Section 5, the urgency of adding direct climate cooling to the international strategy for climate restoration. Conclusions are presented in Section 6.

2 The Need for Relevant Climate Change Metrics and Goals

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 (IPCC, 2021, Figure SPM.1). The IPCC and Conference of Parties (COP) 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 heavy precipitation, flooding, and prolonged heat waves (Bhutto, 2022).

The global-average increase in temperature is also a metric that few locations actually experience. Warming is greater over land than over the ocean, especially in mid- and high latitudes (and very especially in the poles), so most people are experiencing (and in the future will be experiencing) warming that is greater than the global average (Fendt, 2021). For those living in low-latitude regions that experience warming 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 (Pearce et al., 2022).

Neither the global average temperature metric nor the focus on projections out to 2100 provide 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 (NASA, 2011b). 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 (Jouzel et al., 2007). 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 ice sheets. There is geological evidence that ice sheet decay occurs much more rapidly than ice sheet formation and would be very hard to stop once initiated (Box et al., 2022). A 2021 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 (Genz et al., 2022).

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 (2018): "Net zero *carbon dioxide (CO_2)* emissions are achieved when *anthropogenic* CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period." 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 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 (Gatti et al., 2021). 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 stable isotope studies, a profound realization of a potential tipping point, and methane levels are now almost three times higher than they were pre-industrially (Lan et al. 2021; NOAA, 2023; Ming et al., 2022).

In many of the model simulations of the potential for direct cooling, studies tend to focus on offsetting warming from two or even four times the preindustrial CO_2 concentration to achieve high signal-to-noise in their results (Zhou et al., 2021). 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 (Irvine, 2017).

As an overall goal, a reasonable policy approach in deployment of direct cooling would be to first, not let the situation get worse and only then take actions to moderate 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 delay engaging in field research. 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. Deploying options that permit adjustment is preferable to deploying ones that do not..

3 The Risk of Not Immediately Slowing or Reversing Polar Amplification

Lenton et al. reported in 2019 that, 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.

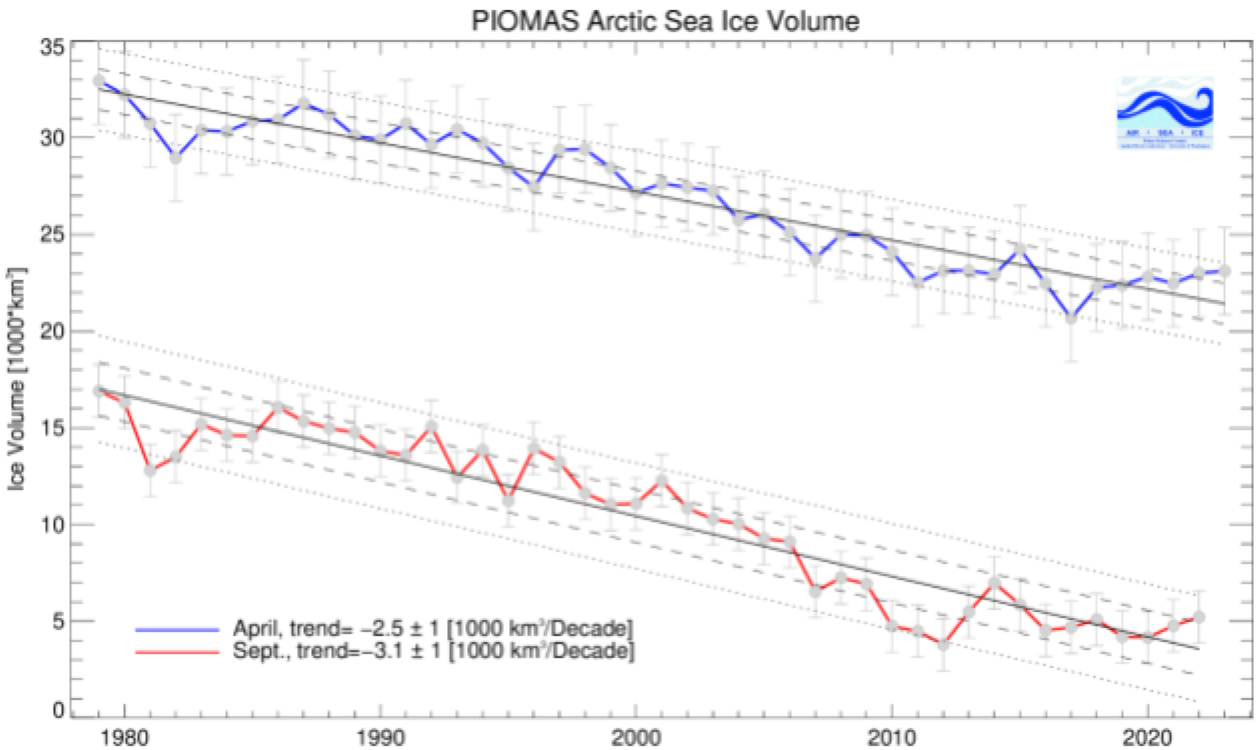

Figure 1: 1979-2022 Monthly Sea Ice Volume from PIOMAS for April and Sep.

Source: [http://psc.apl.uw.edu/wordpress/wp-content/uploads/schweiger/ice_volume/BPIOMASIceVolumeAprSepCurrent.png.](http://psc.apl.uw.edu/wordpress/wp-content/uploads/schweiger/ice_volume/BPIOMASIceVolumeAprSepCurrent.png) Downloaded 8/11/2023 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 (Pistone et al., 2019; Baiman, 2021, footnote 6).

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 suite of CMIP Phase 5 models, with no model simulating as much reduction in sea ice cover as the observations. More recently, Mallet et al. (2021) found that from 2002 to 2018 Arctic ice has thinned 60% more than climate models have projected, and Heuze et al. (2023) find that newer climate models continue to underestimate Arctic sea-ice.

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 (AMAP, 2021; McSweeney, 2019; Rantanen et al., 2022). Disproportionate warming has affected all three poles, including the Himalayan 'pole' at the top of the world, which is a critical source of water for 2 billion people (NASA, 2023; Lee et al., 2021; National Research Council, 2012). This "polar amplification" is contributing to the accelerated loss 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 *Wall Street Journal* article noted that bad weather was 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 (Christian Aid, 2021; Dezember, 2021). 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 (McKay et al., 2022).

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 achieved and legacy concentrations of GHGs are removed from 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 CO_2eq 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 CO_2 from the atmosphere (MacDougall et al., 2020; Hausfather, 2021). This suggests that even after net-zero is achieved, a combination of continued direct climate cooling and drawdown of legacy GHG would be necessary to expeditiously restore and regenerate a stable climate and healthy ecosystem (Schuckmann et al., 2020; Baiman, 2021, footnote 9).

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 (National Academy of Sciences, 2021; American Meteorological Society, 2022; Council on Foreign Relations, 2023; Cambridge Center for Climate Repair, 2023; Climate Overshoot Commission, 2023).

4 Potential Methods for Direct Climate Cooling

The following is a menu of sixteen 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** would use micron-radius hydrosols 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 (Seitz, 2011).
- **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 (Clarke, 2022).
- **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 (Mitchell D.L. & Finnegan W., 2009). 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. CCT can only be effective when cirrus clouds form substantially through homogeneous ice nucleation. A critical need in CCT research is to establish measurement-based constraints on the global spatial and temporal distribution of homogeneous cirrus clouds. Fortunately, recent progress in cirrus cloud property remote sensing is providing such constraints. This satellite remote sensing shows that homogeneous cirrus clouds are common at high- and mid-latitudes, especially during winter. 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 (Mitchell et al., 2018).
- **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 (Clarke, 2022).
- **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 would start to restore arctic 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 (Desch et al., 2017; Clarke, 2021).

- **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 (Twomey S., 1977). 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 (Latham et al., 2012). 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 (Mims, 2009). The Australian government is presently supporting MCB to prevent coral bleaching on the Great Barrier Reef (Brent et al., 2020).
- **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. Implementation is proposed in the contexts of agricultural adaptation (Ortiz-Bobea et al., 2019; Zhang et al., 2022), urban heat island alleviation (Cao et al., 2015), freshwater conservation (McKuin et al., 2021), and renewable energy generation, as well as ecosystem protection (Hughes et al., 2017; Berg et al., 2020). Stationary surface mirrors, optimally oriented, are estimated using 2018 CERES data to have the potential, on average, to reduce the net top of the atmosphere flux by 70 watts per square meter (Wild et al., 2015). Complete neutralization 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 that produce 4.5 watts per square meter of radiative forcing (Thompson et al., 2011). 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. Prototyping and engineering data suggest that devices for the most scalable application in agriculture use a hybrid bamboo-glass material system for structural support. Mirrored roofing tiles would reduce heat wave mortality and energy system overload exacerbated by the urban heat island effect (Millstein and Fischer, 2014; Trlica et al., 2017). Replacing colored nets in agriculture with mirrors could improve productivity by reducing heat stress and agricultural water usage (Munywoki, 2017; Mohawesh et al., 2021). Preliminary experimental data suggest agricultural soil cooling by up to 4°C at a depth of 10 cm at mid-latitude (43°N), with cooler soil storing more carbon (Hartley et al., 2021). Mirrors over freshwater bodies can reduce evaporation from reservoirs, rivers, and aqueducts. Compared to floating photovoltaic systems, floating mirrors would do more to cool the water and reduce evaporation by cooling the air-water interface (Barron-Gafford et al., 2016). Mirror deployment on a 10-100 km2 range could produce regional climate oases by lowering ground and air temperatures by several degrees Celsius, without significant change in rainfall (Campra et al., 2008). 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. MEER has been conducting field experiments in Plymouth and Concord NH USA, and outside of San Francisco USA, to replicate and verify these results.

- **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 (Rau & Baird, 2018; Gleckler et al., 2016). 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** will increase evapotranspiration from the soil and vegetation to cool the planet (Jehne, 2021; Piao et al., 2019; Evans, 2020). 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 biodiversity (Wait, 2021; Ban-Weiss, 2011). The application of Biochar can increase soil water retention and thus evapotranspiration potential (Wang et al., 2017).
- **Seawater atomization (Seatomizers)** are anchored wind turbines that 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 (Clarke, 2022).
- **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 (NASA, 2011a). SAI is the most studied direct cooling method. Research suggests that adverse effects of SAI would be minimal if applied at low levels of aerosol injection. Climate model simulations indicate that SAI might be able to reduce the global mean temperature increase by up to 2° C (MacMartin et al., 2022). 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 estimates a cost of about $ 36 B (in $ 2020) to reduce global warming by 2° C from 2035 to 2100 (Smith, 2020). 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 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 stratosphere more quickly if injection needed to be quickly terminated due to unintended adverse consequences. The cost of reducing global temperatures by 2° C in latitudes above 60 degrees north is estimated to be about $ 11 B (in $ 2022; Smith et al., 2022; MacCracken, 2010). 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 (Quaglia et al., 2021).

- **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 (Field et al., 2018; Field, 2021; Johnson et al., 2022). 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.
- **Tree planting and reflective materials in urban areas** would promote tree planting and using lighter colored pavement materials that 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 local heat island effect reduction. If implemented on a world scale, this strategy could, over time, contribute to global climate cooling (Debbage & Shepherd, 2015; MIT, 2020; Seneviratne et al., 2018; Kalkstein et al., 2022; Oleson et al., 2010).

- **Tropospheric photosensitive aerosols for climate cooling (Climate catalysts)** would photo-catalyze atmospheric methane depletion in the lower troposphere by mimicking the photochemistry of mineral dust aerosol in the marine boundary layer. In addition, they harness chemical, physical, and biological mechanisms that provide cooling effects in both the tropospheric environment and the ocean's photic zone.

  Naturally occurring photocatalytic aerosol particles typically consist of: Iron-containing airborne mineral dust originating from deserts, volcanic eruption ashes, or

glacial meltwater sediments; Chloride from gaseous hydrochloric acid produced by reaction of atmospheric oxidants with sea spray aerosol, sulfur-organics, combustion SO_2, and NOx.
These react to produce iron(III) chloride, which is hygroscopic. The particle then forms an aqueous coat from water vapor from the air.

Climate catalyst particles contain the same substances as naturally occurring marine aerosol particles. The main difference is the quartz content is replaced by an amorphous silica gel condensate, and we added titanium peroxo-hydroxide for its exceptional photosensitivity. The following list of climate catalyst particle constituents has photosensitive compounds: ferric iron ions, ferric iron oxides, titanium hydroxides, chloride, nitrate, aluminum ions, silicic acid (gelatinous).

The aluminum and silicon compounds make the particles hygroscopic. They also induce flocculation when particles sediment into the sea. This is essentially a gelation process that removes any nano-particle hazard. The gel eventually degenerates to become clay mineral.

The active constituents of the aerosol particles are chloride, and one or more compounds containing nitrate, iron(III) and/or titanium(IV). The compounds operate in either an ionic state or bound to oxygen or peroxide. Nitrate, iron, and titanium compounds are photo-activated mainly by the UV component of sun radiation. Driven by sunlight, these photosensitive compounds convert chloride ions to chlorine radicals (single uncharged atoms), which are emitted into the air. In the air they rapidly oxidize methane molecules. The HCl educt is recycled back to the photosensitive aerosol particles in a heterogeneous photocatalytic cycle.

Tropospheric ozone exists naturally in low concentrations throughout the troposphere. Driven by UV, it produces OH radicals that deplete methane and other volatile organic carbons (VOCs). Methane and other VOCs are greenhouse gasses with a much stronger greenhouse potential than CO_2. However, tropospheric ozone is also a strong greenhouse gas, which can build up in higher concentrations by reaction with methane sources. It is also harmful to human health and reduces crop yields. Chlorine radicals also deplete tropospheric ozone.

A recent paper (Li et al., 2023) modeled a chlorine only intervention and concluded that the atmospheric methane sink would only be strengthened beyond a certain level of added
chlorine, owing to Cl removal of tropospheric ozone. However, such an intervention would be very different to plumes of climate catalyst that operate more intensively for a limited time in a photocatalytic cycle, before then raining out.

Since large ocean areas lack iron as a micronutrient, climate catalyst with an iron content could be used in regions far away from ice sheets to boost the productivity of phytoplankton. That would reduce surface acidification, feed downstream oceanic ecosystems, and increase their dimethyl sulfide (DMS) emissions. DMS naturally oxidizes in the lower troposphere to form sulphuric acid aerosol. Being hygroscopic, this aerosol acts as cloud condensation nuclei (CCN), which generates and brightens clouds in the marine boundary layer of the lower troposphere. In clear skies climate catalyst initially generates a long-lived haze that similarly generates and brightens clouds over time. Low lying haze and clouds in low latitudes provide a powerful cooling influence.

Photosynthetic growth also induces atmospheric CO_2 absorption, and curbs oceanic CO_2 outgassing.

The UV index is strongly correlated with an increased hydroxyl and chlorine radical amount (Rohrer & Berresheim, 2006; Lelieveld et al., 2002) and thus with a faster methane depletion rate. VOCs are mainly removed by OH and Cl radicals formed naturally in the air by UV light. The rate of generation of these radicals depends directly on UV intensity. The back-reflection of UV from haze, clouds, snow, and ice removes significant additional methane and other VOC greenhouse gasses from the air. That is because UV light is efficiently reflected by white objects owing to its high refractive index. Bright snow surfaces reflect around 90% of the UV that reaches them (de Paula Corrêa & Ceballos, 2008; Chadysiene & Girgzdys, 2008). Cloud surfaces reflect up to 30% UV (Weaver et al., 2020). Hence any kind of albedo increase produced in the troposphere by the effects of climate catalysts increases the rate of photochemical greenhouse gas depletion, as described above. Reducing the lifetime of powerful warming agents this way reduces their atmospheric concentration, thereby reducing their overall global warming effect.

The most important cooling effects achieved by climate catalysts are methane depletion, haze generation, cloud whitening and cloud generation. To use the emitted climate catalyst aerosols with optimal methane depletion the preferred ocean areas are those with the most elevated UV index. Tropical latitudes receive more than double the UV intensity of mid latitudes (Mckenzie et al., 2003; Kujanpää & Kalakoski, 2015; Liley & McKenzie 2006). During the whole year within tropical and subtropical regions the UV index is 2 to 5 times higher than the UV index in middle, polar and subpolar latitudes. Since low latitudes also typically have the lowest cloud fraction the most effective locations for climate catalyst interventions are therefore the tropical and subtropical oceans.

A largely unrecognized problem is that of black soot particles inducing convection that carries them up into the stratosphere, driven by sun heating. Soot particles actively collect and store halogenated gasses from the air and deliver them to the stratosphere. Soot particles therefore have a disproportionately damaging effect on the stratospheric ozone layer. Since the stratosphere migrates generally poleward, some of these black carbon particles contribute to Arctic haze, and eventually sediment in snow, discoloring it and thereby increasing its melting rate. Climate catalyst lightens soot particles and changes their water-repelling (hydrophobic) nature to water-attracting (hygroscopic). This both reduces their convection effect, and makes them wash out in rain more easily, preventing them from ascending to the stratosphere and polar regions.

Polar and subpolar soot-contaminated gray ice sheets can be whitened directly by a colorless formulation of climate catalyst. This formulation contains no iron or nitrate, leaving only a titanium photosensitive content. The non-fertilising, oxidative nature of titanium compounds makes them suitable for protecting ice sheets by preventing the growth of moss, algae, and microbial biofilms. These otherwise discolor ice sheets, also accelerating their melt rates. The colorless formulation is also suitable for shielding melting ice from direct sunlight during summer months, by generating haze and by forming/brightening clouds. By decelerating melt rates, the peak melt rate reached may be much lower. Thus, a significant amount of ice may be preserved by the end of the summer season.

The technology is proven. The original Iron Salt Aerosol (ISA) climate catalyst proposal contained only ferric chloride as an active photo-catalyst. ISA's methane depletion activity was observed and measured in atmospheric chemistry research laboratories around 10 years ago. It was described in several papers (Wittmer et al., 2015; Wittmer & Zetzsch, 2017; Oeste et al., 2017). In 2023 the same chemical mechanism in mineral dust was measured in field trials in the Caribbean and Cape Verde islands marine boundary layer (van Herpen, 2023). The main differences with our more recent formulations are: OH radical production, in addition to Cl radicals; lower cost – we estimate up to 10 times less mass of aerosol is needed to achieve the same effect; colorless formulations for use near icefields, and to protect ice sheets. The new formulations are now entering the test phase in laboratories in California and Denmark. Haze and cloud formation tests are about to begin in a spray tunnel under the supervision of Prof Stephen Salter, pioneer of Marine Cloud Brightening (MCB).

In the following list Short-Lived Warming Pollutants (SLWP) are assumed to be methane, tropospheric ozone, black carbon aerosol, and other VOCs including oxidable halogenated gasses such as chloromethane: albedo increase, by direct haze and cloud generation, and cloud whitening; Indirect SLWP depletion increase, by direct haze and cloud generation, and cloud whitening; indirect albedo increase, by ice sheet whitening; indirect SLWP depletion increase, by ice sheet whitening; direct SLWP depletion increase, by increasing the level of atmospheric Cl and OH radicals; indirect albedo increase, by haze and cloud generation; cloud whitening, by Fe nutrition-induced photosynthetic increase of phytoplankton DMS emissions; and indirect CO_2 absorption increase and outgassing decrease, by Fe nutrition-induced photosynthetic increase of phytoplankton.

- **WOXON Ocean Heat Conversion (WOHC)** uses the self-ionization effect in water to enable the conversion of aqueous heat to chemically stored energy. Water is not a resting substance but constantly splits into its ionic components OH- and H3O+ with the process kinetics and 80 Watt/liter endothermic reaction energy known (Eigen & DeMayer, 1955). This is however not easily observed, as the exothermic reverse reaction is one of the fastest known in Chemistry. The WOHC process intends to interrupt the immediate recombination and convert the aqueous ions to hydrogen as the waste energy storage system. Water will run through highly scalable offshore rigs installed in the top layers of global fast warm currents, such as the Gulf Stream and the Kuroshio in the Northern Hemisphere or the Agulhas, East Australia or Brazil in the Southern Hemisphere. H_2 by itself or combined with CO_2 or N_2 forms the starting point of many energy value chains, such as H_2, CH_4, NH_3 and CH_3OH as gaseous and liquid fuels of commercial interest. The production of solid carbon for sequestration making use of excess hydrogen via known routes is of specific interest to ensure the captured heat is not released again (Zuraiqi et al., 2022). It is the balancing option between sequestration and production for sustainable consumption which makes this a bankable cooling alternative.

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

Based on the most recent IPCC AR6 WG3 estimates, net global anthropogenic GHG emissions would have to be reduced to 33 GT CO_2eq by 2030 to achieve net zero emissions by 2050 and keep global warming below 1.5°C through the 21st Century, and to 44 GT CO_2eq by 2030 to achieve net zero emissions by 2070 and keep global warming below 2.0°C (IPCC, 2022, Table SPM.2). Assuming global GHG emissions of roughly 58 GT CO_2eq in 2022, remaining below 1.5°C would then require average global emissions reductions of 6.8% a year from 2022 to 2030, and to remain below 2.0 °C, would require 3.4% of reductions a year (Kharas et al., 2022). While perhaps theoretically possible, insufficient and unfulfilled government commitments, economic realities, and the sheer magnitude of the task make it unrealistic to think that anthropogenic global GHG emissions can be reduced by 3.4% to 6.8% a year to stay "well below 2.0°C" through the 21st century in accordance with the Paris Agreement.

It is becoming more and more likely that, without direct climate cooling, the 1.5°C and 2.0°C thresholds will be breached before 2100. 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 2026 (WMO, 2022). 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 (Zhou et al., 2021). 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 (Samset et al., 2018). As such emissions are reduced over time to address 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 (Lindsey & Dahlman, 2021; Dvorak et al., 2022).

Extreme heat waves, polar ice melting in all three 'poles', and disastrous weather events and impacts tell us that the consequences of the Earth's increasing 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 that returns 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 capacity to reduce the legacy concentrations of CO_2, methane, and other GHGs 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. 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 (Healthy Planet Action Coalition, 2022, A Time Table for Urgent Action). A decision to rely solely on emissions reductions and removal will preclude the possibility of directly cooling the Earth to reduce climate disruption, preserve ecosystems and, most importantly, save lives in the 21st Century.

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 could take effect fast enough to moderate near-term climate emergencies, complementing essential emissions reduction, GHG removal, and ecological regeneration. With climate disasters increasing and because a complete transformation of global industrial civilization is not required, establishing agreement on governance mechanisms for direct cooling might well be more feasible than achieving the rapid and deep emission cuts necessary to avoiding further warming. Wisely implemented, direct climate cooling could moderate and even partly reverse ecosystem disruption, and protect and enhance biodiversity by making many areas that are becoming too hot to live habitable again. By immediately reducing the likelihood of extreme weather, direct cooling could also reduce loss of human life, livelihood, property, and communities. Lower temperatures could decrease sea level rise reducing the need for coastal residents to emigrate and the potential for political conflict.

Although some fossil fuel interests have played detrimental roles in the climate crisis (and should be held accountable), fossil fuel use in general is not an "original sin." Rather, it was the basis for modern industrial development and enhanced quality of life for many.

Addressing the climate crisis is, at least in the short-term, primarily a practical environmental and technological problem that must be tackled 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 and removal 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 fossil fuel and mineral mining-based economies dependent on discovering and mining fossil fuels and minerals to potentially more equitable, prosperous and ecologically sustainable civilizations. This transformation would be based on use of renewable energy, reusable materials, the ability to harvest energy and the utilization of minerals from the ocean and carbon from the air to synthesize needed materials, almost everywhere on the planet (Eisenberger, 2020; Baiman, 2021). 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 United Nations Sustainable Development Goals that provide opportunity and a safety net for all.

Gaining global approval for researching and, where appropriate, implementing cooling influences along with 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 thirteen 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 (CDM, 2018). In contrast, the Paris Agreement voluntary Green Climate Fund (GCF) over the eight years from 2014 - 2021 raised only $18.2 billion (GCF, 2022). 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 (Baiman, 2022, Table 2).

Quite clearly, the GCF will not be adequate for assisting in both recovery from disasters and aggressive efforts to reduce GHG emissions. Both 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 is essential to limiting further warming and preventing human-induced climate change from spiraling out of control. Only the application of emergency cooling "tourniquets," applied as soon as is reasonably advisable, has the potential to slow and 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 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.

Acknowledgments

None of the authors have received any direct financial support for their work on this paper. Authors Sev Clarke, Clive Elsworth, Leslie Field, Achim Hoffmann, John MacDonald, Franz Dietrich Oeste, Stephen Salter and Ye Tao are members of non-profit or commercial entities working on cooling methods discussed in this paper.

We wish to acknowledge the encouragement and support of the national and international environmental and climate cooling organizations and groups that we have participated in and benefited from, including: the Healthy Climate Action Coalition (HPAC), the Nature Based Oceanic and the Atmospheric Cooling (NOAC) group, the Planetary Restoration Action Group (PRAG), the Healthy Climate Alliance (HCA), and the Mirrors for Earth's Energy Rebalancing (MEER) group; the geoengineering and (geoengineering@googlegroups.com) and carbon dioxide removal google groups (carbondioxideremoval@googlegroups.com); and the "Reviewer 2 does Geoengineering" and "Challenging Climate" podcasts.

Open Research

Two cited documents that have not been published are included with this submission:

1) Clarke W.S. (2021) Ice shield strategies. Winwick Business Solutions. September 9: https://doi.org/10.17632/k6r7ycg7hk.1

2) Clarke, W.S. (2022). More climate solutions. Winwick Business Solutions. May: https://doi.org/10.17632/n6vsy3zgg6.1

These documents include hypotheses and preliminary results for four of the sixteen proposed direct climate cooling methods discussed in the submission for which peer reviewed and published data is not yet available. Though the hypotheses and results discussed in these documents are preliminary, we believe that providing references (and links) for this material is important for readers who wish to more fully understand the proposed designs and applications of these methods. These documents have been deposited in the Mendeley Digital Commons data archive and can be accessed through the links provided in the references to them in the submission.

References

AMAP. (2021). Arctic Climate Change Update 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

American Meteorological Society (2022). A policy statement of the American Meteorological Society. Adopted by the AMS Council on 2 February 2022: https://www.ametsoc.org/ams/assets/File/aboutams/statements_pdf/AMS_Statement_Climate_Intervention_Final.pdf

Baiman, R. (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: https://doi.org/10.1177/04866134211032396

Baiman, R. (2022) Our two climate crises challenge: short-run emergency direct cooling and long-run GHG removal and ecological regeneration. *Review of Radical Political Economics*, 54(4), 435-45. https://doi.org/10.1177/04866134221123626

Ban-Weiss G.A., Bala G., Cao L., Pongratz J., Caldeira K. (2011). Climate forcing and response to idealized changes in surface latent and sensible heat. *Environmental Research Letters*: https://doi.org/10.1088/1748-9326/6/3/034032

Barron-Gafford G.A., Minor R.L., Allen N.A., Cronin A.D., Brooks A.E. & Pavao-Zuckerman M.A. (2016). The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Scientific Reports* 6(35070): https://doi.org/10.1038/srep35070

Berg J.T., David C.M., Gabriel M.M., & Bentlage B. (2020) Fluorescence signatures of persistent photosystem damage in the staghorn coral Acropora cf. pulchra (Anthozoa: Scleractinia) during bleaching and recovery. *Marine Biology Research* 16(8-9): 643-655: https://doi.org/10.1080/17451000.2021.1875245

Bhutto, Fatima. (2022) What is owed to Pakistan, now one-third underwater. Sep. 3, *New YorkTimes*: https://www.nytimes.com/2022/09/03/opinion/environment/floods-in-pakistan-climate-change.html

Biermann, F., Oomen J., Gupta A., Ali S.H., Conca K., Hajer M.A., et al. (2022). Solar geoengineering: the case for an international non-use agreement. *WIREs Climate Change*, 13(3), e754: https://doi.org/10.1002/wcc.754

Box, J.E., Hubbard, A., Bahr, D.B., Colgan W.T., Fettweis, X., Mankoff K.D., et al. (2022). Greenland ice sheet climate disequilibrium and committed sea-level rise. *Nature Climate Change*, 12, 808-812. https://doi.org/10.1038/s41558-022-01441-2

Brent K., Jeffrey McGee J., McDonald J. & Simon M. (2020). Putting the Great Barrier Reef marine cloud brightening experiment into context. *C2G Guest Post*: https://www.c2g2.net/putting-the-great-barrier-reef-marine-cloud-brightening-experiment-into-context/

Campra P., Garcia M., Canton Y. & Palacios-Orueta A. (2008). Surface temperature cooling trends and negative radiative forcing due to land use change toward greenhouse farming in southeastern Spain. *Journal of Geophysical Research* 113: https://doi.org/10.1029/2008JD009912

Cao, M., Rosado P., Lin Z., Levinson R. & Milstein D. (2015) Cool roofs in Guangzhou, China: Air temperature reductions during heat waves and typical summer conditions. Environ. Sci. Technol. 49(24: 14672-14679: https://doi.org/10.1021/acs.est.5b04886

CDM. (2018). Achievements of the Clean Development Mechanism: 2001-2018. UNFCCC: https://unfccc.int/sites/default/files/resource/UNFCCC_CDM_report_2018.pdf

Christian Aid. (2021) Counting the cost: A year of climate breakdown. December 27.

Cambridge Center for Climate Repair (2023). Refreeze the Arctic: https://www.climaterepair.cam.ac.uk/refreeze

Chadysiene R. & Girgzdys A, (2008) Ultraviolet radiation albedo of natural surfaces. *Journal of Environmental Engineering and Landscape Management* 16(2) 83-88: https://doi.org/10.3846/1648-6897.2008.16.83-88

Clarke W.S. (2021) Ice shield strategies. Winwick Business Solutions. September 9: https://doi.org/10.17632/n6vsy3zgg6.1

Clarke, W.S. (2022). More climate solutions. Winwick Business Solutions. May: https://doi.org/10.17632/k6r7ycg7hk.1

Clean Development Mechanism. (2018). Achievements of the Clean Development Mechanism: https://unfccc.int/sites/default/files/resource/UNFCCC_CDM_report_2018.pdf

Climate Overshoot Commission (2023). How should the world reduce the risks of climate overshoot? https://www.overshootcommission.org/

Council on Foreign Relations (2022). Reflecting sunlight to reduce climate risk priorities for research and international cooperation. Stewart M. Patrick. April: https://www.cfr.org/report/reflecting-sunlight-reduce-climate-risk

de Paula Corrêa M. & Ceballos J.C. (2008) Uvb surface albedo measurements using biometers. *Revista Brasileira de Geophisica* 26(4) 411-416: https://doi.org/10.1590/S0102-261X2008000400002

Debbage, N. & Shepherd,J.M. (2015). The Urban Heat Island effect and city contiguity. *Computers, Environment and Urban Systems* 54: 181-194: https://doi.org/10.1016/j.compenvurbsys.2015.08.002

Desch S.J., Smith N., Groppi C., Vargas P., Jackson R., Kalyaan A., et al. (2017). Arctic ice management. *Earth's Future* 5(1): 107-127: https://doi.org/10.1002/2016EF000410

Dezember, Ryan. (2021) Blame bad weather for your bigger bills. *Wall Street Journal* December 28: https://www.wsj.com/articles/blame-bad-weather-for-your-bigger-bills-11640640525

Dvorak, M. T., Armour K. C., Frierson D. M. W., Proistosescu C., Baker M. B., & Smith C. J. (2022). Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming. *Nature Climate Change*: 547–552: https://doi.org/10.1038/s41558-022-01372-y

Eigen M. & DeMayer L. (1955) Untersuchungen über die Kinetik der Neutralisation. *Z. Elektrochem* 59 (986): https://doi.org/10.1002/bbpc.19550591020

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 .

Evans D. (2020). Saving our Soils for Future Generations. *AWE International*. February 11: https://www.aweimagazine.com/articles/saving-our-soils-for-future-generations/

Fendt L. & Schlosser L. (2021). Which parts of the planet are warming the fastest and why? *MIT Climate*. August 17: https://climate.mit.edu/ask-mit/which-parts-planet-are-warming-fastest-and-why

Field, L., Ivanova D., Bhattachartyya, S., Mlaker V., Sholtz, A., Decca, R., et al. (2018). Increasing Arctic sea ice albedo using localized reversible geoengineering. *Earth's Future* 6(6): 882–889: https://doi.org/10.1029/2018EF000820

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

Gatti L.V., Basso L.S., Miller J.B., Gloor M., Dominques L.G., Cassol H.L.G., et al. (2021). Amazonia as a carbon source linked to deforestation and climate change. *Nature* 595:388–393: https://doi.org/10.1038/s41586-021-03629-6

Genz A.S., Krasting J.P., Larour E., Marcy D., Marra J.J., Obeysekera J., et al. (2022). Global and regional sea level rise scenarios for the United States: Up- dated mean projections and extreme water level probabilities along U.S. coastlines. NOAA Technical Report: https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

Gleckler P. J., Durack R.J., Stouffer R.J., Johnson G.C., Forest C.E. (2016). Industrial-era global ocean heat uptake doubles in recent decades. *Nature Climate Change*: https://doi.org/10.1038/nclimate2915

GCF. (2022). Status of pledges (IRF and GCF-). April: https://www.greenclimate.fund/document/status-pledges-all-cycles

Hansen j., Sato M. & Ruedy R. (2012). Perception of climate Change. *PNAS* 109(37): https://arxiv.org/ftp/arxiv/papers/2212/2212.04474.pdf

Hansen J., Makiko S., Simons L., Nazarenko L.S., Sangha I., Schuckmann K.V., Loeb G.N., et al. (2022). Global warming in the pipeline. *Atmospheric and Oceanic Physics* submitted 12/8, last revised May 2023, v3: https://arxiv.org/ftp/arxiv/papers/2212/2212.04474.pdf

Hartley I.P., Hill T.C., Chadburn S.E., Hugelius G. (2021). Temperature effects on carbon storage are controlled by soil stabilization capacities. *Nature Communications* 12(6713): https://doi.org/10.1038/s41467-021-27101-1

Hausfather, Z. Explainer: will global warming 'stop' as soon as net-zero emissions are reached? (2021). April 29: https://www.carbonbrief.org/explainer-will-global-warming-stop-as-soon-as-net-zero-emissions-are-reached/

Healthy Planet Action Coalition. (2022). Vision for a healthy planet. Oct. 10: https://pdfhost.io/v/r91pQBnNc_HPAC_Vision_document_FINAL_102222

Heuze C., Zanowski H., Karam S. & Muilwijk M. (2023). The deep Arctic Ocean and Fram Strait in CMIP6 models. *The Journal of Climate* 36(6): https://doi.org/10.1175/JCLI-D-22-0194.1

Hughes T. P., Kerry J. T., Álvarez-Noriega M., Álvarez-Romero J. G., Anderson K. D., Baird A. H., et al. (2017). Global warming and recurrent mass bleaching of corals. *Nature* (543): 373–377

IPCC. (2018). Special report on global warming of 1.5 C.: https://www.ipcc.ch/sr15/

IPCC. (2021). Climate change 2021: The physical science basis: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf

IPCC. (2022). Climate change 2022: Mitigation of climate change: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf

Irvine P. J., Kravitz B., Lawrence M. G., Gerten D., Camminade C. K., Gosling, S.N. et al. (2017). Towards a comprehensive climate impacts assessment of solar geoengineering. *Earth's Future*: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000389

Jebari J., Taiwo O. O., Andrews T. M., Aquila V., Beckage B., Belaia M. et al. (2021). From moral hazard to risk-response feedback. *Climate Risk Management* 33: https://doi.org/10.1016/j.crm.2021.100324

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

Johnson D., Manzara A., Field L. A., Chamberlin D. R., Sholtz A. (2022). A Controlled Experiment of Albedo Modification to Reduce Ice Melt. Earth's Future 10(12): https://doi.org/10.1029/2022EF002883

Jouzel J., Masson del Monte V., Cattani O., Dreyfus G., Falourd S., Hoffmann G. ,et al. (2007). Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science* 317 (5839): https://www.science.org/doi/10.1126/science.1141038

Kalkstein L.S., Eiserman D.P., de Guzman E.B. & Sailor D.J. (2022). Increasing trees and high-albedo surfaces decreases heat impacts and mortality in Los Angeles, CA. *International Journal of Biometeorology* 66: 911-925: https://doi.org/10.1007/s00484-022-02248-8

Kharas H., Fengler W., Sheoraj R., Vashold L. & Yankov T. (2022). Tracking emissions by country and sector. *Brookings*. Nov. 29: https://www.brookings.edu/articles/tracking-emissions-by-country-and-sector/

Kujanpää J. & Kalakoski N. (2015). Operational surface UV radiation product from GOME-2 and AVHRR/3 data. *Atmospheric Management Techniques Discussions* 8 4537-4580: https://doi.org/10.5194/amtd-8-4537-2015

Lan X., Basu S., Schwietzke S., Bruhwiler L.M.P., Dlugokencky E.J., Michel S.E., et al. (2021). Improved constraints on global methane emissions and sinks using δ13C-CH4. *Global Biochemical Cycles* 35(6): https://doi.org/10.1029/2021GB007000

Latham J., Bower K., Choularton T., Coe H., Connolly P., Cooper G., et al. (2012). Marine cloud brightening. *Phil. Trans. R. Soc. A.* 370: 4217–4262: http://doi.org/10.1098/rsta.2012.0086

Lee E., Carrivick J.L., Quincy D., Cook S.J., James W.H.M. & Brown L.E. (2021). Accelerated mass loss of Himalayan glaciers since the Little Ice Age. *Scientific Reports* 11. Dec. 20: https://www.nature.com/articles/s41598-021-03805-8

Lee W., MacMartin D., Visioni D. & Kravitz B. (2020). Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs". *Earth System Dynamics* 11(4):1051–1072: https://doi.org/10.5194/esd-11-1051-2020

Lelieveld J., Peters W., Dentener F. J. & Krol M. C. (2002): Stability of tropospheric hydroxyl chemistry. *Journal of Geophysical Research* 107(D23): https://doi.org/10.1029/2002JD002272

Lenton T. M., Rockström J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H.J. (2019). Climate tipping points – too risky to bet against. *Nature* 575, Nov. 28: https://www.nature.com/articles/d41586-019-03595-0

Li, Q., Meidan, D., Hess, P., Ariel J. A., Cuevas C. A., Doney S., et al. (2023): Global environmental implications of atmospheric methane removal through chlorine-mediated chemistry-climate interactions. *Nat Commun* 14(4045): https://doi.org/10.1038/s41467-023-39794-7

Liley J. B. & McKenzie R. L. (2006) Where on Earth has the highest UV? Conference: UV Radiation and its Effects - an update. *RSNZ Misc Series* 68 36-37: https://www.researchgate.net/publication/255173450_Where_on_Earth_has_the_highest_UV#fullTextFileContent

Lindsey, R. & Dahlman L. (2021). Climate Change: Global Temperature. NOAA. March 15: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

MacCracken M. (2010). SAI restoring Arctic ice field trial proposal for 2015: https://drive.google.com/file/d/1cziCp2wZDHDvrLVAgO04I2dZ9qmfzQgp/view?usp=sharing

MacDougall, A.H., Frölicher, T.L., Chris D.J., Rogelj J., Matthews, H.D., Zickfeld, K., et al. (2020). Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2. *Biogeosciences*, 17(11), 2987–3016: https://doi.org/10.5194/bg-17-2987-202

MacMartin D.G., Visioni D., Kravitz B., Richter J.H., Felgenhauer T., Lee W.R., et al. (2022). Scenarios for modeling solar radiation modification, PNAS. Aug 8: https://doi.org/10.1073/pnas.2202230119

Mallett, R.D.C., Stroeve, J.C., Tsamados, M., Landy, J.C., Willatt, R., Nandan, V., & Liston, G. E. (2021). Faster declineand higher variability in the sea ice thickness of the marginal Arctic seas when accounting for dynamic snow cover. *Cryosphere* 15: 2429–2450: https://journals.ametsoc.org/view/journals/clim/aop/JCLI-D-22-0194.1/JCLI-D-22-0194.1.xml

Manshausen P., Watson-Parris D., Christensen M.W., Jalkanen J., & Stier P. (2022). Invisible ship tracks show large cloud sensitivity to aerosol. *Nature* 610: 101–106: https://www.nature.com/articles/s41586-022-05122-0

McKay D.I.A., Staal A., Abrams J.F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S.E., & et al. Exceeding 1.5°C global warming could trigger multiple climate tipping points (2022). *Science* 377 (6611): https://www.science.org/doi/10.1126/science.abn7950

McKenzie R.L., Bjorn L. O., Bais A. & Ilysad M. (2003). Changes in biologically active ultraviolet radiation reaching the Earth's surface. *Photochemical and Photobiological Sciences* 2 5-15: https://doi.org/10.1039/b211155c

McKuin B., Zumkehra J., Taa R., Balesa J. H., Viersa T., Pathaka J. E.& Campbell B. (2021) Energy and water co-benefits from covering canals with solar panels. *Nature Sustainability* 4: 609–617: https://doi.org/10.1038/s41893-021-00693-8

McSweeney R. (2019). Q&A: How is Arctic warming linked to the 'polar vortex' and other extreme weather? *Carbon Brief*. January 31: https://www.carbonbrief.org/qa-how-is-arctic-warming-linked-to-polar-vortext-other-extreme-weather/

Millstein D.E. & Fischer M.L. (2014). Reflective 'cool' roofs under aerosol-burdened skies: radiative benefits across selected Indian cities. *Environmental Research Letters* 9(10): https://iopscience.iop.org/article/10.1088/1748-9326/9/10/104014

Mims, C. (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/

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): https://doi.org/10.1016/j.apr.2021.02.017

Ming, T., Li W., Yuan Q., Davies P., de Richter R., Peng C., et al. (2022). Perspectives on removal of atmospheric methane. *Advances in Applied Energy*: https://www.sciencedirect.com/science/article/pii/S2666792422000038

MIT. (2020). Mitigating climate change with reflective pavements. CSHub Topic Summary, November: https://cshub.mit.edu/sites/default/files/images/Albedo%201113_0.pdf

Mitchell D. L. & Finnegan W. (2009). Modification of cirrus clouds to reduce global warming. *EnvironmentalResearch Letters* 4(4): https://iopscience.iop.org/article/10.1088/1748-9326/4/4/045102/pdf

Mitchell D. L.,Garnier A., Pelon J. & Erfani E. (2018). 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

Mohawesh O., Albalasmeh A., Deb S., Singh S., Simpson C., AlKafaween N., et al. (2021). Effect of Colored Shading Nets on the Growth and Water Use Efficiency of Sweet Pepper Grown under Semi-arid Conditions. *Hort. Technol.* 32(1): 21-27: https://doi.org/10.21273/HORTTECH04895-21

Munywoki J.N. (2017). Influence of different coloured agronet covers on water use efficiency, insect pest populations, yield and quality of french bean (Phaseolus vulgaris l.) Maters Thesis. Egerton University 2017-05: http://41.89.96.81:8080/xmlui/handle/123456789/1521

National Academy of Sciences (2021). Reflecting sunlight: Recommendations for solar geoengineering research and research governance. Washington, D.C.: The National Academies of Science, Engineering and Medicine: https://nap.nationalacademies.org/catalog/25762/reflecting-sunlight-recommendations-for-solar-geoengineering-research-and-research-governance

NASA. (2011a). Global effects of Mount Pinatubo. June 15: https://earthobservatory.nasa.gov/images/1510/global-effects-of-mount-pinatubo

NASA. (2011b). Paleoclimate record points toward potential rapid climate changes. December 8: https://phys.org/news/2011-12-paleoclimate-potential-rapid-climate.html

NASA. (2023). Vital signs of the planet, ice sheets. July 26: https://climate.nasa.gov/vital-signs/ice-sheets/

National Research Council (2012). Himalayan glaciers: Climate change, water resources, and water security. Washington, DC: *The National Academies Press*: https://doi.org/10.17226/13449

NOAA. (2021). New analysis shows microbial sources fueling rise of atmospheric methane. June 17: https://research.noaa.gov/2021/06/17/new-analysis-shows-microbial-sources-fueling-rise-of-atmospheric-methane/

NOAA. (2023). Carbon cycle greenhouse gasses, trends in CH_4. Global Monitoring Laboratory, Earth System Research Laboratories, July 5: https://gml.noaa.gov/ccgg/trends_ch4/

Oeste, F. D., de Richter R., Ming T. & Caillol S. (2017) Climate engineering by mimicking natural dust climate control. *Earth System Dynamics* 8(1):1–54: https://doi.org/10.5194/esd-8-1-2017

Oeste F. & Elsworth C. (2023). Tropospheric photosensitive aerosols for climate cooling ("Climate catalysts"). September: https://drive.google.com/file/d/1WbHhGQMlW7LlRsC1zGNbwdQ-gSlPqAfd/view?usp=drive_link

Oleson K.W., Bonan G. B., Feddema J (2010). Effects of white roofs on urban temperature in a global climate model. *Geophysical Research Letters*. February 3: https://doi.org/10.1029/2009GL042194

Oschlies A., Pahlow M., Yool A. & Matear R.J. (2010). Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters* 37(4): https://doi.org/10.1029/2009GL041961

Ortiz-Bobea A., Wang H., Carrrilo M.C. & Ault T.R. (2019) Unpacking the climatic drivers of US agricultural yields. *Environmental Research Letters* 14(6): https://iopscience.iop.org/article/10.1088/1748-9326/ab1e75/ampdf

Pearce R., Prater T & Goodman J. (2022). Mapped: How climate change affects extreme weather around the world. *Carbon Brief*. August 4: https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/

Piao S., Wang X., Park T., Chen C., Lian X., He Y., et al. (2019). Characteristics, drivers and feedbacks of global greening. *Nature Reviews Earth and Environment* 1: 14–27: https://doi.org/10.1038/s43017-019-0001-x

Pistone K., Eisenman I. & Ramanathan V. (2019) Radiative heating of an ice-free Arctic ocean. *Geophysical ResearchLetters* 46(13):7474–7480: https://doi.org/10.1029/2019GL082914

Quaglia I., Visioni D., Pitari G. & Kravitz B. (2021) An approach to sulfate geoengineering with surface emissions of carbonylsulfide. *Atmospheric Chemistry and Physics* 22(9): https://acp.copernicus.org/articles/22/5757/2022 /

Rantanen M., Karpechko A.Y., Lippone A., Nordling K., Hyvärinen O., Ruosteenoja K., et al. (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

Rohrer F. & Berresheim H. (2006) Strong correlation between levels of tropospheric hydroxyl radicals and solar ultraviolet radiation. *Nature* 442(13): https://doi.org/10.1038/nature04924

Rau, G. & Baird J.R. (2018) Negative-CO2-emissions ocean thermal energy conversion. *Renewable and Sustainable Energy Reviews* 95:265-272: https://doi.org/10.1016/j.rser.2018.07.027

Samset B.H., Sand M., Smith C.J., Bauer S.E., Forster P.M., Fuglestvedt J.S., et al. (2018) Climate impacts from a removal of anthropogenic aerosol emissions. *Geophysical Research Letters* (45)2: 1020–1029: https://doi.org/10.1002/2017GL076079

Schuckmann, K. V., Cheng L., Palmer M.D., Hansen J., Tassone C., Aich V., et al. (2020). Heat stored in the earth system. *Earth System Sci.* 12(3): 2013-2041: https://doi.org/10.5194/essd-12-2013-2020

Seneviratne S.I., Phipps S.J., Pitman, A.J., Hirsch A.L., Davin E.L., Donat M.G. et al. (2018). Land radiative management as contributor to regional-scale climate adaptation and mitigation. *Nature Geoscience* 11: 88–96: https://doi.org/10.1038/s41561-017-0057-5

Seitz, R. (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

Simons, L., Hansen J.E. & Dufour Y. (2021) Climate impact of decreasing atmospheric sulphate aerosols and the risk of a termination shock. Annual Aerosol Science Conference, Nov.: https://www.columbia.edu/~jeh1/Documents/Simons.2021.RiskOfATerminationShockAerosolConference.pdf

Smith W. (2020). The cost of stratospheric aerosol injection through 2100. *Environ. Res. Lett.* 15(114004): https://iopscience.iop.org/article/10.1088/1748-9326/aba7e7

Smith W., Bhattarai U., MacMartin D.G., Lee W.R., Visioni D., Kravitz B., et al. (2022). A subpolar-focused stratospheric aerosol injection deployment scenario. *Environ. Res. Commun.* 4(095009): https://doi.org/10.1088/2515-7620/ac8cd3

Steven J.D., Smith N., Groppi C., Vargas P., Jackson R., Kalyaan A., et al. (2017). Arctic ice management. *Earth's Future* 5(1): 107–127: https://doi.org/10.1002/2016EF000410

Thompson A.M, Calvin K.V., Smith S.J., Kyle G.P., Volke A., Patel P., et al. (2011). RCP 4.5: A pathway for stabilization of radiative forcing by 2100. *Climate Change* 109(77): https://doi.org/10.1007/s10584-011-0151-4

Trlica A., Hutyra L.R., Schaaf C.L., Reb A., Wang A. (2017). Albedo, land cover, and daytime surface temperature variation across an urbanized landscape. *Earth's Future* 5(11): 1084-1101: https://doi.org/10.1002/2017EF000569

Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds. *J. Atmos. Sci.* 34(7): 1149–1152: https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2

van Herpen, M. M J W., Li Q., Saiz-Lopez A., Liisberg J. B., Rockmann T. , Cuevas C. A., et al. (2023). Photocatalytic chlorine atom production on mineral dust–sea spray aerosols over the North Atlantic. *Proc Natl Acad Sci USA* Aug. 120(31) e2303974120: https://doi.org/10.1073/pnas.2303974120

doi: 10.1073/pnas.2303974120Wait L. (2021). Planting forests may cool the planet more than thought. Princeton University High Meadows Environmental Institute. Aug. 9: https://engineering.princeton.edu/news/2021/08/09/planting-forests-may-cool-planet-more-thought

Wang T., Stewart C.E., Sun C., Wang Y. & Zheng J. (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

Weaver C. J., Wu D. L., Bhartia P. K., Labow G. J. & Haffner D. P. (2020). A long-term cloud albedo data record since 1980 from UV satellite sensors. *Remote Sensing* 12(1982): https://doi.org/10.3390/rs12121982

Wittmer J., Bleicher S., Ofner J. & Zetzsch C. (2015). Iron(III)-induced activation of chloride from artificial sea-salt aerosol. *Environmental Chemistry* 12(4) 461-475: https://doi.org/10.1071/EN14279

Wittmer J. & Zetzsch C. (2017). Photochemical activation of chlorine by iron-oxide aerosol. *Journal of Atmospheric Chemistry* 74(2) 187-204: https://doi.org/10.1007/s10874-016-9336-6

Wild M., Foloni D., Habuka M. Schar C., Senevirantne S.I., Kato S., et al. (2015). The energy balance over land and oceans: an assessment based on direct observations and CMIP5 climate models. *Climate Dynamics* 44: 3393-3429: https://doi.org/10.1007/s00382-014-2430-z

WMO. (2022). May 9: https://public.wmo.int/en/media/press-release/wmo-update-5050-chance-of-global-temperature-temporarily-reaching-15%C2%B0c-threshold

Zhang Q., Bi G., Li T., Wang Q., Xing Q., LeCompte J. & Harkess R.L. (2022). Color shade nets affect plant growth and seasonal leaf quality of Camellia sinensis grown in Mississippi, the United States. *Frontiers in Nutrition* 9: 786-421: https://doi.org/10.3389/fnut.2022.786421

Zhou C., Zelinka M.D., Dressler A.E. & Wang M. (2021) Greater committed warming after accounting for the pattern effect. *Nature Climate Change* 11, Feb: https://doi.org/10.1038/s41558-020-00955-x

Zuraiqi K., Zavabeti A., Clarke-Hannaford J., Murdoch B. J., Shah K., Spencer M. J. et al. (2022). Direct conversion of CO2 to solid carbon by Ga-based liquid metals. *Energy & Environmental Science*: https://doi.org/10.1039/D1EE03283F