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Addressing the Urgent Need for Direct Climate Cooling: Rationale and Options

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Key Points

- Global warming will continue to accelerate, and its detrimental impacts become more severe during the 21st century until increases in the warming influences are eliminated, which, to be substantially accomplished during the 21st century, will require deliberate action to cool the planet.
- Direct climate cooling approaches, while needing further research to varying degrees, have the potential to offset local and global warming influences, thus lowering the rate and magnitude of temperature increase overall.
- Because greenhouse gas (GHG) emission reduction and removal alone will not halt warming for many decades, much less begin a return to the 20th century conditions that have proved generally beneficial for the environment and society, one or more of three near-term globally-scalable solar radiation modification (SRM) direct climate cooling (DCC) approaches, supplemented as needed by an assortment of regional and locally-scalable SRM and thermal radiation modification (TRM) DCC approaches drawn from among the fourteen discussed in this paper and perhaps others, merit consideration for early deployment to prevent the ongoing intensification of extreme impacts.

Abstract

Emissions reduction and removal are not proceeding at a pace that will limit global average warming to less than the Paris Agreement targets of 1.5°C or 2.0°C. Accelerating global warming is indicated by record high 2023-24 monthly temperatures and annual 2023 global mean surface temperatures around 1.5°C above pre-industrial levels. Only direct climate cooling has the potential to avert continued temperature rise in the near term and moderate at least some projected climate change disruption including extreme weather, sea level rise, loss of sea ice, glacier and permafrost melting, and coral reef die-off. Strategically deployed at scale, starting in the near term, several cooling measures have the potential to reduce or reverse global warming. Others can exert local or regional cooling influences. The world needs an approach to climate change that extends beyond sole reliance on emission reductions and removal. We propose a) researching, field testing and deploying one or more large-scale cooling influence(s) perhaps in polar regions and applying local and regional cooling measures that also support adaptation, b) accelerating emissions reductions with an early prioritization of short-lived climate drivers, and c) deploying large scale carbon removal to draw down legacy greenhouse gas. The authors make no attempt to determine what measures or mix of measures is

optimal. That will depend on modeling and experimentation. Only by including properly researched emergency cooling "tourniquets," in the near-term to our "bleeding" Earth can we slow and then reverse ongoing and increasingly severe climate change in the 21st Century.

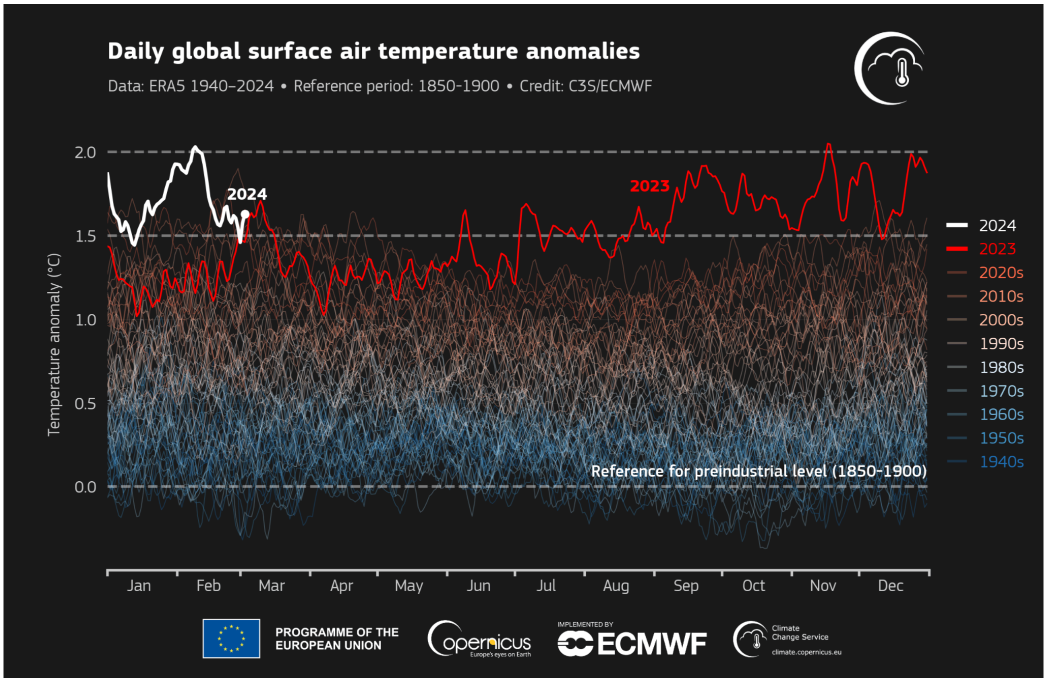
Plain Language Summary

Climate change has already caused enormous damage and elevated the risk of catastrophic harm to humans, ecosystems, the global economy, and international security. An increasing number of direct climate cooling (DCC) approaches have the potential to moderate at least some of the projected disruption when applied at scales ranging from local to global. Without deployment of at least some of the cited cooling approaches, the multi-decade average temperature increase will soon exceed the 1.5°C or 2.0°C limits agreed to in the Paris Accord in 2015. The 2023 exceedance of 1.5°C is already a clear indication of urgency. On a global scale, restoring the relatively beneficial climatic conditions of the 20th Century will require a restoration plan to return global warming to well below 1°C. To be effective, such a plan would need to include a) researching, field testing, and deploying one or more large-scale cooling influence(s) perhaps initially in polar regions and applying local and regional cooling measures that also support adaptation, b) accelerating emissions reductions with an early prioritization of short-lived climate-drivers, and c) deploying large scale carbon removal to draw down legacy greenhouse gas. Only by applying emergency cooling "tourniquets" to our critically injured Earth will there be a near-term possibility to limit the worst climate disruption while emissions reduction and removal take effect over the long-term. As approaches may be selected and implemented in a wide variety of ways, locations, times, and intensities, no attempt has been made here to determine what mix is optimal. That will depend on modeling, experimentation and learning by doing.

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, much less forge a pathway toward net zero emissions [1]. As a result, there has been no progress in reversing the increasing occurrence and intensity of climate-change induced impacts. With the pace of global warming increasing [2], model calculations made several years ago suggested that net zero emissions must be achieved no later than 2050 to limit global warming to 1.5°C, or by 2070 to limit global warming to 2.0°C. These are the values called for in the Paris Agreement to avoid "dangerous anthropogenic interference in the climate system" [3](Table SPM.2)[4]. The first step proposed by IPCC in the path intended to limit warming is reducing global emissions by 43% from 2022 to 2030. Nonetheless, global emissions continue to increase. Record breaking 2023 (see figure 1) and January 2024 monthly [5] global mean surface temperatures, and a 2023 annual average global mean surface temperature of 1.36°C - 1.48°C [6,7] above pre-industrial (1850 - 1900), suggest that impacts like those already occurring and producing significant loss and damage and loss, will, in the absence of urgently applied and effective direct climate cooling, continue to worsen, causing much disruption and destruction. For example, a 2024 report on 'billion-dollar' (inflation adjusted) climate and weather disasters in the US shows a steady increase in such disasters: 33 costing a total of $217.3 billion in the decade of the 1980s, 57 costing $331.4 billion in the 1990s, 67 costing $615.5 in the 2000s and 131 totaling $985.8 billion in the 2010s [8].

Figure 1: Daily global average surface air temperature anomalies (°C) relative to estimated values for 1850-1900 plotted as time series for each year from 1 January 1940 to 3 March 2024. The year 2024 is shown with a thick white line, the year 2023 with a thick red line. Other years are shown with thin lines and shaded according to the decade, from blue (1940s) to brick red (2020s). Dashed horizontal lines highlight the 1850–1900 reference and 1.5°C and 2°C above this reference.



Source: ERA5. Credit: C3S/ECMWF.
https://climate.copernicus.eu/copernicus-february-2024-was-globally-warmest-record-global-sea-surface-temperatures-record-high

An increasing number of indicators suggest that no plausible cutback in emissions will be sufficient to keep warming below levels that could trigger very disruptive tipping points [9,10]. For example, the Greenland and Himalayan melt rates are strong indicators of accelerated warming that would in turn lead to more frequent and severe climate calamities. More rapid loss of glacial ice in all three poles (i.e., including the Himalayas) is accelerating the rate of sea level rise. Polar warming is also triggering a change in the mid-latitude atmospheric circulation that is leading to an increasing incidence of extreme weather, fundamental disruption of natural systems, and a high risk that major critical tipping points will be overstepped to a state beyond repair.

However, such an irreversible outcome is not yet inevitable. Limiting global warming with one or more direct global-scale climate cooling influences while also moderating the worst impacts using one or more of the regional cooling influences (commonly referred to as 'geoengineering') might well reduce the likelihood and severity of destructive climate calamities over the next few decades. This would give emissions reduction and removal time to achieve net-zero and then net negative levels, lowering CO2 and other greenhouse gas concentrations in the atmosphere to the habitable levels of the 20th Century. Deploying cooling influences to limit global warming, especially peak global warming, would reduce stresses on ecosystems, thus helping to reinvigorate the natural environment over the longer term [11].

Despite recognition that potential cooling approaches exist, research and considerations of deployment of direct climate cooling, whether localized or global, co-deployed or not, have been held back by several opposing arguments [12].[1] A primary argument has been that pursuing such approaches constitutes a "moral hazard" because implementation might well slow GHG emissions mitigation efforts. However, the claim of "moral hazard" was for

[1] Others, while not directly opposing DCC deployment, have suggested numerous checkpoints that do not seem to take into account the risk-risk tradeoff of excessively delaying deployment [13]. See section 6 for further discussion.

example applied to climate adaptation as a substitute for mitigation before climate impacts became more severe [14], and there appears to be little solid evidence for this when applied to "direct climate cooling" (DCC) [15]. Now that costs for renewable energy have fallen below the costs of fossil-fuel energy this argument appears to have turned on its head as markets have begun to favor renewables, but global GHG emissions are still increasing. The real "moral hazard" is the failure to pursue cooling approaches that can reduce ecological and human disasters and costs. Another concern expressed is that cooling technologies could have severe unanticipated consequences, although increasingly detailed climate modeling has not supported this speculation [16]. Finally, some climate cooling opponents argue that though cooling influences may be beneficial for a while, were they to be stopped for some reason, the climate would warm up relatively quickly resulting in "termination shock" and worse impacts than if the cooling influences had not been deployed at all.

Against the termination shock hypothesis, projected costs and challenges of maintaining cooling influences, when compared to GHG removal, are much less than other approaches to limiting warming. Responsible global actions would require continuance of direct cooling given the severe consequences of not doing so. In the face of these concerns, equitable and responsible global governance of cooling approaches will be crucial. The Montreal Protocol success in repairing the ozone layer suggests this is possible over an extended term [17,18]. However, the level of impact has now been allowed to increase so much that adaptation is becoming critical. Climate restoration measures to mitigate the increasing threats to global sustainability and governance must be stronger than the UNFCCC has endorsed [19].[2]

The needed governance for comprehensively limiting global warming is not yet in place. This is suggested by the failure to consider the climatic effects of the 2020 International Maritime Organization (IMO) regulations aimed at reducing sulfur emissions from the "bunker fuel" used to power cargo ships to protect public health.

Observations of accelerated warming estimate that the regulations have unintentionally triggered rapid global warming of 0.1-1.0 W/m^2 not unlike the suggested 'termination shock' [2,21–25]. Considering that recent (i.e., January 2020 - June 2023) CERES data on the total Earth Energy Imbalance, or total excess energy from the sun absorbed by the earth, averages 1.37 W/m^2 compared an earlier (Jan 2015 to Dec. 2019) average of 1.12 W/m^2, all of these estimates suggest that a significant global heating impact has resulted from the regulations, as there are no other indications of such a large positive forcing [2,22,26]. This sudden warming should lead to IMO and governments coming together to respond to the problem by assessing relevant direct cooling influences as proposed in [23].

A further concern regarding the potential deployment of cooling influences has been whether there are means to verify their performance before proceeding beyond very limited deployment. For most of the proposed cooling approaches described in this paper, pilot testing would have only local and transitory effects and could be conducted transparently under local to national governance without requiring special approval and oversight by international governance bodies. Global climate models and other methods that simulate the climatic responses to both natural and human-induced forcings make it possible in many cases to evaluate major potential impacts on the atmosphere, oceans, and biosphere of the various types of cooling influences with reasonable confidence. Unfortunately, sufficient research funds have yet to be provided for many of the proposed approaches even though the cost would be very small compared to the likely benefits their deployment would deliver [27].

[2] By these statements regarding the governance problem of achieving rapid and at-scale emissions reductions, we do not mean to suggest that, particularly global-scale, DCC implementation and governance is not a challenge. Rather, using SAI as an example, it poses a different kind of governance challenge, having less to do with overcoming a costly resource intensive free-rider public good problem, and more to do with transparency and public trust for a very inexpensive, almost "free-driver", global leverage problem [20]. See further discussion in Section 6.

Concerns represented in opposing arguments need to be addressed in any program advancing direct climate cooling, as discussed further in Section 6 of this paper. However, the reality of accelerated warming, more intense catastrophic events and ever-increasing damage and loss has not enabled overall reduction in GHG emissions, much less support for a comprehensive research and demonstration effort focused on possible cooling approaches. The moral hazard no longer lies in researching and deploying climate cooling approaches, but now in the failure to explore all feasible approaches to reduce near-term global warming. How best to proceed can only be settled by a 'risk-risk approach', comparing, and contrasting the possible risks of outcomes in which climate cooling approaches are applied against those that lie ahead if directly cooling the climate is not pursued [2].

Many of the climate cooling approaches are low-tech and can be responsibly deployed at local to regional scales with few, if any, potential risks and often, many co-benefits. Similarly, various of the global-scale approaches can be tested and implemented at low intensity using an 'apply, evaluate, adjust' sequencing because their effects are readily reversible if unexpected, potentially deleterious consequences arise. Climate change and especially polar amplification, or disproportionate warming of polar regions relative to mid-latitudes, have already caused enormous damage. Further loss of sea ice and particularly of glacial ice seem likely to accelerate the risk of catastrophic impacts worldwide.

This paper describes more than a dozen potential direct climate cooling approaches that merit initial consideration. More approaches, including variants of those presented here, continue to emerge. The summaries of the approaches that follow have been prepared primarily by those who are currently researching or promoting them. They are listed here in alphabetical order rather than, at this point, seeking to group them by metrics or qualitative characteristics (see section 5, tables 1 and 2). They are:

- Afforestation, Reforestation, and Soil and Vegetation Restoration (ARSVR)
- Buoyant Flakes
- Cirrus cloud thinning (CCT)
- Fizz Tops (Fiztops)
- Ice shields to thicken polar ice
- Marine Cloud Brightening (MCB)
- Mirrors for Earth's Energy Rebalancing (MEER)
- Mixed-phase Cloud Thinning (MCT)
- Ocean Thermal Energy Conversion (OTEC)
- Seawater atomization (Seatomizers)
- Stratospheric Aerosol Injection (SAI)
- Surface Albedo Modification of Ice and Snow
- Tree planting and reflective materials
- Tropospheric Aerosol Injection (TAI)

We do not claim that this is an exhaustive list of all possible cooling approaches. For example, we have not included a summary of potential space-based DCC approaches that proponents suggest "be seriously considered in the long term" [28] (Abstract) rather than the near-term (next few decades) time-period during which we believe DCC is urgently necessary.[3]

With GHG emission reduction and removal proceeding at insufficient pace or scale to effectively keep warming below 1.5°C, 2.0°C or higher, we believe it is essential that direct climate cooling be added to the frontal set of policy options being considered by international negotiators and national governments. While GHG emissions reduction and removal

[3] Other examples are the sixty-one mostly geophysical 'climate intervention' approaches listed in [29], with some overlap with our paper but with a specific Arctic region focus rather than urgent *global* DCC.

may have the potential to achieve net-zero emissions in the second half of the 21st century and, over time, to reduce GHG concentrations, direct cooling options provide the only way to impel global warming back toward 1°C and below before even more key tipping points are passed.[4]

A credible and effective plan to restore the relatively beneficial climatic conditions of the 20th century would require that negotiators develop a three-component strategy: a) researching, field testing, and deploying one or more large-scale cooling influence(s) perhaps initially in polar regions and applying local and regional cooling measures that also support adaptation, b) accelerating emissions reductions with an early prioritization of short-lived climate drivers[5], and c) deploying large scale carbon removal to draw down legacy greenhouse gas.

Humanity has never faced an existential threat so critical to the survival of civilization and our fellow living species on this planet. Over at least the next several decades, and possibly much longer, direct cooling influences will be needed to keep climate change and its especially severe adverse impacts from spiraling out of control. Only the application of such emergency cooling "tourniquets," applied as soon as reasonably feasible in a evaluating/learning/adjusting strategy, has the potential to slow or reverse ongoing climate disruption and avoid crossing critical tipping points of no return over coming decades.

The following sections address five key issues: Section 2, the inadequacy of the global warming metric for portraying to the public and decision makers the urgency and severity of the current situation; Section 3, the risks of not immediately slowing and then reversing the pace of climate change; Section 4, the potential benefits of adding direct cooling technologies to the policy mix; Section 5, an overview of a representative set of approaches for direct climate cooling and Section 6, challenges and opportunities for coordination, governance and deployment' Section 7, a further discussion of objections to and possibilities for adding approaches for direct climate cooling to the international strategy for climate restoration. Conclusions are presented in Section 8.

2. The Need for COP Policy to Reach Beyond Averaged Global Warming Metric and Net-Zero Emissions

The IPCC "Average Global Warming" metric, central to setting and publicizing policies dealing with climate change, is inadequate and misleading. Defined as "an increase in combined surface air and sea surface temperatures averaged over the globe and over a 30-year period," the metric yields an approximation to global average temperature increase that is time-lagged by a decade behind the current level of warming [30]. This smoothing of data aims to provide a scientifically rigorous metric for determining when the Paris Accord peak-temperature goals are exceeded. However, by suppressing variability the metric defers recognizing essential thresholds that would indicate crossing of tipping points [10].

Though useful as a summary metric (as in figure 1), the Average Global Warming metric fails to convey the significance of the warming taking place in real time or reveal regionally important vulnerabilities. The oceans, which cover 71% of the Earth's surface, have a very large heat capacity that keeps its average warming well below the increase occurring over land surfaces. Averaging ocean and land surface temperatures together understates the rapidly increasing impacts on people and the terrestrial biosphere [31].

In the Northern Hemisphere's high latitudes, polar amplification is resulting in warming that is more than three times the global average, accelerating permafrost thawing, loss of sea ice, and loss of mass from the Greenland ice sheet

[4] The rationale for a global warming threshold of 1°C is discussed at the end of section 3.
[5] Net human emissions must be cut to zero, global warming induced increases in natural emissions must be offset with negative human emissions and over a trillion tons of legacy CO2eq GHG of *all* types that has *accumulated* in the atmosphere and oceans removed, to restore a stable climate not counting already triggered irreversible feedbacks that may continue for centuries [11] (footnote 9) [2]. However, as the *rate of emissions* of short-lived GHG such as methane is *directly* correlated with warming these should be prioritized to urgently achieve DCC.

[32]. In mid-latitudes, measures of the increases in extreme precipitation and duration of heat waves would better characterize the pace and significance of weather disruption [33]. The heat and discomfort index is a much more appropriate metric for indicating the significance of global warming in hot, humid regions [34]. Extremes in precipitation can cause the worst impacts on those living in wet, tropical regions where increased ocean evaporation leads to more intense rain and flooding [35]. Current events and observations are making it clear that short-term weather extremes [36] are increasing at a rate far faster than the slowly rising multi-decadal average of the global temperature increases.

Use of the global average warming metric, even with projections out to 2100, provides no direct insight into the ongoing and committed amounts of sea level rise. Paleoclimatic analyses suggest an equilibrium sea level sensitivity exceeding 12 meters per degree change in global average temperature [37]. The present rate of warming is at least 10 times greater than the average during the multi-millennial deglaciation following the Last Glacial Maximum. Sea level rise then averaged more than a meter per century for 100 centuries while the average temperature in Antarctica was rising at an average rate of one degree every 10 centuries [38].

The IPCC assurances that the rise in sea level by 2100 would be less than a meter [39] are questionable given the destabilization and increasing rate of flow of glacial streams from the Greenland and Antarctica ice sheets [40]. Geological evidence makes clear that ice sheet decay occurs much more rapidly than ice sheet formation and that melting is very hard to stop once it starts [41]. NOAA estimates in a 2021 technical report that even if net-zero GHG emissions were rapidly achieved, sea level rise along the US coast by 2100 would exceed half a meter [42], threatening destruction of all low-lying infrastructure. There is virtually no public understanding of committed future sea level rise and the impacts it will have on future generations [43].

The scientific community may view the global average warming metric, properly interpreted, as a suitable public and policy surrogate for climate change, but its use leaves many members of the public, most business leaders, and many lawmakers ill-informed about the urgency of effective climate action. Most citizens, and even political leaders, do not have access to expert climate advisors. A variety of more meaningful metrics and a revised approach to communicating the urgency of incorporating credible cooling research and responsible deployment into global climate change policy are needed.

3. The Risks of Not Slowing the Pace of Global Climate Change

Greatly complicating the risk is that the warming to date, officially recognized as about half of 2.5°C (1.18°C for 2023) is already starting to trigger natural positive feedbacks and pass tipping points [44]. These impacts are likely to outweigh the progress current policy approaches envision, progress that is failing to materialize as many nations lag behind in implementing their National Determined Contributions [9,10,45]. Even achieving net-zero emissions is not enough. As defined by the IPCC [46], "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 where the natural emissions and uptake rates of greenhouse gases holding constant or GHG removal measures could be easily scaled up. They are not. GHG removal sufficient to achieve cooling would require large net negative emissions that will take many decades to achieve while the world heats up [47] [11] (footnote 9).

The internationally proposed goal is to reach net-zero emissions early in the second half of the 21st century. The expectation is that this will stop further global warming and associated climate change. However, fossil fuels still supply about 80% of global energy needs [48] and global emissions are still rising despite the increasing deployment of solar, wind and other renewables. If emission reduction alone is the only policy approach, the time it is likely to take to replace the present fleets of automobiles, trucks, airplanes, trains, heating and industrial systems, power plants, and more will result in global emissions that could raise annual global average temperature to well above 2.5 C above the pre-industrial level making some tropical areas virtually unlivable and committing the world to tens of meters of sea level rise over coming centuries [2] (figures 24 and 31) [11] (Section 1) [19] (Sections 4-5).

The Earth's natural carbon cycle is already being altered. The Arctic and the Amazon basin have shifted from being natural sinks of CO_2 to natural sources [49,50]. The thawing of permafrost, warming of coastal sediments, ongoing forest conversion to farmland, increased occurrence of wildfires, and more are reducing natural carbon uptake and storage by the terrestrial biosphere and contributing to natural emissions.

Atmospheric methane concentrations are now almost three times higher than they were pre-industrially. NOAA analyses are showing a super-linear increase in methane emissions year over year that, based on stable isotope studies, has a biogenic origin, suggesting proximity to a potential Boreal Permafrost Collapse methane releasing tipping point that could lead to an increasingly strong warming influence [9,51–53].

Ocean carbon uptake is also being affected. The Atlantic Meridional Overturning Circulation (AMOC), which carries CO_2 taken up by the ocean from the surface to ocean depths, is showing indications of slowing and even potentially collapsing in coming decades [54,55]. If less ocean water is going down, as the ocean becomes more stratified, there will be less nutrient-carrying ocean water coming up. The reduction in nutrients will reduce the biological activity and biomass in the upper ocean that play a role in transferring carbon absorbed from the atmosphere to ocean depths. A collapse of AMOC would lead to large and relatively rapid declines in temperatures in Europe, as the warming now provided by the Gulf Stream would be removed [56].

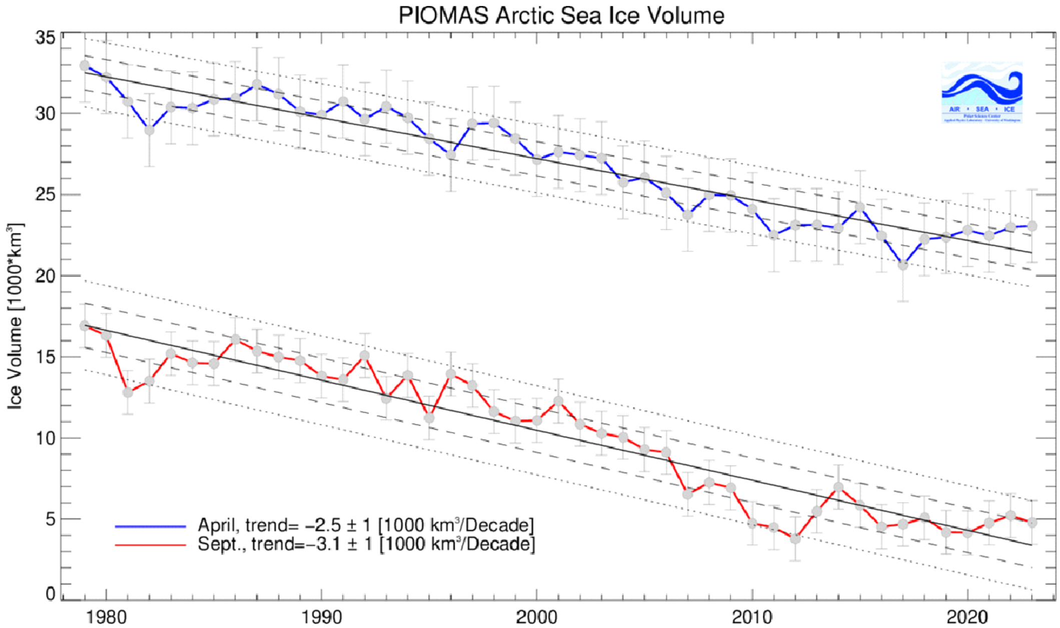
By the time human-induced emissions could possibly reach zero, human-induced climate change will have altered the global carbon cycle so much that net natural terrestrial emissions will have increased and net carbon transfer to ocean depths reduced. Both results will contribute to increasing atmospheric CO_2 concentration.

As emissions reduction efforts fail to limit global warming to less than 1.5°C and natural systems' capacity to take up carbon declines, researchers and policymakers are giving increasing attention to carbon dioxide removal (CDR). Approaches considered include reforestation and afforestation, enhanced rock weathering, ocean fertilizing, and direct air capture [11]. The costs of aggressively implementing CDR would be far less than the prospective costs of impacts from not doing so. However, counterbalancing both stubborn-to-eliminate anthropogenic and increasing natural emissions with human-generated negative emissions of CDR will be very challenging given the magnitudes of the carbon fluxes involved [2](p. 25 and figures 24 and 31).

Not only is the natural carbon cycle being activated by human-induced climate change in ways that will make it more difficult for policymakers to bring an end to increasing climate disruption, but also, the human-induced warming is threatening to pass climatically powerful tipping points and directly alter the global energy balance [9,10]. As one example, the planet is poised to begin crossing the critical 'Arctic summer sea ice melting' tipping point. In addition to year-round thinning, as shown in Figure 2, the Arctic Ocean is projected to become ice-free during the entire month of September within the next two decades.

The current degree of sea ice melting indicates that there will be increasingly less ice cover sustained through the summer and that melting will begin earlier each summer. As sea ice melts, Arctic surface albedo is diminished, and much greater solar radiation is absorbed in the summer.

Figure 2: 1979-2023 Monthly Sea Ice Volume from PIOMAS for April and September



Source:
http://psc.apl.uw.edu/wordpress/wp-content/uploads/schweiger/ice_volume/BPIOMASIceVolumeAprSepCurrent.png.
Downloaded 3/13/2024 from the Polar Science Center, Applied Physics Laboratory, University of Washington, USA.

Estimates from multiple studies using different data and methodologies suggest that earlier surface melting and ice thinning and loss will lead to an increase in global radiative forcing, from 1979 to an ice-free Arctic, of 0.65 - 0.825 W/m^2. This is equivalent to the warming effect of roughly 20 years of GHG emissions of 40 GT CO_2eq/yr [57] [11](footnote 6) [58–60]. Model simulations showed rapid retreat of sea ice, however, Pistone et al. [57] found that observed Arctic Ocean sea-ice retreat per degree of global warming was roughly twice as fast as calculated by the CMIP Phase 5 suite of models. No model simulated as much reduction in sea ice cover as the actual observations were showing.

More recently, Mallet et al. [61] found that from 2002 to 2018 Arctic Ocean Sea ice has thinned 60% more than climate models are estimating. Heuze et al. [62]found that newer climate models with improved parameterizations are continuing to underestimate Arctic sea-ice loss, perhaps because they do not adequately account for storm contributions to ice fractionation and melting. These accelerating melt observations suggest that a tipping point beyond which cryosphere loss may amplify further with cascading implications may be close to being, or already has been, passed.

Combined with the warming influence of rising CO_2 concentration and water vapor feedback, the warming influence of ice-albedo feedback led to a warming in the high northern latitudes from 1979 to 2021 that was nearly four times greater than the warming indicated by the increase in the global average surface temperature [32,63,64]. Disproportionate warming is also affecting Antarctica and the Himalayan 'pole' at the top of the world, which is a critical source of water for 2 billion people [65–67]. Amplified warming is accelerating loss of mass and destabilization of glacial ice streams in Greenland and Antarctica, releasing freshwater to neighboring ocean waters that increases ocean stratification and is starting to alter oceanic circulation [54].

The multi-decade average of the global average temperature has increased relatively slowly, and yet, there has been a rapid acceleration of short-term global weather disasters. A 2021 report by Christian Aid found that the six years with the costliest (over $100 billion) climate disasters have all occurred since 2011. A *Wall Street Journal* article noted that bad weather was 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 [68,69]. A 2020 International Monetary Fund report estimated that direct damage from climate disasters from 2010 to 2019 was about $1.3 trillion, or roughly 0.2% of world GDP per year [70]. This is about 6.3% of average 2010-2019 world GDP growth of 3.15 % per year during this period [71].[6]

Hansen et al. have extended their analysis of the likelihood of extremely hot summers on Northern Hemisphere land areas. They found that the likelihood of extremely low probability (three-sigma or greater) extremes in the mid-20th century has increased over two-hundred-fold (by a factor of 221) and that extreme warmth that would have been virtually impossibly improbable (six-sigma) events in the mid-20th century are now starting to occur [72](figure 1).

As noted above, the officially reported global average warming metric is about 1.18°C [44]. Given that (as of December 2023) projections based on current national policies, targets and pledges, are for roughly a doubling of warming to 2.1°C - 2.7°C by 2100, catastrophe seems inevitable [73,74].

Moreover, current policy focuses on mitigation that limits peak warming in the long term and ignores the possibility of returning to less than 1.0°C of warming as was experienced in the mid-20th century.[7] And yet, a goal of limiting global warming to below 1.0°C seems prudent. We are seeing evermore frequent and severe extreme climate events at current global average warming of roughly 1.2°C. Recent assessments conclude global warming of ~1.1°C is within the lower end of five critical climate tipping point uncertainty ranges, and that six, and possibly ten are likely to be passed at 1.5°C - 2.0°C of global warming including Greenland and West Antarctic ice sheet collapse, low-latitude coral reefs die offs, and widespread abrupt permafrost thaw [9] (Structured Abstract).

Even if accompanied by drawing down carbon dioxide and reducing short-lived GHG emissions such as methane whose rate of emission (rather than accumulated stock of emissions as with long-lived GHG emissions like CO_2) is directly correlated with warming [75,76], the mitigation-only policy offers little likelihood of achieving a stabilized climate in the 21st Century that we can pass on with pride rather than remorse to future generations.

4. The Potential Benefits of Adding Direct Cooling Technologies to the Policy Mix

Emissions reduction and carbon removal policies have yet to propel global GHG emissions onto a downward trajectory, much less onto a credible path to net-zero emissions. To the contrary, with anthropogenic and natural GHG emissions continuing to increase and global warming accelerating, catastrophic consequences lie ahead. This will be the case especially if global tipping points are triggered that make even 100% emissions reductions unable to halt warming and influence a return to pre-industrial temperature and carbon concentration levels.

Waiting a century and more for these policies to become effective is not the only option. Adding deployment of direct cooling technologies to the suite of climate change policies has the potential to counterbalance at least some of the ongoing warming and to moderate the worst impacts of global warming. This will make it easier to implement a greater array of effective adaptation and resilience measures at a lower cost. Without stabilizing and then reducing global warming, tipping points will likely be crossed and climate disruption and associated environmental and societal

[6] As noted in the introduction, at least for the US, decadal average loss and damage from climate change grew faster than GDP growth over this period. Inflation adjusted loss and damage from climate change grew from $217.3 billion over the decade of the 80s, to $331.4 billion over the decade of the 90s, a decadal average increase of 52.5% that is greater than the 32.1% produced by real GDP growth of 3.15% per year compounded over ten years [8].

[7] We are, of necessity, using the IPCC's global average warming metric here as currently both climate policy targets and tipping-point research are framed around it. Our point in section 2 is not that the average global warming measure is always useless, but that it is overused.

impacts will undoubtedly further intensify, at least until net-zero global GHG emissions are achieved and legacy GHGs are removed and permanently sequestered [9]. Even with urgent DCC deployment some tipping point risks may not be reduced [77].

Recent modeling suggests that, in the absence of direct climate cooling, if net-zero emissions for both anthropogenic and natural emissions can be achieved by the time total emissions reach 1000 GtC (i.e., about 3700 $GtCO_2eq$), global warming would remain at roughly 2.0° C for most of the rest of the century due to continued rebalancing of atmosphere-ocean heating and ocean uptake of legacy CO_2 from the atmosphere [78,79]. With cumulative anthropogenic 1850 - 2021 world GHG emissions estimated at about 3,390.7 GTCO2eq [48], already nearly totaling this amount, a combination of continued direct climate cooling and drawdown of legacy GHG would be necessary to expeditiously restore a stable climate that exerts much less stress on global ecosystems [47] [11] (footnote 9). As cumulative emissions continue past the 1000 GtC mark, as seems inevitable, overall impacts and the incidence of catastrophic extremes will continue to increase unless an even stronger application of direct cooling approaches is targeted more effectively to counterbalance the additional warming. Thus, even when net-zero is achieved, it appears that DCC may be necessary along with intensive CDR and ecological regeneration to permanently restore a healthy planet [19].

Assertions that the risks of trying to cool the climate, regardless of the approach, will always be greater than the risk of not attempting to do so, do not appear to be supported by any of the proposed moderate and balanced applications of our DCC approaches. Moreover, projections of the relative risks of deploying DCC versus continuing on the present path need to be considered on a case-by-case basis using likely intensity of DCC application rather than the very large intensities used in many modeling evaluations seeking to get strong signal-to-noise results. Many of the approaches to offset climate warming mimic natural influences on the climate or the inadvertent influence of everyday human activities such as planting trees and using white paint to cool cities, buildings, and cars, in the summer that have long been accepted. In any event, if unforeseen adverse consequences did emerge as DCC is being scaled up, deployment could be scaled back or terminated because, unlike the natural persistence of the GHG perturbation, effort such as continued aerosol generation is needed to maintain the highest leverage (and therefore highest risk) proposed interventions.

Climate intervention has been recognized as potentially necessary for over 60 years [80], but research on its applications has been limited in the hope that emissions reductions and adaptation would prove sufficient to moderate climate change and its impacts. Clearly, this is not the case. Further delay in accelerating climate intervention research and initial deployment to offset at least some global warming will make more warming, human suffering, and ecosystem disruption, inevitable.

The inadequacy of the mitigation-only approach and the potential need for application of cooling measures has been increasingly recognized by prominent national and international scientific and policy bodies and think tanks, including the US National Academy of Sciences [81], the American Meteorological Society [82], the Council on Foreign Relations [83], the Cambridge Centre for Climate Repair [84], and the Climate Overshoot Commission [85]. Open letters authored and signed by numerous climate scientists urging support for research on Solar Radiation Modification (SRM)[8] have also been published and publicized [87,88]. Unfortunately, with few exceptions, national or international climate decision-making bodies have failed to respond.[9]

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[8] A commonly proposed category of DCC as shown in table 1. For further discussion of Thermal Radiation Management (TRM), see [86].

[9] In February 2024 Switzerland proposed a United Nations Environmental Program expert working group on solar geoengineering that was subsequently rejected [89,90]. In 2023, the U.S. Congress mandated that a geoengineering research plan be produced by the Biden Administration. A plan was produced but the White House Office of Science and Technology

Section 5 presents a number of promising measures being investigated and in some cases pilot tested, generally on shoestring budgets and without the urgency that the level of climate disruption and rapid approach to passing tipping points warrant.

5. Potential Approaches for Direct Climate Cooling

The authors consider the fourteen proposed direct climate cooling approaches below worthy of investigation for potential application on local to global scales. Table 1 presents a typology of these methods.

stated that it "does not signify any change in policy or activity by the Biden-Harris Administration" [91]. There are also reports that Canada, the EU and the UK have started geoengineering research programs [92–94].

Table 1: Typology of Approaches to Direct Climate Cooling (DCC)

Typology of Direct Climate Cooling (DCC) Methods			
		Key:	SRM - Solar Radiation Management
			TRM - Thermal Radiation Management
Method	**Category**	**Active Elements**	**Medium**
Afforestation, Reforestation, and Soil and Vegetation Restoration (AFSVR)	TRM	Terestrial biotic pump	Land EvapoTranspiration
Buoyant Flakes	SRM	Phytoplankton	Water Albedo
Cirrus Cloud Thinning (CCT)[1]	TRM	Ice nuclei	Cirrus Cloud Cover
Fizz Tops (Fiztops)[2]	SRM and TRM	Nanobubbles	Water Albedo & Evaporation
Ice Shields to Thicken Polar Ice	SRM	Ice & Snow	Ice and Snow Albedo
Marine Cloud Brightening (MCB)	SRM	Seawater mist	Cloud Albedo
Mirrors for Earth's Energy Rebalancing (MEER)[3]	SRM and TRM	Mirrors	Land & Still Water Albedo
Mixed-phase Cloud Thinning (MCT)[1]	TRM	Ice Nuclei	Reducing Cloud Cover
Ocean Thermal Energy Conversion (OTEC)	TRM	Sea Surface Heat	Heat to hydrogen conversion & Reverse heat pump
Seawater Atomization[4]	TRM and SRM	Sea water & Seawater droplets	Sea water evaporation & Cloud cover
Stratospheric Aerosol Injection (SAI)	SRM	Aerosols	Stratospheric Albedo
Surface Albedo Modification of Ice and Snow	SRM	Reflective Materials	Ice and Snow Surface Albedo
Tree Planting and Reflective Materials[5]	TRM and SRM	Plants and ground water & Reflective materials	Land EvapoTranspiration & Sunlight Reflection
Tropospheric Aerosol Injection (TAI)[6]	SRM and TRM	Increased clould condensation nuclei & photocatalytic sources of oxidative radicals.	Increased cloud reflectivity & Methane Removal
Notes: 1) CCT and MCT are often described as SRM, but they are TRM as they reduce insulating cloud cover to increase the release of thermal rediation, 2) SRM from nanobbuble IR reflection and TRM from evaporation, 3) SRM from IR reflection and TRM from thermal IR radiation into the atmospheric transparency window, 4) TRM from seawater evaporation and SRM from droplets increasing cloud reflectivity, 5) TRM from land evapotranspiration and SRM from reflective materials, 6) SRM from increased cloud reflectivity and TRM from methane removal.			

The short summaries that follow were prepared primarily by those in support of the approach and then reviewed by the rest of the authors. Many of these proposed direct cooling approaches may also have substantial co-benefits such as contributing to greenhouse gas removal (GGR), promotion of biospheric regeneration, generation of renewable energy, and more, that would add to the benefits resulting from their cooling influences. We recognize that some approach estimates may be optimistic as they are listing possibilities pending further analysis. Section 6 includes a more general discussion of how these approaches might urgently be applied.

- **Afforestation, Reforestation, and Soil and Vegetation Restoration** (ARSVR) can increase evapotranspiration that can reduce a region's peak temperatures in a process sometimes referred to as 'the terrestrial biotic pump' [95–98]. Increased evapotranspiration can also increase cloud formation in some regions, the increased albedo of which can add to the cooling influence. The extent to which afforestation reduces dryland albedo vs. decreasing thermal radiation and the timeframe over which these effects will occur influence its overall cooling potential [99]. The interaction of temperature, wind, vegetation species, soil water retention capacity, water availability, current land use albedo, and altitude are critical factors in determining where and how this solution could and should be applied [100–102]. Incorporating biochar into agricultural soils can increase soil water retention and thus increase the potential cooling influence via evapotranspiration [103].

ARSVR involves both solar radiation and thermal radiation to exert a cooling influence. Additional co-benefits can include run-off and erosion reduction, flood protection, carbon drawdown and sequestration, and promotion of increased biodiversity [104,105]. There is some tension between the need for agricultural land vs. afforestation considering the increasing demand for food and impacts on local economies. Implementation would best aim for a complementarity achieved through a global land stewardship approach that balances need while maximizing benefits of afforestation, reforestation, regenerative agriculture, and agroforestry [102,106].

- **Buoyant Flakes"** as a cooling approach refers to the dissemination onto nutrient-deficient ocean surface waters of rice husks coated with a mix of hot-melt, water-insoluble lignin (e.g., Organosolv) and rice water glues, urea leavening agent, and waste mineral powders rich in the phytoplankton nutrients of iron, phosphate, opaline silica and trace elements that are typically deficient in warm surface waters. The ultra-slow release of these nearly insoluble minerals is intended to provide a sustainable basis for an enhanced, marine food web. Buoyant and slow release reduces the risk of eutrophication, nutrient robbing, toxicity, or transport of nutrients wastefully to dark ocean depths. The nutrient-laden flakes would contribute in various ways to cooling on scales depending on how widely they are deployed. The most important for short term cooling is reduction of solar energy absorption by the ocean, which is the primary storage location for GHG-trapped radiation, because the phytoplankton fed by the flakes are of lighter color than the deep blue of the open ocean and thus reflect more sunlight. Where Buoyant Flakes are disseminated and drift they have the potential to increase oligotrophic ocean albedo from 0.06 to as much as 0.12 for up to a year. Secondary benefits include: that krill and other diurnally vertically migrating (DVM) species would, in effect, carry much of the CO_2 taken up by the additional biomass to depths as excreta and exhalation where it would no longer be affecting the climate; that photosynthesis by phytoplankton will transform some of the absorbed sunlight, carbon dioxide, and mineral nutrients into biomass and oxygen; and that , many species of phytoplankton produce DMS (dimethyl sulfide) that, when emitted into the atmosphere, can serve as cloud condensation nuclei, tending to make marine stratus clouds more reflective [107] and thus reducing solar absorption. The net effect would be reduced warming of mid waters by shading, increased oxygenation of surface waters, increased oceanic uptake and sequestration of atmospheric carbon dioxide, and an increase of fish stocks. Done over a sufficiently wide area, the "Buoyant Flakes" approach would likely tend to return the regional marine food webs to conditions closer to their pre-industrial state, although done to excess might also contribute to benthic hypoxia unless offset by increased downwelling of chilled and oxygenated brine, which might be promoted by induced cooling from this and other such approaches leading to increased formation of sea ice. The buoyant flakes are specifically designed to overcome some of the potential limitations of ocean fertilization [108].

- **Cirrus Cloud Thinning (CCT)** proposes seeding wintertime, high-latitude (and high-altitude) tropospheric cirrus clouds with ice nuclei to make these clouds thinner and their coverage reduced. This occurs due to a change in the formation mechanism of ice crystals, from homogeneous to heterogeneous ice nucleation. This change increases the flux of long-wave terrestrial radiation to outer space, thus cooling the high latitudes when solar radiation is scarce or absent [109]. Several anticipated tipping points in the climate system exist at high latitudes [110], making such cooling critical. Any efficient ice nucleating particle (INP) can be used, such as potassium feldspar [111]. However, the weight of the seeding material may be an important consideration for potential deployment, making silver iodide (used in operational cloud seeding) or Bismuth Triiodide [109] a better option since these seeding aerosol sizes are on the order of 0.1 microns and thus can nucleate many more ice particles per unit mass relative to feldspar INPs.

Research on the potential influence of cirrus cloud thinning has so far been entirely based on global and regional modeling that involve various assumptions that impact the cirrus cloud response to seeding. To date, results are mixed due to some poorly constrained variables governing the partitioning of homogeneous (hom) and heterogeneous ice nucleation. A critical need in CCT research is to establish measurement-based constraints on the global spatial and temporal distribution of hom-affected cirrus clouds (i.e., hom cirrus). Fortunately, recent progress in cirrus cloud property remote sensing is providing useful information on various parameters. For example, satellite remote sensing shows that hom cirrus clouds are common at high- and mid-latitudes, especially during winter (e.g., [112]). This is fortuitous because seeding of such clouds is most effective when sunlight is minimal (i.e., during winter). These recent findings will need to be incorporated into cirrus cloud parameterizations in climate models to determine the potential efficacy of CCT.

While the potential remains, studies critical of CCT include Tully et al. [113,114], which investigated the efficacy of CCT in a state-of-the-art global climate model (GCM). They found that CCT will likely not work for global-scale cooling. However, in their studies, orographic gravity waves (OGWs), which are critical for formation of hom cirrus [112,115,116] were "turned off" so that predicted ice particle number concentrations would agree better with aircraft observations. Another limitation of their studies was the treatment of "pre-existing ice" (i.e., ice present before ice nucleation occurs), which determines whether hom cirrus can occur--the more pre-existing ice, the less likely hom cirrus will form [117]. Typical cirrus clouds are ~ 1400 m thick [118]. In GCMs, the vertical resolution at cirrus levels is presently ~ 700 m, so often treating cirrus as two layers with the amount of pre-existing ice based on its mean value in each layer. The remote sensing study of Dekoutsidis et al. [119] found that most ice in cirrus clouds is formed through homogeneous nucleation near cloud top where the cloud ice water content (IWC) is much lower than the mean IWC in a 700 m layer. By estimating the pre-existing IWC as the mean layer value, GCMs may thus be strongly underestimating the amount of homogeneous ice nucleation in cirrus clouds.

● **Fizz Tops (Fiztops)** are table sized, floating, lightweight, solar-powered units that are designed to inject low-diameter microbubbles into the top centimeter of ocean which, whilst rising, lose some gas and shrink to become nanobubbles into the less than a millimeter thick sea surface microlayer (SSML) which are stabilized by concentric shells of surfactants, ions and gas-saturated water. Often buoyant surfactants are generated continuously in the ocean from organisms and degrading biomass. Nanobubbles occur naturally throughout the surface ocean. Fizz Top units 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 up to six months in the SSML. They may also increase overall planetary cooling by, counter-intuitively, warming the SSML by refracting solar energy sideways, thereby releasing ocean heat to the troposphere by evaporation and convection where it may then be better radiated to space [107], though this is less important for cooling than their albedo impact. This effect is much less than that of albedo increase. Fiztops might carry a variety of sensors to record and transmit current environmental conditions and activities there. The main risks are encrustation, cluttering the ocean, maintenance costs, and whether sufficient power could be generated by the flexible, conical photovoltaics. They should also have some additional benefits such as scarce floating habitat. Some groups, such as illegal fishers, might not welcome Fiztops' surveillance capabilities. As the microbubbles shrink to become nanobubbles they are not dissolved in seawater [120,121]. As nanobubbles larger than the wavelength of light are highly reflective and long-lived, the limited amount of energy provided by the photovoltaics should be effective at cooling waters down-current of them.

● **Ice Shields** describes an approach to thickening polar sea ice by intermittently pumping up and then spreading sea water on the surface winter sea ice such that it forms an ice array of linked, very low-inclination, ice lenses, shields or mountains. The ice would thicken much faster than sea ice, because the thin sheet of flowing water would be exposed to both the frigid air and the frigid ice base. Nor would the water be insulated by the thickening ice. In winter, heat released by freezing would be radiated upward, eventually being emitted to space, while during sunlit months, the increased surface albedo would reduce solar absorption by the sea ice and so slow its melting. Power from co-located wind turbines could be used to power the seawater pumps, although operation in such cold environments can be problematic, so some of the energy would have to be used to keep them operational. The objective would be to form multi-meter thick sea ice lenses (or "shields") of some 2 km diameter. Arrays of close-packed ice shields would likely freeze solidly together, despite the rejected brine falling in rivulets off their sides. Ice shields might initially be grown outwards from the land or land-fast ice, first in shallow areas along the shore, where they could be grounded, or be created to be free-floating in the Antarctic Circumpolar Current or open areas of the Arctic Ocean. Increasing the presence of sea ice would start to restore arctic albedo; if undertaken with sufficient intensity, broader cooling of ocean waters might be able to help stabilize glacial stream fronts and ice shelves or be deployed to reduce sea ice exiting the region between islands. Dense, frigid brine residual to ice formation would not require freezing but would concentrate salt, CO_2 and oxygen in the seawater surrounding the created sea ice, causing this dense water to descend from near the surface to where the oxygen would be expected to benefit deeper marine life. If done over sufficient areas and time, the dense, chilled brine flow might help increase the overturning currents, which have been dangerously weakening recently and the overall cooling could potentially moderate climate change impacts outside the region. Hence, regional cooling and biosphere restoration could be promoted [122,123]. Related geophysical DCC approaches to "conserve the frozen north" are listed and discussed in von Wijngaarden et al. [29]. Zampieri & Gossling [124] find that the methods they considered of sea ice targeting geoengineering can delay sea decline but not global warming. As shown in the "scalability" column of table 2, we generally agree with this assessment.

Deep, fresh ice and snow provided by Ice Shield deployment should provide major albedo cooling in the sunlit seasons to polar and subpolar regions where they are deployed. As well, thermal radiative cooling in the dark, winter months from the relatively warm surface ocean should be released to the troposphere as part of the pumped seawater is frozen, and as any residual sea surface warmth is concentrated in the polynyas and channels interspersing the ice shield arrays.

● **Marine Cloud Brightening (MCB)** is a climate cooling approach that lofts an atmospheric mist of extremely small aerosols (often referred to as cloud condensation nuclei, or CCN) that would make marine clouds more reflective of sunlight. If MCB could be deployed in a suitable distribution of marine stratus clouds around the world, there is the possibility that the collective effect could increase the reflectivity of the Earth by as much as 0.5% [125–127] which would roughly counterbalance the present radiative influence of the human-induced higher concentrations of greenhouse gasses.

A particular benefit of using MCB to influence the atmospheric energy balance is that, because the lifetime of the brightened clouds would be of order days, the aerosol injections could be rapidly adjusted or terminated should adverse consequences arise. Latham et al. [127] modeled changes to rainfall patterns of MCB with double CO2 simulations, finding MCB would have the potential to considerably reduce rainfall extremes. Parkes et al. [128] used coded manipulation (dividing the ocean seeding areas into 98 sections) to calculate impacts on specific land areas, such as the Amazon Basin.

As well as the global impacts, Latham et al. [127] and Parkes et al. [129] found that MCB could lead to significant regional cooling, with modeled impacts of a particular global implementation even tending to reverse cryospheric warming, weaken hurricanes and reduce coral bleaching [130,131]. Parkes et al. [129] and Lui et al. [132] show that relatively rapid cooling of the planet could be achieved by seeding all ocean areas with MCB, even where there are no clouds (sometimes called marine haze brightening or marine sky brightening (MSB)).

Calculations suggest that local or regional deployment might be feasible at relatively low cost, with testing possible within geographically confined national jurisdictions. Suitable low-level clouds cover more than 18% of the oceans. Research has shown that cloud reflectivity depends on both the number of CCN and the size of cloud drops. Assuming the same amounts of cloud water, a larger number of smaller drops of water reflect more sunlight than a smaller number of larger drops [133]. MCB requires a mist that produces roughly equal-sized small drops of filtered salt water (monodisperse submicron aerosol) to form cloud condensation nuclei. Latham [127] proposed an optimal drop size of

0.8 microns to increase cloud formation, brightness and durability. Recent publications suggest spraying much smaller particles, which is more energy efficient from a radiation perspective (e.g., [134]).

Professor Stephen Salter (deceased 2024) designed MCB generation and deployment systems [135–138] and founded the Lothian School of Technology to help test and validate his work. Design of wind driven MCB vessels that would also be capable of providing the energy to power the CCN injection process has been carefully thought through [135,139]. The Australian government is presently supporting the application of MCB in an attempt to reduce ocean warming and thereby moderate coral bleaching on the Great Barrier Reef [140]. Neukermans [141], working in cooperation with scientists at the University of Washington are completing ongoing work on alternative methods of generating the needed CCN spray, as are researchers from Southern Cross University in Australia [142].

The optimal spray size is very important to minimize the mass of sprayed seawater and optimize longevity and brightness of clouds (e.g., [134]). Because the CCN are short-lived and subject to being washed out by encounters with rain, forecasts of humidity, wind speed, and direction a few days ahead might enable targeted MCB deployment by region and season to optimize results. With sufficient forecasting capabilities, the potential might even exist to deploy MCB in ways capable of moderating storms, droughts and floods, and cooling of ocean currents such as those flowing into the Arctic. Whilst it has yet to be proven that MCB has this potential, providing submicron cloud condensation nuclei has a strongly modeled cooling effect [125,133] that might offer the possibility of moderating weather extremes. For example, Latham et al. [130] argued that MCB deployment in the Atlantic 'hurricane nursery' throughout the period of spring warming of ocean waters might be capable of moderating the intensity of hurricanes later in the season because of the overall reduction of sea surface temperature.

If its full potential effectiveness is to be realized, large-scale MCB deployment, together with other cooling methods, would require strongly coordinated international research, governance, and effective planning to ensure beneficial rather than unintended adverse impacts [143,144]. Modeling work is required to assess timing and location and volume of potential MCB deployments so that, for example, cooling benefits to Europe are not at the expense of worse weather in Africa. It matters immensely where, when, and how MCB is applied.

● **Mirrors for Earth's Energy Rebalancing (MEER)** involves deploying mirror arrays on the Earth's surface to reflect excess downwelling solar radiation and to focus outgoing thermal infrared radiation into the atmospheric transparency window (8-13 micrometers) to decrease local, regional, and global temperatures. Goals of deployment include promotion of agricultural adaptation [145–148], urban heat island alleviation [149], freshwater conservation [150], renewable energy generation [151], ecosystem protection [152,153], as well as enhancement of ecosystemic atmospheric carbon dioxide capture [148]. Optimally oriented stationary surface mirrors, enhanced with a top layer of spectrally selective infrared emitter, are estimated using 2018 CERES data, other direct observations, and CMIP5 climate models to have the potential to reduce the net top of the atmosphere flux by 70 W/m^2 on average [154]. 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 W/m^2 of radiative forcing by the end of the century [155]. This coverage would be likely to improve total agricultural output due to the water savings [156,157], drought protection [158], and thermal alleviation provided by the solar collectors [159]. Solar reflector devices can be upcycled from glass bottles, aluminum cans, and PET packaging. Preliminary data in Freetown Sierra Leone show 5-7°C indoor cooling. Mirrored roofing tiles and panels could thus reduce heat wave mortality and energy system overload exacerbated by the urban heat island effect [160,161]. Preliminary experimental data suggest agricultural soil cooling by up to 4°C at a depth of 10 cm at mid-latitude (43°N). Replacing colored nets and mulching in agriculture with mirrors could improve productivity by reducing heat stress and agricultural water usage [162,163] and promote carbon storage in the cooler soil [164]. Preliminary pan evaporation-scale experiments suggest evaporation suppression by 40% at 50% mirror coverage and water cooling up to 10°C. Large mirror arrays over freshwater bodies can reduce evaporation from reservoirs, rivers, and aqueducts. Compared to floating photovoltaic systems, mirrors would do more to cool the water and reduce evaporation by cooling the air-water interface [165]. 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 [166]. 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 [145,157,166–169]. MEER has been conducting field experiments in Plymouth and Concord NH USA, outside of San Francisco USA, as well as in low-income residential communities in Freetown, Sierra Leone and in Pune, India, to quantify the local adaptation benefits towards improved understanding of thermal and circulation impacts.

● **Mixed-phase Cloud Thinning (MCT)** has been proposed by Villanueva et al. [170] for changing the microphysical properties of mixed phase clouds in the Polar Regions during winter by injecting them with ice nucleating particles or INP (like CCT). By absorbing upward directed infrared radiation from the surface, these clouds act to trap heat in the mid- to lower troposphere, reducing the rate of cooling that would occur in clear skies. By injecting mixed phase clouds with INPs, the ice phase loading can increase while the liquid phase loading decreases. In conjunction with this transformation, the total cloud condensate will end up being depleted by falling snow, which allows more heat to escape to space. While such clearing is pursued now in special local situations such as to keep airports open, implementing this approach does require monitoring for suitable weather conditions at particular locations and then maintaining a schedule of injections as the INPs have a relatively short atmospheric lifetime [171] (p. 44). As such, the most appropriate applications might be, for example, to increase MCT's cooling influence over warming glacial streams and adjacent ocean waters, areas of rapid permafrost thawing, and between-island channels that allow escape of sea ice from the Arctic. See also [172] for a discussion of field research that may be supportive of this approach.

● **Ocean Thermal Energy Conversion (OTEC)** would utilize the temperature difference between surface and deeper ocean waters to transfer ocean heat down into the ocean to reduce near-term surface temperatures while generating baseload energy and increasing CO_2 uptake from the atmosphere [173–175]. While most often thought of to provide a 24-hour a day source of renewable electricity for regions where other less expensive renewable sources might not be sufficient, the large heat capacity of the deep ocean does provide a possible sink for the additional energy being trapped by the increasing concentrations of GHGs. Indeed, the ocean is where the Earth system is presently storing over 90% of the trapped energy and what OTEC would mostly do (on human relevant time scales) is augment this process and spread out the effects of the down welled energy on climate over time as the switch away from fossil fuels is completed. Economies of scale for deployment of a one-gigawatt plant that would have a local to regional impact in reducing ocean surface heat, has been estimated to potentially reduce the discounted cost of OTEC electricity to be cost competitive with other forms of renewable energy [173]. Current estimates of ocean heat and heat flows suggest that heat displacement from the surface of the ocean to a depth of about 1000 meters caused by a global scale OTEC deployment would have negligible impact on deep water ocean temperature [173]. However, gradual deployment would be accompanied by the need for continued monitoring and adjustment to avoid unintended adverse impact.

OTEC has minimal direct impact on the transport of solar and thermal radiation through the atmosphere because it is a redistribution of heat within the ocean. By influencing sea surface temperatures however, it can indirectly impact ocean-atmosphere heat exchange, and ocean currents leading to localized modifications in the radiation budget and potentially contributing to broader climatic shifts when the technology is deployed at a large scale. But these modifications mainly return climate conditions to their preindustrial state by reducing GHG emissions, enhancing oceanic carbon uptake, mitigating ocean warming, and supporting climate adaptation and resilience.

● **Seawater Atomization** is a suggested, but as yet only conceptual, approach proposing to generate cloud and humidity in coastal regions, but also on the high seas, with the intent of increasing ocean evaporation and reflective low clouds. Drawing electricity from offshore wind farms when their production of electricity is not being fully utilized (such as at night), the notion is that pumps would force water through high-flow rate spray nozzles atop specially designed towers to separately generate both humidity and an appropriate level of cloud condensation nuclei (CCN) from seawater. The main effects intended are brightening and perhaps forming of marine stratus clouds that would increase reflection of solar radiation. Secondary effects would include evaporative cooling, coral reef shading, and beneficially influencing downwind precipitation by using tri-phasic pressures and the cyclonic action of baffles to control CCN size. Addition of sublimated ferric chloride pellets to produce iron salt aerosols (ISA) could lead to the photo-catalytic reduction of the atmospheric loading of methane and smog to provide further meteorological effects [107]. Carried out inappropriately, adverse consequences might, rightly or not, be attributed to the effort, potentially creating liability. The means for determining and then generating the right humidity, CCN increment, and droplet size distribution and optimizing to flow rate have been described but are yet to be determined and optimized. Incorrect droplet sizes could generate adverse results. The ISA method is similarly still to be refined. Modeling and gated field tests are required to establish the cooling and irrigation potential of the method.

Seatomizer deployment would result in increasing both reflective cloud area cover and thickness. In addition, the transfer of ocean surface heat into evaporated humidity, convection, condensation, and its release at altitude should enhance thermal radiative cooling, particularly at night.

● **Stratospheric Aerosol Injection (SAI)** is a proposed means for exerting a global climate cooling influence that mimics the cooling effects following injections of reflective sulfate aerosols into the stratosphere by relatively large volcanic eruptions. For example, the sulfate aerosol loading created by the 1991 Mount Pinatubo eruption reduced the global average surface temperature by ~0.6°C for 15 months [176].

SAI is the most studied and best understood approach to exerting a global or near-global direct cooling influence. Research suggests that low to moderate levels of stratospheric aerosol injection could be deployed in patterns that would quite uniformly offset much of the warming and precipitation influences of the increasing concentrations of greenhouse gasses with, if done in optimal ways, minimal departures that would be considered noticeably adverse. For example, climate model simulations indicate that a particular SAI scenario would be able to reduce the increase in global mean temperature by up to 2° C [16]. In the face of the warming that has occurred to date and is projected over the next few decades, an optimal deployment approach would likely involve building up initially to offset ongoing warming and then slowly intensified to offset an increasing fraction of past warming to bring the overall temperature increase toward an order of half its present value (i.e., near the warming of the mid-20th century to which much of the world's infrastructure and agricultural practices are optimized). 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 to minimize regional risks that might develop. A leading study estimates a cost of about $36b per year (in $ 2020) to reduce global warming by 2° C from 2035 to 2100 [177] and would be proportionally less if the increase in global average temperature increase were taken back to its mid- to late-20th century level. While significant reductions of the warming could likely be accomplished,

Another possible starting approach might be to focus on reducing amplified global warming in the Polar Regions. Gradually increasing latitudinally and seasonally targeted SAI with high-latitude injections in spring as warming reduces the albedo and sea ice retreats has been proposed as a potential approach to moderating polar amplification. As intense solar radiation is only present for several summer months, the aerosol injection could be in the lowest stratospheric altitudes so that it would be removed by natural processes within a few months. This would greatly reduce the risk of increasing springtime stratospheric sulfur to levels that would cause sufficient sulfur deposition on wintertime snow to contribute to acidification of springtime runoff. What has been noted in simulations of attempting just cooling high latitudes of the Northern Hemisphere is that this leads to a shift in the Intertropical Convergence Zone (ITCZ) in order to readjust the latitudinal heat balance [178,179]. This unintended consequence can be moderated somewhat by injection of aerosols in the lower stratosphere over the Southern Ocean, which would also have the benefit of reducing heat uptake by the Southern Ocean that contributes ultimately to the loss of sea ice and ice shelves around Antarctica. There are several additional considerations that favor an initial SAI focus on high latitudes. First, the injection is more easily accomplished with existing aircraft because of the lower altitude of the stratosphere and the preferred height of injection. Second, cooling the high latitudes does draw heat in from the middle latitudes, exerting a beneficial cooling influence at those latitudes. Third, the injection does not need to be made year-round, simplifying the need for a prolonged injection period, and the area where the injection is done is smaller. And fourth, while a relatively greater amount of aerosol is needed per square meter, this requirement is somewhat ameliorated because the relative response per increment of aerosol mass is greater in high latitudes than for low latitude or global injections because of the closer proximity to the latitude where the ice-albedo feedback is active [178,180]. The cost of reducing temperatures in northern and southern latitudes above 60 degrees north by ~2° C is estimated to be about $11B/year in $ 2022 [177].

SAI simulations indicate that the initiation of unintended adverse consequences is least likely for hemispherically balanced applications when the amount of cooling is less than 2°C [77,180,181]. This suggests that SAI has the potential to significantly reduce or reverse many of the changes in climate caused by the increasing concentrations of greenhouse gases [77]. A recent literature review by an advisor to the Climate Overshoot Commission summarized the result of a review of roughly a hundred studies as “shockingly strongly favorable” [18]; and research on commonly cited natural risks such as monsoon disruption [179], stratospheric ozone depletion [182] and methane accumulation [183] have not found significant risks. Consequently, much of the concern over SAI has focused on questions of geopolitical risk and how to coordinate and govern a gradual and moderate scale-up of hemispherically balanced deployment, as discussed in section 6.

● **Surface Albedo Modification of Ice and Snow** is an approach being researched by Bright Ice Initiative to brighten ice and snow by applying a surface layer of harmless reflective materials to maintain ice reflectivity (albedo) in order to slow the melt of ice and snow. This has been demonstrated to be effective in small, well-monitored field tests, conducted with full permissions, with safety tested in laboratories, and small-scale field research tests followed up with monitoring to determine any environmental impact. This approach can be applied locally in collaboration and co-leadership with Indigenous and local experts, in specific targeted areas of critical need, to enhance local resilience and sustainability. Bright Ice Initiative and local collaborators have performed well-monitored field testing on a pond in Minnesota co-led by local experts from Minnesota-based Ice Conservation Engineers, LLC.

Testing has also been done on a glacier in Iceland, co-led with the Icelandic Meteorological Office. In this well-monitored work, albedo was measured before and after the ice brightening materials were applied to the test area, while the control area was left untreated. The automated weather stations continued to monitor the albedo and weather parameters after the team left the site. Detailed analysis of the data collected is still underway, but preliminary assessment shows an initially significant enhancement of albedo which persisted for some time. The work will be published in a suitable journal as soon as possible. A key agreement has recently been signed that allows teams from India and the US to collaborate on a first small-scale research test of the Surface Albedo Modification approach on a Himalayan Glacier. The participants are from IIT-Indore, Bright Ice Initiative, Healthy Climate Initiative, and Ice Conservation Engineers, as well as an independent PhD contractor, Indigenous to the region, who is expert in environmental impact and water quality assessments.

This approach is meant to increase the resilience of local communities affected by glacial melt. The melting can cause flooding, damage to people's homes, and destruction of the hydroelectric dams needed to bring clean power to the communities. The ice melt is accelerated by climate change and by loss of reflectivity, due to ice loss itself and to darkening of the ice from layers of deposited dark materials such as silt or soot exposed as newer, cleaner ice and snow are lost. The melting can lead to diminished water supplies at critical times in the growing season as the historical inventory of ice and snow in the region is lessened, and this can compromise vital agriculture, water, and food supplies in the affected regions.

Once permissions are granted for use at a wider scale, this approach has the potential of sustaining, and even increasing, the overall reflectivity of snow and ice which has the potential to contribute to moderating a range of climate impacts [184–186]. Surface albedo modification is a low-risk, localized method to test the brightening and cooling power of bright materials on ice and snow surfaces, to preserve and potentially rebuild ice and snow, in order to promote community resilience to floods, droughts, and crop failures, and in addition, to reduce the risk of sea level rise from melting of land-based (glacial) ice. The approach has been extensively tested on a Minnesota pond, with results published Dec. 2022 in *Earth's Future* [186]. It has undergone a first glacial test in Iceland, in collaboration with the Icelandic Met Office, in August 2023, for which a further paper will be written. The approach is slated now for a collaborative test in the Himalayas this summer. This approach can be applied in a highly localized manner so that it can be used to help with specific local challenges posed by climate, to help communities, and in the process, build trust and international collaborations.

● **Tree Planting and Reflective Materials.** Tree planting coupled with use of lighter colored infrastructure materials can mitigate the heat island effect in urban environments [187]. Lighter colored pavement materials reflect more sunlight than asphalt. Tree planting can help cool urban environments in addition to providing shade for pedestrians and, when properly placed, reducing heat absorption by buildings. Highly reflective materials include light-colored aggregate, higher slag or limestone content concrete, and reflective coatings. White or light-colored roofs 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. Reflected heat can adversely affect pedestrians and albedo can degrade over time due to darkening or being covered by accumulating dust and dirt. Location relative to buildings is also a factor in effectiveness [188]. Appropriately carried out in the proper settings, integrating reflective pavement, building materials, and roofs coupled with urban tree planting can be an effective local heat island moderation strategy. If implemented on a world scale, this strategy could, over time, contribute to global climate cooling [145,187,189–191]. Radiative materials, reflective to sunlight and emissive to thermal infrared are also in development. Because no solar radiation is absorbed, radiative cooling occurs during both day and night [192,193].

Tropospheric Aerosol Injection (TAI). As global warming is directly correlated with the emissions of short-term GHG species like methane, their faster removal from the atmosphere is a DCC approach. Since preindustrial times, methane's atmospheric concentration, although currently less than 2000 ppb, has nearly tripled. Because the methane molecule is a particularly effective absorber of infrared (IR) radiation (roughly 100 times as effective as an equal mass of CO_2 over a period of 20 years), methane currently contributes over a third of the current radiative forcing causing global warming of around 1.3 W m^{-2} [194]. Its atmospheric lifetime is currently about a decade.

Globally there are millions of methane point sources; however, it is not cost-effective to plug or otherwise eliminate them all, nor is it practical to capture methane emissions from major sources such as wetlands, and rice paddies. An alternative approach to reducing its strong warming influence would be to shorten its atmospheric lifetime by enhancing its natural rate of oxidation using catalytic aerosols. That such aerosols would also exert a cooling influence by creating long-lived haze over the oceans and by brightening clouds would further reduce total radiative forcing.

Methane is removed naturally from the air by a process initiated by oxidative chemical radicals (and by soil methanotrophs [195]). The most prevalent such radicals in the atmosphere are the hydroxyl (OH·) and chlorine (Cl·) radicals. The atmosphere's oxidative capacity (AOC) represented by these radicals is increasingly being chemically consumed by emissions of volatile organic and other compounds from wildfires, burning of agricultural waste, and vehicle and industrial emissions. The proposed hydrogen economy will further stress the AOC because H_2 is a chemical reductant (i.e., reacts with oxidants). H_2 is also a greenhouse gas with a global warming potential 11 times that of CO_2 over 100 years, per unit mass. That is mainly owing to its effect on other greenhouse gases such as methane and tropospheric ozone [196].

TAI enables clouds to cool the oceans in two ways that occur simultaneously, firstly by reflecting away more sunshine and secondly by catalytic methane removal. In recent years, significant production of hydrogen peroxide (H_2O_2) and/or hydroxyl radicals (OH·) by small cloud droplets has been revealed in the lab [197,198]. This suggests that clouds are likely also an important contributor to methane oxidation, because H_2O_2 is split by sun radiation to produce OH· radicals [199] in both the gaseous and dissolved phases [200,201]. H_2O_2 is similarly split to OH· radicals by iron-containing aerosol particles, which are often present in clouds [202–204].

The concentration of H_2O_2 or OH· in cloud micro-droplets depends only on their diameter and is independent of their generation process, whether by nebulization [205] or condensation [206]. By decreasing cloud droplet diameter from 10 µm to 0.05 µm the OH· production rate increases from 10^{-9} M/s to more than 10^{-6} M/s [206]. The smaller the droplets the more their H_2O_2 concentration increases [205] and/or OH· concentration [207]. The droplets naturally release the H_2O_2 they generate into the gas phase.

An additional methane oxidation effect results from increased reflection of solar UV irradiance from scattering by clouds [208]. This scattered reflection increases the UV radiation above closed stratocumulus cloud cover and all-around single cumulus clouds, by scattering UV. The increased volume of air containing reflected UV photons produces more hydroxyl radicals and thereby a corresponding increased methane depletion capacity of the atmosphere [209]. Cloud brightening would increase this methane oxidation effect by UV reflection.

The brightness of clouds is determined by the number and diameter of cloud condensation nuclei (CCN) [210,211]. More droplets provide a larger total surface area for light reflection, even though the total volume of water can be the same. Svensmark et al. [212] revealed that low CCN densities above tropical and subtropical ocean areas can lead to particles as small as ~25 nm diameter operating as CCN, owing to the high supersaturation level reached before droplet nucleation occurs. The average net cooling of clouds is ~20W m^{-2} [213], however marine clouds brightened in the tropics produce a larger cooling effect owing to the increased sun intensity.

Since 2020 global albedo has decreased and atmospheric methane concentration has been accelerating up [214]. In 2020 the rate of increase of methane surged from 0.345 ppb/month to 1.13 ppb/month [215]. This was due to stricter regulation by the IMO on shipping fuel, and reduced pollution during the COVID lockdown period [22]. This is estimated to have reduced sulfuric acid CCN above the ocean by 46 %. All this makes clear that an opportunity exists for cooling the oceans by cloud brightening by increasing the density of CCN aerosol particles.

By increasing the natural OH· radical abundance of clouds and providing a small HCl content we estimate that the rate of methane-depletion by active Cl· radicals could increase by two to three orders of magnitude. That is because Cl· initiates methane oxidation at least 32 times faster than OH· [216]. The reaction produces HCl, and OH· radicals then produce more Cl· radicals from HCl in a catalytic cycle.

The cloud brightening effect increases the reflectivity by clouds of visible and UV radiation by 30 to 50%, which increases the cooling effect of clouds by 30 to 50%. Our photosensitive Climate Catalyst Aerosols could be dispersed in the lower troposphere to deplete methane both in the vicinity of clouds and in cloud free tropical and subtropical marine areas, where a long-lived haze would form, producing immediate cooling by the direct aerosol effect.

Climate Catalyst Aerosols are photosensitive and/or otherwise reactive aerosols/gases that contain one or more chlorides of iron, aluminum, earth alkaline and alkaline metals, ammonium, and hydrogen, and hydroxides of silicon, titanium, and iron. These substances are hygroscopic owing to their molecular polarity, making them ideal CCN. Particle diameters of 100 nm or less are easily achievable, giving a particle density of 1000 particles/cm^3 a small mass of only ~0.2 µg/m^3. They are produced from gaseous/vaporous precursors that condense by chemical reaction to reactive aerosols/gasses that mimic their natural analogues.

We propose increasing the AOC and overall cloud albedo by augmenting naturally occurring atmospheric photocatalysts with the following aerosols: 1. Ammonium chloride salt aerosol formed with a stoichiometric excess of HCl, to increase tropospheric concentration close to that of coastlines – around 1 ppb. That would dramatically increase the overall rate of methane removal; 2. Highly photosensitive (to visible and UV light) titanium peroxo-hydroxide aerosol particles with aqueous chloride/nitrate coats; and 3. Iron Salt Aerosol (ferric chloride) that: a) removes methane by Cl· in a heterogeneous photocatalytic cycle [217], and b) induces bursts of OH· and Cl· radicals in clouds by Fenton reactions.

For further details see [218].

Table 2 below provides schematic summary descriptions of these DCC approaches.

Table 2: Description of Direct Climate Cooling (DCC) Approaches

Table 2: Description of Direct Climate Cooling (DCC) Methods

Approach	Scalability: Local(L), Regional (R), Global (G)	How it works (principles & feasibility)	Zones of Operation	Potential Benefits	Potential Risks & Side Effects	Evidentiary Basis
Afforestation, Reforestation, Soil & Vegetation Restoration (ARSVR)	LR	Increases evapotranspiration which increases cloud formation which contributes to regional cooling.	Land with appropriate temperature, wind, vegetation species, soil water retention capacity, water availability, and altitude.	Run-off and erosion reduction, flood protection, carbon drawdown and sequestration, increased biodiversity, improved agricultural production and nutrient content.	Can cause warming or interfere with weather and ecosystem functions if not used in appropriate locations	Multiple longitudinal studies in various locations throughout the world, e.g., Eastern US, South America and Africa.
Buoyant Flakes	LR	Photosynthesis by phytoplankton. Albedo Enhancement. Carbon sequestration.	Global, nutrient-deficient, surface waters	Albedo cooling sufficient to offset current warming. Restoration of marine biomass & fisheries. Destratification. Oxygenation. Substantial & longterm carbon sequestration.	Benthic hypoxia	Ocean fertilization by aeolian & meteoric dust, volcanoes and 13+ sea trials.
Cirrus Cloud Thinning (CCT)	LR	Cloud seeding changes ice formation mechanism, allowing more thermal radiation to escape to space.	High latitudes during winter	Longwave cooling may be sufficient to offset current warming in Polar Regions, depending on extent of cirrus cloud coverage, low cloud coverage and other factors.	Could alter weather patterns, possibly for the better.	Seasonal changes in mineral dust appear consistent with a "CCT effect" based on satellite remote sensing of cirrus cloud properties.
Fizztops	LR	Twomey Effect. Monodispersed nanobubbles generated efficiently by PV-powered fluidic oscillators.	Warm oceans	Mid term (months) water cooling & shading. Enhanced evaporation. Protection of coral reefs & mariculture operations. Realtime environmental sensing.	Ocean cluttering	Existing ocean sensors
Ice shields	LR	Ice thickens fastest when intermittently-pumped seawater flows thinly over a forming ice cone. Powered by cold-adapted, commercial, anchored wind turbines. Rejected brine carries gasses to the seabed.	Wherever sea ice forms in winter	Albedo, convective and radiative cooling from the new ice and snow generated. Sequestration of oxygen and CO2 in the depths. Reduced warming by currents. Glacial retardation. Polar habitat improvement. Methane and smog removal.	Equipment breakdown.	Successful projects to build ice roads, airfields and drilling platforms.
Marine Cloud Brightening (MCB)	RG	Twomey Effect	Clouds	Targeted regional or global cooling	Warming from incorrect droplet sizes	Marine Stratocumulus Clouds
MEER mirrors	LR	Surface solar reflection and selective emission of thermal infrared in the 8-13 um atmospheric transparency window	Land and calm water surfaces	Strong local cooling of soil and vegetation surfaces. Reduction of transpiration water loss from agricultural land. Cooling and preservation of freshwater bodies. Reduction of residential and industrial cooling and heating energy consumption. Increases soil carbon uptake. Reduces freshwater methane emissions.	Cloud feedback and circulation impact at and beyond regional scales remain to be experimentally evaluated	Field experiments have shown reduction of indoor air temperature by up to 7 degrees C, reduction of evaporative freshwater loss by up to 90%, and reduction of soil surface temperature by 10 degrees C.

Table 2: Description of Direct Climate Cooling (DCC) Methods (continued)

Method	Scalability: Local(L), Regional (R)	How it works (principles & feasibility)	Zones of Operation	Potential Benefits	Risks & Side Effects	Evidentiary Basis
Mixed-phase Regime Cloud Thinning (MCT)	LR	Seeding mixed phase clouds with ice nucleating particles to reduce their water content, coverage, and heat-trapping effect.	High latitudes during winter	MCT could offset about 25% of the expected increase in polar sea-surface temperature due to the doubling of CO2. This is accompanied by an annual increase in sea-ice surface area of 8% around the Arctic, and 14% around Antarctica.	Seeding concentrations > 100,000 per liter may be needed for cooling the Arctic. The impact of MCT on the hydrological cycle and precipitation remains to be assessed.	Conventional cloud seeding operations.
Ocean Thermal Energy Conversion (OTEC)	LR	Thermodynamics, the heat of global warming is partially converted to work in accordance with the First Law of Thermodynamics and a heat pipe facilitates the movement of surface heat to the deep in accordance with the Second Law.	Tropical oceans	Ocean cooling combined with energy production and carbon sequestration.	Working fluid may be toxic to marine life. Mitigated by use of CO2 as working fluid.	A proposed, closed cycle prototype will: reinforce the results of previous ocean thermal energy conversion experiments, and measure CO2 content of both a warm and cooler atmosphere.
Seawater Atomization	LR	Commercial, spray nozzles modified to run at higher and triphasic pressures on masts linked to floating wind turbines. Sublimation of iron salt aerosols (ISA) . Large droplet removal via cyclonic baffles.	Most oceans	Cooling derived from seawater evaporation, convection, marine cloud formation, condensation and precipitation plus that due to sea salt aerosols and ISA photocatalytic oxidation. Amelioration of extreme weather. Irrigation & afforestation	Insufficient narrowness of topmost, seawater particle size distribution	Current, internally-mixed, biphasic, misting nozzles.
Stratospheric Aerosol Injection (SAI)	RG	Solar reflection	Stratosphere	Global, possibly regionally focused (e.g., polar regions)	Large, unbalanced and abrupt deployment, or cessation of deployment, may disrupt monsoons and other weather patterns or lead to termination shock. They may also have moderate impacts on stratospheric ozone, and natural atmospheric methane depletion. The biggest challenge appears to be one of global coordination and governance.	Volcanoes and climate model studies
Surface Albedo Modification of Ice and Snow	LR	Solar reflection	Cryosphere	Reduces daytime peak and average temperatures	In some cases reflected solar energy might instead be used to generate electricity while also limiting daytime peak and average temperatures.	Hollow glass microspheres and clay based reflective materials
Tree Planting and Reflective Materials	LR	Urban canopy provides shade and through evapotranspiration, limits storage of heat in urban surfaces. Reflective and radiative roofing, hardscape, and building materials increase albedo so sunlight and solar energy are reflected back to space rather than absorbed and retained by surfaces and mass.	Land when reforestation sites and species are selected to maximize cooling effect. Reflective and radiative materials (gray infrastructure) are effectively used to mitigate urban heat and can also be used in agriculture settings.	Regional atmospheric cooling, increased albedo in urban settings to reduce heat island effect.	Poor siting practices and maintenance can exacerbate heating, limit cooling effect, increase pedestrian heat exposure, and increase heating requirements in cold season.	Multiple longitudinal studies in various locations throughout the world, e.g., European parts of Asia, and US cities.
Tropospheric Aerosol Injection (TAI)	RG	Twomey effect, and increased methane removal by naturally increased oxidative radical production by cloud droplets and photocatalysis.	Low lying clouds and haze, mainly stratocumulus, 30% of the ocean. Buoys, shipping, power plants, gas flares. Photoreactors.	Cool the oceans, halve methane concentration, protect ozone layer, reduce black carbon aerosol (soot) reaching stratosphere and polar ice sheets.	Potential for controllable weather alteration, could enable rainfall pattern restoration. Protects ozone layer by removing black carbon aerosol and long-lived halogenated gases. Could help refreeze polar ice by nucleating ice particles in winter and brightening clouds in summer.	Numerous lab tests and peer reviewed papers.

Note: Column headings from left to right refer to: a) name of the DCC approach, b) its potential near-term scalability or level of cooling impact, c) summary technological description of how the method would potentially work, d) where it would likely be most effective, e) its possible risks and side effects and f) current evidence for its DCC potential.

6. Challenges and Opportunities

With global warming near to exceeding the 1.5°C Paris Agreement target, there is a clear, urgent need to find approaches that could, if implemented, exert near-term cooling influences around the globe. We mean that within a decade, commitment to research and initiate deployment of such interventions must be incorporated into the Conference of the Parties policies and agreements if we hope to stabilize global temperatures and avert the most catastrophic climate change impacts.

The set of Direct Climate Cooling (DCC) approaches presented in Table 2 reflects the authors' assessment of initially researched approaches that, appropriately deployed in the *near-term*, could be used to exert a local, regional, or global cooling influence. DCC methods designated as RG could be deployed to have 'medium to large leverage' as their influences would be broadly exerted in the stratosphere or via the troposphere's clouds and winds. DCC methods designated as LR could be deployed to have 'small to medium leverage' as their influences would be generally confined to local or regional areas. Taken together, the approaches presented here exhibit a range of characteristics (e.g., low-leverage to high-leverage; low to higher cost; rapidly scalable to global scales or not; with or without major co-benefits; most useful at local to global scales; already initially deployed to only minimally researched; etc.).[10] Here we simply present possibilities, leaving to further research and consideration which ones, deployed singly or together with others, would best be deployed as part of an integrated approach to complement the emissions reduction and removal and abate the intensifying climate emergency.

As indicated throughout Sections 1-5, and in view of the high likelihood that GHG emissions reduction and removal will not limit temperature rise and associated climate change impacts in this century, we argue that not trying to deploy DCC is the 'moral hazard' now confronting humanity. We acknowledge that the potential for unintended consequences merits attention and that further research and establishment of a governance structure are needed [144,219]. Our position is that the need for DCC is urgent and must immediately begin to be met.

Waiting until full governance is wholly in place to begin climate intervention will be too late. Delays in establishing critical globally agreed upon deployment protocols may lead to abrupt, unilateral, unjust, and/or non-transparent deployments of very high-leverage DCC methods by individual countries or coalitions to benefit themselves. Such actions could cause serious political or economic tensions and conflicts with powerful actors who do not judge the deployment to be in their own best interest [220]. We believe that in many cases national and local jurisdictions can apply protocols that enable transparent research and pilot testing to be conducted and establish a process for responsibly scaling up deployment to local and regional levels within their jurisdictions. For these and other reasons we do not believe it is necessary or prudent to restrict current DCC efforts to research and localized field trials, as proposed in many of the documents supporting DCC research [81–83,85,87,88].[11]

As discussed in the DCC method summaries, several DCC methods can be applied at local scale to exert a cooling influence and provide other benefits at little to no risk. Some regional scale efforts seem unlikely to have significant "cross- boundary" impacts. For example, the ongoing efforts to "save the Great Barrier Reef" using MCB seem unlikely to have long-term effects [142,221]. These applications are of short duration and mainly targeted at limiting extreme ocean heating events. The gyre pattern of ocean currents around the Great Barrier Reef would also limit potential "cross-boundary" impact [142,221] It may also be possible to coordinate regional DCC interventions that could have 'cross-boundary' impacts by building upon current bilateral or regional legal frameworks that address

[10] Technical feasibility is not addressed in table 2 but is discussed in detail in many of the approach summaries.

[11] These reports and open letters generally, and sometimes inaccurately, refer to DCC as 'SRM'. For example, the National Academy of Science SRM report [81] labels CCT, MCB, and SAI as SRM though as noted in figure 3 CCT is based on thermal radiation modification (TRM) rather than SRM. They often also use the term SRM but implicitly or explicitly are focused on abrupt, or rapidly ramped up, large-scale global SAI deployment (commonly referred as 'geoengineering'). These inaccuracies and ambiguities in nomenclature have unfortunately contributed to discussions that are not always well-informed with regard to the benefits or risks of SAI or DCC.

concerns arising from "cloud seeding" that enhances precipitation in some locations but might increase harmful climate outcomes in others [222].
Climate interventions that are more likely to cross national boundaries pose a greater challenge [223]. But again, scaling DCC methods like MCB for regional application may be more easily coordinated across national boundaries than current common geophysical engineering projects such as building a dam on a major river that blocks or reduces the flow of water downstream.

It may be possible to pilot-test and gradually deploy high-leverage DCC methods, like SAI, at a regional scale without global governance and coordination by following the Great Barrier Reef MCB example. SAI could be pilot tested with consent from affected communities and authorities in accordance with an international, voluntary and transparent 'coalition of the willing' agreement. If successful, such an endeavor could build global trust and confidence in the same way as the international space station has done [224].[12]

In some cases, sufficient authority to deploy a cooling mechanism may already be in place. The International Maritime Organization (IMO) could, for example, address the unintended global warming produced by its (well-intended to protect human health) maritime fuel sulfate content restrictions, under its existing authority [2,23,225]. First, it could immediately adopt an emergency regulation relaxing 2015 and 2020 shipping fuel sulfate content restrictions in the "high seas". The intent would be to resume sulfate aerosol cooling over the high seas while avoiding significant human health impacts on coastal and island populations. Second, as a long-term solution, the IMO could support research and implement regulations requiring use of alternative fuels or power sources (see section 5) and the emission of aerosol precursors more benign than sulfates to human and environmental health, to replace the prior beneficial global cooling from using fossil fuels [23]. As noted in section 1, these measures alone could produce significant, urgently needed, DCC.

It is unlikely that high-leverage regional and global scale DCC methods could be effectively weaponized, as has been hypothesized by some [220,226]. The DCC method that is most often discussed in this context is SAI. However, modeling indicates that SAI could not be specifically targeted over nation states with reasonable accuracy. Although it might be possible to influence some geographic and seasonal variations in precipitation with carefully modulated SAI deployments, latitudinal and longitudinal mixing in the stratosphere make geographically specific outcomes exceedingly difficult, if not impossible [227,228]. It appears that only general latitudinal targeting is possible with SAI. That is why polar SAI deployment in the spring has been proposed as the most practical and efficient way to pilot regional-scale SAI efforts to produce summer polar cooling [16,229].

An additional practical impediment to weaponized deployment of SAI is that only a small number of countries either have, or have the capability to develop, aircraft that could loft the large payloads necessary for an effective SAI program, and the military propulsion technology necessary for this is not available for sale or purchase without at least tacit acquiescence by nations that have this technology such as the US, UK, EU and possibly a few others [228,230]. Also, it appears that only one country, the US, currently has aircraft that can loft large enough payloads to the stratosphere to initiate an effective pilot SAI program, though new customized planes would need to be developed to do this efficiently over a long period [177,228]. The US SABRE (Stratospheric Aerosol processes, Budget, and Radiative Effects) program is in fact currently using two high-altitude research aircraft that can loft payloads into the stratosphere, equipped with sampling instruments, to measure the properties of aerosols in the upper troposphere and lower stratosphere [231,232].

[12] Pending further polar *winter* cloud cover research, gradual pilot testing of polar CCT or MCT might also be advisable as part of a comprehensive coordinated effort to 'save the Arctic and Antarctic polar regions' (and possibly these and other DCC methods in all three 'polar' regions including the Himalayan 'third pole').

Finally, as with much of modern infrastructure, it might be possible to interrupt an SAI program by sabotaging its infrastructure or supply chain in hopes of ending the deployment.[13] However, it is hard to understand what the incentive for this would be given the "shockingly strongly favorable" results from roughly a hundred studies that suggest pervasively beneficial impacts of SAI [18]. And, as with other critical infrastructure, this risk, and the possible "termination shock" risk that could result from an abrupt and complete cessation over an extended time, could be significantly reduced through redundancy and protective measures that make it more unlikely.

The ultimate goal and need is to develop comprehensive DCC governance and coordination for DCC efforts with significant cross-regional or global impact. Both implicit and explicit global coordination governance regimes are likely to evolve over time as the scale of DCC deployment grows larger. Building global, public, and political trust and confidence through gradual, local, and regional pilot testing of potential DCC efforts is critical to the development of comprehensive DCC global coordination and governance frameworks.[14] Pilot testing and "learning by doing" to complement continued research will enable a fuller understanding of the potential impacts, positive and negative and near- and long-term, of large-scale DCC.

7. The Necessity for Direct Climate Cooling as a Policy Complement to Emissions Reductions and Carbon Removal

Based on the most recent IPCC AR6 WG3 estimates, net global anthropogenic GHG emissions would have to be reduced to 33 GT CO2eq by 2030 and reach net zero emissions by 2050 to put the Earth's climate on a path that keeps average global warming below the Paris Agreement's 1.5°C target through the 21st century. To stay under 2.0°C, emissions would have to be below 44 GT CO2eq in 2030 and net zero emissions reached by 2070 [3]. Global GHG emissions were roughly 58 GT CO2eq in 2022 [4]. Remaining below 1.5°C would therefore require average global emissions reductions of 6.8% a year from 2022 to 2030, and 3.4% a year to remain below 2.0 °C.

Though 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 at rates ranging from 3.4% to 6.8% a year to stay "well below 2.0°C" through the 21st century. It is becoming more and more likely that, without direct climate cooling, the 1.5°C and 2.0°C thresholds will be breached well before 2050. The World Meteorological Organization conservatively estimated in 2022 that there was a 50 percent chance that the annual average global temperature increase would exceed 1.5°C in at least one year by 2026 [235]. As shown in figure

[13] Though this may be more difficult than with other critical technologies as, for example, there is an abundant supply of sulfur in the world [233].
[14] It should also be noted that, depending on the DCC approach, there are significant overlaps between the governance expected to be needed for deployment of DCC approaches, and of GHG emissions reduction and carbon removal programs. For example, the key issues for the latter efforts include the collective-action free-rider problem, and the need to mobilize massive resources rapidly and fairly through public and private mechanisms. The challenge of funding actions needed to achieve a global 'public good' through a negotiating process that lacks mandatory global governance and cannot mandate rapid resource transfers from rich to poor, has been a principal cause of our current inability to bring climate change under control [19]. To be deployed at scale, some forms of DCC similarly need large public and private resource mobilizations to exert a sufficient cooling influence, thus providing a global benefit with large externalities. However, initiating polar-focused SAI, and later, global SAI deployment would likely require a much smaller mobilization of public and private resources to achieve global benefits. As in the case of GHG emissions reductions and drawdown efforts, in the absence of a public effort private actors have begun filling the void by initiating DCC efforts based on 'cooling credits' that exploit the (almost) pure 'public good' characteristics of mid-latitude SAI [234]. However, this un-coordinated private sector approach to DCC only works in this case because it has an insignificant impact on global cooling. As noted, in the body of the paper above, only a small number of national actors have the potential ability to deploy or sanction the deployment of an *effective at-scale* SAI program.

1, 2024 daily and monthly average global surface temperatures have already exceeded 1.5°C, putting this year on trend to fulfill the WMO projection.

Analyses carried out by Zhou et al. [236], indicate that even if emissions were stopped immediately, long term thermal equilibrium would lead to warming of more than 2.0°C by 2100. This is consistent with the modeling results and estimates that cumulative anthropogenic 1850 - 2021 world GHG emissions were about 3,390.7 $GtCO_2eq$, or almost at 1,000 Gt CO_2 (or 3700 $GtCO_2eq$), in 2021, as discussed in section 2 [78,79,237].

In addition, the global cooling from fossil-fuel generated aerosols, notably sulfur from combustion of coal, and (until recently as noted in section 6) use of bunker fuel by ships, exert an estimated 0.5° - 1.1°C cooling impact [2,238]. As sulfur emissions are reduced over time to address other environmental and health concerns and as coal plants are shuttered, the warming influence of legacy GHG loadings in the atmosphere and oceans would very likely result in decadal-average increases in global average temperature exceeding 1.5°C, and possibly even 2.0°C [239,240].

Extreme heat waves on land and in the sea, glacial ice melting in all three 'polar' regions and increasing occurrence of both drought and intense storms are already putting the United Nations Sustainable Development Goals out of reach. With neither emissions reductions nor carbon removal able to reverse the warming trend over the next few decades, only deployment of direct cooling approaches has the potential to reduce the inevitability of increasingly frequent and severe catastrophic impacts. Metaphorically acting as tourniquets intended to save our bleeding planet, DCC approaches, applied thoughtfully, have the potential in the near-term to limit and offset warming until national efforts to cut emissions and build capacity to remove CO2 and other greenhouse gasses can sustainably halt and then reverse warming to pre-industrial levels. To moderate global warming before key impacts become irreversible requires a credible climate restoration plan that aims to push back global warming to no more than 1°C by 2050 be adopted and promptly implemented. Such a plan would have three complementary components:

1. Researching, field testing, and deploying one or more large-scale cooling influence(s) perhaps initially in polar regions and applying local and regional cooling measures that also support adaptation,
2. Accelerating emissions reductions with an early prioritization of methane and other short-lived warming agents.
3. Deploying large scale carbon removal to reduce the legacy loadings of CO_2.

In the absence of a committed effort to apply DCC to offset at least some of the increasing warming, the accumulation of GHGs in the atmosphere is projected with high confidence to continue driving harmful climate change and sea level rise. Severe impacts affecting the environment, coastlines, water supplies, and human health and wellbeing would continue for generations to come, with the world's poorest and most vulnerable nations and populations bearing the greatest burden.

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 require a fundamental transformation of the global economy [11,19,241]. Efforts to adapt to already committed warming will impose global population redistributions, coastal city relocations, and landscape transformations over coming decades, disrupting and reducing the vital ecological services provided by the Earth's ecosystems [2,40,242]. Focusing only on emissions reductions, even if augmented by carbon removal, will preclude the possibility of bringing the global average temperature increase back to levels that adequately moderate the accelerating pace of biodiversity loss, ecosystem disruption, severe storm amplification, and sea level rise and allow societies the time needed to manage the transition.

Deployment of appropriate direct cooling approaches is not a substitute for GHG emissions reduction and removal, which are essential. But these efforts have come too late and are progressing too slowly to avoid irreparable and irreversible harm to people and the environment. Choosing not to pursue direct climate cooling through a process and system that includes managing uncertainties is akin to not taking drugs to treat cancer because of possible side effects. Direct climate cooling can allow the time needed for GHG emissions reduction and legacy GHG removal to take effect while greatly reducing suffering in the process.

However the world proceeds, equity and environmental justice issues must also be addressed, especially to meet the United Nations' Sustainable Development Goals that aim to provide wellbeing, opportunity, and a safety net for all. Gaining global approval for researching and, as appropriate and needed, deploying cooling influences alongside GHG emissions reduction and removal measures will require attention to issues such as: providing a safe harbor for climate refugees, assisting in overcoming loss and damage from climate disruption, and transferring technology and funds for climate restoration and ecological regeneration from rich to poor countries and populations. Doing this rapidly (within decades) and at-scale will require significant funding.

At present, because fossil fuel combustion provides about 80% of the world's energy, the transformation to a new energy system based wholly on renewable energy is going to take time and place substantial demand on mineral resources. To meet this demand will require harvesting minerals from the ocean and carbon from the air to produce needed renewable and reusable energy materials and components worldwide [11,243]. Transforming supply chains and replacing today's single-use and other non-sustainable practices to create a circular economy is going to take time—and if climate change continues unconstrained the transition will take longer and be more difficult and require more funding and resource redistribution.

Over the thirteen years from 2006 - 2018 the Clean Development Mechanism that was part of the mandatory Kyoto Protocol transferred $303.8 billion from rich countries to poor countries for mitigation and adaptation [[244]. In contrast, the Paris Agreement voluntary Green Climate Fund (GCF) over the eight years from 2014 - 2021 raised only $18.2 billion [245]. To be equitable, GHG emissions reductions would need to proceed in parallel with sustainable economic development to offset the estimated $4 trillion in foreign exchange from oil and related products that countries depended on in 2019 for over 10% of their total export revenue. These countries comprise 1.1 billion people or 14.2 percent of world population [19] (Table 2). Quite clearly, the GCF is not adequate for assisting in recovery from disasters, aggressive GHG emissions reductions, and sustainable economic development.

More funds and financing mechanisms are needed. Meanwhile, throughout the transition, DCC can improve livability and reduce the damage and expense of climate impacts in these countries.

8. Conclusion

Global warming is accelerating, and its impacts are intensifying. Emissions reduction efforts are not forging the path to net zero emissions that was promised would relieve the world from climate change. Direct climate cooling is the only near-term option available for limiting further warming and moderating its devastating consequences. Many direct climate cooling approaches presented in this paper could begin implementation before 2030. Complemented with aggressive GHG emissions reductions and removal with an early prioritization of short-lived gasses such as methane, DCC measures have the potential to slow and possibly reverse the accelerating pace of temperature rise and corresponding extreme weather, polar ice sheet destabilization, loss of sea ice, and disruption of ocean currents, as well as diminish the threat of crossing critical tipping points.

The road to climate stability and a sustainable planet will ultimately require a complete transformation of global industrial civilization's economies, systems, and practices [11,19]. As the climate change crisis accelerates to catastrophic proportions worldwide, the current global policy construct only offers more aggressive depth and pace of emissions reduction and removal to respond. But the scope and pace of this response that would be required to avert ever more catastrophic warming in this century is not realistic within the existing political and economic world order. In contrast, it appears that deploying DCC incrementally in the near-term can realistically reduce and perhaps reverse climate change harm and risk, while proceeding in parallel with development of national and international governance capabilities and procedures. Overall, this approach appears both more politically and economically feasible to implement and more effective in reducing near-term climate calamity.

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. Existing social, governance, and economic norms have developed in concert with this way of life. This makes addressing the climate crisis, at least in the short-term, primarily a practical environmental and technological problem that must be tackled within existing social and economic systems. Direct Climate Cooling is a potential solution to this problem.

During at least the next several decades (and possibly longer), direct cooling will be essential to reducing peak 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. Humanity has never faced an existential threat so critical for the long-term survival of human civilization and the ecosystems on which we depend. Foregoing deployment of feasible direct cooling influences seems very likely to impose intolerable costs on future generations. Our time is limited but we have a choice – will we leave a legacy worthy of pride instead of remorse?

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In memoriam: our beloved colleague Stephen Hugh Salter, inventor, born 7 December 1938; died 23 February 2024, a pioneer in marine cloud brightening and first author of the marine cloud brightening section in this paper.

Open Research

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

1) Baiman, R. (2024). Incremental Polar SAI, the International Space Station, and Great Barrier Reef MCB. Mendeley doi: 10.17632/5z3t72n6rd.1
2) Clarke, S. (2021). Ice Shield Strategies. Mendeley Data: doi: 10.17632/n6vsy3zgg6.1
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7) Salter S. (2020). Sea level rise and ice recovery. Mendeley Data v2: https://data.mendeley.com/drafts/3sb9zk9rc9

These documents include proposals, hypotheses and preliminary results for which published, or peer reviewed, analyses are not yet available. Though the proposals, 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 discussions in the main body of the submission where these documents are cited. 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.

Archived Figures and References

1) Figure 1 archived 5/25/2024 in "OOCC cooling paper resubmission figures 1 and 2", Mendeley Data, V2, doi: 10.17632/xcxjv6dtj7.2
2) Figure 2 archived 5/25/2024 in "OOCC cooling paper resubmission figures 1 and 2", Mendeley Data, V2, doi: 10.17632/xcxjv6dtj7.2
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Conflict of Interest Statements

I, *Ron Baiman*, have no conflicts of interest to declare. I have read and agree with the contents of the manuscript and have no financial interest to report. I am a co-founder of and volunteer my time to the Healthy Planet Action Coalition (HPAC), which advocates research and rational deployment of direct climate cooling.

Jim Baird (contributor to OTEC approach summary) conflict of Interest Statement: I can claim no financial interest in the paper because my patent has been abandoned for lack of funding and my work has all been self-funded.

As an author of this paper and independent researcher I, *Sev Clarke*, have no conflict of interest, save that I am the inventor of the Buoyant Flakes, Seatomiser/ISA, Ice Shields and Fiztop approaches. The basic concept of none of these is to be, or has been, patented.

I, *Leslie Field*, have no conflicts of interest to declare. I have no financial interest to report. I have patents on the Surface Albedo Modification approach which is part of the research I am continuing through my current 501c3 nonprofit, Bright Ice Initiative. I volunteer a limited amount of my time to the Healthy Planet Action Coalition (HPAC), which advocates research and rational deployment of direct climate cooling.

The co-authors of the submitted publication titled: "Addressing the Urgent Need for Direct Climate Cooling: Rationale and Options," *Clive Elsworth* and I, *Franz D. Oeste*, are co-owners of the 2024 start-up company Climate Catalyst Research LLC (CCR). This company is located in Dover DE 19901, United States. The main task of this company is the research, research funding and development of climate cooling based on several natural atmospheric processes. These are: Oxidative depletion of the greenhouse gasses methane, VOC and hydrogen; cooling processes by sunlight reflection, plant-, microbial-, physical and chemically induced cloud aerosol interactions; and artificial approaches to trigger these natural interactions in the sense of maximizing oxidation and reflection without harming ecosystems and human health. These existing natural processes are all driven by aerosol photocatalysts which enhance cloud reflection by cloud condensation nuclei (CCN), and chemical reactions that generate photocatalysts (H_2O_2, HCl). Mineral dust, sea salt and our proposed artificial aerosols contain the photocatalysts ($FeCl_3$, TiO_2, $NaNO_3$) and the chemical catalysts (HCl). All this relates to our part of the text: Atmospheric Methane Removal with Iron Salt Aerosols.

I, *Michael MacCracken*, have no conflicts of interest to declare. I have read, edited, and agree with the contents of the manuscript and have no financial interest to report. I volunteer limited time to the Healthy Planet Action Coalition (HPAC), which advocates research and rational deployment of direct climate cooling.

I, John Macdonald, have inventions in the fields of marine cloud brightening and bright water which may in the future have commercial aspects in terms of cooling technologies.

*I, David L. Mitchel*l, have no conflicts of interest to declare. I have read and agree with the contents of the manuscript and have no financial interest to report. I am a co-founder of and volunteer my time to the Healthy Planet Action Coalition (HPAC), which advocates research and rational deployment of direct climate cooling.

I, *Suzanne Reed*, have no conflicts of interest to declare. I have read and agree with the contents of the manuscript and have no financial interest to report. I am a co-founder of and volunteer my time to the Healthy Planet Action Coalition (HPAC), which advocates research and rational deployment of direct climate cooling.

I, *Herb Simmens,* have no conflicts of interest to declare. I have read and agree with the contents of the manuscript and have no financial interest to report. I am a co-founder of and volunteer my time to the Healthy Planet Action Coalition (HPAC), which advocates research and rational deployment of direct climate cooling.

Ye Tao is the Founder and Director of MEER, a 501c3 fiscally sponsored project of Social and Environmental Entrepreneurs. Donations to MEER pay Dr, Tao's expenses for MEER's research, humanitarian and outreach programs.

Robert Tulip owns the internet domain rebrighten.com which may in future work on commercial aspects of cooling technologies.