Our Two Climate Crises Challenge: Short-Run Emergency Direct Cooling and Long-Run GHG Removal and Ecological Regeneration

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Forthcoming: *Review of Radical Political Economics* 54 (4)

Unedited Preprint

(Edited: 7/31/2022)

Abstract

We are facing a short-term cooling crisis and a long-term GHG draw down planetary ecological crisis. We must address both. The first requires emergency direct cooling, or temporary “triage” or a “tourniquet, for our bleeding planet”. The second requires rapid GHG emissions reductions and draw down and natural planetary regeneration that realistically will take at least a few decades and may take a century or more. Conflating the challenge and opportunity of the second crisis with a response to the first crisis will not produce a rapid and credible global response to the second crisis because of structural economic inequity and fossil fuel dependency that is deeply embedded in the current global economy. Realistically, we need emergency direct climate cooling to address the first crisis and a long-term binding global cap and trade emissions trading system to address the second. The Florin proposal that conditions SAI direct climate cooling on credible GHG emissions and draw down is a step in the right direction, but omits other direct climate cooling methods and effectively makes the deployment of SAI contingent on a global ETS that may not be possible before the deployment of SAI becomes necessary. Rather than conflating our two climate crises, or conditioning the solution of the first on a solution to the second, we need to address both on an emergency basis by putting all options on the table as called for in the HPAC proposal.

Introduction

We have not one but two climate crises. The first one is a short-run global warming emergency including amplified polar warming and global ice melt, that is causing an unraveling of the global climate, and risks pushing us over a possibly irreversible climate tipping point within decades. The second is a long-term greenhouse gas (GHG) removal and ecological regeneration crisis that will take at least several decades and possibly a century or more resolve. This paper attempts to discuss and outline a strategy for addressing both. It has five sections: 1) Our Two Climate Crises, 2) Background Political Framing, 3) The Limits of the Current Moral Suasion and Breakdown Strategies, 4) How Can Short-Run Emergency Direct Cooling, and Long-Run GHG Removal and Ecological Regeneration be Achieved, and 5) Conclusion.

1. Our Two Climate Crises

The current average global warming level of 1.2 degrees C above pre-industrial levels is causing irreversible and catastrophic damage to us and to other species. In the absence of efforts to immediately cool our planet, and particularly the polar and Himalayan regions (the "third pole"), we will forego the possibility that at least some of this catastrophic harm could be reduced or avoided. The global climate unraveling, much of which may be directly or indirectly attributed to the Arctic warming at three times the mid-latitude rate, or "Arctic Amplification", is already increasing the number and severity of extreme climate events and raising commodity prices (Sweeny 2019) (Artic Monitoring and Assessment Program 2021).

At current levels of warming we may begin to cross the first climate tipping point, a melting of summer Arctic sea ice, as early as this decade, see figure 1 (Lenton et al. 2020).

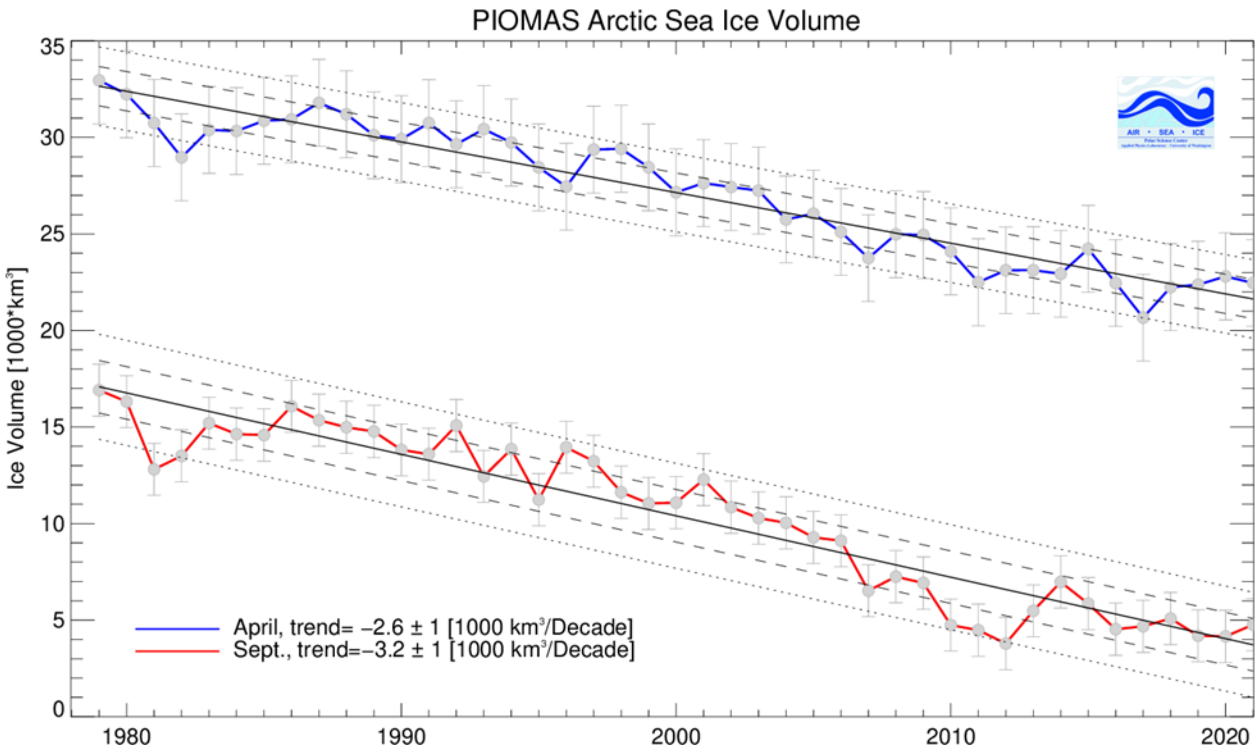

Figure 1: 1979-2021 Monthly Sea Ice Volume from PIOMAS for April and September

Source: Polar Science Center, Applied Physics Laboratory, University of Washington accessed December 26, 2021 at: http://psc.apl.uw.edu/wordpress/wp-content/uploads/schweiger/ice_volume/BPIOMASIceVolumeAprSepCurrent.png.

Estimates included in Pistone, Eisenman, and Ramanathan (2019), and corroborated by multiple other studies using different data and methodologies cited in this paper, suggest that crossing this tipping point would have a radiative forcing impact equivalent to that of 25 years of GHG emissions at current rates. Resetting this estimate to a 2016 baseline reduces this to 17.3 years of additional GHG emissions from 2016 to a completely ice-free summer Arctic (Baiman 2021: footnote 6).

A November report by Swiss Re, one of the world's largest reinsurance companies, estimates that at the current trajectory, global temperature is likely to rise to 2.6 degrees Celsius above pre-industrial levels and will reduce world gross domestic product (GDP) by $23 trillion by 2050 (Swiss-Re 2021). Poor countries will suffer the most. To put this in perspective, current (2020) world GDP is estimated at $84.54 trillion (Statistica 2022). In the Swiss Re scenario, the potential GDP of the United States, United Kingdom, Canada, and France would decline by 6 - 10 percent, while the GDP of Malaysia, the Philippines, and Thailand would be reduced by one third.[1] But these are most likely underestimates, as the Swiss Re report (2021: 30) acknowledges that: "Importantly, the framework does *not* consider tipping points, events such as the partial disintegration of ice sheets, biosphere collapses, or permafrost loss, that pose a threat of abrupt and irreversible climate change. This is because it is thought that tipping points will materialize well after the model horizon of mid-century only."

But the assumption that tipping points will not materialize until after mid-century (2050) is almost certainly incorrect. Based on the trend shown in figure 1, we are on track to begin crossing the first tipping point, the complete loss of summer Arctic sea ice, by 2034.[2] Based on the trends shown in figure 1, by 2050 the Arctic will be ice free for several months. This will

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[1] Chapter 16 of the 2022 IPCC AR6 WGII report, just released though subject to final edits, contains a plot of statistical modeling estimates of percentage loss in global GDP for different levels of global warming "Figure Cross-Working Group Box ECONOMIC.1" (IPCC 2022). Panel a) of this figure shows estimates of approximately 5–25 percent GDP loss from global warming of 2.6 degrees Celsius from "Statistical modeling" of past trends. Panels b) and c) show much smaller, estimated approximately 0–5 percent GDP loss ranges, from "Structural modeling" or economic climate models like the sharply critiqued Nordhaus Dynamic Integrated Climate-Economy model (Keen 2020), and (prior) "Meta analysis" of the literature. Interestingly, like the Swiss Re report, the end of chapter 16 includes a discussion of the now greater global risk from "Large-scale Singular Events" (referred to elsewhere in the literature as "tipping points") that could significantly affect these economic impact estimates. A number of the most concerning of these are discussed but curiously there is no reference to the almost certain (in the absence of emergency direct cooling) imminent crossing of the first tipping point, the complete melting of summer Arctic sea ice (Lenton et al 2020).

[2] Figure 1 indicates ice volume of about 4 (1,000 km3) in September 2021 and a trend of -3.2 (1000 km3) loss per decade. As 4/3.2=1.25, this suggests September zero ice volume in 2021+ 12.5 = 2033.5, or by 2034.

increase the risk of crossing other potentially more catastrophic tipping points, such as massive methane release from Siberian permafrost melting and a collapsed Atlantic Gulf stream—both related to Arctic amplification, that appear also to be starting far earlier than previously estimated (Lenton 2020; Kindy 2021).

In fact, current levels of warming can already be linked to increasing climate catastrophe and rising commodity prices. Though it is impossible to directly link any single catastrophe to climate change, a 2021 report by Christian Aid found that the six years with the costliest (over $ 100 billion) climate disasters have occurred since 2011 (Christian Aid 2021), and a recent *Wall Street Journal* article also notes that extreme weather is a major factor in the 2021 run-up in regional and global and energy and commodity prices including: wheat, tin, coffee beans, natural gas, fertilizer, cement, steel, and plastic, including resins, additives, and solvents (Dezember 2021).

There is no doubt that in the long run, until we are able to stop emitting GHGs and are able to draw down atmospheric GHG by well over a trillion tons of carbon dioxide equivalent (CO_2eq) these impacts will worsen. This effort will likely take at least several decades and possibly more than a century.[3]

For all these reasons it is imperative that we implement emergency direct cooling measures, with a particular focus on restoring ice or slowing ice melt in the polar regions (including the Himalayan "third pole") immediately. We cannot afford to wait for three decades, and probably

[3] For example, my own estimates from data in Schuckmann et al (2020) suggest that about 1,700 billion tons of CO_2 would be needed to be removed to get back to the 1989 level of 353 parts per million CO_2 in the atmosphere.

longer, to achieve zero emissions and remove sufficient GHGs from the atmosphere to prevent continued and accelerating climate deterioration.

2. Background Political Framing

The dominant discourse on climate change has for many years been framed as a Manichaean battle. The "deny or do nothing" position is most prevalent in the United States and a handful of other countries. This view has presumably weakened as calamitous climate events that can be traced to global heating occur more frequently. However framing the climate crisis as a dichotomous, moralistic (fossil fuel use is an "original sin"), political left/right, existential fight for survival continues to hold sway.

This frame has become dominant for good reasons. It contains kernels of truth. Special interests including fossil fuel interests, right wing billionaires, media moguls, and oligarchic elites, have conspired to deny the truth and block GHG mitigation and adaptation efforts. The resulting faltering political response, particularly at the critical global level, has been wholly inadequate and dispiriting. And of course, in an already unconscionably inequitable world, the poorest and most vulnerable have and will suffer the most.

Though this frame is understandable, it has become an obstacle to practical progress as it:

a) Does not offer hope, particularly in the face of repeatedly backsliding or inadequate political responses.

b) Frames climate change in purely moralistic or political terms and ignores physical infrastructure, and other embedded social and political constraints, that block or slow GHG mitigation.

c) Fails to fully account for the imperative of lifting up standards of living for billions of people even as GHG emissions are reduced.

d) Most importantly, it offers no immediate relief for climate change induced suffering due to already "baked in" effects that will be ongoing and worsening even if GHG emissions are reduced to zero now and does not recognize that addressing the climate crisis in the short term is a practical problem of urgently applying *a technological tourniquet to a critically bleeding planet*. It also does not acknowledge that the longer term GHG emissions reduction and draw down, necessary for climate restoration and ecological regeneration, must take place within *existing* social and economic systems that themselves will take much longer to evolve.

An alternative frame will recognize that:

a) Closing the carbon cycle is a long run *opportunity* for human civilization to evolve from "industrial hunter gatherer" dependent on discovering and mining fossil fuels and minerals in particular locations, to a potentially more equitable, prosperous and ecologically sustainable, "industrial farmer-cultivation" civilization (Baiman 2020). This new civilization will be based on a "Renewable Energy and Materials Economy" able to cultivate and harvest energy, and use minerals from the ocean and carbon from the air to synthesize materials, almost everywhere on the planet (Eisenberger 2020).

b) Fossil fuel use was not an "original sin", but the basis for modern industrial civilization and addressing the climate crisis is, at least in the short term, not fundamentally a moral and political problem, but a practical and technological problem that must be addressed within existing social and economic systems.

c) We must address equity or our efforts will fail (section 3 b).

d) During the critically important short-term (at least several decades but possibly much longer) transition period we must keep the climate from spiraling out of control by applying an emergency "tourniquet" to try to slow or reverse the worst climate impacts, and particularly the first imminent Arctic sea ice melting tipping point (section 1).

An even more comprehensive framing can also be found in a proposal put forth by the Envisionation group (Pearce 2022). This plan estimates that regenerating land and ocean fertilization to prior levels of life could potentially sequester organic carbon equal to roughly 87 percent of the carbon draw down necessary to achieve a sustainable global climate that is no warmer than 0.5 C above preindustrial by 2050. The rest of the sequestration would be roughly divided between natural biological and geological methods, and mechanical methods. Natural methods could include: expanding forests and marine life, rock weathering, and biochar and basalt soil carbon enhancements (Baiman 2020). Mechanical methods could include "Direct Air Capture" like the negative emissions (better than zero emissions) electric power generation, and "Carbon Capture Sequestration and Use" technologies (Baiman 2021).

Though Direct Air Capture and other technological methods may be orders of magnitude faster and less land intensive than pure nature-based methods, this general proposal would address the natural ecological devastation on multiple fronts incurred by "hunter gatherer," one-way carbon cycle burning, industrial civilization, that will be needed for long run sustainable human and other species survival on the planet (Pearce 2021: 67, 77; Baiman 2021; Steffen et al. 2015).[4]

3. The Limits of Current Moral Suasion and Breakdown Strategies

In addition to opposition by vested interests and misguided or corrupt actors, two important factors are standing in the way of practical solutions to our short-run and long-run climate crises: a) disciplinary siloization, and b) real economic and political constraints to implementing a meaningful and rapid transition to a renewable and sustainable economy (Baiman, 2021).

a) Disciplinary Siloization

Climate scientists have been documenting the looming Arctic climate tipping point and the abrupt and potentially catastrophic impact of its crossing for years but do not see themselves as responsible for proposing solutions. On the other hand, social scientists, who are working on trying to develop plans and estimates for solutions, are focused on politics, economics, and technology, that are rightly viewed as the fundamental source of the problem. Emergency direct cooling therefore falls outside the traditional scopes of both climate scientists who are focused on documenting and understanding climate change, and social scientists and engineers focused on GHGs emissions. The possibility and urgency of attempting to slow or reverse the crisis and the

[4] Some Direct Air Capture methods such as Klaus Lackner's "mechanical trees" are reportedly able to draw down carbon 1,397 times faster than natural trees so that a "forest" of only 250 square miles of these trees (at 120,000 trees per square mile) could draw down about one gigaton of CO_2 a year (Baiman, 2021: 617), At scale Carbon Dioxide Removal pessimists generally omit low cost or profitable natural and technological options such as Kelp arrays with ocean upwelling (a 2022 winner of a one million dollar xprize for carbon removal) and Direct Air Capture using waste heat from natural gas power plants that transforms electricity generation into a negative emissions technology (Genevieve 2022; Climate Foundation 2022; Eisenberger 2020) They also appear oblivious to the fact that there is no alternative but to implement Carbon Dioxide Removal as simply cutting emissions—even to zero, will not stabilize the climate due to already accumulated GHGs in the atmosphere and oceans.

first climate tipping point is thus not being addressed by any government or international body. This lack of action persists, despite relatively modest cost estimates of $ 1–10 billion for some of the well-known proposals (Baiman 2021, table 1: 8).

b) Political and Economic Constraints to Rapid Global GHG Removal

Two examples starkly demonstrate the political and economic constraints to rapid GHG removal.

In 2007, President Correa of Ecuador, a poor and highly indebted country, asked wealthy countries and donors to pay Ecuador $3.6 billion into a fund to offset half of the estimated $7.2 billion future revenue from newly discovered oil in in the Ecuadoran rainforest one of the most diverse ecosystems on the planet and the home of three indigenous tribes. But by 2013 the fund has raised only $13 million and $200 million in promises, so Correa dissolved it and oil drilling began (Goldman 2017).

More recently, in 2020, Equip, the state oil company of Norway, an environmental leader and one the wealthiest per-capita countries in the world, opened up a giant new North Sea oil field estimated to contain oil that could, using “green” extraction technologies, generate more than $100 billion for Norway (Kottasovana 2020).

Aggregate data show that these economic and political constraints are not limited to a small number of countries. Table 1 shows that in 2019 over 1.5 billion people (20 percent of the global population) lived in small, or low and medium income, states for which on average (weighted by population) 26 percent of total exports are liquid fossil fuels and related products that in 2019 generated approximately $149 billion of vital foreign exchange for these countries.

Fuel Exports as a Share of Total Exports and GDP (2019, 72 ECA, OSS, and SSA Countries)					
Country Name	**Country Code**	**Pop 2019 (millions)**	**Fuel Exports % Total Exports**	**Fuel Exports % GDP**	**Fuel Exports $ (millions)**
Europe & Central Asia excluding high income (ECA)	ECA	418.8	27.3%	9.1%	$85,733.1
Other Small States (OSS)	OSS	31.4	45.5%	26.3%	$43,037.8
Sub-Saharan Africa excluding high income (SSA)	SSA	1106.9	25.7%	6.1%	$20,181.8
Weighted Avg by Pop			26.5%	8.2%	
Total		1557.1			$148,952.8
Share of Global Total		20.2%			

Table 1: Fossil Fuel Export and GDP Share of Small States, and low income Sub-Saharan African and Europe and Central Asian, Countries, Comprising 20 percent of the Global Population.

Source: Author's calculations from World Bank data accessed November 28, 2021 at: www.worldbank.org/indicator/. Fuel Exports are SITC Revision 3, "3. Mineral Fuel, Lubricants, and Related Materials." ECA countries (20) are: Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Georgia, Kazakhstan, Kosovo, Kyrgyz Republic, Moldova, Montenegro, North Macedonia, Romania, Russian Federation, Serbia, Tajikistan, Turkey, Turkmenistan, Ukraine, Uzbekistan. OSS countries (33) are: The Bahamas, Barbados, Antigua and Barbuda, Bhutan, Guinea-Bissau, Guyana, Iceland, Jamaica, Kiribati, Lesotho, Maldives, Malta, Marshall Islands, Mauritius, Federated State of Micronesia, Montenegro, Namibia, Nauru, Palau, Qatar, Samoa, San Marino, Sao Tome and Principe, Seychelles, Solomon Islands, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname, Timor-Leste, Tonga, Trinidad and Tobago, Tuvalu, Vanuatu. SSA countries (19) are: Angola, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Tanzania, Togo, Uganda, Zambia, and Zimbabwe. Note: Guinea-Bissau (2019 Pop. 1.9 million) is included in both the OSS and SSA countries.

A similar analysis by country shown in table 2 indicates that in 2019 1.1 billion people (14.2 percent of the roughly 7.7 billion global population) lived in countries for which liquid fossil fuel exports and related products constitute over 10 percent of total exports, and these generated over $4 trillion of foreign exchange for these countries.[5]

[5] Proposals for a "Renewable Energy and Materials Economy" transition in developing countries are outlined in this recent "Energy Equity and the Climate Crisis" Summit Report (ECI Energy Equity 2022).

Fuel Exports Percent of Total Exports and Value (2019, Current $, By Country)							
Rank	Country Name	Fuel Exports % of Total Exports	Fuel Exports $ (millions)	Cumulative Fuel Exports $ (millions)	Pop (millions)	Cumulative Pop (millions)
1	Brunei Darussalam	82.2%	6,412.0	6,412	0.4	0.4
2	Kuwait	79.9%	898,052.9	904,465	4.2	4.6
3	Qatar	70.4%	64,774.0	969,239	2.8	7.5
4	Norway	54.3%	21,680.7	990,920	5.3	12.8
5	United Arab Emirates	50.8%	1,280,868.5	2,271,788	9.8	22.6
6	Russian Federation	45.3%	218,119.3	2,489,907	144.4	167.0
7	Kazakhstan	42.6%	1,332.1	2,491,239	18.5	185.5
8	Ecuador	35.1%	8,746.3	2,499,986	17.4	202.9
9	Mongolia	34.1%	2,135.5	2,502,121	3.2	206.1
10	Nigeria	31.7%	842.5	2,502,964	201.0	407.1
11	Malta	24.3%	349,875.3	2,852,839	0.5	407.6
12	Barbados	22.9%	929.6	2,853,769	0.3	407.9
13	Cyprus	20.7%	1,051.2	2,854,820	1.2	409.1
14	Indonesia	20.5%	13,365.7	2,868,186	270.6	679.7
15	Belarus	17.6%	8,142.2	2,876,328	9.4	689.1
16	Fiji	16.0%	1,367.7	2,877,695	0.9	690.0
17	Samoa	15.7%	99,321.6	2,977,017	0.2	690.2
18	Jamaica	15.3%	136,454.8	3,113,472	2.9	693.1
19	Australia	15.2%	51,294.1	3,164,766	25.4	718.5
20	Ghana	14.6%	12,017.4	3,176,783	30.4	748.9
21	Egypt, Arab Rep.	14.5%	7,680.4	3,184,464	100.4	849.3
22	Senegal	11.8%	77,796.1	3,262,260	16.3	865.6
23	Brazil	11.4%	30,313.6	3,292,573	211.0	1,076.7
24	Lithuania	11.2%	725,712.2	4,018,286	2.8	1,079.5
25	Malaysia	10.7%	402.2	4,018,688	31.9	1,111.4

Table 2: Countries With Over 10 Percent Liquid Fossil Fuel Export Shares (2019)

Source: Author's calculations from World Bank Indicators accessed October 28, 2021 at: www.worldbank.org/indicator/. Fuel Exports are SITC Revision 3, "3. Mineral Fuel, Lubricants, and Related Materials." Some countries: The Russian Federation, Nigeria, Malta, Barbados, Belarus, Ghana, and Senegal, that are also included in this table are also included in one of the table 1 country groups.

4. How Can Short-Run Emergency Direct Cooling and Long-Run GHG Removal and Ecological Regeneration be Achieved?

The Healthy Planet Action Coalition (HPAC), a recently formed broad international coalition of leading climate scientists, policy experts, and activists, that includes the author, has proposed an "all options must be on the table" climate strategy.[6] The proposal was formulated in two letters sent to G20 and COP26 delegates, each signed by 33 and 46 climate scientists and public policy leaders, respectively. The latter also became a petition that was signed in short order by over 500 people (Healthy Planet Action Coalition 2021).

In our COP26 letter we asked that: "COP26 adopt a resolution committing to develop a climate restoration plan no later than 2023 to limit global warming to well below 1° C. An effective and responsible plan will need to integrate three approaches:

1. Cooling the planet, particularly the polar regions and the Himalayas,
2. Reducing GHG emissions, including methane and other short-lived warming agents
3. Removing legacy CO_2, methane, and other GHGs from the atmosphere."

Needless to say, HPAC has received no serious commitment or response from COP26 to this letter or from the G20 to our earlier letter. Nonetheless, we firmly believe that there is no other reasonable path forward for addressing the climate crisis.

Point 2, and now increasingly 3, have broad theoretical support in the climate science and policy making community, though that theoretical support has not translated into a robust political reality. But, per the discussion above, point 1 has little support, and with some notable and growing exceptions (National Academy of Sciences 2021; Council on Foreign Relations 2022;

[6] The author is a founding member of HPAC and serves on the HPAC Steering Circle.

American Meteorological Society 2022), is generally viewed as off the table for mainstream climate discussion.[7] But as section 1 documents, we are now in a climate crisis. And as discussed in section II, we need to immediately apply direct cooling or climate triage (point 1 above) to limit the harm and suffering to humans and other species as we try to reduce and remove GHGs as quickly as possible to stabilize the climate. A recent paper by Marie-Valentine Florin (2021) expresses a policy view that offers a strategic path forward but that unfortunately may also, as with the exclusive reliance on GHG reduction, be too late to implement.

a) The Florin Stratospheric Aerosol Injection (SAI) Implementation Framework

Florin addresses her remarks exclusively to SAI and points out that long term and extensive deployment of SAI carries with it physical and political risks. For the purposes of this paper I do not take issue with the widely held views of the potential physical risks of long-term SAI enumerated by Florin, though I believe that all are debatable and require further study, unlike the known and already present risks of continued warming discussed in section I.[8] I also do not address the potential "rogue actor" security risks, though as aerosols rapidly disperse in the stratosphere, it is not clear how a rogue actor would benefit or not be quickly shut down by international authorities backed by global powers.

[7] On May 9, 2022 the World Meteorological Organization report estimated a 50 percent chance of global warming temporarily increasing over 1.5 degrees Celsius above preindustrial in the 2022–2026 period (World Meteorological Organization 2022).

Though Florin cites a number of possible SAI risks, her primary concerns, and that of climate scientists and policy makers more generally, about SAI is that it presents is a “moral hazard” that would slow GHG mitigation efforts, could have unanticipated consequences and lead to “termination shock” or harmful climate destabilization if abruptly ended, and would be difficult to govern equitably (Biermann et al. 2021). But these are general arguments that could be applied to many other efforts to reduce climate and environmental harm. Climate adaptation, for example, was initially opposed as a potential moral hazard that could reduce pressure to cut emissions (Jebari et al. 2021). Regulations to reduce harmful sulfur emissions from cargo ship bunker fuel have reportedly had the unintended consequence of causing a significant global warming termination shock (Simmons et al. 2021). As has been discussed in section 3 above, equitable world governance is probably even more of a problem for rapid, and at scale, global emissions reductions. These arguments cannot be settled a priori and do not properly compare the possible risks of some climate cooling methods against the known risks of not attempting to directly cool the climate (Jebari et al. 2021).

Given the enormous inertia in the way that current global governance is organized and operates, it is possible that successful SAI could make global political paralysis on GHG emissions and draw down worse. But it is also possible that a successful global direct cooling effort would provide the motivation and hope for the implementation of a serious mandatory global emissions reduction and draw down regime that, as argued below, is necessary for credible GHG draw down.

Florin proposes a “shaving the peak” or “buying time” temporary role for SAI per figure 2, that is based on an adaptation of the widely publicized plot by Long and Shepard (2014).

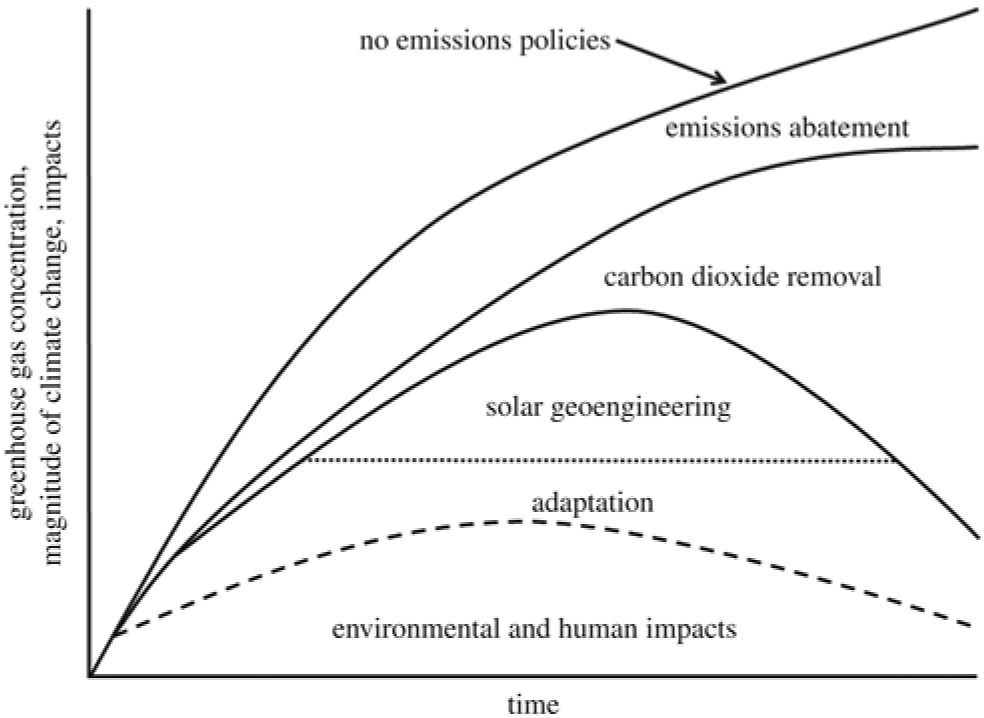

Figure 2: "Shaving the Peak" Implementation of Stratospheric Aerosol Injection Solar Geoengineering

Source: A reproduction of Reynolds (2019: figure 3). This figure and Florin (2021: figure 1) are based on a similar figure in (Long and Shepherd 2014).

She proposes a non-emergency risk management decision framework for temporary deployment of SAI that specifies SAI should not be implemented unless a credible global draw down plan is in place so that a clear date for ending SAI without abrupt warming can be specified.[9]

I understand the thinking behind the Florin proposal and applaud the effort to devise a workable strategy that may allow SAI to be seriously considered in dominant climate policy circles. By sequencing the start of SAI direct cooling after a credible GHG emissions reduction plan, and SAI cessation after a credible GHG draw down plan, Florin's proposal goes some way toward acknowledging and responding to the two climate crises that we are facing.

Unfortunately, even the Florin plan may not be adequate. Given the imminent melting of polar ice, we need emergency cooling now, and may need local or global SAI before a credible rapid and at scale global GHG emissions reduction and removal plan (that will require a binding international cap and trade agreement) can be implemented.

b) SAI is not the only form of climate triage or direct cooling, and local direct cooling methods are urgently needed now

Many different cooling methods have been proposed with very different local, regional, and global, ranges of potential impacts. All need to be carefully studied, piloted, and (if believed to be safe and effective) very gradually implemented pending the outcomes of continuous assessment.

Second, the evaluation of risks of these methods should always be in the context of the certainty of increasing climate catastrophe if we are unable to cool the planet, particularly the poles.

Third, reducing global warming may be one of the most important immediate things that we can do for global climate equity, as estimates discussed in section 1 suggest that a disproportionate share of near-term harm from climate catastrophe will be borne by the most disadvantaged countries and individuals.

The claim therefore, without evidence or study that the risks of attempting to cool, regardless of method attempted, will always be greater that the risk of doing nothing to save the Arctic sea ice and reduce or reverse the certainty of increasing climate catastrophe (that will occur as long as the stock of GHGs in the atmosphere is increasing), cannot be justified. Such inaction could cause immeasurable, and potentially avoidable, increased human and species suffering.

To the contrary, just listing some of the cooling methods that have been proposed shows that the range of possible impacts (with some relatively confined, to others with greater scope for unanticipated adverse impacts) is very large. These impacts cannot be peremptorily dismissed as unacceptable, particularly when compared with the risks of not doing anything.

Global SAI mimics the known impact of large volcano eruptions like Mount Pinatubo in 1991. That eruption in 1991 was estimated to have lifted 15 million tons of sulfur into the stratosphere and to have cooled the planet by about 0.6 degrees Celsius for 15 months (NASA 2011). Though SAI is one of the more studied and inexpensive methods (a leading study estimates a capital cost of $3.6 billion over 7 years and operational cost of $2.25 billion a year over 15 years to inject 3.3 million tons of sulfur per year), it comes with risks due to its scale and the uncertain nature of its impacts that will depend on how it is deployed (MacMartin, Ricke, and Keith 2018; National Academy of Sciences 2021). Its cost could be reduced if aerosol is only injected in polar regions in the spring, as this could potentially be done with conventional aircraft due to the lower stratosphere in polar regions (Lee et al. 2020). Modeling of stratospheric aerosols from forest fires also suggest that it may also be possible to mix aerosol with a small percentage of solar radiation absorbing material like black carbon that will cause it to loft so that it can be injected in the troposphere with conventional aircraft (Gao et al. 2021).

Other proposed direct cooling methods include: marine cloud brightening, mirrors for earth's energy rebalancing, wind driven sea water pumps, surface albedo modification (formerly floating sand), iron salt aerosol, cirrus cloud thinning, ocean thermal energy conversion, seawater atomization, urban heat island cooling, restoring soil and vegetation, and stimulating plankton blooms to increase ocean and marine cloud reflectivity.

Marine Cloud Brightening mimics the brightening effect of "ship tracks" over the ocean by spraying seawater aerosols into marine clouds to make them more reflective (Latham et al. 2012). Wind driven turbines could be deployed to pump polar sea water to the surface to try to thicken winter ice (Desch et al. 2017). Iron Salt Aerosol mimics the impact of fossil fuel aerosols in cooling the planet by 0.5–1.1 degrees Celsius, by spraying iron salt aerosols into the troposphere to increase reflectivity (Oeste et al. 2017; Samset et al. 2018; Baiman 2021: 615-616). Unlike most other solar radiation modification methods that cool by reflecting or blocking incoming solar radiation, Cirrus Cloud Thinning would attempt to seed high-altitude tropospheric cirrus clouds with ice nuclei that cause them to release more outgoing radiation (Mitchell and Finnegan 2009). Surface Albedo Modification works by applying glass microspheres to young low-reflectivity ice to conserve it and convert it to high-reflectivity multi-year ice (Field et al 2018). Mirrors for Earth's Energy Rebalancing would offer local and regional cooling solutions based on deployment of arrays of mirrors on the earth's surface (MEER 2022). Wind driven sea water pumps could increase Arctic winter ice formation, slowing summer ice melt and methane release (Desch et al. 2017). Ocean Thermal Energy Conversion would harvest ocean thermal energy to produce clean, dispatchable and portable hydrogen fuel, and cool the ocean surface, while also sequestering atmospheric carbon (Rau and Baird 2018). Seawater atomization by anchored wind turbines would spray sea water droplets into the lower atmosphere with the goal of increasing the rate of evaporation of sea water and the subsequent long-wave radiation of its released vapor heat content, mainly at night (Clarke 2022). Making building and paving material more reflective and planting trees in urban areas would tend to cool urban heat islands by, respectively, increasing reflectivity and evapotranspiration (Debbage and Shepherd 2015). Restoring soil and vegetation would cool the planet through evapotranspiration, capture carbon, and regenerate ecosystems (Jehne 2021; Baiman 2020: section 4: Piao et al. 2020). Finally, marine algal bloom stimulation would try to stimulate large scale plankton and other algae blooms to cool the planet by increasing ocean or marine cloud reflectivity (McCoy et al. 2015).

c) Mandatory global cap and trade regimes are necessary to achieve credible GHG draw down

It is widely recognized that the politics of climate change are currently paralyzed. We can’t have credible GHG reduction and removal without a sustainable REME economic transition in developing countries. However, developing countries cannot afford to do this without massive financial and technological help that equalizes life opportunities across the globe going forward. The only way to achieve this is through a binding global cap and trade system that would induce a mandatory flow of funding and technology for both emissions and withdrawal from rich to poor countries (Chichilnisky and Bal 2019).

Moral suasion and Paris Accord voluntary "Nationally Determined Commitments" are unrealistic and unworkable paths for rapid global GHG emissions reduction and draw down in the next few decades. The binding global cap and trade induced Kyoto "Clean Development Mechanism" transferred $ 303.8 billion from rich countries to poor countries for mitigation and adaptation (United Nations Climate Change 2018).[10] In contrast, the Paris Accord voluntary "Green Climate Fund" over the period 2014–2021 (as of 3/31/2022) had raised only $18.2 billion.[11] An alternative would be for the United States to simply create the global currency (US dollars) necessary to fund a climate transition, but this appears less politically feasible than an enhanced Kyoto-like global cap and trade regime, a version of which has been implemented but then very unfortunately was allowed to lapse in 2015 (Baiman 2020).

The European Union (EU) was the only major region of the world that continued to internally enforce a Kyoto-like cap and trade internal Emissions Trading System (ETS) after the global mandatory Kyoto accord was replaced in 2015 by the voluntary Paris Climate Agreement. The EU ETS, with individual country carbon taxes on sectors not yet covered by it, has been the only major region of the world to significantly cut, by 24 percent from 1990 to 2019, its GHG emissions (EC Emissions Cuts 2022). In contrast, US GHG emissions increased by 2 percent over this period (US EPA 2021).[12] The 1990-2020 the population of the EU grew 20.4% more

[10] According to this 2001–2018 UNFCCC report, the Clean Development Mechanism led to the investment of $ 303.8 billion in climate and sustainable development projects that resulted in an almost 2 GT CO2eq emissions reduction in the developing world.

[11] $8.31 billion for Initial Resource Mobilization and $9.87 billion for First Replenishment (Green Climate Fund 2022).

[12] The Kyoto Protocol set binding emission reduction targets for 37 industrialized countries and economies in transition and the European Union averaging 5 percent emission reduction compared to 1990 levels over the five-year period 2008–2012 (UNCC 2022). US emissions declined from a peak of 18.1 percent above 1990 levels in

slowly than that of the US, but from 1997 (earliest available data) to 2019 the real value of manufacturing output (value-added) of the EU grew only 7.3% more slowly than that of the US, suggesting that neither factor can fully account for the 26% greater decline in EU GHG emissions relative to the US (Eurostat 2022) (World Bank Manufacturing 2022).[13] During this period both regions outsourced manufacturing, particularly to China.

Carbon pricing mechanisms now apply to about a fifth of global GHG emissions (World Bank Group 2020), and the EU may impose a "carbon border adjustment mechanism" that could increase their coverage (EC Taxation and Customs Union 2022). However, per tables 1 and 2, and the discussion above, it appears that a *global* ETS that generates enforceable transfers of investment from rich to poor countries is necessary to achieve global GHG reduction and removal.

The proposed EU carbon border adjustment mechanism is a reminder that serious efforts to transform the global economy require mandatory and enforceable rules like that of the WTO. The collapse of the Bretton Woods system and implementation of the (mathematically erroneous and economically harmful) global free trade doctrine is nonetheless a good example of how a globally transformative political economic regime can be realistically implemented (Baiman 2017). I don't think any serious free trade proponent would suggest that a global free trade regime could be *voluntarily* implemented. How can we expect a more radical and fundamental

2004 to 3.4 percent above 1990 levels in 2012 (World Bank US 2022). EU emissions declined from a peak of -1.7 percent below 1990 levels in 1991 to -17.4 percent below 1990 levels in 2012 (World Bank EU 2022).

[13] GDP growth, as opposed to manufacturing growth, is less likely to be correlated to GHG emissions, as particularly in the US, this was disproportionally in the lower GHG emitting service sector. For example, "Financial Intermediation Services Indirectly Measured", newly added to GDP accounting after 2008, and an increasingly important part of US GDP in particular, is arguably fictitious output that does not reflect increased economic activity (Mazucato 2018, Chap. 3) (Baiman, 2014).

global transformation to a renewable energy and materials economy to be achieved through voluntary Paris Accord Nationally Determined Contributions and Green Climate Fund philanthropy?

The long run climate crisis should be viewed as a challenge and opportunity for humanity to evolve from a fossil fuel and mineral mining "industrial hunter-gatherer" civilization to a potentially more equitable, prosperous and ecologically sustainable "industrial farmer-cultivation" civilization. Global, national, and local political economic policies necessary to expedite this transition to "the other side" are proposed in Baiman (2021: Section 4).[14] These long-term but essential sharp reductions in GHG emissions, massive levels of GHG removal, and ecological regeneration, will require a complete transformation of global industrial civilization and of our relationship to nature. Contrary to claims made by, for example Biermann et al. (2022), general "moral hazard" and "termination shock" arguments can be applied to all kinds of efforts to reduce environmental and climate harm. The transformation of human civilization necessary to address the long-run climate restoration and ecological regeneration climate crisis will likely be much slower, costlier and more difficult from a governance perspective, than implementing emergency direct climate cooling to address the immediate short run global warming climate crisis (Jebari et al. 2021).

[14] See also Graciela Chichilnisky and Bal (2019), and Eisenberger and Chichilnisky and colleagues, proposals at the Elk Coast Institute Energy Equity 2022 and Climate Mobilization 2020 Summits (ECI DAC 2020; ECI Energy Equity 2022).

5. Conclusion

We are facing both a short-term emergency cooling crisis and a long-term GHG draw down planetary ecological crisis. We must address both. The first requires emergency direct cooling, or temporary “triage” or a “tourniquet, for our bleeding planet”. The second requires rapid GHG emissions reductions and draw down and natural planetary regeneration that realistically will take at least a few decades and may take a century or more. Conflating the challenge and opportunity of the second crisis with a response to the first crisis will not produce a rapid and credible global response to the second crisis because of structural economic inequity and fossil fuel dependency that is deeply embedded in the current global economy. Realistically, we need emergency direct climate cooling to address the first crisis and a long-term binding global cap and trade emissions trading system to address the second. The Florin proposal that conditions SAI direct climate cooling on credible GHG emissions and draw down is a step in the right direction, but omits other direct climate cooling methods and effectively makes the deployment of SAI contingent on a global ETS that may not be possible before the deployment of SAI becomes necessary. Rather than conflating our two climate crises, or conditioning the solution of the first on a solution to the second, we need to address both on an emergency basis by putting all options on the table as called for in the HPAC proposal.

Bibliography

American Meteorological Society. 2022. *Climate intervention*. February. Accessed at: https://www.ametsoc.org/ams/assets/File/aboutams/statements_pdf/AMS_Statement_Climate_Intervention_Final.pdf

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

Baiman, Ron. 2014. Unequal Exchange and the Rentier Economy. *Review of Radical Political Economics* 46 (4): 536-557.

———. 2017. *The Global Free Trade Error: The Infeasibility of Ricardo's Comparative Advantage Theory*. New York: Routledge.

———. 2020. Financial bailout spending would have almost paid for thirty years of global green new deal: Triage, regeneration, and mitigation. *Review of Radical Political Economics* 52 (4): 616–625.

———. 2021. In support of a renewable energy and materials economy: A global green new deal that includes arctic sea ice triage and carbon cycle restoration. *Review of Radical Political Economics* 53 (4): 611–611.

Biermann, Frank, Jeroen Oomen, Aarti Gupta, Saleem H. Ali, Ken Conca, Maarten A. Hajer, Prakash Kashwan, Louis J. Kotzé, Melissa Leach, Dirk Messner, Chukwumerije Okereke, Åsa Persson, Janez Potočnik, David Schlosberg, Michelle Scobie, Stacy D. VanDeveer. 2022. Solar geoengineering: The case for an international non-use agreement. *Wires Climate Change* 13 (3). Accessed at: https://wires.onlinelibrary.wiley.com/doi/full/10.1002/wcc.754

Chichilniski, Graciela and Peter Bal. 2019. *Reversing Climate Change*. Singapore: World Scientific Publishing Co. Pte. Ltd.

Christian Aid. 2021. *Counting the cost 2021: A year of climate breakdown*. December 27. Accessed at: https://reliefweb.int/report/world/counting-cost-2021-year-climate-breakdown-december-2021

Climate Foundation. 2022. *The Climate Foundation wins million-dollar milestone XPRIZE for carbon removal.* Accessed at: https://www.climatefoundation.org/xprize.html

Clarke, William S. 2022. *More climate solutions.* May. Available upon request from the author: sevclarke@icloud.com.

Council on Foreign Relations 2022. *Reflecting sunlight to reduce climate risk: Priorities for research and international cooperation*, by Stewart M. Patrick. April. Accessed at: https://www.cfr.org/report/reflecting-sunlight-reduce-climate-risk

Desch, Steven J, Nathan Smith, Christopher Groppi, Perry Vargas, Rebecca Jackson, Anusha Kalyaan, Peter Nguyen, Luke Probst, Mark E. Rubin, Heather Singleton, Alexander Spacek, Amanda Truitt, Pye Pye Zaw, Hilairy E. Hartnett. 2017. Arctic ice management. *Earth's Future* 5 (1): 107–127

Debbage, Neil and J.Marshall Shepherd. 2015. The urban heat island effect and city contiguity. *Computers, Environment and Urban Systems* 54: 181–184.

Dezember, Ryan. 2021. *Blame bad weather for your bigger bills. Wall Street Journal* December 28.

Eisenberger, Peter. 2020. Renewable energy and materials economy. Paper submitted to *Physics and Society* December 29. Accessed at: https://arxiv.org/pdf/2012.14976.pdf

ECI Energy Equity. 2022. *Energy equity and the climate crisis.* Accessed at: https://elkinstitute.files.wordpress.com/2022/03/energy-equity-report-eci.pdf

ECI DAC. 2020. *Finance Working Group Report*. Accessed at: https://elkinstitute.files.wordpress.com/2020/09/working-group-reports-dac-climate-mobilization-summit-.pdf

EC Emissions Cuts. 2022. *Kyoto 2nd commitment period (2013–20).* Accessed at: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/progress-made-cutting-emissions_en

EC Taxation and Customs Union. 2022. *Carbon border adjustment mechanism.* Accessed at: https://ec.europa.eu/taxation_customs/green-taxation-0/carbon-border-adjustment-mechanism_en

Eurostat. 2022. Population and population change statistics. Accessed at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Population_and_population_change_statistics

Field, L, D. Ivanova, S. Bhattachartyya, V. Mlaker, A. Sholtz, R. Decca, A. Manzara, D. Johnson, E. Christodoulou, P. Walter, and K. Katuri. 2018. Increasing Arctic sea ice albedo using localized reversible geoengineering. *Earth's Future* 6 (6): 882–901.

Florin, Marie-Valentine. 2021. *Using stratospheric aerosol injection to alleviate global warming: when?* Ecole Polytechnique Federale De Lausanne (EPFL), International Risk Governance Center. Accessed at: https://infoscience.epfl.ch/record/290678

Gao, Ru-Shan, Karen H. Rosenlof, Bernd Karcher, Simone Tilmes, Owen B. Toos, and Christopher Malon. 2021. Toward practical stratospheric aerosol albedo modification: Solar-powered lofting. *Science Advances* 7. May 14. Accessed at: https://www.science.org/doi/10.1126/sciadv.abe3416

Genevieve, Guenther. 2022. Carbon removal isn't the solution to climate change. *The New Republic* April 4.

Goldman, Jason G. 2017. *Ecuador has begun drilling for oil in the world's richest rainforest. Vox.* January 14. Accessed at: https://www.vox.com/energy-and-environment/2017/1/14/14265958/ecuador-drilling-oil-rainforest

Green Climate Fund. 2022. *Status of pledges (IRF and GCF-1).* April. Accessed at: https://www.greenclimate.fund/document/status-pledges-all-cycles

Hahnel, Robin. 2012. Left clouds over climate change policy. *Review of Radical Political Economics* 44 (2): 141–159.

Healthy Planet Action Coalition. 2021. *Urgent action for a healthy climate.* COP26 and G20 open letters. Accessed at: https://www.healthyplanetaction.org/

IPCC. 2022. *Climate change 2022: impacts, adaptation and vulnerability.* Unedited final report February 27. Accessed at: https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

Jebari, Joseph, Olúfẹ́mi O.Táíwo, Talbot M.Andrews, Valentina Aquila, Brian Beckage, Mariia Belaia, Maggie Clifford, Jay Fuhrman, David P. Keller, Katharine J.Mach, David R. Morrow, Kaitlin T.Raimi, DanieleVisioni, SimonNicholson, Christopher H.Trisos. 2021. From moral hazard to risk-response feedback. *Climate Risk Management* 33. Accessed at: https://www.sciencedirect.com/science/article/pii/S221209632100053X

Jehne, Walter. 2021. *The importance of vegetation for the water cycle and climate*. December 8. UNEP and German Scientific Forum. Accessed at: https://www.youtube.com/watch?v=aZDkwWA8iB8

Keen, Steve. 2020. The appallingly bad neoclassical economics of climate change. *Globalizations* 18 (7): 1149–1177.

Kindy, David. 2021. Permafrost thaw in Siberia creates a ticking 'methane bomb' of greenhouse gases, scientists warn. *Smithsonian Magazine*. August 5.

Kottasovana, Ivana. 2020. *Norway says its new giant oil field is actually good for the environment. CNN*. January 19. Accessed at: https://www.cnn.com/2020/01/19/business/norway-oil-field-climate-change-intl/index.html

Latham, John, Keith Bower, Tom Choularton, Hugh Coe, Paul Connally, Gary Cooper, Tim Crafts, Jack Foster, Alan Gadian, Lee Galbraith, Hector Iacovidess, David Johnston, Brian Launers, Brian Leslie, John Meyer, Armand Neukermans, Bob Ormond, Ben Parkes, Phillip Racsh, John Rush, Stephen Salter, Tom Stevenson, Hailong Wang, Qin Wang, and Rob Wood. 2012. Marine cloud brightening. *Philosophical Transcripts of the Royal. Society* 370 (1974): 4217–4262.

Lee, Walker, Douglas MacMartin, Daniele Visioni, and Ben Kravitz 2020. Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs. *Earth System Dynam*ics 11 (4): 1051–1072.

Lenton, Timothy M, Johan Rockstrom, Owen Gaffney, Stefan Rahmsdorf, Katherine Richardson. Will Steffan, and Hans Joachim Schellnhuber. 2020. Tipping Points too Risky to Bet Against. *Nature* 575 (7784). Accessed at: https://pubmed.ncbi.nlm.nih.gov/31776487/

Long, Jane C. S. and John G. Shepherd. 2014 The strategic value of geoengineering research. *Global Environmental Change*: 757–770. SpringerLink reference work entry. Accessed at: https://link.springer.com/referenceworkentry/10.1007/978-94-007-5784-4_24?noAccess=true

MacMartin, Douglas G., Katharine L. Ricke and David W. Keith. 2018. Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. *Philosophical Transactions of the Royal Society A* 376 (2119). Accessed at: https://royalsocietypublishing.org/doi/10.1098/rsta.2016.0454

Mazzucato, Mariana. 2018. *The Value of everything: Making and taking in the global economy*. UK: Allen Lane.

McCoy Daniel T., Susannah M. Burrows, Robert Wood, Daniel P. Grosvenor, Scott M. Elliott, Po-Lun Ma, Phillip J. Raschand, Dennis L. Hartmann. 2015. Natural aerosols explain seasonal and spatial patterns of Southern Ocean cloud albedo. *Science Advances* 1 (6). Accessed at: https://www.science.org/doi/10.1126/sciadv.1500157

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

MEER. 2022. *Cooling the planet with surface reflectors*. Accessed at: https://www.meer.org/

Mitchell, David L., and William Finnegan. 2009. Modification of cirrus clouds to reduce global warming. *Environmental Research Letters* 4 (4). Accessed at: https://iopscience.iop.org/article/10.1088/1748-9326/4/4/045102/meta

NASA. 2011. Global Effects of Mount Pinatubo. Earth Observatory. June 15. Accessed at: https://earthobservatory.nasa.gov/images/1510/global-effects-of-mount-pinatubo

National Academy of Sciences. 2021. *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance.* Washington, D.C.: The National Academies Press. Accessed at: https://nap.nationalacademies.org/catalog/25762/reflecting-sunlight-recommendations-for-solar-geoengineering-research-and-research-governance

Oeste, Franz Dietrich, Renaud de Richter, Tingzhen Ming, and Sylvian Caillol. 2017. Climate Engineering by Mimicking Natural Dust Climate Control. *Earth System Dynamics* 8 (1): 1–54.

Pearce, Bru 2022. *Envisionation: biosphere restoration plan*. February. Envisionation (https://www.envisionation.org/). Accessed at: https://online.fliphtml5.com/aacla/aqyx/#p=1

Piao, Shilong, Xuhui Wang, Taejin Park, Chi Chen, Xu Lian, Yue He, Jarle W. Bjerke, Anping Chen, Philippe Ciais, Hans Tommervik, Ramakrishna R. Nemani. 2020. Characteristics, drivers and feedbacks of global greening. *Nature Reviews Earth and Environment* 1: 14–27.

Pistone, Kristina, Ian Eisenman and Veerabhadran Ramanathan. 2019. Radiative heating of an ice-free Arctic Ocean. *Geophysical Research Letters* 46 (13): 7474–7480.

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

Reynolds, Jesse L. 2019. Solar geoengineering to reduce climate change: a review of governance proposals. *Proceedings of the Royal Society A*. September 4. Accessed at: https://royalsocietypublishing.org/doi/10.1098/rspa.2019.0255

Samset, B. H., M. Sand, C. J. Smith, S. E. Bauer, P. M. Forster, J. S. Fuglestvedt, S. Osprey, and C. F. Schleussner. 2018. Climate impacts from a removal of anthropogenic aerosol emissions. *Geophysical Research Letters* 45 (2): 1020–1029.

Schuckmann, Katrina von, Lijing Cheng, Matthew D. Palmer, James Hansen, C aterina Tassone, Valentin Aich, Susheel Adusumilli, Hugo Beltrami, Tim Boyer, Francisco José Cuesta-Valero, Damien Desbruyères, Catia Domingues, Almudena García-García, Pierre Gentine, John Gilson, Maximilian Gorfer, Leopold Haimberger, Masayoshi Ishii, Gregory C. Johnson, Rachel Killick, Brian A. King, Gottfried Kirchengast, Nicolas Kolodziejczyk, John Lyman, Ben Marzeion, Michael Mayer, Maeva Monier, Didier Paolo Monselesan, Sarah Purkey, Dean Roemmich, Axel Schweiger, Sonia I. Seneviratne, Andrew Shepherd, Donald A. Slater, Andrea K. Steiner, Fiammetta Straneo, Mary-Louise Timmermans, and Susan E. Wijffels. 2020. Heat stored in the earth system. *Earth System Science Data* 12 (3): 2013–2041.

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

Smith, Wake and Gernot Wagner. 2018. Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. *Environmental Research Letters* 13 (12). Accessed at: https://iopscience.iop.org/article/10.1088/1748-9326/aae98d/pdf

Statistica. 2022. Global gross domestic product (GDP) at current prices from 1985 to 2026 (in billion U.S. dollars). Accessed at: https://www.statista.com/statistics/268750/global-gross-domestic-product-gdp/

Steffen, Will, Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer,Elena M. Bennett, Reinette Biggs, Stephen R. Carpenter, Wim de Vries,Cynthia A. de Wit, Carl Folke, Dieter Gerten, Jens Heinke, Georgina M. Mace, Linn M. Persson, Veerabhadran Ramanathan, Belinda Reyers, and Sverker Sörlin. 2015. Planetary boundaries: guiding human development on a changing planet. 2015. *Science* 347 (6223). Accessed at: https://www.science.org/doi/10.1126/science.1259855

Swiss-Re. 2021. *The economics of climate change: no action not an option*. April. Accessed at: https://www.swissre.com/dam/jcr:e73ee7c3-7f83-4c17-a2b8-8ef23a8d3312/swiss-re-institute-expertise-publication-economics-of-climate-change.pdf

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

US EPA. 2021. *Climate change indicators: U.S. greenhouse gas emissions*. April. Accessed at: https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions

UNCC 2022. *What is the Kyoto Protocol?* Accessed at: https://unfccc.int/kyoto_protocol

World Bank Group. 2020. *State and trends of carbon pricing.* Washington D.C.: World Bank May. Accessed at: https://openknowledge.worldbank.org/handle/10986/33809

World Bank US. 2022. *Total greenhouse gas emissions (% change from 1990)*- United States. Accessed at: https://data.worldbank.org/indicator/EN.ATM.GHGT.ZG?locati

World Bank Manufacturing. 2022. Manufacturing, value added (constant 2015 US$). Accessed at: https://data.worldbank.org/indicator/NV.IND.MANF.KD

World Bank EU. 2022. *Total greenhouse gas emissions (% change from 1990)* - European Union. Accessed at: https://data.worldbank.org/indicator/EN.ATM.GHGT.ZG?locations=EU&view=chart

World Meteorological Organization. 2022. *WMO update: 50:50 chance of global temperature temporarily reaching 1.5°C threshold in next five years*. May. Accessed at: https://public.wmo.int/en/media/press-release/wmo-update-5050-chance-of-global-temperature-temporarily-reaching-15%C2%B0c-threshold

Zachs, Jeffery. 2019. Getting to a carbon-free economy. *American Prospect*. December 5. Accessed at: https://prospect.org/greennewdeal/getting-to-a-carbon-free-economy/.

Zhou, Chen, Mark D. Zelinka, Andrew E. Dessler, and Minghuai Wang. 2021. Greater committed warming after accounting for the pattern effect. *Nature Climate Change* 11: 132–136.