Review of Radical Political Economics
OnlineFirst

https://doi.org/10.1177/04866134221123626

URPE at the ASSAs

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

Ron Baiman

Abstract

We are facing both a short-term emergency cooling crisis and a long-term greenhouse gas (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 Stratospheric Aerosol Injection (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 emissions trading system (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 Healthy Planet Action Coalition (HPAC) proposal.

***JEL Classification**: Q54, Q55, Q56, Q57, Q58*

Keywords

Arctic sea ice, climate change, geoengineering, emissions trading system, climate equity

Benedictine University, Lisle, IL, USA

Corresponding author(s):
Ron Baiman, Benedictine University, 5700 College Road, Lisle, IL 60532-2851, USA. Email: rbaiman@ben.edu

1. 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, which 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 article attempts to discuss and outline a strategy for addressing both. The next five sections discuss our two climate crises, background political framing, the limits of the current moral suasion and breakdown strategies, and how can short-run emergency direct cooling and long-run GHG removal and ecological regeneration be achieved, and finally, a conclusion.

2. 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 (McSweeney 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).

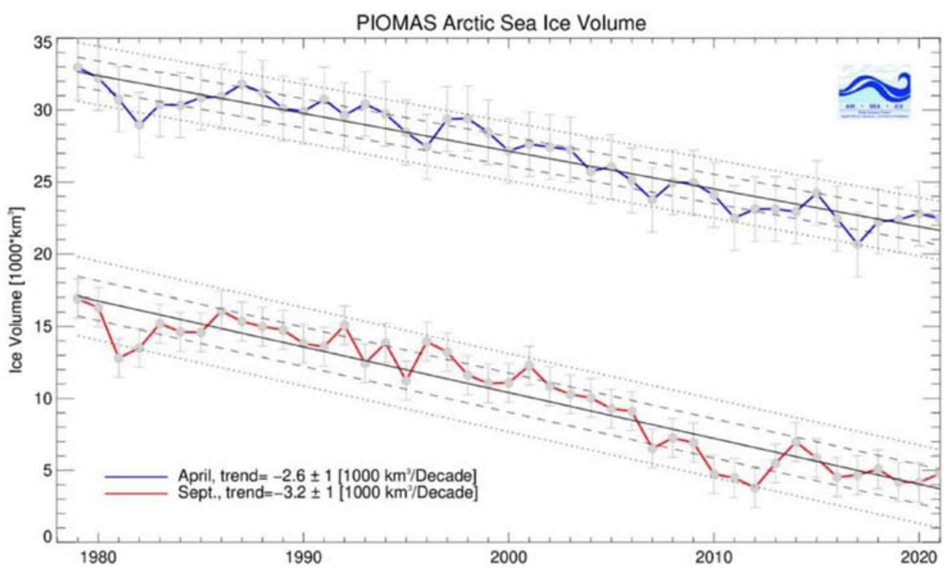

Figure 1. 1979–2021 monthly sea ice volume from PIOMAS for April and September.
Source: Polar Science Center, Applied Physics Laboratory, University of Washington. Accessed at: http://psc.apl.uw.edu/wordpress/wp-content/uploads/schweiger/ice_volume /BPIOMASIceVolumeAprSepCurrent.png.

Estimates included in Pistone, Eisenman, and Ramanathan (2019), and corroborated by multiple other studies using different data and methodologies cited in this article, 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: fn 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 midcentury (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 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, which appear also to be starting far earlier than previously estimated (Lenton et al. 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 can 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 longer, to achieve zero emissions and remove sufficient GHGs from the atmosphere to prevent continued and accelerating climate deterioration.

3. 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:

1. does not offer hope, particularly in the face of repeatedly backsliding or inadequate political responses;

2. 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;
3. fails to fully account for the imperative of lifting standards of living for billions of people even as GHG emissions are reduced; and
4. most importantly, 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 the following:

1. 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);
2. 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;
3. we must address equity, or our efforts will fail (section 4.2);
4. 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 2).

An even more comprehensive framing can 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 2022: 67, 77; Baiman 2021; Steffen et al. 2015).[4]

4. 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).

4.1 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 the politics, economics, and technology, of reducing and removing GHG emissions which 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 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 for direct climate cooling (Baiman 2021: table 1:8).

4.2 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 the Ecuadoran rainforest, one of the most diverse ecosystems on the planet and the home of three indigenous tribes. But by 2013, the fund had 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 of 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.

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 (2019, Seventy-Two ECA, OSS, and SSA Countries).

Country/Region Name	Country Code	Population in 2019 (millions)	Fuel Exports: % Total Exports	Fuel Exports: % GDP	Fuel Exports, $ (millions)
Europe and 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	SSA	1,106.9	25.7	6.1	20,181.8

Sub-Saharan Africa excluding high-income (SSA)	SSA	[illegible]	[illegible]	[illegible]	[illegible]
Weighted average by population			26.5	8.2	
Total		1557.1			148,952.8
Share of global total		20.2			

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 (twenty) 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 (thirty-three) 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, and Vanuatu. SSA countries (twenty-nine) 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 population 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]

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

Fuel Exports Percent of Total Exports (2019, By Country)

Country Name	Fuel Exports: % of Total Exports	Fuel Exports, $ (millions)	Cumulative Fuel Exports, $ (millions)	Population (millions)	Cumulative Population (millions)
Brunei Darussalam	82.2	6,412.0	6,412	0.4	0.4
Kuwait	79.9	898,052.9	904,465	4.2	4.6
Qatar	70.4	64,774.0	969,239	2.8	7.5
Norway	54.3	21,680.7	990,920	5.3	12.8
United Arab Emirates	50.8	1,280,868.5	2,271,788	9.8	22.6
Russian Federation	45.3	218,119.3	2,489,907	144.4	167.0
Kazakhstan	42.6	1,332.1	2,491,239	18.5	185.5
Ecuador	35.1	8,746.3	2,499,986	17.4	202.9
Mongolia	34.1	2,135.5	2,502,121	3.2	206.1
Nigeria	31.7	842.5	2,502,964	201.0	407.1
Malta	24.3	349,875.3	2,852,839	0.5	407.6
Barbados	22.9	929.6	2,853,769	0.3	407.9
Cyprus	20.7	1,051.2	2,854,820	1.2	409.1
Indonesia	20.5	13,365.7	2,868,186	270.6	679.7
Belarus	17.6	8,142.2	2,876,328	9.4	689.1
Fiji	16.0	1,367.7	2,877,695	0.9	690.0
Samoa	15.7	99,321.6	2,977,017	0.2	690.2
Jamaica	15.3	136,454.8	3,113,472	2.9	693.1
Australia	15.2	51,294.1	3,164,766	25.4	718.5
Ghana	14.6	12,017.4	3,176,783	30.4	748.9

Egypt, Arab Rep.	14.5	7,680.4	3,184,464	100.4	849.3
Senegal	11.8	77,796.1	3,262,260	16.3	865.6
Brazil	11.4	30,313.6	3,292,573	211.0	1,076.7
Lithuania	11.2	725,712.2	4,018,286	2.8	1,079.5
Malaysia	10.7	402.2	4,018,688	31.9	1,111.4

Source: Author's calculations from World Bank Indicators. Accessed 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 included in this table are also included in one of the table 1 country groups.

5. 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, which 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 thirty-three and forty-six 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).

The letter to COP26 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. (Healthy Planet Action Coalition 2021: ¶ 3).

Needless to say, HPAC has received no serious commitment or response from COP26 to this letter nor 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; Patrick 2022; American Meteorological Society 2022), is generally viewed as off the table for mainstream climate discussion.[7] But as section 2 documents, we are now in a climate crisis. And as discussed in section 3, we need to immediately apply direct climate 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 article 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.

5.1. The Florin stratospheric aerosol injection implementation framework

Florin addresses her remarks exclusively to stratospheric aerosol injection (SAI) and points out that long-term and extensive deployment of SAI carries with it physical and political risks. For the purposes of this article, 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 2.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.

Though Florin cites several possible SAI risks, her primary concerns, and that of climate scientists and policy makers more generally, about SAI is that it presents 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 4, 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 rapid 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 Shepherd (2014).

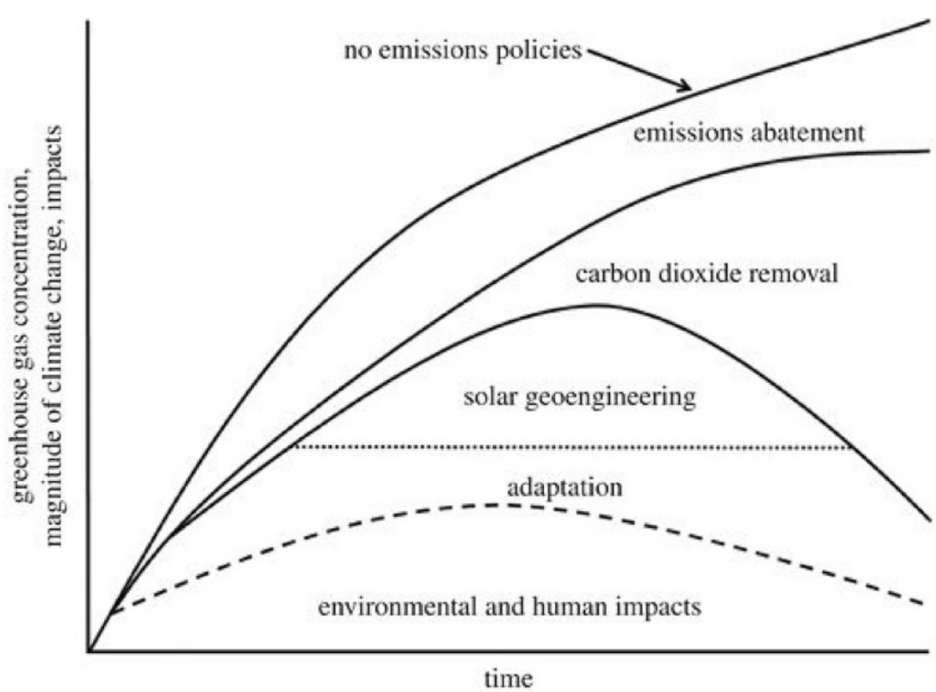

Figure 2. "Shaving the peak" implementation of stratospheric aerosol injection solar geoengineering.
Source: A reproduction of Reynolds (2019: figure 3). This figure and Florin (2021: figure 1) are based on a similar figure in Long and Shepherd (2014).

She proposes a nonemergency 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.

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.

However, 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.

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

Many different direct climate 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 2 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 than 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 fifteen months (NASA 2011). Though SAI is one of the more studied and inexpensive methods (a leading study estimates a capital cost of $3.5 billion over fifteen years and an operational cost of $2.25 billion a year for fifteen years after that to reduce anthropogenic forcing per decade by a half), it comes with risks because of its scale and the uncertain nature of its impacts that will depend on how it is deployed (Smith and Wagner 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 because of the lower stratosphere in polar regions which would also cause it to fall out of the troposhere more rapidly allowing for more abrupt cessation if necessary (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). 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: 615–16). 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 multiyear 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 (Mirrors for Earth's Energy Rebalancing 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).

5.3. 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 cannot have credible GHG reduction and removal without a sustainable renewable energy and materials 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 (UNCC 2018).[8] In contrast, the Paris Accord voluntary “Green Climate Fund” over the period 2014–2021 (as of March 31, 2022) had raised only $18.2 billion.[9] 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 was implemented but then unfortunately allowed to lapse in 2015 (Baiman 2020).

The European Union was the only major region of the world that continued to internally enforce a Kyoto-like cap-and-trade internal emissions trading system after the global mandatory Kyoto accord was replaced in 2015 by the voluntary Paris Climate Agreement. The EU emissions trading system, 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 (European Commission 2022a). In contrast, US GHG emissions increased by 2 percent over this period (US EPA 2021).[10] In 1990–2020, the population of the European Union grew 20.4 percent more slowly than that of the United States, but from 1997 (earliest available data) to 2019 the real value of manufacturing output (value added) of the European Union grew only 7.3 percent more slowly than that of the United States, suggesting that neither factor can fully account for the 26 percent greater decline in EU GHG emissions relative to the United States (Eurostat 2022; World Bank Manufacturing 2022).[11] 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 European Union may impose a “carbon border adjustment mechanism” that could increase their coverage (European Commission 2022b). Per tables 1 and 2 and the discussion above, it appears that a *global* emissions trading system 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 do not 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 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).[12] 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. 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.

6. 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 emissions trading system 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.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Ron Baiman https://orcid.org/0000-0002-0492-8493

Notes

1 Chapter 16 of the 2022 Intergovernmental Panel on Climate Change Sixth Assessment Report by the Working Group II (Impacts, Adaptation, and Vulnerability), 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 km^3) in September 2021 and a trend of –3.2 (1,000 km^3) loss per decade. As 4/3.2=1.25, this suggests September zero ice volume in 2021 + 12.5 = 2033.5, or by 2034.

3 For example, my own estimates from data in Schuckmann et al. (2020) suggest that about 1.7 trillion 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.

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 $1-million prize 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 because simply cutting emissions—even to zero—will not stabilize the climate because of already accumulated GHGs in the atmosphere and oceans.

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 (Elk Coast Institute 2022).

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

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).

8 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.

9 $8.31 billion for initial resource mobilization and $9.87 billion for first replenishment (Green Climate Fund 2022).

10 The Kyoto Protocol set binding emission reduction targets for thirty-seven 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 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).

11 GDP growth, as opposed to manufacturing growth, is less likely to be correlated to GHG emissions, as particularly in the United States, 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 an arguably fictitious output that does not reflect increased economic activity (Mazzucato 2018: ch. 3; Baiman 2014).

12 See also Chichilnisky and Bal (2019), and Eisenberger and Chichilnisky and colleagues, proposals at the Elk Coast Institute Energy Equity 2022 and Climate Mobilization 2020 Summits (Elk Coast Institute 2020, 2022).

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Author Biography

Ron Baiman is Associate Professor of Economics at Benedictine University in Lisle, IL outside of Chicago. He is the author of three books and numerous academic papers on topics in radical political economics. His most recent articles on the climate crises, both published in the *Review of Radical Political Economics*, are: “In Support of a Renewable Energy and Materials Economy: A Global Green New Deal That Includes Arctic Sea Ice Triage and Carbon Cycle Restoration” (2021) and “Financial Bailout Spending Would Have Almost Paid for Thirty Years of Global Green New Deal: Triage, Regeneration, and Mitigation” (2020). He is also a founding member of the Healthy Planet Action Coalition (www.healthyplanetaction.org) and the Chicago Political Economy Group (www.cpegonline.org) where many of his public policy reports and blog postings can be found.