The Laissez-Faire Scenario:
Climate Effects of Profit-Seeking Geoengineering

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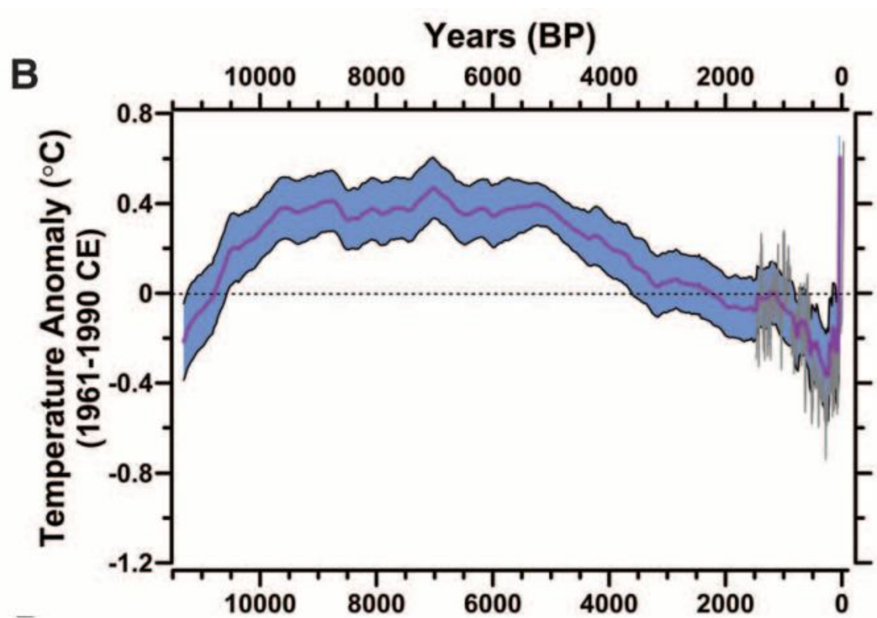
Abstract

This paper analyzes the proposal of stratospheric aerosol injection (SAI) from a humanitarian and economic-leftist perspective. The argument is made that SAI is best understood as a component of a "laissez-faire scenario" where collective action to limit emissions does not materialize, leading private entities to enact symptom-level fixes out of economic self-interest. Adverse climate impacts for the global South are stressed.

I. Thermostatic Equilibrium

For about ten thousand years, from 8000 B.C. to around 1950, the Earth was in a state of thermostatic equilibrium. Temperature would vary seasonally, as it does, and regular oscillations in oceanic and atmospheric circulation patterns would cause noticeable temperature fluctuations on the time scale of years or decades. But throughout this period, known as the Holocene epoch, the 50-year average global surface temperature remained within a remarkably narrow band of about 1 ºC. For one hundred centuries, the coolest 50-year stint saw an average global surface temperature of about 13.3 ºC (55.9 ºF) and the warmest was about 14.3 ºC (57.7 ºF).[1]

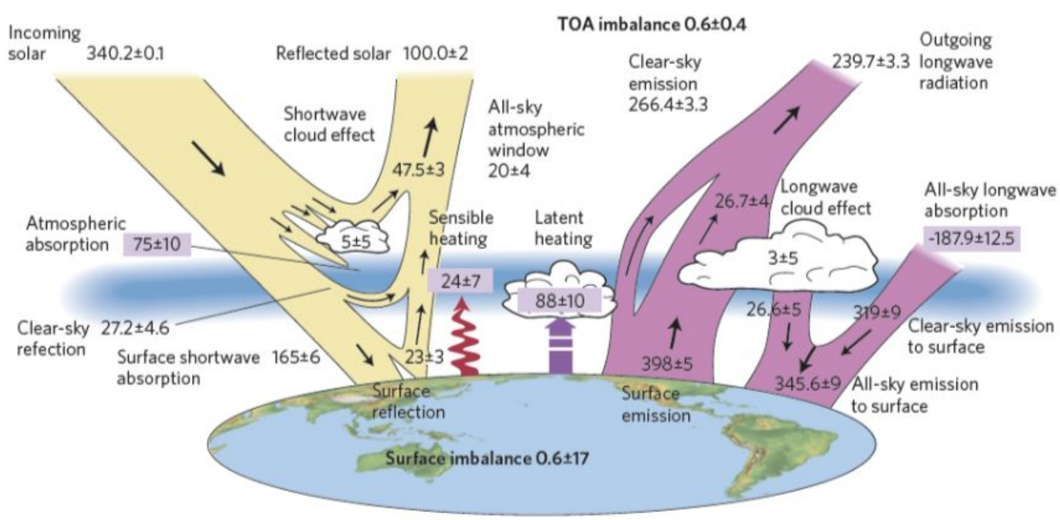


Reconstruction of average global surface temperature anomaly relative to 1961–1990.
Error range in blue. From Marcott et al. (2013).

[1] Absolute surface temperatures are included for intuitive reference, though the error bars on absolute temperatures are in reality wider than those for temperature anomalies.

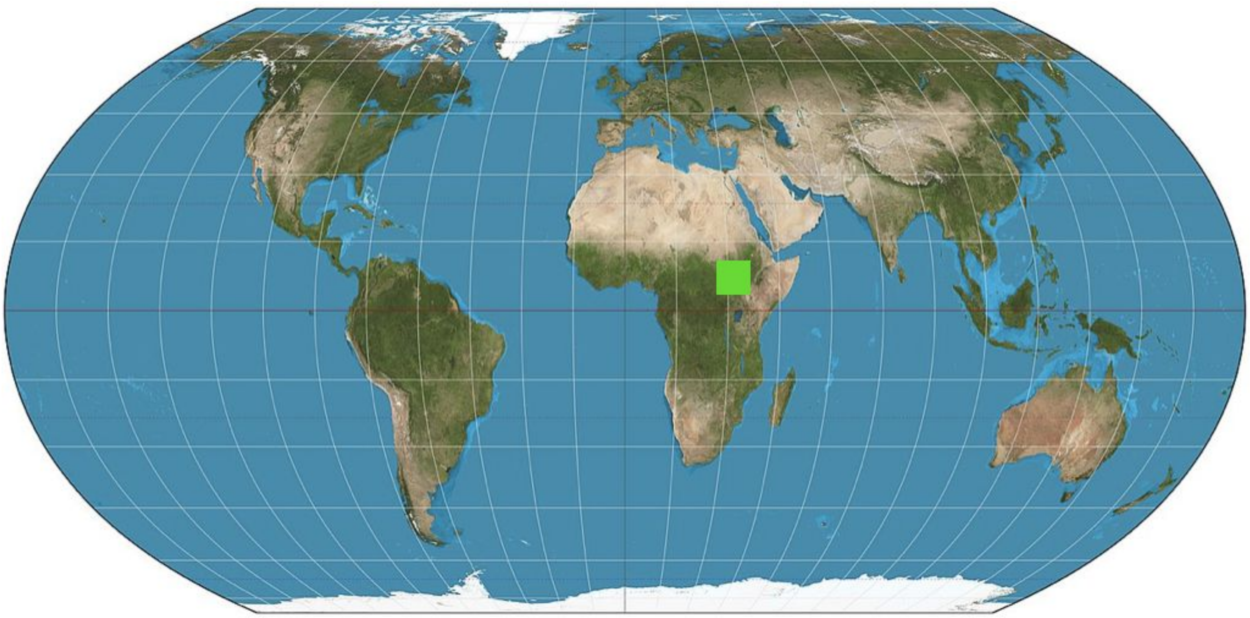
This temperature stability is thought to have contributed directly to a flourishing of plant and animal populations across the globe; most organisms are, after all, optimized to prosper only within a small range of temperatures. The Holocene calm also permitted a dramatic shift in the structure of human societies, from migratory forager cultures to permanent settlement and agriculture, in turn leading to the development of metropolises and supra-community-level social organization, the invention of writing, and the full canon of recorded history prior to 1950. It is not a stretch to say that we owe our civilization to this long-term functioning of the Earth's natural thermostat.

How was this equilibrium maintained? Net zero radiation balance. Throughout the Holocene epoch, the amount of incoming solar radiation entering the top of Earth's atmosphere precisely matched the amount of outgoing terrestrial radiation exiting the same boundary, with only brief stochastic fluctuations. The incoming radiation flux — determined primarily by the sun's temperature, sun-to-Earth distance, global cloud cover, atmospheric ozone concentration, and reflective sea spray and dust — was ~342 W/m^2. The outgoing radiation flux — determined primarily by the Earth's temperature and atmospheric concentrations of water vapor, carbon dioxide, methane, and nitrous oxide — was also ~342 W/m^2. None of these variables remained precisely constant; for instance, the surface temperature of the sun varies decadally due to unpredictable sunspots. Nonetheless, over a given 50-year window, the Earth would warm just as much as it cooled, and there were no long-term directional trends in global surface climate.



Overview of incoming solar and outgoing terrestrial radiation pathways in the Anthropocene.
From Stephens et al. (2012).

Human societies prospered within this steady state for the first 80% of the Holocene epoch, at a relatively stable global population of about 5–50 million. Given that an adult human consumes food energy at a rate of about 100 W to sustain her body's basic functions, and given that the primary economic activity during this period was agriculture, we may conservatively estimate that the total energy consumption of the human species was no more than 15 GW during this stretch of thermostatic equilibrium. A high-efficiency crop such as rice could capture this total energy requirement from the sun via photosynthesis with as little as 960,000 sq. km of land area,[2] less than 1/8th the area of modern-day Brazil.



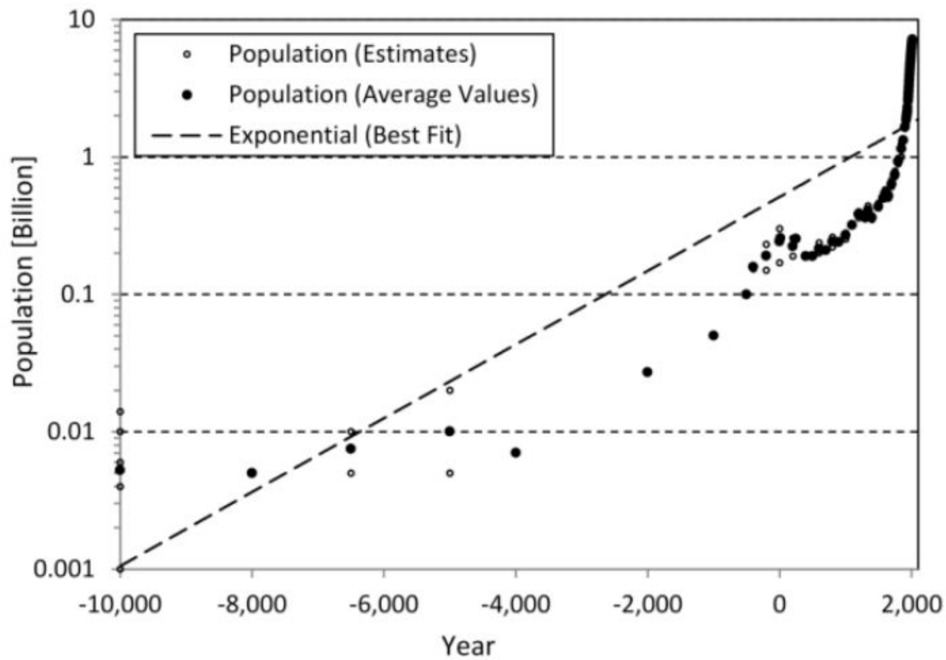
Estimated area of crop land required to sustain pre-capitalist global human populations for the duration of the Early Holocene. Original image.

II. Industrial Capitalism and Loss of Equilibrium

Then something changed, arguably in England, arguably in the 1300s or 1400s; economic historians call it the "economic revolution." The world began gradually to shift from stable-state traditional economies to a single interconnected market economy predicated on perpetual growth. Economic activity, population, and energy consumption began to increase at an

[2] Calculated from the following assumptions: energy consumption = 2000 Calories/person*day, population = 50 million persons, energy consumption efficiency = 1/3, rice yield = 1 ton/hectare*year, rice energy content = 590 Calories/pound.

exponential rate, requiring advances in farming technology and even still threatening the upper limits of land availability. At the end of the 1700s, English demographer and economist Thomas Robert Malthus wrote that “the power of population is indefinitely greater than the power in the earth to produce subsistence for man,” predicting eventual catastrophe. He has not yet been proven wrong.

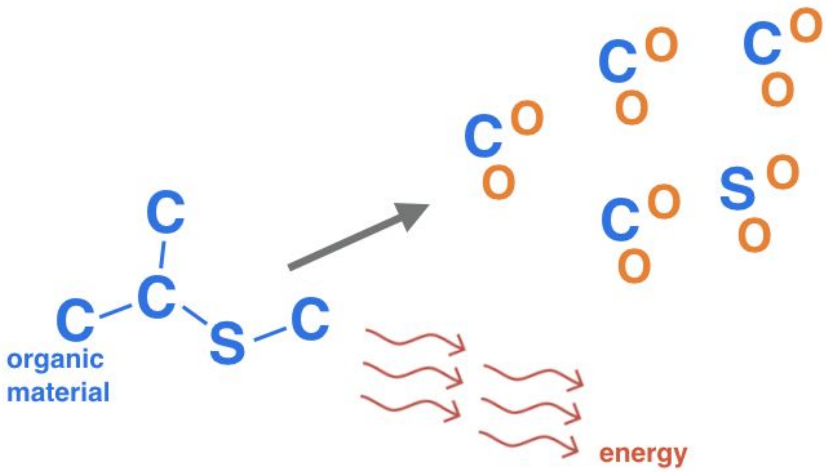


Reconstructed human population estimates throughout the Holocene, showing super-exponential increase in the second millennium AD. From Nielsen (2016).

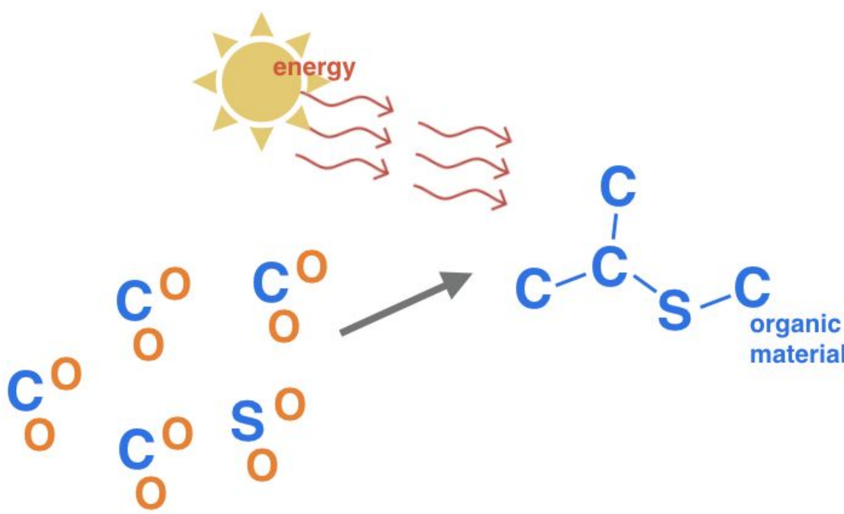
Humans did, of course, manage to bypass the natural energy limits of agriculture with the discovery of fossil fuels — an unthinkably rich, albeit finite, cache of chemical energy buried underground. The First Industrial Revolution (coal) and Second Industrial Revolution (oil and natural gas) led to an explosion in population unmatched in history, as well as an increase in the prevalence of energy-consuming technologies. Today, there are over 7.57 billion humans who each consume energy at a rate of 2380 W (9210 W for the average American), a total of 18,000 GW worldwide. The vast majority of this quantity (87%) is drawn from the fossil fuel cache.

The combustion of fossil fuels is an oxidation reaction, breaking large, complex carbon-based molecules into particulates such as CO_2, NO_x, and SO_2 and in the process releasing bond energy which can be applied to industrial processes. It is precisely the opposite of photosynthesis, a reduction reaction which combines particulates into large, complex carbon-based molecules, storing the sun's energy in chemical bonds. Combustion and photosynthesis were in balance throughout the early Holocene, but the opening of the fossil fuel cache tipped the balance in favor of combustion.

(a)



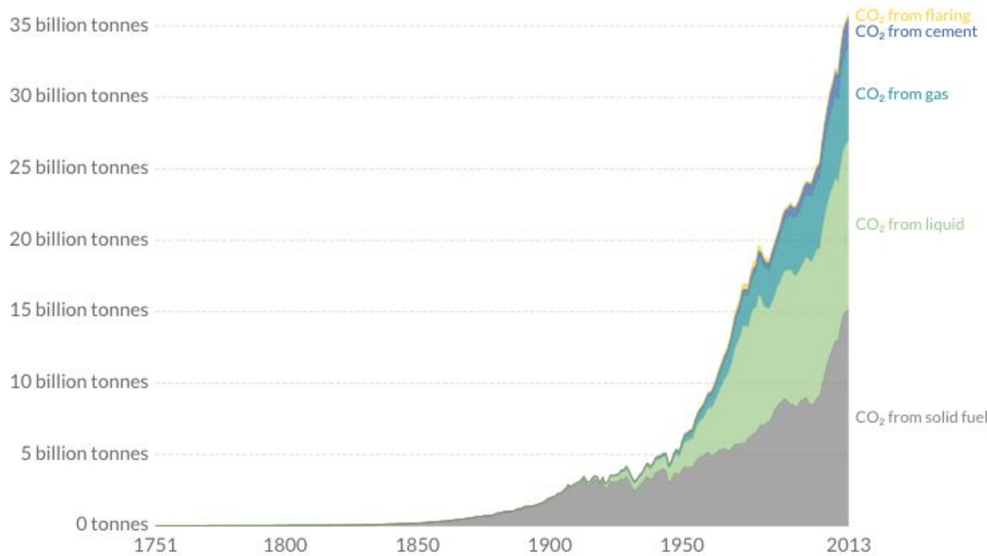
(b)



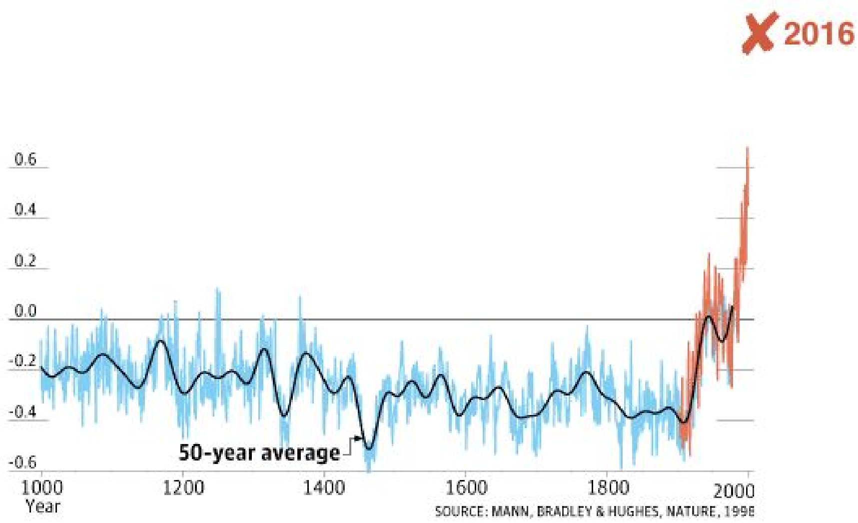
Intuitive schematization of (a) combustion, an oxidation reaction; and
(b) photosynthesis, a reduction reaction. Original image.

As a consequence, the production of particulate oxides (especially CO_2) in combustion reactions today greatly outpaces their consumption in photosynthesis reactions. As of 2014, the fossil fuel industry releases 9.79 billion tons of CO_2 into the atmosphere every year.

Furthermore, ongoing deforestation reduces the amount of CO_2 consumed in photosynthesis by 0.85 billion tons each year. Thus the atmosphere contains 10.64 billion tons more CO_2 at the end of each year than it did at the start— a number that is still *increasing*. This sharp uptick in atmospheric CO_2 concentration has upset the net radiation balance of the Earth, trapping outgoing terrestrial heat. The long period of thermostatic equilibrium ended in 1950; in the subsequent 70 years, the global average surface temperature has increased by 1.1 ºC, more than the entire temperature range of the preceding 10,000 years.



Annual (*not* cumulative!) CO_2 emissions from coal (gray), oil (light green), and natural gas (dark green). Most emitted CO_2 does not enter the atmosphere. From Boden et al. (2017), image from *Our World in Data*.



Average land surface temperature, Northern hemisphere, 50-year average. From Mann et al. (1998), image from *The Economist*, edited.

If we achieved carbon neutrality tomorrow, the amount of CO_2 already present in the atmosphere would still lead us to a new long-term equilibrium temperature about 8 ºC (14 ºF) above the present value, on the time scale of 1,000 years— an unthinkable and genuinely apocalyptic level of warming for all life on Earth. To avoid such a scenario, we need to achieve carbon drawdown (net negative emissions), gradually reversing the last 170 years of emissions until we return to the Holocene balance. As of now, we are still putting an additional 10.64 billion tons of CO_2 into the atmosphere each year; there is no long-term equilibrium for continued emissions, and the planet will continue warming until the Earth's climate resembles that of Venus.

III. Stratospheric Aerosol Injection

Recently, a number of influential voices have introduced a proposal to stabilize the Earth's temperature through a process called stratospheric aerosol injection (SAI). Bill Gates has contributed at least $8.5 million in grants from his personal wealth to the Keith Group at Harvard "to produce research that advances solar geoengineering's science and technology frontier, publishing high-impact papers, and disseminating ideas that are taken up by other researchers and government research programs." In 2016, CIA director John Brennan spoke positively about SAI at the Council on Foreign Relations, saying that "an SAI program could limit global temperature increases, reducing some risks associated with higher temperatures and providing the world economy additional time to transition from fossil fuels." The NASA website's information page on aerosols, which formerly read that "scientists have much to learn about the way aerosols affect regional and global climate … we are even unsure whether aerosols are warming or cooling our planet," has been updated as of August 2017 to say that "the effect of the aerosols [from industrial pollution], however, will be opposite to the effect of the increasing atmospheric trace gases - cooling instead of warming the atmosphere."

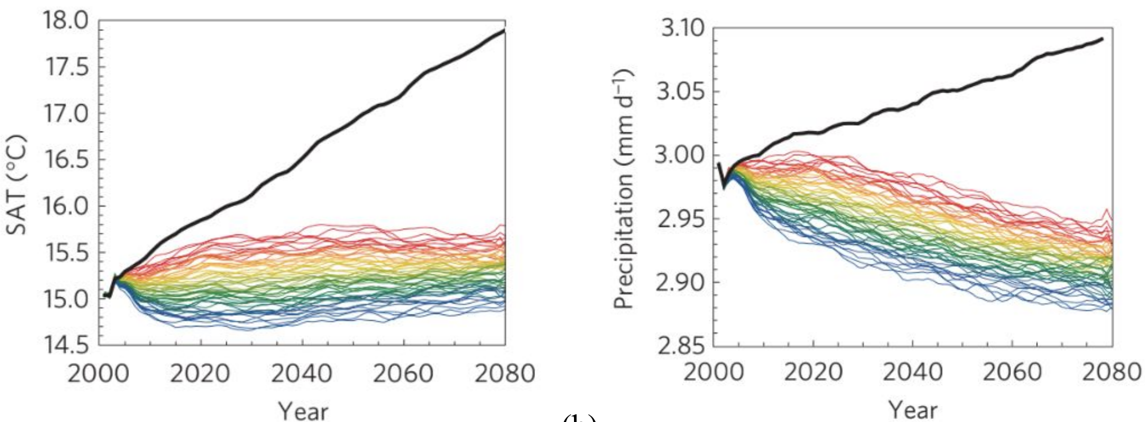
Stratospheric aerosol injection proposes to deposit sulfate aerosols into the lower stratosphere, likely by altering the chemical composition of airplane fuel, thus absorbing and reflecting a small portion of the incoming solar radiation. The mechanism is intended to mimic the way volcanic eruptions are observed to dramatically reduce the surface temperature of surrounding regions. In the case of SAI, by contrast, the particulates would have to form a uniform blanket across the Earth's stratosphere. This process is expected to cool the troposphere, where human society and weather activity takes place, while warming the stratosphere where the particulates will be located. The idea, in other words, is to restore net zero radiation balance not by reducing CO_2 emissions and allowing outgoing terrestrial radiation to return to Holocene levels, but by *increasing* SO_2 emissions in the hopes of reaching a new Anthropocene equilibrium: less heat out, less heat in.

The particulates in the proposed injection scenarios, referred to by climate scientists as aerosols, are known to chemists as sulfur dioxide (SO_2), hydrogen sulfide (H_2S), and sulfuric acid (H_2SO_4), and are perhaps best known by the public as components of smoke, soot, and smog. These chemicals, like carbon dioxide, are combustion products which are presently emitted industrially during the oxidation of impure fossil fuels containing sulfur groups. Sulfur dioxide, the aerosol which has received the most attention in the context of SAI, is also recognizable as the primary cause of acid rain; in recent years, stricter limits on tropospheric SO_2 emissions (affecting, for instance, oil refineries) have been introduced to combat increasing acidification.

As of 2010, 97 million tons of SO_2 are emitted by the fossil fuel industry each year, almost exclusively into the troposphere. This number that has decreased from a high of 151 million tons in 1980 due to acid rain prevention regulations in many jurisdictions. By comparison, volcanic eruptions account for 7–8 million tons of SO_2 per year, affecting both the troposphere and the stratosphere. The amount of stratospheric SO_2 emission under discussion in contemporary SAI research ranges from 1–10 million tons.

IV. Known Effects

Since stratospheric SO_2 emissions at the magnitude required to achieve temperature stabilization under SAI have never been attempted, relatively little is known about the short- and long-term climate impacts of such a program. A 2010 paper by Katharine L. Ricke, M. Granger Morgan, and Myles R. Allen uses the HadCM3L climate model to run 54 simulations of SAI calibrated to stabilize global temperature at 1990 levels through 2080. As expected from such a parametrization, most of the SAI simulations show a stabilization of global average surface temperature through 2080. The variance between simulations, however, is larger than the entire Holocene temperature range, with the warmest simulations reaching a global temperature anomaly over +0.7 ºC and the coolest simulations experiencing a decrease of –0.3 ºC. It should be stressed that these values are *global averages* and thus significantly understate the level of regional temperature variability, which will be discussed in Section V.

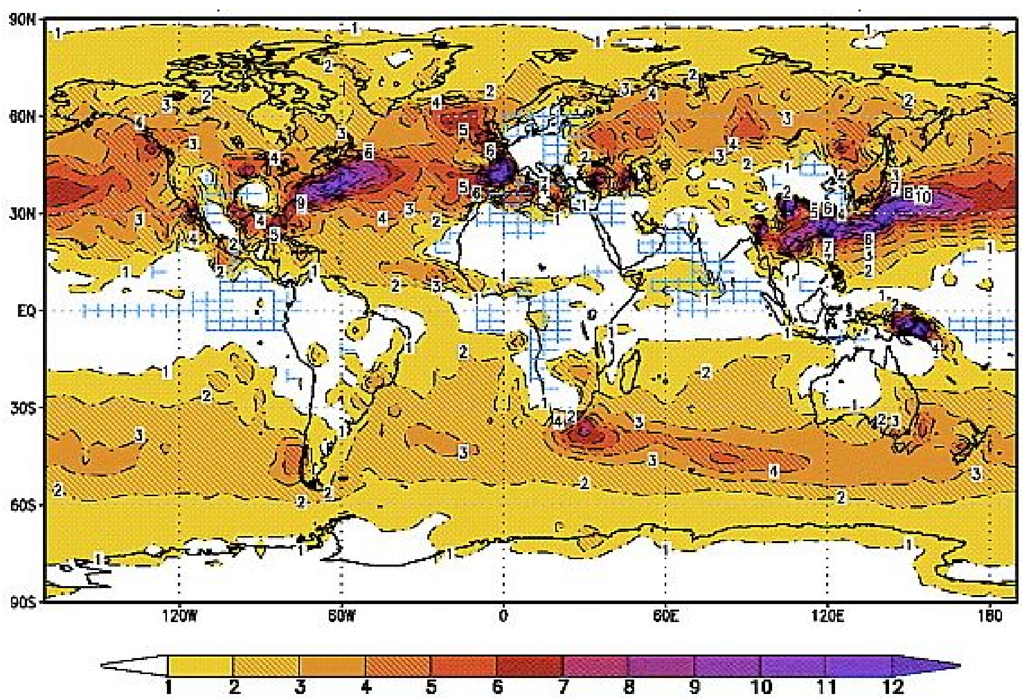


(a) (b)

(a) Temperature projections under 54 simulations of SAI shows stabilization on average with high inter-simulation variability.
(b) Precipitation projections under 54 simulations of SAI shows consistent decrease across all simulations. From Ricke et al. (2010).

Temperature stabilization is associated with a dramatic decrease in average global precipitation, consistent across every simulation. This global decrease in rainfall relative to both Holocene and present-day norms can be explained theoretically by the anticipated warming of the stratosphere (where the particulates would be located) relative to the troposphere. Warming the cool stratosphere while cooling the warm troposphere would decrease the environmental lapse rate, reducing the amount of moisture-carrying convection and thus the amount of cloud formation and precipitation. Because this decreased lapse rate is inherent in SAI cooling, Ricke et al. report that “it is not physically possible to stabilize global precipitation and temperature simultaneously” under the proposal.

Finally, it is expected that SAI would “be a small contributor to the total global source of ‘acid rain’” and would cause a slight acceleration of ongoing ocean acidification. Gas phase SO_2 readily oxidizes in the atmosphere and then combines with atmospheric moisture to form sulfuric acid (H_2SO_4) which is subsequently rained out on land and in the ocean. In extreme cases, volcanic emission of SO_2 has been observed to lower the pH of rainfall as low as 2 (the acidity of vinegar or lemon juice), clearing the surrounding area of vegetation. SO_2 deposited into oceans in coastal regions would also contribute to ocean acidification and ecological consequences such as coral bleaching, though by an amount equivalent only to a few percent of the ongoing ocean acidification due to CO_2 deposition.



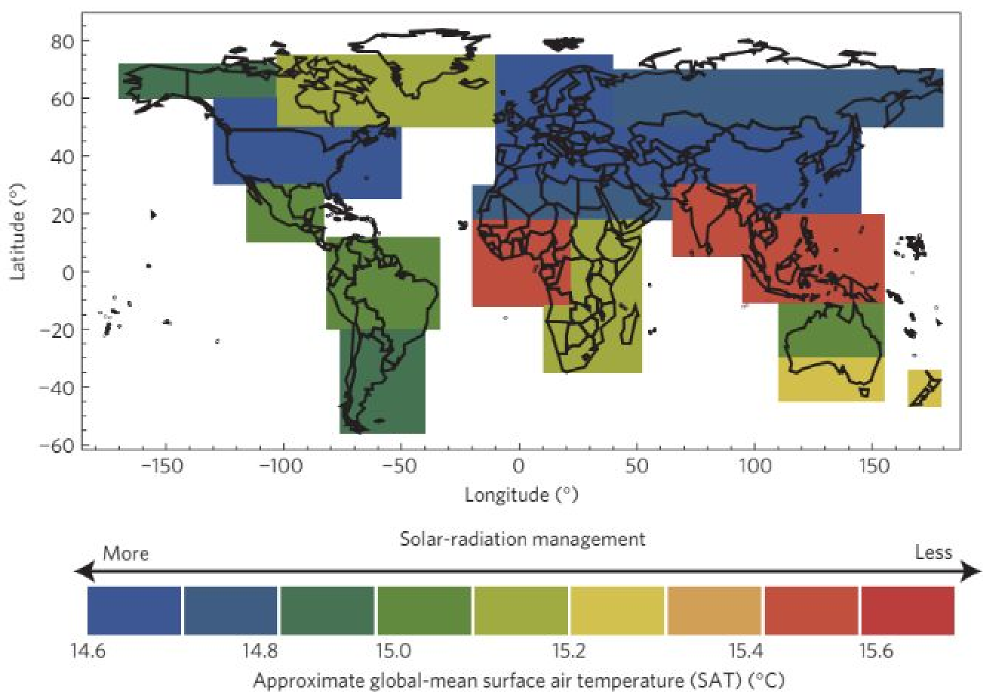
Projected annual sulfuric acid deposition (in units of 10^{-4} kg/m^2) under an SAI scenario of 5 million tons injected annually at the tropics. From Kravitz et al. (2009)

V. Unknown Effects

Perhaps the most pertinent unanswered questions about SAI have to do with regional variation in climate impacts. Regardless of where the sulfur compounds are injected, there is significant uncertainty surrounding the subsequent motion of the stratospheric smog, how it might disperse or collect over time, and what the consequences would be for regional climates. The hypothetical image of a uniform sulfur cloud spread thinly over the lower stratosphere is clearly an optimistic oversimplification; the analogy to clouds of volcanic ash suggests that the particulates would spread unevenly depending on prevailing winds, causing abnormal weather patterns as it does. Communities located beneath “holes” in the aerosol layer would experience unabated CO_2

warming, while densely concentrated sulfur patches would cause unseasonably cool weather, dim and red-tinted skies, and strongly acidic rains. The frequency and magnitude of such localized events relative to global or even regional averages is unknown.

The model used by Ricke et al. reveals that, even averaged over 54 simulations, the climate effects of SAI have a strong regional component. In particular, what Ricke et al. define as the "optimal scenario" for SAI (minimum combined temperature and precipitation anomalies relative to the 1990s) cannot be achieved for all parts of the globe at the same time: the "optimal" amount of SAI is far greater for the high latitudes than the tropics. Thus, regardless of which regions SAI is calibrated to stabilize,[3] distant regions could expect to experience the aforementioned abnormal weather patterns not merely as a result of local fluctuations but as a long-term climatic norm.



Relative quantity of stratospheric aerosol injection required to achieve minimal combined temperature and precipitation anomalies relative to 1990s, in 2070. Low desirability of SAI in West Africa, India, and Southeast Asia is due to the expected interruption of the monsoons. From Ricke et al. (2010).

It is also crucial to mention the possibility of modeling error in the above analysis. As all simulations were computed from a single theoretical model of the Earth's climate, which is of

[3] Bear in mind that "stabilize" in this context refers to minimal combined temperature and precipitation anomaly; as discussed in Section IV, it is not possible to simultaneously stabilize temperature and precipitation for any region.

course an imperfect representation of the Earth's true climate system, we should add additional error bars on all of the predictions produced by this model. In the words of Ken Caldeira, a climate scientist at the Carnegie Institution for Science's Department of Global Ecology, "I don't think climate modelling is at the point where we should trust one single model at that scale."

Finally, there are of course myriad other considerations beyond temperature, precipitation, and acidity which have never been modeled under an SAI scenario and which might be affected by increased stratospheric sulfur concentrations. For one, the analogy to volcanic clouds should raise concerns about the possibility of ozone depletion, as the ozone layer near volcanoes has been observed to thin significantly after eruption events. This would increase the flux of harmful UVB radiation, causing adverse human health impacts and crop damage. It is also not known what impact the particulates would have on atmospheric circulation or ocean overturning, to name two more highly significant considerations.

VI. The Laissez-Faire Scenario

Why would such a program be enacted, given the immense uncertainty around its implementation and the known adverse effects? We are necessarily considering a suboptimal scenario in which collective action to achieve carbon drawdown and return to Holocene CO_2 concentrations has failed.[4] SAI is under present consideration essentially because it is cheap and easy: a single actor could begin injecting SO_2 into the stratosphere at any time. The incentives amount to what economists Martin Weitzman and Gernot Wagner call a *free-driver problem*: "The difficulty would not be motivating countries to deploy aerosols but stopping them from doing too much too soon."

The remainder of this paper will consider, speculatively, the logical endpoint of this line of reasoning: what if collective action on climate change never materializes? We will explore the "laissez-faire scenario" in which all actors with significant emissions potential continue to act in their own near-term economic interest, responding to a changing climate exactly when and how it is profitable to do so. What would be the long-term global and regional effects on climate and human life in such a scenario?

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[4] Some climate scientists view SAI as a temporary patch to stabilize temperature after drawdown is achieved but while atmospheric CO_2 concentrations are still dangerously high; this will be discussed in Section VIII.

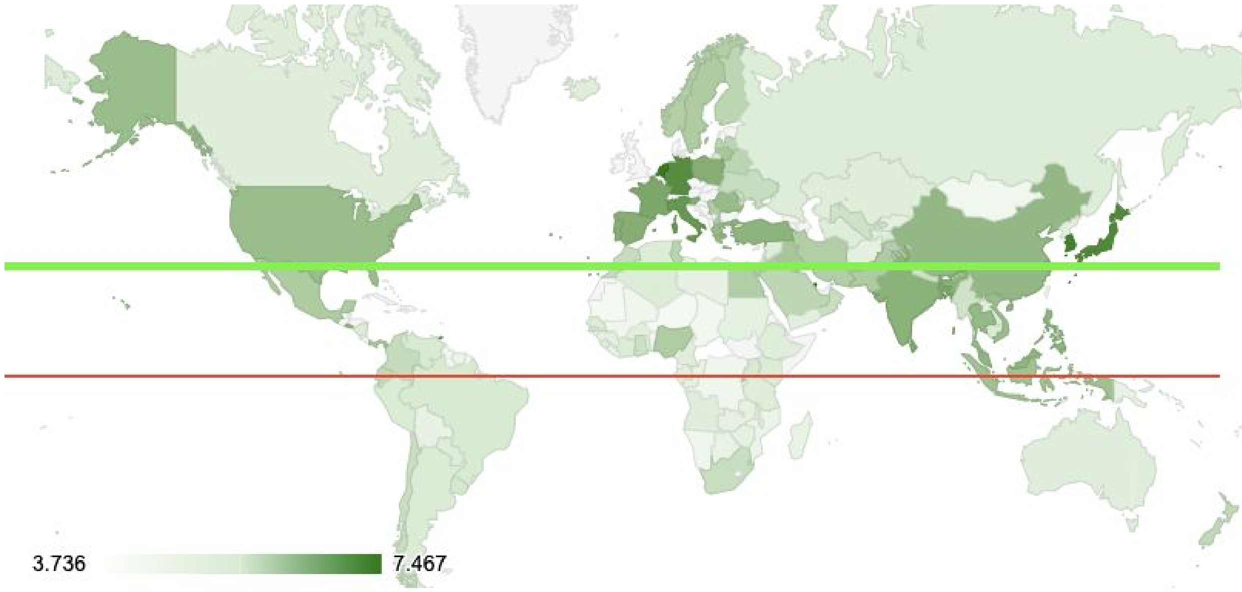
SAI would be expected to play a role in this scenario in either of two ways: private emissions or regulatory capture. As mentioned above, SO_2 is generated as a byproduct in oil refineries, after which it is generally sold to the chemical industry. If a wealthy corporation or individual found their profitability threatened by a warming climate, they could simply purchase large quantities of SO_2 from an oil company and begin injecting it into the stratosphere. Alternatively, if an oil company found it profitable to engage in SAI, they could simply do so. If this seems unlikely, consider that Ken Croasdale, a senior researcher for Exxon, wrote in 1991 that continued greenhouse gas emissions would be beneficial for Exxon as "global warming can only help lower exploration and development costs" in the Arctic, expanding drilling season "from two months to as many as five months." This is the path of private emissions.

The other path to the laissez-faire scenario would be regulatory capture, in which SAI is carried out by a national government or by a private company on a contract with a national government, but the optimization function of the national government is aligned with business interests rather than human welfare. Given that the present chief of the Environmental Protection Agency is a former coal lobbyist, it is perhaps not a stretch to imagine that U.S. government climate policy could soon involve purchasing SO_2 from oil refineries, or perhaps even contracting the job directly to oil companies, for the purpose of GDP-maximizing SAI.

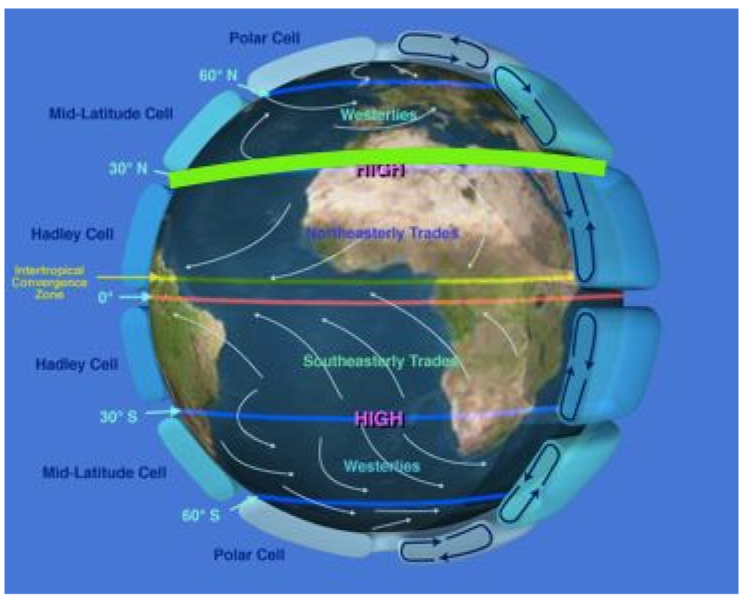
In either case, the material situation is identical: unabated CO_2 emissions; stratospheric SO_2 injection to stabilize temperature in wealthy areas; floods, droughts, forest fires, and other symptom-level climate crises responded to "as needed" to protect valuable real estate and capital. Consider, by way of example, the paltry government responses to Hurricanes Katrina (2005) and Maria (2017), alongside the prevalence of private firefighters combating wildfires on private property in Beverly Hills throughout 2018.

VII. Impact in the Global South

Wealth is concentrated in the high latitudes. This is due to the concentration of land at high latitudes, and because of European imperialism, which amounts to a centuries-long wealth transfer from low to high latitudes.



Global wealth density (units of USD/km^2), log scale (i.e. 4.000 = $10,000 per sq. km).
Calculated from World Bank estimates of GDP PPP (2017) and CIA World Factbook (2018).
Red line represents equator, green line represents 30ºN. Original image.



Geometrically accurate map for comparison, as Mercator projection greatly skews areas.
Red and green lines as above. From Wikimedia Commons, edited.

As such, we can expect the laissez-faire scenario to involve SAI optimized for the wealthy North, and thus greatly exceeding the magnitude which would be desirable for the global South. In particular, the data from Ricke et al. suggest that combined temperature and precipitation anomalies can be minimized in the United States, Europe, and Northern China (all at latitudes around 30º–50º N) approximately simultaneously, while leading to disastrous climate effects in West Africa, India, and Southeast Asia.

Most significantly, analysis of regional climate responses to volcanic eruptions by Robock et al. suggests that stratospheric aerosols "weaken the Asian and African monsoons causing precipitation reductions. In fact, the 1783–1784 Laki eruption produced famine in Africa, India, and Japan." The climate simulations run by Ricke et al. strengthen the argument that Northern optimization might produce equatorial crop failures and famines. Robock et al. conclude that "both tropical and Arctic SO_2 injection would disrupt the Asian and African summer monsoons, **reducing precipitation to the food supply for billions of people**." This point must be repeatedly emphasized in any discussion of SAI.

This is not to mention the drastic increase in floods and natural disasters which are already beginning to plague the tropics as sea surface temperature increases and Arctic glaciers melt. Many island communities, particularly in the West Pacific and Caribbean, exist entirely within a few meters of sea level; these regions will be uninhabitable due to constant flooding within a generation or two. (Barbuda was evacuated during Hurricane Irma and remains uninhabited as of May 2019.) We can expect a global migrant population on the order of hundreds of millions or billions and, realistically, we can expect mass death.

It is quite likely that present-day human population exceeds the Earth's carrying capacity and that a sizable reduction in population is inevitable. It is worth mentioning, though, the catastrophically racist and classist nature of the scenario just outlined. It is almost exclusively the wealthy, white countries of the North who have brought us into our current predicament; 48% of all CO_2 emissions since 1750 have come from the United States and Europe, home to 11% of the world's population. And yet it is almost exclusively the poor, black and brown countries of the South who would suffer mass famines, floods, and general habitat reduction if carbon emissions continue alongside profit-seeking geoengineering. I do not believe it is a stretch to say that the laissez-faire scenario described above would amount to global genocide on an unprecedented scale.

VIII. Just Say No

It is acknowledged by proponents of SAI that the proposal is not optimal and not meant to be permanent. The rhetoric of "buying time" until we can solve the central problem is often used. It has alternately been proposed that SAI be used only *after* carbon drawdown has been achieved, to maintain global surface temperature within habitable bounds as atmospheric CO_2 returns to Holocene levels. I do not believe any of these arguments can be made in good faith. Until carbon drawdown is achieved, any talk of SAI is at the very best a distraction from the issue at hand and at worst a passive endorsement of the laissez-faire scenario. There is no scientific problem that we need more time to solve. The solution is carbon drawdown.

It is of course standard practice for an academic paper to aim for neutrality and objectivity, to see the nuance on all sides of a debate. I refuse to do this. I believe there is no nuance here and that entire societies are at stake. I would implore anyone with authority in the field of climate science to loudly and publicly agitate against SAI, against SAI research which can be cherry-picked and misrepresented, and against the influential individuals who are promoting and funding SAI research. The only solution is carbon drawdown. There is no other option or "Plan B." We need to remove carbon dioxide from the atmosphere.

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