2019

Geoengineering in 2019

TECHNOLOGY, ISSUES, AND CONCERNS

GEORGE THOMAS JR.

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Executive Summary

As greenhouse gas emissions continue to rise, any hope of limiting global mean temperature rise to the 2015 Paris Agreement goal of 2 degrees Celsius is at risk. And limiting the rise to 1.5 degrees above pre-industrial levels seems on par with delusional wishful thinking.

The 2018 Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5ºC warned there is no single solution to curb rising global temperatures. Alarmingly, the report indicated carbon dioxide removal must be part of the solution to prevent a temperature rise above 1.5 degrees. But such technology is nascent and, currently, cost prohibitive.

Proponents of various geoengineering methods, however, are optimistic, because geoengineering has worked, and is working now – just not always as intended. Geoengineering has been used as a weapon to alter rainfall during the Vietnam War, and currently, unwittingly, to alter weather hundreds of kilometers from coal-burning power plants. Geoengineering also has been linked to earthquakes as well as unpredictable weather patterns.

Projects to experiment on sea ice reflectivity and inject aerosols into the upper atmosphere are progressing despite objections from the scientific and indigenous communities. And, most recently, governance of geoengineering practices has been derailed by fossil-fuel interests.

Critics maintain geoengineering siphons critical funding from transitioning to a green economy, and fails to address the root problem of rising greenhouse gas emissions – which continue to threaten the whole of the marine environment with increased ocean acidity.

Still, without a rapid transition to green, clean energy, and without some means to immediately drawdown CO2 from the atmosphere, proponents see geoengineering as a way to stall or limit rising global temperatures until such global warming mitigation is feasible. Yet research in this area is scant, governance essentially is self-governing, and ethical concerns remain regarding who can implement geoengineering, and at what cost to those who may bear the brunt of its negative and potentially extreme impacts.

Introduction

Global warming continues to steal the headlines in 2019. As scientists gather more data about ocean temperatures, melting ice, and extreme weather events, the trend is clear: human activity -- particularly increasing emissions of greenhouse gases (GHG) -- is disrupting Earth's climate well beyond its natural variability, threatening planetary mass extinction (Kump et al, 2018). Global mean temperatures have risen nearly 1.0 degree Celsius since the industrial revolution, resulting mainly from GHG emissions.

While a seemingly small increase, during the last ice age Earth's global mean temperature was approximately 5 degrees Celsius colder than today.

A dire forecast for humanity was released in October 2018, when the U.N. Intergovernmental Panel on Climate Change (IPCC) issued its special report comparing the projected impacts of Earth's mean global temperature rise of 1.5 degrees Celsius to a 2.0 degree rise. The IPCC, comprised of the world's leading climate scientists, warned that immediate action is needed to halt the rise at 1.5 degrees, and that loss and damage resulting from climate change will be dramatically worse if warming reaches 2.0 degrees. The IPCC warned there is no single solution, and that methods such as carbon dioxide removal (CDR) from the atmosphere must be considered to avoid the catastrophic warming.

Prior to humanity's intervention, the Earth's ecosystem remained in relative balance, even as it shifted from ice age to interglacial period back to another ice age. Such natural variations are related to Earth's wobbling orbit and tilted axis, and can span tens and hundreds of thousands of years (Maslin, 2016).

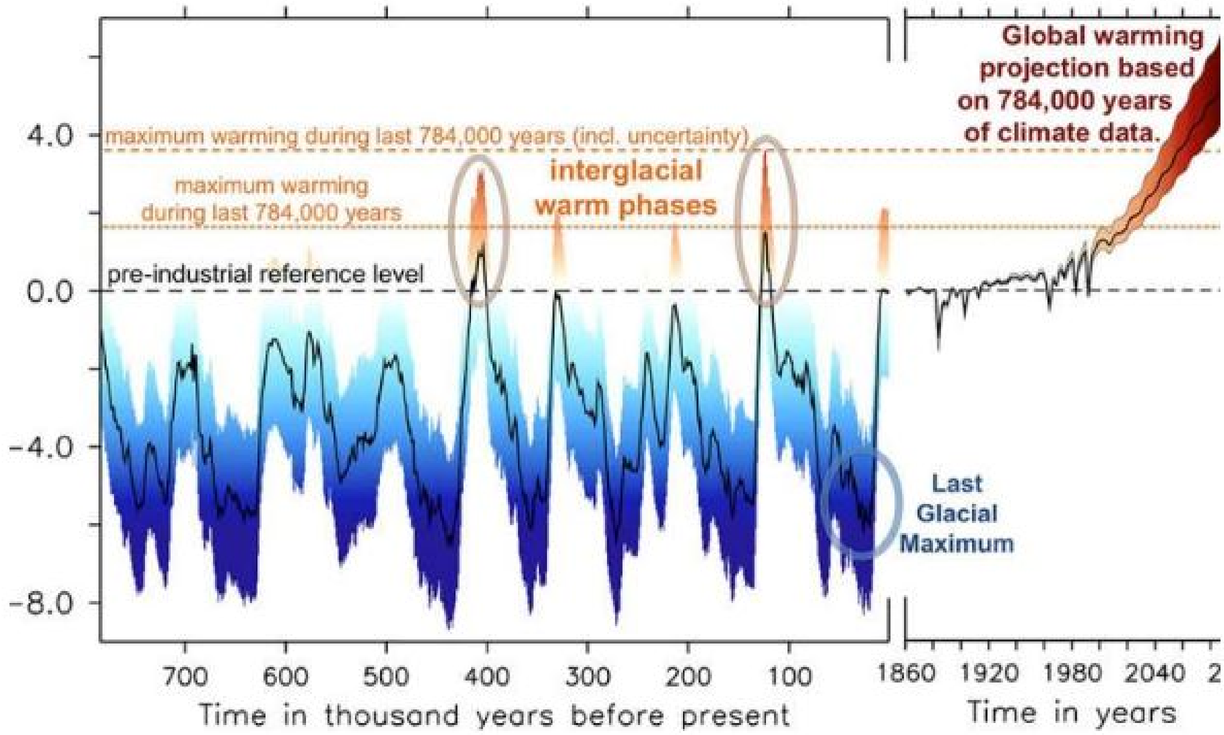

Figure 1: The global mean temperature variation of last 784,000 years, and projections to 2100. The Last Glacial Maximum was Earth's last Ice Age, 5 degrees Celsius cooler than today. pre-industrial reference level. (Source: Tobias Friedrich/International Pacific Research Center/University of Hawai'i at Mānoa)

Further exacerbating the disruption to the climate's natural variation is Earth's inability to naturally absorb and sequester the rapidly rising GHG levels; while the benefits of natural climate solutions can play a significant role in limiting warming to 2 degrees Celsius, GHG emission reductions from industrial and energy sectors is imperative (Anderson et al, 2019).

On the matter of CDR, high costs and technical challenges remain. Project Drawdown, founded in 2014 by author, entrepreneur, and environmentalist Paul Hawken, aims to facilitate solutions to global warming, which span the spectrum from green energy to land use to food security, including carbon capture and sequestration.

But a March 12 story in CleanTechnica noted three problems with carbon capture:

- Capturing the carbon
- Transporting it to storage
- Long-term disposal

The story claims that capturing the carbon in the first place would require global infrastructure "orders of magnitude larger than the entire oil and gas infrastructure that's been built over the past 100 years."

And according to the U.N.'s Global Material Resources Outlook to 2060, merely extracting and processing materials, fuel and food is responsible for nearly half of GHG emissions. The report notes without drastically reforming the global economy to reduce GHGs, the global infrastructure is at risk of collapse. Under the business-as-usual approach, GHGs are projected to nearly double by 2060 -- an unsustainable future, the report cautions.

Despite agreement to the 2015 Paris Accord, in which countries pledged to take measures to help limit global warming to 1.5 Celsius (2.7 Fahrenheit), GHG emissions continue to rise.

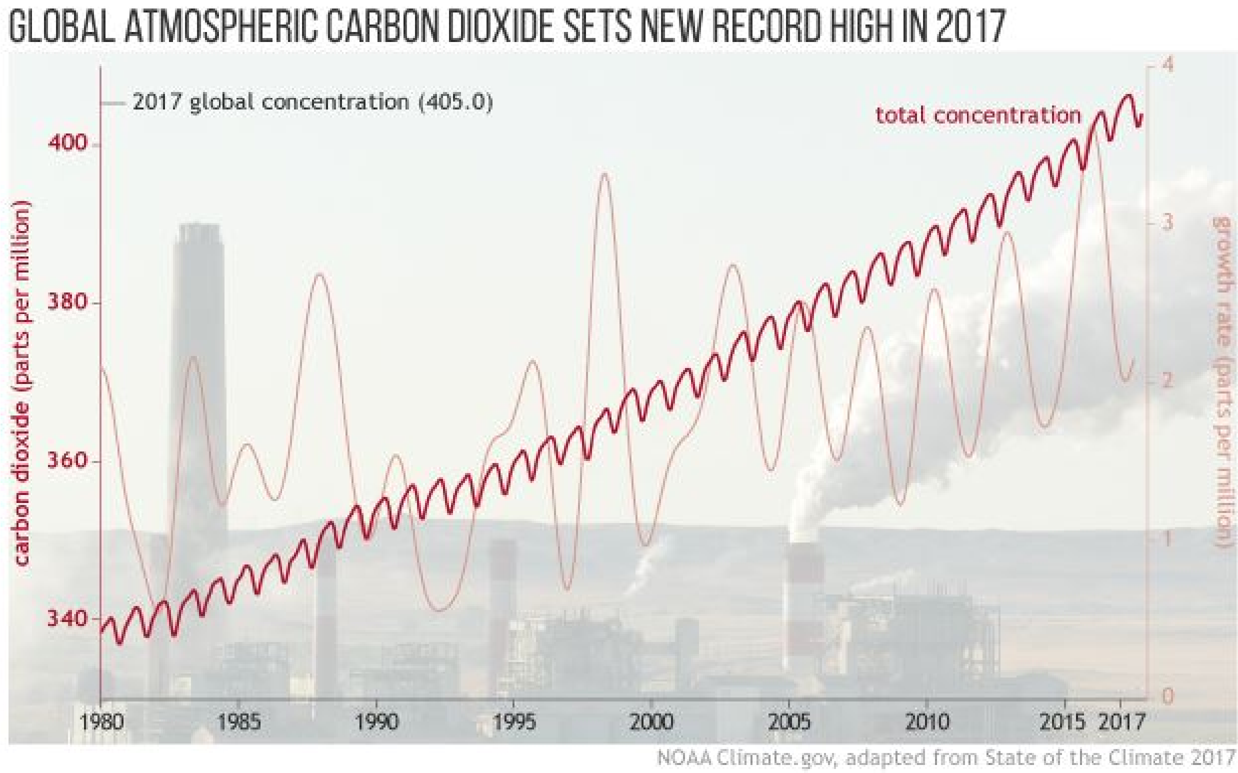

Figure 2: Monthly carbon dioxide in the global atmosphere (dark red line) from 1980–2017 showing the long-term increase along with the smaller ups and downs due to seasonal plant growth and decay. The light red line is the annual growth rate, or the amount by which carbon dioxide increased each year. (Source: NOAA Climate.gov graphic adapted from Figure 2.45a in State of the Climate in 2017. The graphs are overlaid on a photo of Dave Johnson Power Plant in Wyoming by Greg Goebel, used under a Creative Commons license)

Can geoengineering play a role in a sustainable future? And, if so, in what way, and at what cost?

Types of geoengineering

As global temperatures continue to rise, geoengineering as a means of cooling Earth is gaining momentum. Geoengineering primarily concerns the following methods:

- Aerosol injection
- Marine cloud brightening
- Highly reflective crops and buildings
- Ocean mirror
- Cloud thinning
- Space mirrors

Aerosol injection

This approach is modeled after large volcanic eruptions, which spew enormous amounts of sulfur dioxide into the atmosphere that have resulted in short-term global cooling. The sulfur combines with water to form sulfuric acid aerosols, which reflect sunlight. Artificially reproducing this effect has been done on small scales and remains controversial because of its unpredictable impact on a global scale.

Marine cloud brightening

Ships could be used to spray ocean water into clouds, making the clouds larger and brighter, thus reflecting more sunlight. There is limited research in this area, and its global effects are not well understood.

Highly reflective crops and buildings

Regarding buildings, white roofs would reflect more sunlight than black roofs, but heat-reducing effects are likely to be localized -- such as mitigating urban heat waves (Seneviratne et al, 2018). Genetically modifying crops to grow more reflective leaves remains theoretical, and must be considered in the context of food security.

Ocean mirror

Sea foam can be 10 times more reflective than the ocean. Using a fleet of vessels to churn up millions of highly reflective tiny microbubbles could increase the amount of sunlight reflected back to space, but it also would impact life below the surface and reduce the photic zone, which is critical to marine photosynthesis, and, therefore, the food web (Evans et al, 2010).

Cloud thinning

This is another under-researched area that could involve seeding high cirrus clouds with particles to dissipate them, because such high clouds actually trap GHGs and enhance global warming. How this could impact atmospheric circulation is another issue of concern.

Space mirrors

Perhaps the most expensive and far-reaching technological challenge, this geoengineering method entails launching into space a large mirror or fleet of mirrors that intercept Earthbound sunlight and reflect it out into space. Govindasamy Bala of the Divecha Centre for Climate Change at the Indian Institute of Science told carbonbrief.org that a 2-percent reduction in incoming sunlight could offset the warming if CO_2 levels, now at 412 ppm, reach 560 ppm.

Geoengineering at work

Beyond theory, some projects are moving forward, controversy notwithstanding. And controversy has enveloped projects that already have been implemented.

ICE 911

The high reflectivity of the polar ice caps help reflect some of the sun's energy back into space, essentially acting as a heat shield for the planet. But the Arctic has lost 75 percent of its ice since 1979, and is experiencing record high temperatures year after year, accelerating ice loss.

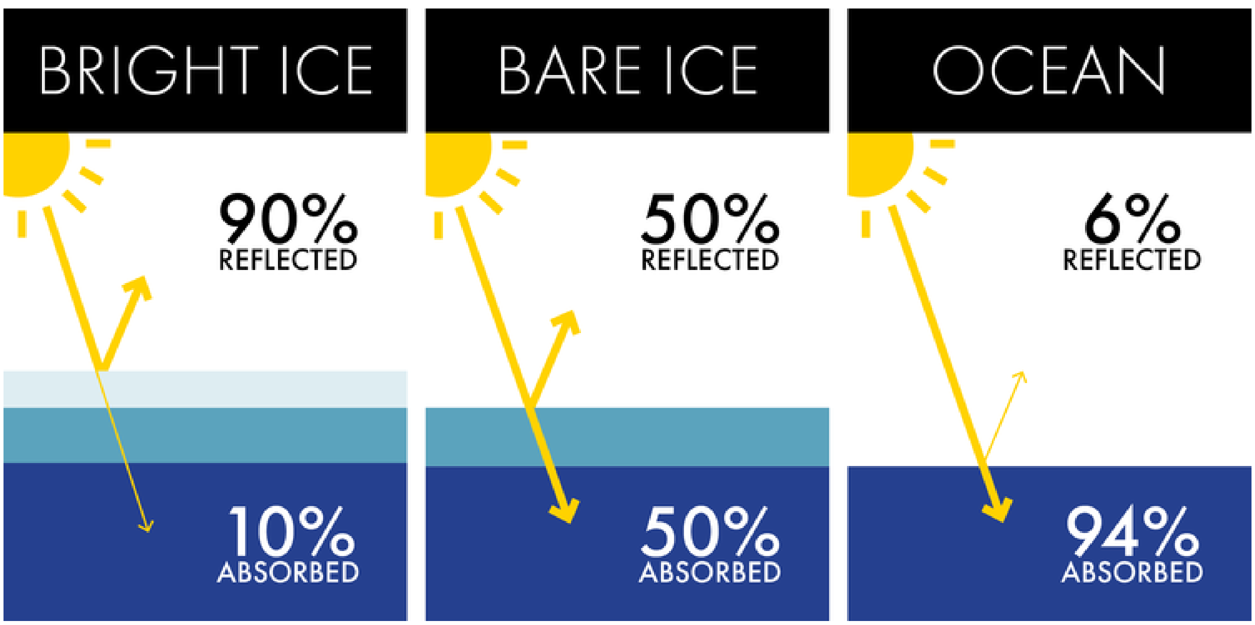

Figure 3: Ice911's material mimics bright ice to reflect heat -- ideally keeping more ice in the Arctic. (Source: Ice911)

The loss of Arctic sea ice is a concern because warmer Arctic Ocean temperatures will contribute to global warming (Scheider von Deimling et al, 2012). The Ice911 project entails spreading highly reflective silica microbeads over the existing poorly reflective ice, thus increasing the level of reflectivity (called albedo), with the expectation of reversing the warming, and extending the ice to its previous levels. The silica eventually will dissolve and feed the existing natural silica cycle, with little impact to the environment, according to the project leaders (Field et al, 2018).

Critics, however, say the project is dangerous and lacks consent of indigenous communities. Inupiaq community organizer Adrienne Titus told geoengineeringmonitor.org not all communities were consulted prior to issuing the permit for the project. The Ice911 team deployed the silica material on 17,500 square meters in 2017 and 15,000 square meters in 2018, "with successful results." But Titus said the supposed success has yet to be defined, and that the impacts on wildlife and the ecosystem have not been thoroughly assessed.

Stratospheric Controlled Perturbation Experiment (SCoPEx)

The Harvard-led SCoPEx project focuses on how stratospheric aerosols will interact with the atmosphere and with solar and infrared radiation (Dykema et al, 2014). The project involves launching a balloon into the upper atmosphere over New Mexico to release ice particles, calcium carbonate and perhaps other materials to form an air mass one kilometer long and 100 meters in diameter, and monitor changes in aerosol density, atmospheric chemistry, and the scattering of light. The SCoPEx team claim the project does not violate the Convention on Biological Diversity, which prohibits climate-related geoengineering activities under most circumstances.

Such a small-scale experiment, however, is unlikely to yield sufficient insight, critics say. Climate scientist Gabriele Hegerl, who co-authored a 2009 article, "Risks of Climate Engineering," said a much larger experiment is required to accurately model the effects of solar engineering (Chen, 2017). As an example, Hegerl cited the complex climate modeling required to determine the global cooling effect of volcanic eruptions. She also criticized solar radiation management, which doesn't address the root cause of global warming: GHG emissions.

Accelerated weathering

In contrast to bioenergy with carbon capture and storage (BECCS) -- burning biomass for energy, and storing the resulting CO2 -- there is another emerging field of study regarding mineral weathering, which is a natural process that, over geological time scales, draws CO2 from the atmosphere and stores it in rocks. If the process can be accelerated, exponentially larger amounts of CO2 can be drawn down and "naturally" stored.

When rain reacts with alkaline rocks, CO2 is dissolved into mineral bicarbonate and carbonate ions, which through runoff makes its way to the ocean. Adding industrially produced alkaline chemicals to surface waters would accelerate the process, but questions of scale and ethical concerns remain.

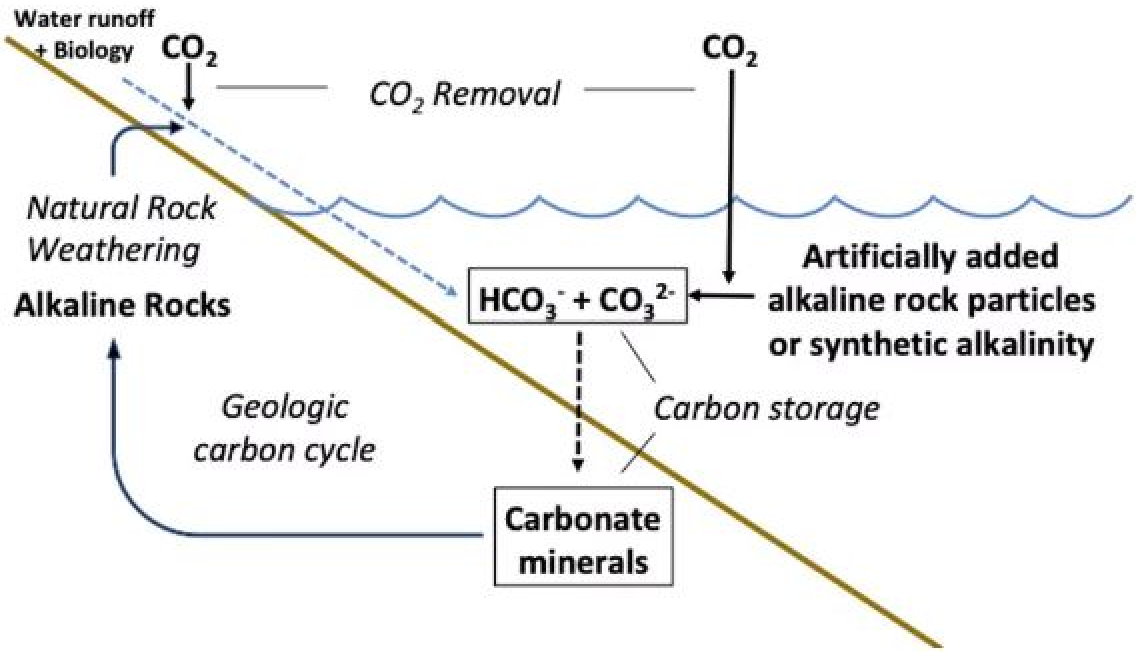

Figure 4: The natural process of mineral weathering starts with rain which absorbs carbon dioxide from the air and then reacts with rock and biota in soils, forming dissolved mineral bicarbonate and a much smaller quantity of carbonate ions. These then run off into the ocean where the carbon is stored in these forms for many millennia before precipitating to the ocean floor as carbonate minerals. The idea of enhanced weathering is to greatly speed up this process by adding crushed rocks or other sources of alkalinity to react with CO2 in seawater, ultimately consuming atmospheric CO2 and adding it as dissolved mineral bicarbonate and carbonate to the already very large reservoir of these compounds in the ocean. (Source: Greg Rau, CC BY)

To be effective, a minimum of 500 gigatons of rock would be required, and potential negative impacts to the marine environment require more research. Also, legal and ethical issues arise in the context of oceanic governance, as noted in the:

- Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter
- Law of the Sea Convention, and its Protocol
- Convention on Biological Diversity

A rogue nonscientific ocean fertilization project

In the summer of 2012, American businessman Russ George raised critical geoengineering ethics issues by conducting an ocean fertilization experiment in international waters off the west coast of British Columbia, much to the chagrin of the scientific community (Gannon et al, 2018). The project also was in violation of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, known as the "London Convention."

George had convinced the Haida Salmon Restoration Corporation to fund the CAD$2.5 million project, which involved dumping 120 tons of iron sulphate and iron oxide into a 5,000 square kilometer section of the ocean, with the promise of restoring dwindling salmon runs and sequestering CO_2. George, who has no scientific background, was criticized for misleading residents of the First Nations Haida village of Old Massett, presenting himself as the world's leading expert on ocean iron fertilization.

While a robust salmon run followed, the abundance of the salmon was not restricted to the area of the study; the entire West Coast enjoyed high salmon runs that year.

The weaponization of geoengineering

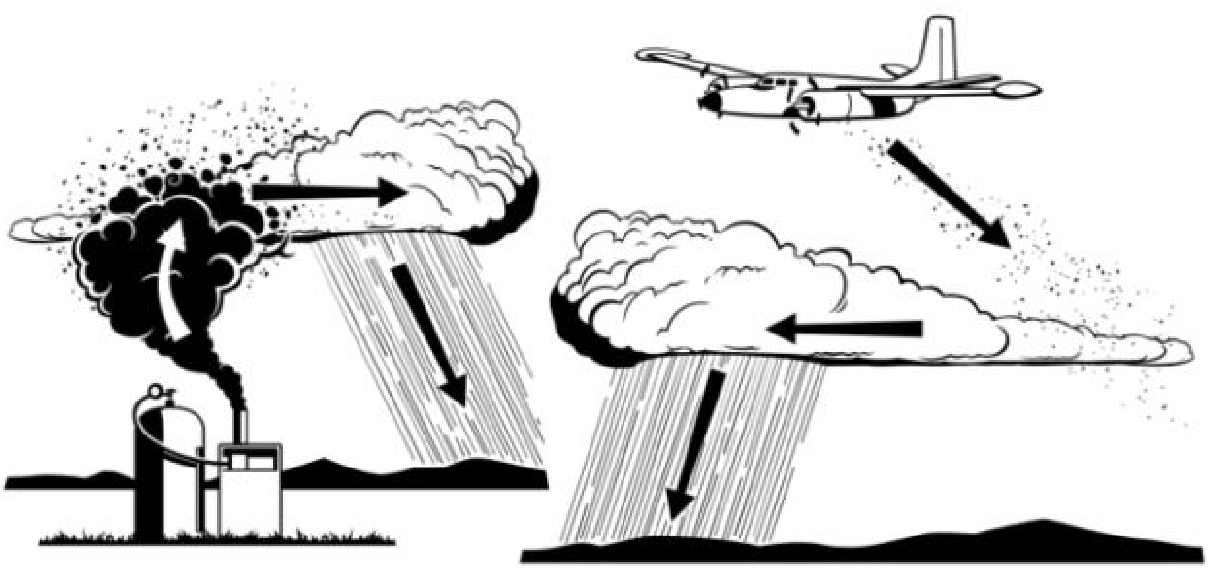

Figure 5: Cloud seeding from a plane or ground-based generator. (Source: Wikimedia Commons)

Critics of geoengineering warn it can be used as a weapon – and during the Vietnam War the United States did just that, according to documents included in the Pentagon

Papers. Operation Pop-Eye, as it was originally called, was a cloud-seeding program initiated by the Central Intelligence Agency to create rainfall in North Vietnam, South Vietnam, and Laos, to disrupt enemy troop movements and ground radar. The program was conducted over several years in an attempt to extend the region's monsoon season in specific areas.

Figure 6: A CIA map of conflict in Indochina, 1950. The shaded areas represent areas where Communist forces allegedly have staged attacks, and the diagonal lines where Communist forces allegedly are challenging authority. (Source: Pentagon Papers)

Operation Pop-Eye was not wholly supported by U.S. government officials. A former State Department official, in an interview with the New York Times, said there was concern the U.S. was using an illegal weapon of war, with disregard for unknown ecological risks (Hersh, 1972). At times, a chemical was used to create acidic rain, which was believed to interfere with radar used by North Vietnamese surface-to-air missile launchers. Additionally, one government official reported the project sometimes would backfire, creating brief torrential rainfall over U.S. camps. The total amount of extra rainfall created during Operation Pop-Eye was not revealed.

Coal-burning power plants disrupt rainfall

One unwitting geoengineering project humans have been conducting for years involves the burning of coal. While it is well established burning fossil fuels increase levels of atmospheric CO2, contributing to global warming, researchers have found that ultrafine dust particles (UDPs) produced by modern coal-fired power stations can modify and redistribute rain patterns. The study, published in the Bulletin of the American Meteorological Society, also found UDPs may even cause extreme weather events (Junkermann et al, 2018).

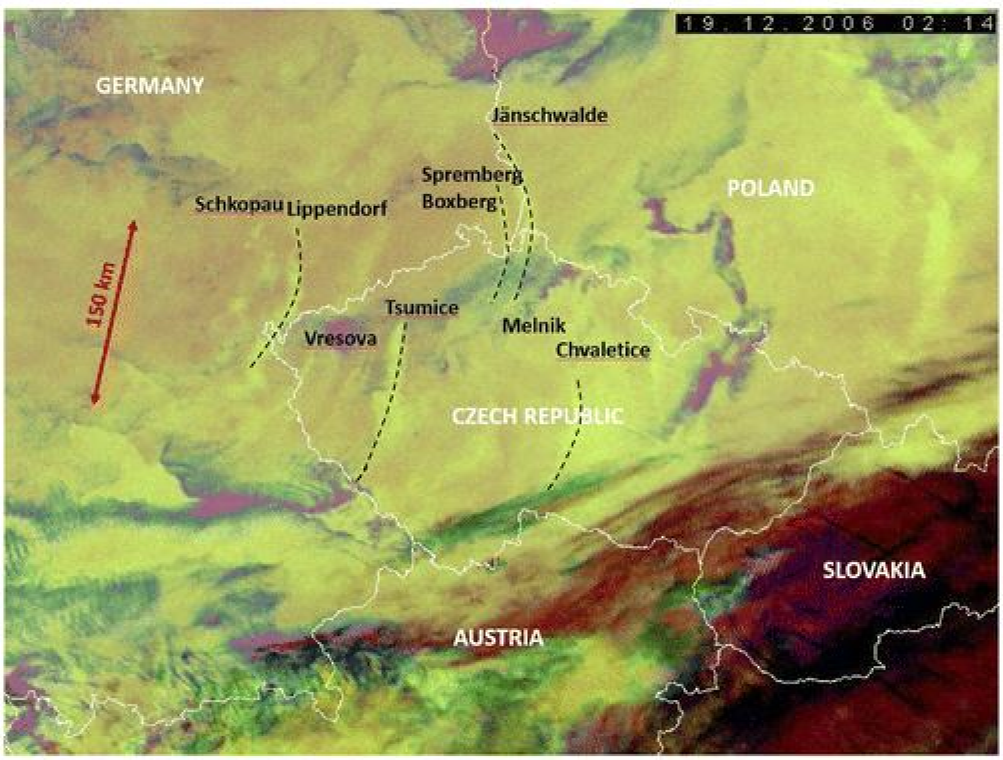

Figure 7: Power station “tracks” showing brighter clouds observed from space within a stratiform cloud deck over Germany, Poland, and the Czech Republic. The plumes under northerly to northeasterly winds, less clear compared to ship tracks over a dark sea surface but marked with dotted lines, originate from the same power stations investigated in more detail in Jun 2012 and 2014 (Fig. 4; campaign 12). Individual power stations can be identified. (Image courtesy of Daniel Rosenfeld, Hebrew University, Tel Aviv, Israel.)

The research is based on a 15-year span of monitoring emissions and tracking the particles over Europe, Australia, Mexico and inner Mongolia, and is an interesting addition to the geoengineering conversation related to injecting particles into the atmosphere. The coal plants' UDPs are smaller than the particles produced by forest fires, volcanic eruptions, and dust storms, and can be transported for hundreds of kilometers, disrupting weather -- increasing drought conditions as well as increasing torrential rainfall -- well beyond its origin.

Geoengineering as a means to slow ice sheet collapse

While the projected rise of sea level remains difficult to predict, scientists recognize the risk of Marine Ice Sheet Instability (MISI), which can result in a runaway collapse, guaranteeing significant sea level rise even if GHG emissions are curtailed. The Thwaites Glacier in West Antarctica is projected to be the largest individual source of future sea level rise, and may have already entered MISI (Wolovick et al, 2018).

Water stratification occurs near melting ice sheets: cold freshwater flows out into sea, buoyed by more dense saltwater below. The newly melted ice is colder than the salty seawater below, but if the warmer seawater can reach the base of the ice sheet, it can exacerbate the melting of the ice sheet, which would increase the rate of sea level rise.

Researchers propose geoengineering an artificial sill – or barrier – to prevent the lower warmer seawater from reaching the ice sheet, thus preventing, or at least delaying, the MISI runaway collapse scenario.

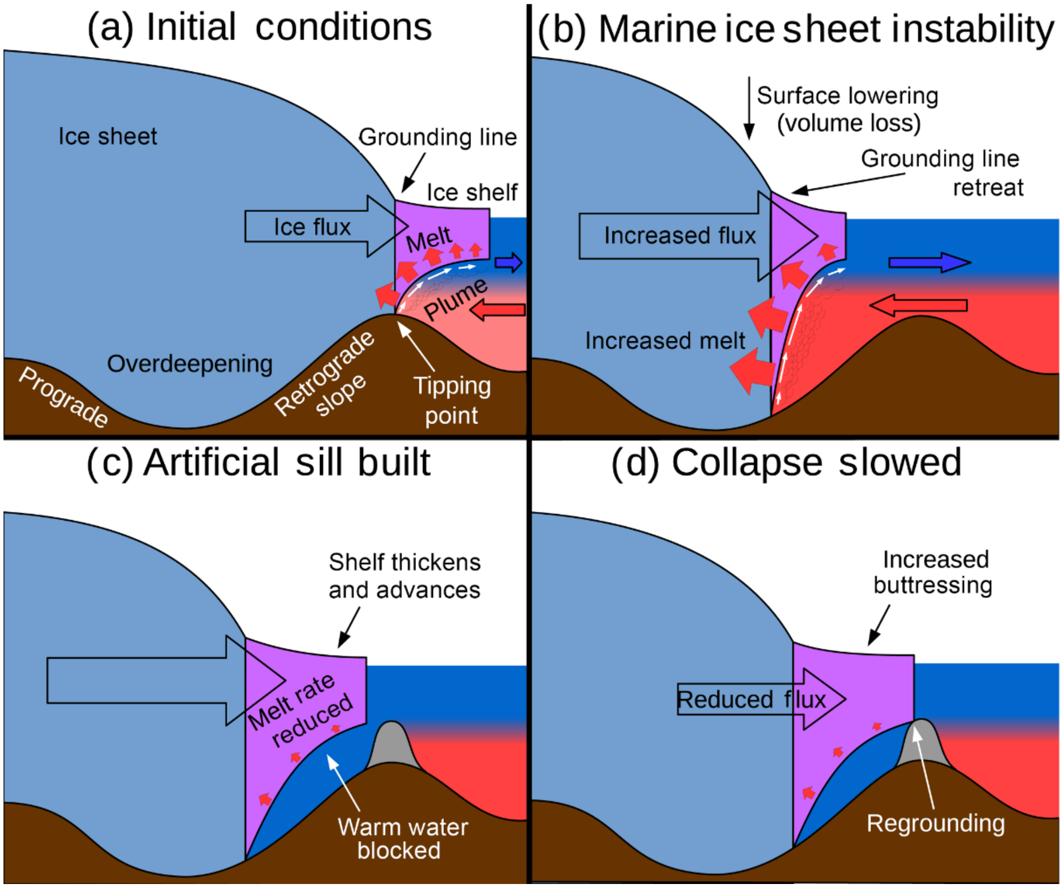

Figure 8: Schematic diagram of marine ice sheet instability and mitigation with an artificial sill. Brown represents bedrock, light blue represents the grounded ice sheet, purple represents the floating ice shelf, and gray represents an artificial sill. Ocean temperatures are drawn to represent the typical stratification faced by marine-terminating ice streams: warm salty water at depth (red) and cold fresh water (blue) near the surface. (Source: Wolovick et al, 2019)

While theoretical, the smallest design the researchers considered is comparable in scale to existing civil engineering projects, but with a 30-percent success rate, with larger designs supposedly more effective.

Geoengineering oceans

In addition to ocean fertilization, other marine geoengineering techniques were discussed at a 2017 University of Tasmania Marine Geoengineering Symposium, and include:

- Enhanced kelp farming
- Ocean upwelling/downwelling
- Alkalization for coral reef recovery/restoration

Kelp removes CO_2 from the oceans, but its extent as a long-term carbon sink is not well understood (Duarte et al, 2017). Kelp also may be used as a biomass to replace fossil fuels and contribute to BECCS.

Ocean upwelling would require large-scale vertical pipes to bring nutrient-rich deep water to the surface. And pipes similarly could be used to pump carbon-rich cold surface waters to be stored in the deep ocean (The Royal Society, 2009).

As the ocean absorbs more CO_2, it becomes more acidic, threatening marine life -- especially coral reefs, which also act to sequester CO_2. Adding alkaline substances such as calcium carbonate to seawater would reduce acidity, but this is not considered viable to protect whole reefs (Feng et al, 2016).

The main conclusion from the symposium is that marine geoengineering governance frameworks will be useless unless carried out through a "genuinely interdisciplinary program of scientists, lawyers, social scientists and ethicists." Additionally, SRM may be a necessity to buy time on the path to decarbonization to help avoid exceeding global temperature increases of 3 degrees Celsius or more.

Is solar geoengineering safe?

Newly published research, to the contrary of previously held concerns, claims that solar geoengineering will not have the catastrophic effects many scientists fear. The study, published March 11 in the peer-reviewed journal Nature Climate Change, argues that altering Earth's atmosphere to eliminate half of the planet's warming would result in worsened climate impact for a miniscule fraction of the population. But unanimity remains elusive.

In an interview with The Guardian, Alan Robock, a geophysics professor and researcher at Rutgers University, cited what he considered a key flaw in the research: excluding spraying aerosols into the atmosphere.

"They focus in this paper on temperature and water availability in different regions," Robock told The Guardian. "Those are only two things that would change with stratospheric aerosols," whereas Robock has identified 27 reasons why injecting aerosols into the atmosphere might be a bad idea (Robock et al, 2016). He also cited its potentially high cost -- hundreds of billions of dollars a year.

Benefits	Risks or Concerns
1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, and sea level rise	*Physical and biological climate system*
2. Increase plant productivity	1. Drought in Africa and Asia
3. Increase terrestrial CO_2 sink	2. Perturb ecology with more diffuse radiation
4. Beautiful red and yellow sunsets	3. Ozone depletion
5. Unexpected benefits	4. Continued ocean acidification
6. Prospect of implementation could increase drive for mitigation	5. May not stop ice sheets from melting
	6. Impacts on tropospheric chemistry
	7. Rapid warming if stopped
	Human impacts
	8. Less solar electricity generation
	9. Degrade passive solar heating
	10. Effects on airplanes flying in stratosphere
	11. Effects on electrical properties of atmosphere
	12. Affect satellite remote sensing
	13. Degrade terrestrial optical astronomy
	14. More sunburn
	15. Environmental impact of implementation
	Esthetics
	16. Whiter skies
	17. Affect stargazing
	Unknowns
	18. Human error during implementation
	19. Unexpected consequences
	Governance
	20. Cannot stop effects quickly
	21. Commercial control
	22. Whose hand on the thermostat?
	23. Societal disruption, conflict between countries
	24. Conflicts with current treaties
	25. Moral hazard—the prospect of it working could reduce drive for mitigation
	Ethics
	26. Military use of technology
	27. Moral authority—do we have the right to do this?

Please also see *Robock* [2008] for explanations of most items.

Table 1: Alan Robock's list of benefits and risks regarding continuous injection of SO2 into the lower stratosphere. He says more research is needed. (Source: Robock, 2016).

The study's co-author, David Keith, a Harvard professor who works in engineering and public policy, told The Guardian he opposes implementing this solution now, because there remains a lot of uncertainty. Keith said the key takeaway of the study is "the possibility that solar geoengineering could really substantially reduce climate risks for the most vulnerable."

Geoengineering as potential earthquake risk

In 2017 a magnitude 5.5 earthquake occurred in South Korea near an enhanced geothermal system (EGS) site, where high-pressure hydraulic injection had been ongoing for two years. Researchers wondered if the EGS activity had contributed to the earthquake, and also if the industrial activity created addition seismic risk in the area (Grigoli et al, 2019).

Unlike conventional geothermal systems, EGS involves injecting high-pressure cold water a few kilometers deep to create new fractures, and, in turn, generate additional heat. The Korean peninsula is considered relatively seismically stable, so the 5.5 event was unusual, though the region has a history of large long-term variation of seismic activity.

The researchers concluded it is plausible the EGS activity influenced the earthquake, which would make it the largest and most damaging earthquake associated with EGS.

Geoengineering governance challenges

At the March 2019 U.N. environment assembly, Switzerland led a proposal to examine the risks of geoengineering – its implications for food supply, biodiversity, global inequality and security. But the U.S. and Saudi Arabia led opposition to the plan, allegedly to protect their country’s fossil fuel interests, according to a story in The Guardian.

Geoengineering, when applied to removing CO2 from the atmosphere, minimizes the need to curb CO2 emissions, thereby benefitting the fossil fuel industry, critics claim. As it stands, there remains no international governance in this area.

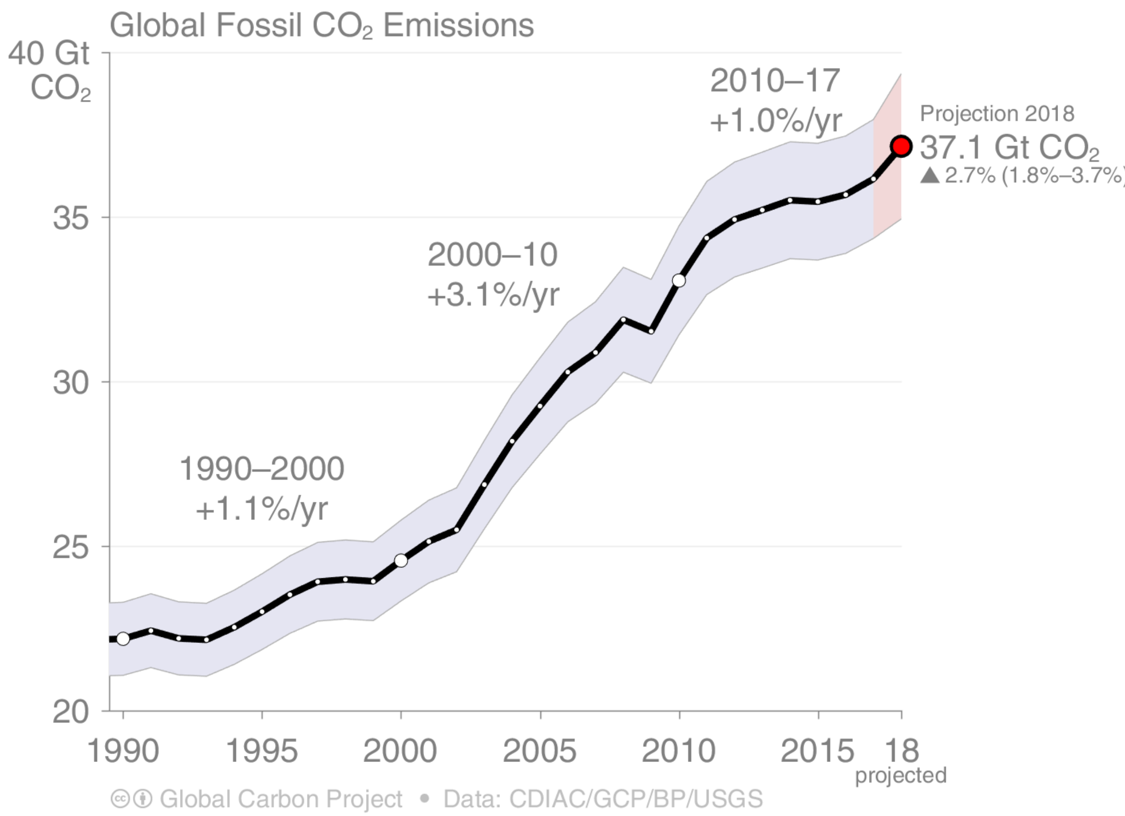

Figure 9: Global CO2 emissions increased nearly 3 percent in 2018 compared to 2017. (Source: Global Carbon Budget 2018)

Yet as the climate crisis worsens and as countries continue to fall behind to meet the GHG reductions they pledged in the 2015 Paris Agreement, geoengineering is emerging as a necessary pathway to deflect some of the sun’s energy as an interim measure to slow global warming.

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