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Climate Modification Schemes

If human activities could change climate, why not change it on purpose, to suit us better? From 1945 into the 1970s, much effort went into studies of weather modification. American entrepreneurs tried cloud-seeding to enhance local rainfall, Russian scientists offered fabulous schemes of planetary engineering, and military agencies secretly explored “climatological warfare.” The hopes and fears promoted basic research on climate change by raising large sums of government money and a few provocative ideas. In the mid 1970s the visionary projects were mostly abandoned. Research turned instead to controversial schemes for “geoengineering” interventions that might restrain global warming if it started to become unbearable. Some proposals for blocking sunlight seemed only too feasible, risking unforeseen consequences and geopolitical conflict. Schemes for removing carbon dioxide from the atmosphere were less perilous, but perhaps not achievable on a planetary scale.

“Intervention in atmospheric and climatic matters . . . will unfold on a scale difficult to imagine at present. . . this will merge each nation’s affairs with those of every other, more thoroughly than the threat of a nuclear or any other war would have done.”

—*J. von Neumann*¹

At the close of the Second World War, a few American scientists brought up a troublesome idea. If it were true, as some claimed, that humans were inadvertently changing their local weather by cutting down forests and emitting pollution, why not try to modify the weather on purpose? For generations there had been proposals for rainmaking, based on folklore like the story that cannonades from big battles brought rain. Now top experts began to take the question seriously. Perhaps they were inspired by the almost unimaginable technical powers demonstrated in the war’s gigantic bomber fleets and the advent of nuclear weapons. Whatever the impulse, at the end of 1945 a brilliant mathematician, John von Neumann, called other leading scientists to a meeting in Princeton, where they agreed that modifying weather deliberately might be possible. They expected that could make a great difference in the next war. Soviet harvests, for example, might be ruined by creating a drought. Some scientists suspected that alongside the race with the Soviet Union for ever more terrible nuclear weapons, they were entering an equally fateful race to control the weather.

As the Cold War got underway, U.S. military agencies devoted significant funds to research on what came to be called “climatological warfare.”² Much of this lay behind a curtain of secrecy,

¹ von Neumann (1955), p. 41 of reprint.

² For this and all the following see Fleming (2006); Fleming (2010); Hamblin (2013). Kwa (2001); Kwa (1994); Keith (2000), p. 252; Fleming (2007a), pp. 54-57; A. Spilhaus, interview by R. Doel, Nov. 1989, AIP.

although enough hints were published for attentive members of the public to see that human manipulation of climate could become a serious issue. For scientists like von Neumann, the main research thrust was plain: the nation needed computer modeling of weather systems. For the chief difficulty in figuring out how to change climate lay in predicting just how the atmosphere might respond to a given type of intervention. The only hope for answering that (aside from trying it out) was with computer models.

Meanwhile, far more visibly, the famous scientist Irving Langmuir and his associates at the General Electric company were exploring a new proposal for rainmaking. Their idea was to “seed” clouds with a smoke of particles, such as silver iodide crystals, that could act as nuclei for the formation of raindrops. Langmuir quickly won support from military agencies, and claimed success in field experiments. A small but energetic industry of commercial “cloud seeders” sprang up with even more optimistic claims. Controversy followed, polarizing scientists, exciting the public and catching the attention of politicians. As soon as some community attempted to bring rain on themselves, people downwind would hire lawyers to argue that they had been robbed of their own precipitation. Concern climbed to high levels of government, and in 1953 a President’s Advisory Committee on Weather Control was established to pursue the idea. In 1958, the U.S. Congress acted directly to fund expanded rainmaking research. Large-scale experimentation was also underway, less openly, in the Soviet Union.¹

Military agencies in the U.S. (and presumably in the Soviet Union) supported research not only on cloud seeding but on other ways that injecting materials into the atmosphere might alter weather. Although much of this was buried in secrecy, the public learned that climatological warfare might become possible. In a 1955 *Fortune* magazine article, von Neumann himself explained that “Microscopic layers of colored matter spread on an icy surface, or in the atmosphere above one, could inhibit the reflection-radiation process, melt the ice, and change the local climate.” The effects could be far-reaching, even world-wide. “What power over our environment, over all nature, is implied!” he exclaimed. Von Neumann foresaw “forms of climatic warfare as yet unimagined,” perhaps more dangerous than nuclear war itself. He hoped it would force humanity to take a new, global approach to its political problems.²

Through the 1960s, plans for cloud seeding and other interventions remained active and controversial. A review by the U.S. National Academy of Sciences tentatively supported some claims of success. Government agencies launched competing programs and conducted several large-scale field trials. The costly research programs were perpetually on the brink of proving something, but never got truly convincing results. Many academic meteorologists came to disdain the whole subject, infested as it was with unfulfilled promises and commercial hucksters.³ Despite these misgivings, the U.S. government spent more than twenty million dollars a year on weather modification research in the early 1970s.

¹ Lambright and Changnon (1989); Byers (1974); Soviet: Keith (2000), p. 250-51.

² von Neumann (1955), pp. 108, 151.

³ National Academy of Sciences (1966); Lambright and Changnon (1989); Byers (1974).

The Soviet Union was determined not to be left behind in any grandiose technology. Little is known of what studies the Soviets undertook on climatological warfare, but some novel ideas did become public. One starting-point was a Russian legacy of hydraulic engineering fantasies, notably an old scheme to divert Siberian rivers. Why not take the water flowing uselessly into the Arctic Ocean, and send it south to turn the parched soils of central Asia into farmlands? The plans were reported in the early 1950s, catching the attention of the public and scientists in the West, although a decade would pass before Soviet scientists examined the details in open publications. These scientists pointed out that the diversion of fresh water would make the surface layers of the Arctic Ocean more salty. Therefore much of the ice pack might not form in winter. Wouldn't that mean increased warmth, a boon to Siberians? A few Russian meteorologists questioned the scheme, even though Communist authorities frowned upon anyone who cast doubt over potential engineering triumphs. O.A. Drozdov, in particular, used weather records to empirically check what could happen around the Arctic in years of less ice, and reported there had been serious changes in precipitation.

An even more gargantuan proposal aimed directly at climate. Around 1956, Soviet engineers began to speculate that they might be able to throw a dam across the Bering Strait and pump water from the Arctic Ocean into the Pacific. This would draw warm water up from the Atlantic. Their aim was to eliminate the ice pack, make the Arctic Ocean navigable, and warm up Siberia. The idea attracted some notice in the United States—presidential candidate John F. Kennedy remarked that the idea was worth exploring as a joint project with the Soviets, and the discussion continued into the 1970s. Such giant engineering projects were in line with traditional American technological optimism, and still more with the Communist dogma that “man can really be the master of this planet.” As the title of an enthusiastic Russian publication put it, the issue was “Man versus Climate.” However, it was hard to tell whether giant projects such as a Bering Dam made sense. Mikhail I. Budyko, the most prominent Russian climate expert, pointed out that the effects of such interventions would be unpredictable, and he advised against them.¹

A more feasible scheme would be to spread particles in the atmosphere, or perhaps directly on the ground. Beginning around 1961, Budyko and other scientists speculated about how humanity might alter the global climate by strewing dark dust or soot across the Arctic snow and ice. The soot would lower the albedo (reflection of sunlight), and the air would get warmer.² Spreading so

¹ Lamb (1971); Lamb (1977), pp. 660-61; for Soviet and other conquest of nature ideology see Josephson (2002). I have not seen Lamb's Russian-language references, which include: for diversion, Adabashev (1966); Drozdov (1966); for dam, Borisov (1962); Budyko (1962); inadvisable: Budyko (1977), pp. 237-38; for U.S. reaction, see e.g., National Academy of Sciences (1966), vol. 2, p. 61; for the whole story, Ponte (1976), pp. 220-29; Keith (2000), p. 251, quoting “master of this planet” from Rusin and Flit (1960).

² For discussion and references, see Lamb (1977), pp. 46, 660-61, 676, 797; I have not checked his Russian references, which include Budyko (1961); Budyko (1962); Rakipova (1966); 1966 Rakipova reports in English translation are cited by Sellers (1969). See Fleming (2010) p. 236-37.

much dust year after year would be prohibitively expensive. But according to a well-known theory, warmer air should melt some snow and sea-ice and thus expose the dark underlying soil and ocean water, which would absorb sunlight and bring on more warming. So once dust destroyed the reflective cover, it might not re-form.

Russian scientists were not sure whether this would be wise, and scientists elsewhere were still more dubious. In 1971 a group of American experts said that “deliberate measures to induce arctic sea ice melting might prove successful and might prove difficult to reverse should they have undesirable side effects.”¹ As the respected British climate expert Hubert Lamb suggested, before taking any action it seemed like “an essential precaution to wait until a scientific system for forecasting the behavior of the natural climate... has been devised and operated successfully for, perhaps, a hundred years.”²

By this time, the early 1970s, feelings about human relations with the natural environment had undergone a historic shift. Many technologies now seemed less a triumph of civilized progress than wicked transgressions. If it were true, as some scientists claimed, that human emissions were inadvertently changing the entire global climate, the chief result seemed to be droughts and other calamities. As for deliberate rain-making attempts, if they were successful (which remained far from proven) they might only be “stealing” the rain from farmers downwind who would have gotten it instead. Such projects might even harm the very people who got the rain. For example, a 1972 U.S. government rain-making operation in South Dakota was followed by a disastrous flood, and came under attack in a class-action lawsuit. One cloud-seeding airplane was even shot at. An increasing number of people objected in principle to any such meddling with natural processes. The idea of changing the weather had shifted from a benign dream of progress to a nightmare of apocalyptic risk. Between 1972 and 1975 the U.S. government dramatically cut its budget for weather modification.³ (Attempts persisted here and there; for example, the Chinese government pursued rainmaking extensively in the early 21st century.)

Meanwhile the U.S. government had secretly been spending many millions of dollars on a grand experiment in actual climatological warfare. The Department of Defense directed extensive cloud-seeding over the Ho Chi Minh Trail, hoping to increase rainfall and bog down the North Vietnamese Army’s supply line in mud. Hints about the program were leaked in 1971, but the public did not learn the full extent of the effort until 1974, two years after it wound down in failure. Many people were dismayed when they learned of the experiment. There followed a series of resolutions, in bodies from the U.S. Senate to the General Assembly of the United

¹ Donn and Shaw (1966) (without reference to Budyko); Fletcher (1966); Sellers (1969) however calculated a temperature rise of only 7°C if the ice pack were destroyed, probably insufficient to keep ice from re-forming; Wilson and Matthews (1971), quote p. 182.

² Lamb (1971), quote p. 95.

³ Ponte (1976), pp. 156-58; Kwa (2001); on all the foregoing Fleming (2006) .

Nations, outlawing climatological warfare. The movement culminated in a 1976 international convention that foreswore hostile use of “environmental modification techniques.”¹

Of course we were already modifying the world’s atmosphere with quantities of polluting aerosols and greenhouse gases vastly beyond anything the most aggressive warrior had imagined. If that raised a risk of damage to climate, some thought we were obliged to prepare a remedy. Now when scientists discussed steps to melt arctic snows or the like, it was not to craft utopian weather, but with the aims implied in the title that Lamb gave a 1971 review article: “Climate-engineering schemes to meet a climatic emergency.”²

Already back in 1965, a Presidential advisory panel had suggested that if greenhouse effect warming by carbon dioxide gas (CO₂) ever became a problem, the government might take countervailing steps. The panel did not consider curbing the use of fossil fuels. They had in mind what later came to be called “geoengineering” schemes—spreading something across the ocean waters to reflect more sunlight, perhaps, or sowing particles high in the atmosphere to encourage the formation of reflective clouds. Some back-of-the-envelope arithmetic suggested such steps were feasible, and indeed could cost less than many government programs.³ In 1974, Budyko calculated that if global warming ever became a serious threat, we could counter it with just a few airplane flights a day in the stratosphere, burning sulfur to make aerosols that would reflect sunlight away.

Meanwhile the rapidly increasing urban smog and other human pollution was already visibly blocking sunlight. For a few years in the early 1970s, new evidence and arguments led many scientists to suspect that the greatest climate risk was not warming, but cooling. A new ice age seemed to be approaching as part of the natural glacial cycle, perhaps hastened by humanity’s pollution. Technological optimists suggested ways to counter this threat too. We might spread soot from cargo aircraft to darken the Arctic snows, or even shatter the Arctic ice pack with “clean” thermonuclear explosions.

Whether we used technological ingenuity against global cooling or against global warming, Budyko pointed out that any action would change climate in different ways for different nations. .

¹ For the public acknowledgment, see *New York Times*, May 19, 1974, p. 1, also Shapley (1974). Indications were already published in 1971 in a Jack Anderson column in the *Washington Post*, 18 March 1971, and in the “Pentagon Papers,” see Seymour Hersh, “Weather as a weapon of war,” *New York Times*, July 9, 1972, p. IV:3; for background and response, see Ponte (1976), ch. 11; Fleming (2006) pp. 13-14. Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques, UN Treaty Ser. 1108:151. See Harper (2017) for the US government and weather control 1950-1980 in general.

² Lamb (1971).

³ President’s Science Advisory Committee (1965), estimated cost \$500 million per year, p. 127; see National Academy of Sciences (1966), vol. 2, pp. 60-62. The term “geoengineering” may have first appeared in Marchetti (1977) but only became common in the 1990s.

The Soviet government, aware that the ability to cool a region by spreading sulfates could be a geopolitical weapon, funded him to lead a massive effort to study the possibilities. In public, he insisted that attempts at modification “should be allowed only after the projects have been considered and approved by responsible international organizations and have received the consent of all interested countries.” The bitter fighting among communities over cloud-seeding would be as nothing compared with conflicts over attempts to engineer global climate. Moreover, as Budyko and Western scientists alike warned, scientists could not predict the consequences of such engineering efforts. We might forestall global warming only to find we had triggered a new ice age.¹

Such worries revived the U.S. military’s interest in artificial climate change on a global scale. A group at the RAND corporation, a defense think tank near Los Angeles, had been working with a computer climate model that originated at the University of California, Los Angeles. This was normal scientific research, funded by the civilian National Science Foundation. Around 1970, however, with opponents of the Vietnam war attacking anything that smelled of militarism, the NSF backed out of funding work with overt military connections. The RAND group had to scramble to find support elsewhere. They turned to the Advanced Research Projects Agency of the Department of Defense. ARPA was meanwhile on the lookout for computing projects that could justify the funds it had lavished on its ILLIAC supercomputer. The menace of Soviet climate engineering schemes gave a plausible rationale. ARPA awarded the project millions of dollars, a secret classification, and a code name, NILE BLUE. The money supported a variety of large-scale computer studies and even some work on ancient climates. Nothing of obvious military significance turned up, but the program’s results proved useful for other climate scientists. After a few years the program was demilitarized. The NSF took over funding as work with the RAND model migrated to the University of Oregon, where it contributed to studies of global warming.²

As environmental concerns grew more widespread and sophisticated, experts and the public alike demanded a cautious approach to any intervention. A 1977 National Academy of Sciences report looked at a variety of grand schemes we might use to reduce global warming, should it ever become dangerous—for example, massive planting of forests to soak up CO₂ from the

¹ Budyko (1977), p. 240; Budyko and Korol (1975), p. 469; for some Soviet context see Eyck Freymann, “Climate Changers,” *The Wire China*, Dec. 18, 2022, online at <https://www.thewirechina.com/2022/12/18/u-s-china-geoengineering/>. Fleming (2010), pp. 241ff.; Landsberg (1970), p. 1268, citing i.a., 1968-69 RAND Corp. reports by J.O. Fletcher. For spreading smog from supersonic transports, see Wilson and Matthews (1971), p. 9; a summary with warnings is Kellogg and Schneider (1974), pp. 169-70.

² Hecht and Tirpak (1995), p. 375; personal communication from John Perry, 2001, and Rapp (1970).

atmosphere. The experts could not muster much optimism for any of these schemes. The panel thought that a turn to renewable energy resources seemed a more practical solution.¹

People nevertheless continued to come up with projects we might pursue if greenhouse warming made us desperate enough. To cite another of the many ideas, we could collect CO₂ from the furnaces where coal was burned, compress it into a liquid, and inject it into the depths of the Earth or the oceans. That sounded like an engineer's fantasy, but studies indicated it might in fact be done at reasonable cost.² Another fantastic yet perhaps feasible proposal was to fertilize barren tracts of the oceans with trace minerals. In the 1990s, calculations and field trials suggested that an occasional tanker load of iron compounds could induce massive blooms of plankton. The creatures would absorb carbon and take it to the ocean bottom when they died. However, scientists could not be sure whether in the end that really would lower the total of greenhouse gases in the atmosphere.³

Dozens of other schemes for mitigating the greenhouse effect were published, ranging from modest practical improvements in energy systems (for example, energy-efficient light bulbs) to futuristic visions (vast mirrors in space to reflect sunlight!). When a National Academy of Sciences panel convened in 1991 to catalog the options, the members got into a long and serious debate over whether to include the grand "geoengineering" ideas. Might hopes of a future fix just encourage people to avoid the work of restricting greenhouse gas emissions? The panel reluctantly voted to include every idea, so that preparations could start in case the climate deteriorated so badly that radical steps would be the lesser evil. Their fundamental problem was the one that had bedeviled climate science from the start—if you pushed on this intricate system, nobody could say for sure what the final consequences might be.⁴

"Weather modification," a participant had written ruefully back in 1974, "is based on sound physical principles that cannot be applied precisely in the open atmosphere because several processes are interacting together in a manner difficult to predict." Moreover, attempts to change the weather "are superimposed upon natural processes acting, perhaps indistinguishably, to the same or opposite effect.... Therefore it should not be surprising that the history of weather modification is one of painfully slow progress."⁵ Much the same could be said of research on climate modification.

As the levels of global temperature and greenhouse gases both continued to climb in tandem, the debate dragged on, largely below the level of public awareness. In 1997 the famous nuclear-bomb expert Edward Teller caught some attention with an essay in the *Wall Street*

¹ National Academy of Sciences (1977); for discussion of Academy reports, see Keith (2000).

² Notably Marchetti (1977).

³ Coate et al. (1996); Chisholm (2000).

⁴ Schneider (2001), p. 418; National Academy of Sciences (1992).

⁵ Byers (1974), p. 3.

Journal, claiming that it would cost only a billion dollars a year to put a sun-screen in the stratosphere. He argued that “if the politics of global warming require that ‘something must be done’,” America should devote its technical prowess to preparing such a response. Most people who followed the debate distrusted that kind of high-technology vision (which Teller represented only too well, as chief proponent of a multi-billion-dollar “Star Wars” project that had ignominiously failed to invent lasers that could shoot down ballistic missiles).¹ Others continued to insist that the world should prepare to take emergency action, just in case. But few were willing to plunge into studies, and still fewer wanted to fund them.

As the world began to visibly suffer from global warming, scientists revisited the issue. In 2004 a group gathered at a symposium in Cambridge, England to review the possibilities for climate “Macro-Engineering”. Wider attention converged on the issue in 2006 after Paul Crutzen, widely respected for his Nobel Prize-winning work on ozone, sent the leading journal *Climatic Change* an article that called for more research on climate engineering. “Given the grossly disappointing international political response” to calls to restrict greenhouse emissions, Crutzen argued that such research should no longer be “tabooed.” His submission roused passionate opposition from some senior colleagues, who insisted it would be irresponsible to publish the article. Eventually they accepted a compromise that gave them space for counter-arguments.

Suppose the climate turned so bad that some nation insisted on launching a geoengineering project? Crutzen and his supporters argued that it would be best to have research on hand in advance to point out the true possibilities and pitfalls. Another respected senior climate scientist followed up with calculations reaffirming that it was economically feasible to spread sulfate particles in the stratosphere to hold back warming. Yet Crutzen himself admitted there was a risk that hopes for a cheap technical fix would be used “to justify inadequate climate policies.”²

Over the next few years the hope that geoengineering would solve the problem of global warming was indeed taken up by people who opposed government regulation of greenhouse gases. The debate grew intense. Not only a single nation, but even a private group, could engage in climate engineering. Two companies were founded that proposed to fertilize the oceans and get paid for offsetting carbon emissions elsewhere. Sea trials failed to prove that the results would be beneficial, and legal battles erupted, exposing the lack of any framework of international law to deal with such initiatives. In 2008 an international agreement declared a

¹ Teller, “The Planet Needs a Sunscreen,” Oct. 17, 1997. Oct. 17. Teller’s 2002 technical paper on the subject is at www.llnl.gov/global-warm/148012.pdf

² Crutzen (2006); see the entire *Climatic Change* special issue on geoengineering, with commentaries by Cicerone and others (vol. 77 nos. 3-4, Aug. 2006). On Crutzen see the essay on “Other Greenhouse Gases.” Sulfate calculations: Wigley (2006); a more recent calculation that “solar radiation management” would be easy and cheap: Smith and Wagner (2018). Press reports include Kerr (2006b) and William J. Broad, *New York Times*, June 27, 2006. For the history see also Morton (2007).

moratorium on large-scale ocean fertilization experiments. Pressure for studies of every option persisted; in 2021 the National Academy of Sciences called for a substantial research program on ocean fertilization, along with related ideas such as large-scale seaweed farming (the marine equivalent to planting forests). By this time, however, public and scientific misgivings were effectively blocking even small-scale experiments on injecting materials in the atmosphere or sea.¹

Ocean fertilization was only one approach to what was coming to be called “Carbon dioxide removal” (CDR). During the 2010s it became increasingly clear that the world would not cut its emissions of greenhouse gases rapidly enough to prevent dangerous global warming, or at least not without radical political, economic and social transformations. But perhaps we could get to safety by pursuing “net zero” emissions, compensating for emissions that were difficult to eliminate by removing a comparable amount of gas from the atmosphere.

Even easier, it seemed, would be to capture a power plant’s CO₂ emissions before the gas ever got out into the atmosphere. The captured gas could be pumped underground or deep into the oceans (although it might be hard to guarantee it would stay there). Indeed since the 1970s some plants had captured the gas for commercial uses, and each of the following decades saw dozens of pilot projects for “carbon capture and storage” (or “sequestration,” CCS either way). The efforts allowed corporations to make airy promises of a future “clean coal,” but were otherwise fruitless. Scaling up ran into countless technical difficulties with no clear path to economic viability. Anyway CCS could only address a fraction of CO₂ emissions. More ambitious “net zero” plans proposed building special facilities to remove CO₂ directly from the atmosphere, for example by combining it with calcium or through some other chemical or physical process. In the 2020s entrepreneurs, dreaming of a technological breakthrough that would make massive carbon removal economically feasible, plowed money into hundreds of companies with visionary proposals.

The most popular plans, however, relied on biology. If ocean fertilization didn’t work we might, for example, store carbon in soils through improved agricultural practices. Forestry attracted the greatest attention. Campaigns to halt the destruction of forests, at first for their own sake more than to slow global warming, dated back to the rise of environmentalism in the 1970s. Preserving or planting trees became a mainstay of the market in “carbon offsets,” which in the 2010s grew to a billion-dollar (and largely fraudulent) economic activity. Controversial scientific claims about

¹ A good summary: Strong, (2009). Debate: e.g., the best-selling Levitt and Dubner (2009) and a report issued by Lomborg’s center, Bickel and Lane (2009). Good discussions include Inman (2010), Blackstock and Long (2010), Keith et al. (2010), all three published in the same month. National Academies of Sciences (2021).

the benefits of reforestation encouraged people up to U.S. President Donald Trump to tout tree planting on a gargantuan scale as the solution to global warming.¹

The promise that nations made in the 2015 Paris Agreement to keep the global temperature rise below 2°C could not, in fact, be met without such “negative emissions.” The approach was politically attractive, for it would allow fossil fuel burning to persist indefinitely. But only the most sanguine imagined that sequestering carbon could make a clear path to net zero. To offset a meaningful volume of emissions would mean rapidly building novel land-management or industrial systems on a scale approaching the entire global oil industry, run in reverse. Anyway none of this addressed the emissions of methane and other potent greenhouse gases.²

Computer modelers and experimenters, collaborating under the auspices of the World Climate Research Program, meanwhile continued to explore “solar radiation management,” a disturbingly hubristic term for blocking sunlight. Ideas ranged from methods for increasing cloudiness to enhancing the reflectivity of the oceans, but injecting sulfates into the stratosphere remained the most plausible scheme.

Any intervention was bound to produce winners and losers, as in the old fights over rainmakers “stealing” precipitation from folks downwind. (That problem rose to the international level when global warming reduced rainfall in the Near East, prompting governments to experiment with cloud seeding; in 2018 an Iranian general accused Israel and others of “working to make Iranian clouds not rain.”) Preliminary computer studies of sulfate injection suggested that, among other things, it might shut down the Asian monsoons. Would India and China stand idly by while drought starved their populations?

Still more worrisome, once an intervention began it would have to continue for centuries, regardless of economic disruptions or wars. If anything paused the program for a decade or so, global temperatures could snap to a catastrophically higher level (a “termination shock”). As one

¹ For reforestation see Bastin et al. (2019), Mo et al. (2023), Catrin Einhorn, “How Much Can Trees Fight Climate Change? Massively, but Not Alone, Study Finds,” New York Times (Nov. 13, 2023), online at <https://www.nytimes.com/2023/11/13/climate/trillion-trees-research.html?searchResultPosition=1>

² N.b. to fully restore the climate it would not suffice to remove all the extra CO₂ that is now in the atmosphere; roughly half of our emissions have been absorbed in the oceans, plants and soil, and it would take centuries to capture this as it slowly returned to the atmosphere: Cao and Caldeira (2010). For “climate modification” (i.e., mitigation) through reduction of emissions, probably the most cited paper is Pacala and Socolow (2004). (Unusually, the approach is named after the second author: “Socolow wedges.”) The vast literature on carbon dioxide reduction and removal (CDR) is summarized in IPCC (2022) and earlier IPCC reports; for a critique see Center for International Environmental Law and the Heinrich Boell Foundation (2022).

team explained, “Coming generations would have to live with the danger of this ‘Sword of Damocles’ scenario, the abruptness of which has no precedent in the geologic history of climate.” Most ominous of all was the likelihood of unexpected consequences. Computer teams, asked to model atmospheric physics and chemistry never seen on a planetary scale, could scarcely guess how a given intervention might change weather patterns.

Some of the scientists who advocated research on climate engineering wanted to be prepared in case cataclysmic climate changes forced a last-ditch attempt to save civilization. Others expected that their findings would persuade people that an intervention was too risky to attempt. In any case it would be far safer and far easier to negotiate restrictions on greenhouse gas emissions now than to deal with the international repercussions of an intervention during a climate crisis.¹

The problem was not only means, but ends: whose goals would climate engineering serve? Even the nightmare of climatological warfare could stalk back into history, strengthened by scientific advances. As a historian asked, “Who would have the wisdom to dispense drought, severe winters, or the effects of storms... If, as history shows, fantasies of weather and climate control have chiefly served commercial and military interests, why should we expect the future to be different?”² The technical, political and ethical problems raised by deliberately influencing the global climate remained at least as great as the problems raised by our ongoing unintended influence.

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¹ One computer model: Jones et al. (2010), see Eastham et al. (2021). For the Geoengineering Model Intercomparison Project (GeoMIP) see their site, <https://climate.envsci.rutgers.edu/GeoMIP/index.html>. Iranian general: Brig. Gen. Gholam Reza Jalali, 2018, quoted in Alissa J. Rubin, “Cloud Wars: Mideast Rivalries Rise Along a New Front,” *New York Times*, Aug. 28, 2022, online at <https://www.nytimes.com/2022/08/28/world/middleeast/cloud-seeding-mideast-water-emirates.html>. Damocles: Brovkin et al. (2009), p. 255. For post-1965 history in general see Caldeira and Bala (2017). One broad overview of geoengineering ideas: Boettcher and Schäfer (2017).

² Fleming (2007), p. 60.