

ADVANCED REVIEW

Proactive and reactive geoengineering: Engineering the climate and the lithosphere

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Abstract

In recent years, the idea of geoengineering, understood as large-scale interventions in the planet's climate to counteract anthropogenic climate change, has steadily increased its visibility. Presented explicitly as an approach to climate change, geoengineering is positioned as a *response*, a reactive fix. Geoengineering, however, has a longer and broader history than the current climate crisis. It has long been an umbrella term for large-scale projects in which various Earth sciences meet dreams about human ecosphere interventions, especially regarding lithosphere and climate and weather modifications. In this paper, we review the history of geoengineering, focusing specifically on climate geoengineering and lithosphere geoengineering. We draw attention to the difference between “proactive” (“high-modernist”), aimed at mastery over nature, and “reactive” forms of geoengineering, hoping to address anthropogenic environmental degradation technologically. Additionally, we trace historical (dis)continuities between the older, proactive, form of geoengineering and their recent reframing as a technological fix—specifically around the question to what extent nature's complex systems can be known and controlled. Finally, we argue for the need to further research the intersections and shared histories between various forms of geoengineering.

This article is categorized under:

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climate change, climate engineering, geoengineering, history of technology, science and technology studies

1 | INTRODUCTION

In recent years, deliberate large-scale, even planetary scale, interventions have come into view as a possible approach to addressing climate change. Highly controversial, these interventions are commonly described as “geoengineering” (e.g., Royal Society, 2009), but also as climate engineering, solar geoengineering 2015, climate intervention (e.g. National Research Council, 2015), and climate manipulation. Proponents of such interventions argue that conventional

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mitigation and adaptation might not suffice to avert climate catastrophes. In their eyes, research into these speculative technologies is timely because the potential risks of anthropogenic climate change might make this a “bad idea whose time has come” (Kintisch, 2010).

Climate-related geoengineering technologies typically fall in one of two categories: albedo modification (solar radiation modification [SRM]), which attempts to limit the influx (or enhance outflux) of solar energy in the climate system, and carbon dioxide removal (CDR), which aims to capture and store carbon long-term. Such interventions are coming under increasing scrutiny. The Intergovernmental Panel on Climate Change (IPCC) has included carbon capture proposals into assessments since 2013, detailing some of its uses in the subsequent reports (IPCC, 2018). It also makes explicit (but non-committal) mention of SRM technologies. In this narrative, geoengineering technologies appear as an explicit response to anthropogenic climate change. Yet as has been noted often, the idea of deliberately intervening in climate and weather systems is older than the current climate crisis (Baskin, 2019; Bonnheim, 2010; Fleming, 2010a; Oomen, 2021). At least since WWII, interest in climate geoengineering has waxed and waned within the environmental sciences. Moreover, “geo” engineering need not refer explicitly to climate change. Contemporary *climate* geoengineering stands in relation to a long history of large-scale technological interventions. In fact, the term geoengineering is also used to refer to counter-acting hypoxic dead zones in oceans, seas, and lakes (Lüring et al., 2016), as well as invasive engineering projects that transform the upper part of the lithosphere such as sea canals, dam systems, land reclamation projects, or large-scale tunnels.

In different communities, “geoengineering” adopts different meanings. Despite using the same terminology, these different forms of “geoengineering” the Earth’s systems, both biological and inanimate, rarely acknowledge their relationship to one another. By and large, researchers present their interventions as technological solutions for specific problems. This narrow focus on the specificity of technologies constricts what James Fleming has called “the usable past” (Fleming, 2010b) of geoengineering, the past that presents itself as the repertoire for ideas about the present and future. Scholarship of climate geoengineering, despite attempts to broaden it, remains narrowly focused on *climate* (and weather) geoengineering. Social scientists and historians have, for example, addressed the “framing” of climate geoengineering (e.g., Cairns, 2014; Huttunen & Hildén, 2014; McLaren & Corry, 2020), questions of public perception and expert opinion (Dai et al., 2021; Oldfield, 2013), and concerns about technocracy and epistemology (Beck & Mahony, 2018; Flegal & Gupta, 2018; McLaren, 2018; Oomen, 2019). Such assessments focus either on (a) the (problematic) history of climate geoengineering (e.g., Baskin, 2019; Fleming, 2010a; Hamilton, 2013; Keith, 2000; Oomen, 2021), (b) the inherent undesirability of climate geoengineering, especially SRM (e.g., Hulme, 2014; Preston, 2013), or (c) what responsible research and governance of geoengineering might be (e.g., Low & Buck, 2020; Reynolds, 2019; Stilgoe, 2015). Typically, such scholarship focuses insularly on *climate* geoengineering.

This narrow focus on technologies proposing to “fix” the climate overlooks the similarities and shared histories between different strains of geoengineering. In this article, we aim to expand that narrow vision on *climate* geoengineering by explicitly connecting it to other forms of geoengineering. Viewing “geoengineering” simply as a reaction to anthropogenic climate change overlooks the more complex history of large (geo-)scale interventions—as well as its lessons and warnings. Specifically, we juxtapose *climate geoengineering* with what we call (upper) *lithosphere geoengineering*, which provides a compelling parallel (and warning) for the future of *climate* geoengineering. We observe a gradual (and by no means absolute) shift from “proactive” geoengineering, aimed at mastery over and exploitation of nature, to more “reactive” forms of geoengineering that hope to address anthropogenic environmental degradation technologically. In doing so, we draw out notable continuities between proactive and reactive forms of geoengineering, but point to significant differences as well. This comparison allows us to draw tentative conclusions about the prospects of climate geoengineering—and to draw out risks that become visible through the expansion of geoengineering’s (usable) past.

2 | HISTORICIZING GEOENGINEERING

The history of geoengineering can be understood as a trajectory from pro-active dreams of control to more modest—but still techno-optimist—reactive ideas about managing human-made technological and environmental risks. “Proactive geoengineering,” relying on what James Scott once described as “a strong, one might even say muscle-bound, version of the self-confidence about scientific and technical progress...[and] master of nature” (Scott, 1998, p. 4), aims at gaining control of ecosystems or geographies in order to further a(n often narrowly defined) human agenda. Such socio-technical interventions are typically envisioned as furthering a form of development concerned with economic growth

and (geo)political power. “Reactive geoengineering” is newer. With climate geoengineering as its most visible representation, this type of geoengineering aims to solve the unintended consequences of human development technologically. While not necessarily less hubristic, the aims of reactive geoengineering are, by and large, understood not as of a form of exploitative control but rather in terms of damage control and risk management. In this section, we introduce the different usages of geoengineering, subsequently showing their respective trajectories in Sections 3 and 4.

At the start of the 2010s, there were multiple usages of geoengineering. In the public eye, there was climate geoengineering, a reaction to climate change. Through fears about climate change, geoengineering has become most closely associated with “large-scale interventions in the planet’s climate to counteract anthropogenic climate change” (Royal Society, 2009, p. ix). Yet geoengineering is (and has long been) an umbrella term for other large-scale projects in which Earth sciences meet dreams about human ecosphere interventions too. In academia, there was climate geoengineering, but also an institutionalized community of lithospheric geoengineers, as well as pockets of ecosystem geoengineering and hydrological geoengineering. Particularly, geoengineering has become a popular umbrella term describing the intersection of civil engineering and geology. Combining geology, hydrology, and civil engineering, geoengineering also came to be used as a short-form for “geotechnical engineering” or “geological engineering” (Agapito et al., 1977; Kujundžić, 1974; Stallard & Anschutz, 1963). In yet another field, marine biology, geoengineering has come to refer to actively intervening in hypoxic “dead zones” in lakes and seas (Lürling et al., 2016; Stigebrandt et al., 2015).

Climate geoengineering is deeply controversial. The term “geoengineering” first appeared in relation to climate in 1977, when the Italian physicist Cesare Marchetti suggested storing carbon dioxide in thermohaline currents in oceans (Marchetti, 1977), a proposal largely ignored at the time. The term “geoengineering,” however, stuck. It came to refer to a great variety of speculative large-scale interventions, including (but not limited to) the stratospheric injection of aerosols and direct air capture of carbon dioxide and its subsequent storage. In 1992, The National Academy of the Sciences in the United States published an assessment of the “policy implications of greenhouse warming” in which “geoengineering” referred to “large-scale engineering of our environment in order to counteract the effect of changes in atmospheric chemistry” (National Academy of the Sciences, 1992, p. 433). In the same year, David Keith and Hadi Dowlatabadi published a paper about “taking geoengineering seriously” (Keith & Dowlatabadi, 1992). Early critics also adopted the term, solidifying the link between “geoengineering” and climatic intervention (Jamieson, 1996). In 2000, David Keith published a long article called “Geoengineering the Climate: History and Prospect,” the first serious attempt to define the research field (Keith, 2000). In this article, Keith outlined the history of large-scale weather and climate intervention, assessed the prospects of these technologies for the global climate problem, and defined geoengineering as “intentional large-scale manipulation of the environment” in relation to climate change. Climate geoengineering further took shape when Paul Crutzen called for research into stratospheric aerosol injection and related technologies in 2006. According to Crutzen, a Nobel Prize winner in Chemistry for his work on the ozone-layer, the suboptimal solution of geoengineering should be taken more seriously due to global inaction on climate change making dangerous climate change increasingly likely (Crutzen, 2006). Many criticized Crutzen for opening up a debate about climate geoengineering, because it might damage conventional mitigation commitments (Cicerone, 2006). By 2009, the British Royal Society published the first dedicated overview of possible climate geoengineering technologies, defining climate geoengineering as “deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change” (Royal Society, 2009, p. ix). Finding resonance, geoengineering increasingly came to refer to *climate* geoengineering, at least publicly. As a result, to many, geoengineering became synonymous with a *reaction* to environmental degradation, specifically climate change.

Around the same time, largely out of the public eye, another scientific community started to use “geoengineering” as an umbrella term for a set of diverse disciplines that analyze and modify the upper lithosphere. Such collaborations between engineers and geologists had evolved since the mid-19th century, often in the context of large-scale infrastructure projects. While the word “geo-engineering” had sporadically been used in geotechnical and geological engineering publications since the 1960s, its use only proliferated around the turn of the 21st century. First attempts to unify “the growing sphere of [engineers] who deal with geo-materials (both natural and man-made) and systems,” under the label “geo-engineer” reach back at least to a workshop of US civil engineers in 1994 (CERF, 1994). Since 2000, the use of “geoengineering” in the geotechnical sense has institutionalized and found its way into names of international scientific societies, journals, and handbooks. At the *GeoEng*-conference in Melbourne in 2000 geoengineering appeared as a common umbrella term describing the relationship between various geological and geotechnical disciplines (Morgenstern, 2000; Steenfelt, 2000), whose complex interrelatedness has also historically “never been free of ambiguity” (Bock, 2006, p. 209). Subsequently, the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), the International Society for Rock Mechanics (ISRM), and the International Association for Engineering Geology and the

Environment (IAEG), three important representatives of geological and geotechnical engineering, agreed on forming a Joint European Working Group (JEWG) in 2002. The JEWG was tasked to “strengthen the co-operation” across the three societies and identify “common ground,” because at the time “differing professional definitions and accreditation rules” for engineers and geologists existed in Europe while there was at the same time “a growing demand” for “geo-engineering solutions” (JEWG Report, 2008, p. 7). In 2008, the JEWG published a report detailing what the respective competences of the different disciplines offered for geoengineering collaboration. Soil mechanics excelled at understanding “the mechanical behavior of soil and granular masses (solid-fluid interaction).” Rock mechanic engineers on the other hand focused on “the mechanical behavior of rock and fractured material.” Both these sub-disciplines rely on the analysis of the structures they encounter at the construction site using data base parameters, laboratory, and field work. The third pillar of lithosphere geoengineering, the engineering geologists, provides expertise of “geological features and processes and the genesis of geological formations at the construction site” (JEWG Report, 2008, p. 19). In parallel to this effort to codify geoengineering collaboration by the JEWG, the Federation of International Geo-Engineering Societies (FedIGS) also formed a formal network of lithosphere geoengineering. This network included all three engineering societies mentioned above, supplemented by the International Geosynthetics Society (IGS). The interest in geoengineering furthermore culminated in the founding of various geotechnical journals and book series on the topic—for example, the *International Journal of Geoengineering Case Histories* (founded in 2004), the *Journal of GeoEngineering* (2006), *Geomechanics and Geoengineering* (2006), the *Journal of Geo-engineering Sciences* (2013), and the book series *Geo-Engineering* (Elsevier) and *Geomechanics and Geo-engineering* (Springer). The lithosphere geoengineering community is also remarkably global, with a majority of its members in Asia and North America but significant numbers from Europe, Central and South America, and Africa too (Athanasopoulos & Zekkos, 2006). Although less visible to the general public than climate geoengineering, then, lithosphere geoengineering is strongly institutionalized.

Despite only recently institutionalizing, climate and lithosphere geoengineering share a longer history—a history connected by shared dreams of modifying and controlling the environment for human purposes. In both fields, the term “geoengineering” may have gained traction after 2000, but neither field arrived from a historical vacuum. Both types of geoengineering are technological interventions that have a longer history, a history traceable through shared scientific and cultural ideas about human–nature relationships, using the environment as a resource for exploitation, and a shared search for interdisciplinary expertise.

3 | INTERDISCIPLINARY (LITHOSPHERE) GEOENGINEERING

The history of lithosphere geoengineering tells an ambivalent story about the ambition to modify and control nature on the one hand and an apparent recognition of natural agency and complexity on the other hand. The roots of applied geological knowledge can be traced far back in time, to early modern land reclamation endeavors or even to ancient canal or irrigation projects (Kiersch, 1991). In modern scientific societies, such interests solidified in the form of scientific disciplines such as engineering and geology, including its subdiscipline of “engineering geology.” Correspondent industrialization, and the shift to fossil fuels led to disciplinary competition but also to new forms of collaboration. In the second half of the 19th century expanding railroad networks, tunneling, and large-scale sea canal infrastructure projects intensified contacts between civil engineering and geology in Europe and the United States (Bock, 2006; Hatheway, 2005; Kiersch, 1991). Other regions in the world soon followed. In his inaugural speech as rector of the Technische Hochschule in Vienna, the Austrian geologist Ferdinand von Hochstetter coined the term “Ingenieurgeologe” (“engineering geologist”) in 1874 (Wiener Zeitung, 1874, p. 149). Following an article series in the magazine *The Engineer* the British geologist William Henry Penning published the first handbook carrying the title “Engineering Geology” (Penning, 1880). In his classic *Conquest of Nature* (2006), David Blackbourn describes the ideas of planners in this period as shifting “over the years, from the sunny Enlightenment optimism of the eighteenth century to the earnest nineteenth-century belief in science and progress, to the technocratic certainties that marked so much of the twentieth century” (Blackbourn, 2006, p. 3). Blackbourn accurately captures the attitude of leading engineers and geologists at the turn of the 19th century. At the same time, the technocratic certainty Blackbourn points to was always mediated by a resistant and unpredictable environment, forcing the adaptive methods and practices that paved the way for modern lithospheric geoengineering.

An important example can be found in the Panama Canal. After the French failed in their efforts to build a sea canal through the Isthmus of Panama in the 1880s, the United States gained concessions to complete the works.

Immediately, the United States formed a Board of Consulting Engineers of top quality civil and army engineers to assess the feasibility of a Panama Canal. The chairman of the body, army engineer Georges W. Davis—largely unimpressed by the failure of the French efforts—concluded “that the United States Government must surmount only physical difficulties, and fortunately these are so well known that the element of uncertainty is reduced to small limits.” Emphasizing that the canal should be treated “not in a provisional but in a final, masterly way” (Report of the Consulting Engineers for the Panama Canal, 1906, pp. 142–143), Davis argued that much larger rivers than the Chagres rivers imagined to be part of the Panama Canal had come “under the complete control of men.” During the construction of the canal, however, heavy land-slides obstructed the canal repeatedly (see Figure 1). Facing these challenges, a permanent resident geologist and a landslide committee, consisting of engineers as well as geologists, were appointed (James & Kiersch, 1991; Meiske, 2021). This increased interdisciplinary collaboration led to a better hydrogeological understanding of such large-scale intervention, but it did not succeed in a “final” stabilization of the canal-surroundings. Even in 1915, the first year of the canal’s service, land-slides blocked the Panama Canal for more than 7 months. Consequently, the landslide committee concluded that the “slides have not everywhere reached a condition of permanent equilibrium [and that the] observation and study of the canal banks should be kept up indefinitely” (Report of the Committee of the National Academy of Sciences on Panama Canal Slides, 1916, pp. 1, 20).

Such engineering failures, and the need to address them in an interdisciplinary manner, stood at the heart of the development of lithosphere geoengineering. At the first meeting of the International Society for Soil Mechanics and Foundation Engineering at Harvard University in June 1936, its president, Karl von Terzaghi, attributed the start of modern soil mechanics—a central branch of the slowly emerging field of engineering geology—to three “engineering failures”: the cuts on the Swedish State Railways, the collapse of a just completed quay wall at the Kiel Canal in Germany in 1893, and the landslides at the Panama Canal mentioned above. Terzaghi underlined that “in the United States, the catastrophic descent of the slopes of the deepest cut on the Panama Canal issued a warning that we were overstepping the limits of our ability to predict the consequences of our actions [and demonstrated] alarming gaps in our knowledge of so called *terra firma*” (von Terzaghi, 1960, p. 62). Terzaghi was aware of the challenges his emerging discipline faced, remarking that, “[u]nfortunately, soils are made by nature and not by man, and the products of nature are always complex” (von Terzaghi, 1960, p. 63).

According to Josephson (2002), US historian and expert on soviet history of science and technology, “throughout the twentieth century, nations with quite different political systems and economic orientations all pursued this same technological subjugation of nature.” From the Grand Coulee Dam in the United States over the Kuibyshev Dams in the Soviet Union to the Three Gorges Dam in China, hydropower projects alone have markedly changed the lithosphere in the attempt to harness natural resources. Increasingly ambitious interventions in natural systems and landscapes



FIGURE 1 Pro-active geoengineering experiencing limits of controlling nature: landslides at the construction site of the Panama Canal in May 1913. Courtesy of The Linda Hall Library of Science, Engineering & Technology; LHL, A. B. Nichols Collection, Notebook Vol. 48B, p. 65

needed increasing interdisciplinary collaborations and new types of engineering knowledge. Growing “governmental and state or province participation in irrigation, flood control, and hydroelectric projects, along with the broadening of soil conservation measures in the 1930s” also played a central role in integrating geological expertise in large-scale planning (Kiersch, 1991, p. 25). Here a key example is the unprecedented transformation of the Tennessee Valley, started at the end of the interwar period. For Franklin D. Roosevelt the Tennessee Valley region, suffering not only the Great Depression but also regular floods and long-term mismanagement of natural resources, played an important role in his New Deal program. In 1933, a congressional act formed the Tennessee Valley Authority (TVA). Brandishing the slogan “electricity for all,” it promised left behind communities “technological modernity,” introducing more efficient farming methods, revitalizing industries, and guaranteeing safety through efficient flood and disease control (Carter, 2014; Creese, 1990; Downs, 2014; Ekbladh, 2010). While this approach retained high-modernist ideas about infrastructure planning, it also presented an emerging institutional recognition for the extractive character of forestry and farming, which had led to severe erosion and economic decline in the region. In recognizing such environmental mismanagement, the TVA shifted the focus from technological infrastructure planning to a more holistic integrated regional planning approach that provided “the first example of multifaceted conservation” (Black, 2002, p. 158). An interdisciplinary institution, the TVA also aimed at fixing mistakes made altering the surface of the earth of the past. In this attempt, the TVA consisted of the world’s largest engineering geology department, departments for Agricultural Relations, Forestry, and Chemical Engineering, and a Chief Conservation Engineer, who was responsible for questions of sustainable land use. Rebuking thoughtless extractivism, TVA’s director for the Department of Forestry Relations remarked that “for more than three centuries, America has been regarded as a land of freedom and opportunity. ... The country’s vastness of area and great wealth of resources made it possible for this freedom of initiative to be expressed in policies of exploitation, which led us even to condone waste and extravagance” (NARA-Baker, 1942, p. 2). TVA’s conservationism, however, did not aim to restore the environment but rather presented a form of “organic planning” that tried to find a new “middle ground between nature and civilization” (Black, 2002, p. 160). It still aimed to exploit natural resources, only more sustainably. In the words of the TVA chairman David E. Lilienthal, “I believe men may learn to work in harmony with the forces of nature, neither despoiling what God has given nor helpless to put them to use” (Lilienthal, 1948, p. xii). The Swiss-French architect Le Corbusier celebrated Lilienthal as having setup “a reign of harmony” in the valley with the “end result a territory as large as France snatched from the grip of erosion” (Le Corbusier, 1947, pp. 53–54).

Ostensibly, the TVA’s restorative mission was a more reactive and humble form of lithosphere geoengineering. Techno-fixing environmental damages resulting from earlier human systems—much like today’s climate geoengineering supposes—the TVA appeared motivated to restore damage done by human activity. But as Eric Carter has shown for the case of its malaria control efforts, the TVA oscillated between two “competing ideological threads of its master ethos of integrated regional planning: *socio-ecological holism* and *techno-scientific reductionism*” (Carter, 2014, p. 112). Indeed, the TVA deepened extractive practices. The TVA was at the heart of the activities which lead to what Christopher Jones has described as “landscapes of intensification” in which sociotechnical systems ever intensify human influence and make extractive practices “not only possible but likely” (Jones, 2014, p. 8). The engineering geology department played a crucial role in this intensification. In 1935, Chief geologist Edwin C. Eckel identified the search for “mineral resources” in the region as one of his team’s central tasks, especially since “completed power plants will render available electricity which can profitably be used in certain electrochemical and electro-metallurgical industries based on mineral raw materials” (NARA-Eckel, 1935). The TVA intensified human influence in various ways. First, the agency opened the “great era of dam building,” which has led to a multitude of environmental and social problems such as severe changes in the global waterflow, erosion, and relocation of millions of people (World Commission on Dams, 2000). Second, the TVA had a formative effect on the large-scale production and global application of industrial fertilizer (especially through the TVA’s involvement in the rise of international development aid following WWII), which changed the natural circulation of phosphate and nitrogen significantly. Finally, the TVA used hydro-power to produce aluminum and enrich the uranium used for the nuclear bombs the US Army dropped on Nagasaki and Hiroshima in 1945. These processes left deep scars in the regional ecology of the valley. Despite a more reactive justification of their lithosphere geoengineering, the TVA ended up furthering the hubristic conquest of nature. Its endeavors helped to intensify human activities, contributing to the current global crises of many natural systems. In the words of Joachim Radkau, the TVA is “a classic example of how the attempt to solve environmental problems through radical measures on a grand scale can create new and often more intractable problems” (Radkau, 2014, p. 49).

This tension between reactive, almost restorative ideas about sociotechnical systems on the one hand and extractive, hubristic drivers, often supported by powerful socioeconomic, military, and geopolitical interests, on the other,

remained central to engineering geology. Still, in the course of the 20th century, the focus of engineering geologists increasingly shifted away from dam-building to “foundation exploration for much of the construction industry” and “environmental investigation, restoration and compliance” (Erwin & Conn, 1995, p. 513). The first statutes of the International Association for Engineering Geology (IAEG, founded 1964) described engineering geology as “the application of the Earth Sciences to Engineering planning, construction, prospecting, testing and processing of related materials” (Knill, 2002, p. 8). In the 1970s and '80s, a growing public awareness of environmental degradation through human activities left clear marks on the field. It became common practice and part of its portfolio to identify adequate sites for waste disposal and storage and the anthropogenic changes resulting from, “waste disposal, quarrying, shallow mining and fluid abstraction” (Knill, 2002). In 1997, the International Association for Engineering even added “and the Environment” to its name (Dupray et al., 2014, pp. 39–40). Accordingly, the Bulletin of the society described engineering geology (working under the umbrella of “geoengineering” shortly thereafter) as “the science devoted to the investigation, study and the works and solution of engineering and environmental problems which may arise as the result of the interaction between geology and the works or activities of man, as well as the prediction and development of measures for the prevention or remediation of geological hazards” (Knill, 2002, p. 8). A more clearly defined reactive, ecological point of view grew—at least ostensibly.

Lithospheric geoengineering emerged as a response to an increasing demand for knowledge about how to fruitfully manipulate the environment, such as through the digging of canals or the building of dams—and through these infrastructures, often also the extraction of resources. By the late 20th century, however, lithospheric engineers expanded their portfolio to environmental issues, such as “waste disposal, ground and groundwater pollution [or] soil and coastal erosion” (Oliveira, 2014, p. 26) due to the increasingly visible scars left on the world's ecosystem. Its history provides a clear warning about the risk of reactive technofixes in extractive systems. As such, it provides a compelling warning for climate geoengineering, where the reactive form of geoengineering is rapidly gaining scientific traction.

4 | MASTERING WEATHER AND CLIMATE: ATMOSPHERIC INTERVENTIONS

The history of climate geoengineering mirrors that of lithosphere geoengineering in many ways. For contemporary researchers, climate geoengineering presents itself primarily as a reaction to climate change, a reactive fix of climate damages brought on by human systems. But climate intervention also started as a dream of environmental control, its history entangled with the history of weather engineering. It traces back at least to the 19th century, when scientists suggested that with a better scientific understanding of the weather, rain could be conjured at will (Fleming, 2010a; Spence, 1980). When the Swede Svante Arrhenius, the first scientist to quantify the effects of carbon dioxide as a greenhouse gas, calculated the greenhouse effect in 1896, he and his fellow Swede Nils Ekholm soon speculated about the possibility of utilizing the greenhouse effect to *warm* the Earth, as they imagined a warmer climate would benefit agricultural production. Arrhenius's calculations made the scientific understanding of climate into a primarily atmospheric affair (Fleming, 1998). They also tied into an increasingly mathematical understanding of atmospheric behavior, both in terms of weather and climate. In the early 20th century, the work of Scandinavian scientists Vilhelm Bjerknes and Carl-Gustaf Rossby, who both played a large role in the institutionalization of meteorology in the United States, rendered the atmosphere mathematically describable and modelable (Bjerknes, 2009; Fleming, 2016). For both weather and climate, the implication was that weather and climate “should be calculable—and hence predictable” (Oomen, 2021, p. 46). With the interest in a predictable weather and climate, a dream of *controlling* both weather and climate co-evolved. Particularly in the aftermath of WWII, enthusiasm for climate and weather modification intensified. John von Neumann, influential polymath, went as far as saying that “all stable processes we shall predict. All unstable processes we shall control” (Von Neumann, as quoted in Fleming, 2010a, p. 194). Both Soviet and American researchers anticipated and worked towards control over natural systems such as the weather and climate (Bonnheim, 2010; Oldfield, 2013). The Cold War never being far from scientific minds, Edward Teller, “father of the hydrogen bomb,” even went as far as stating that “conflict over weather control is the likely cause of the ‘last war on earth’” (as recounted by Stone, 1988). In Teller's eyes, “we would be unfaithful to the tradition of Western civilization if we shied away from exploring what man can accomplish, if we failed to increase man's control over nature” (Teller, 1962, p. 56). According to Jeremy Baskin, these post-WWII dreams of weather and climate control were “characterized by dreams and assumptions of mastery” (Baskin, 2019, p. 27). Such dreams of mastery were buoyed by Cold War competition between the Western and Eastern blocs, but also by increasing international collaboration between scientists. This increasing collaboration

culminated in initiatives such as the period International Polar Years Geophysical Year (1957), the International Biological Program (since 1964), and the Global Atmospheric Research Program (1967), all of which also had important Cold War considerations.

Initially, the vast majority of atmospheric manipulation research focused on weather control (Harper, 2017). In 1933, the USSR had already set up a large research institute on rainmaking in Leningrad. After WWII, the United States followed suit. In 1946, Vincent Schaeffer and Irving Langmuir discovered that supercooled clouds could be induced to rain using dry-ice particles (Schaefer, 1946). The discovery sparked many cloud-seeding programs. A particularly influential example was Project Stormfury in the 1960s. Successor to the National Hurricane Research Project (1955), Stormfury attempted to further scientific understanding of hurricane formation. This included forecasting hurricane trajectories and, if possible, altering those trajectories using cloud-seeding. It also tied into the increasing interest in predictability. As part of the project Jules Charney and Arnt Eliassen, pioneering weather and climate modelers, developed a computer model of hurricanes to predict their behavior (Charney & Eliassen, 1964). There were many more projects. Some were large, such as Project Climax (1960–1970), aimed at increasing snowpack in Colorado, or Project Skywater (1960s), a federal weather modification research project. Many other research projects were small, regional, and commercial. Although there are obvious differences between these early weather modification projects and (contemporary) climate engineering technologies, most notably in the proposed scales (regional vs. global), weather and climate interventions were initially often grouped together (e.g., Fedorov, 1974; Fletcher, 1968; Hess, 1974). Both were understood as influencing atmospheric circulation, and large-scale cloud-seeding was occasionally suggested as a possible way to alter local climates. Influencing the “heat budget of the surface/atmosphere system” (Fletcher, 1968, p. 14), large-scale cloud-seeding—but also other interventions such as enhancing arctic albedo or changing ocean surface temperature—was seen as one option for climate modification, albeit a highly uncertain one. The National Science Foundation funding program for “Weather modification” in the 1960s also included “some basic work on climatic change and possible climate control” (Fletcher, 1968, p. 16). In the USSR too there was a sustained interest in climate modification, perhaps even more pronounced than in the United States (Fletcher, 1968; Keith, 2000; Oldfield, 2013).

Interest in weather and climate modification influenced the initial scientific reception of anthropogenic climate change. Indications of anthropogenic climate change met with suggestions to (thoroughly) explore “possibilities of deliberately bringing about countervailing climatic changes” (The White House, 1965, p. 127). Over the course the 1960s and 1970s, however, views on climate and weather modification changed, for several reasons. For one, weather and climate modifications became increasingly understood as separate interests. As climatology changed into climate science, its predominantly regional understanding of the climate also changed into a more global view (Edwards, 2010). As a result, the coupling between weather and climate modifications, uneasy in the first place, grew increasingly untenable. Weather modification became (almost) exclusively concerned with specific effects at specific locations, with regional scales. Climate modification, always closely tied to increasing worries about anthropogenic climate change, became an (almost) exclusively global affair—and increasingly a *reaction* to anthropogenic climate change. This tied into to a second change. Increasingly, both public and science viewed an increasingly *global* Earth as a fragile and interconnected whole. Through publications such as Rachel Carson’s *Silent Spring* (1962), which documented the environmental consequences of the large-scale application of herbicides and pesticides, the famous 1968 Earthrise photograph, the “blue marble in space,” Paul Ehrlich’s *The Population Bomb* (1968), and the 1971 *Limits to Growth* report, a public understanding of a global Earth threatened by industrialization grew. Thirdly, scientists started to consider a system sciences approach, which saw the Earth as a system of complex interactions between biology, geography, meteorology, and human systems. A 1988 report Earth System Sciences Committee, initiated by NASA’s Advisory Council in 1983 as a response to dramatically falling budgets for space exploration, describes this development from earth sciences to earth system sciences. It recognized, that “most of [the] knowledge about the earth has been assembled within historically distinct Earth-science disciplines.” “Within the past several decades” however, “...three momentous developments have converged to reveal to us ... a new view of the Earth as an integrated system.” According to the report, the first of these developments was “the maturation of many of the disciplines themselves.” Although “global connections among the Earth’s components began to be recognized in the last century,” it was “only relatively recently that scientists in one discipline have had to confront the need for major contributions from other disciplines in order to achieve substantial research advances” (NASA-ESSC, 1988, p. 12). While the early foundations of earth system sciences could indeed be located in the ideas of 19th century intellectuals such as James Croll or Alexander von Humboldt (Fleming, 2006; Jackson, 2009), the NASA report rightfully underlined—and this marks the second development—that “we now have access to a new view of the Earth from space that is both global and synoptic.” A third development, from their point of

view, was that “the past several decades have brought into sharp focus the role of increasing human activity—demographic, technological, and economic—in the generation of global change” (NASA-ESSC, 1988, p. 12).

The changing conception of not only the atmosphere and the climate, but the Earth as a whole—and humanity’s relationship to it—also changed geoengineering, both in terms of the climate *and* in terms of the lithosphere. As Kwa (2001) aptly articulates, during the 1960s and 1970s the conception of nature changed from something risky and wilful that needed to be controlled, to nature itself being *at* risk. These sociocultural changes in both the larger society and in the scientific community had profound effects on the development of “geoengineering.” Geoengineering, in many of its guises, became subject to more uncertainty and much more controversy. Where in the early 1960s, when knowledge of anthropogenic climate change first publicly appeared on policy agendas, the obvious solution was to suggest active (counter)-interventions in the climate system, by the 1990s climate geoengineering was controversial, reserved for a handful of eccentrics and military-industrialists. David Keith, one of the world’s leading climate geoengineering researchers—one of the few who worked on climate geoengineering before Crutzen’s call-to-arms and a forceful advocate for more SRM research—even argues that “for decades a de-facto taboo against serious work on geoengineering discouraged quantitative work” (Keith, 2013, p. 92). While this is too strong a statement, climate geoengineering was (and remains) controversial. When in the mid-1980s global warming hit the political and public mainstream, climate geoengineering was not widely considered to be a feasible or desirable approach to climate change. Even *adaptation* to climate change was eyed critically, described by Al Gore as “a kind of laziness, an arrogant faith in our ability to react in time to save our skins” (Gore, 1992, p. 240). Climate geoengineering received a similar—but icier—reception. As Lawrence and Crutzen (2017), early proponents of climate geoengineering research, outline in a reflection piece on “breaking the taboo on geoengineering,” this antagonism had four main reasons. First, climate geoengineering research might detract from mitigation efforts. Second, climate geoengineering research might cascade into development and deployment. Third, climate geoengineering was seen as a hubristic technological solution to a complex, systemic problem. Lastly, climate geoengineering, especially SRM, might distract from other, equally dangerous effects of rising CO₂ levels, such as ocean acidification. Despite these concerns, however, escalating fears about climate change slowly pushed climate geoengineering back into the scientific mainstream—this time as a *reactive fix* for climate change. Some parts of it, mostly various ways to capture and sequester carbon dioxide, have even made their way into the IPCC’s assessments, renamed as negative emissions technologies (NETs), in the process disconnecting it from its geoengineering roots. Notably, all scenarios in the recent IPCC report on limiting global warming to 1.5 degree above preindustrial levels rely on such NETs to a significant extent (Beck & Oomen, 2021; IPCC, 2018, p. 17).

5 | PRO-ACTIVE AND REACTIVE GEOENGINEERING: TECHNO-FIXES, CONTROL, AND CONQUEST

Climate geoengineering and lithosphere geoengineering share a history. Both began as isolated attempts to improve and control nature, and both later grew into more interdisciplinary *reactive* approaches to environmental degradation. As consciousness of the dark side of industrialization and extractive capitalism spread more widely, the portrayal of what deliberate large-scale interventions in the Earth’s systems might do changed also. In 1986, the same year as the Chernobyl explosion, Ulrich Beck published the book *Risk Society*, in which he signaled that post-modern societies no longer experienced risk predominantly as a feature of fate or nature but rather as human-made. In modern societies, the most pronounced risks were not simply natural but *technological*—such as the Bhopal and Chernobyl disasters. The (partial) shift away from promises of fully controlling natural systems, but rather maintaining (or even restoring) them against human-made degradation corresponds to that changing experience of risk. Where proactive geoengineering aimed to control nature and reduce natural risk, reactive geoengineering attempts to reduce risk that result from human industrial and technological society. Through (proto-)reactive geoengineering endeavors such as the TVA and the redefinition of geoengineering by Cesare Marchetti as a response to *anthropogenic* processes, geoengineering came to be seen as a techno-fix for environmental problems caused by humans—albeit it often one that allowed for intensification of extractive processes. In some ways, these new forms of geoengineering were more modest than their predecessors. No longer did climate geoengineers propose that full control of the weather or climate might be possible. Nor do hypoxic dead zone geoengineers claim that their knowledge of the oceans, seas, and lakes they want to engineer could ever be complete. Rather, they propose a more adaptive management, relying on consistent measuring, modeling, observation, and intervention. These interventions are presented as highly uncertain—and the systems they engage in frighteningly complex—but *necessary*, or at

least a “bad ideas whose time has come.” The uncertainties that geoengineering brings are no greater, in this view, than the uncertainty of not intervening.

It is important to note that this does not mean that reactive geoengineering cannot be hubristic in the ways it looks to science and technology as the solution for environmental degradation. Nor does it mean pro-active geoengineering has disappeared altogether. The history of reactive geoengineering is imbricated with that of more proactive ideas of controlling nature through large scale interventions. From these imbricated histories, various forms of reactive geoengineering have emerged, more and less closely aligned with earlier dreams of controlling nature. More specifically, we identify two types of *reactive* geoengineering. The first type, *reactive intensification*, could be described as a modest reform of proactive geoengineering, which is at least partially motivated by reacting to environmental degradation. It recognizes anthropogenic damage to natural systems, as well as the risks of that damage, but sees interdisciplinary collaboration in geoengineering as potential solution. Reactive geoengineering typically deepens extractive practices, continuing the use of large-scale interventions for the economic exploitation of resources. In contrast, the second reactive form of geoengineering, *reactive risk-reduction*, is the proverbial “technofix.” It is mainly motivated by anthropogenic environmental degradation and its risks, proposing (speculative) technologies and infrastructures to mediate and limit those risks. While economic logics still play a role of course, reactive risk-reduction more prominently departs from a logic of risk, at times even precaution or restoration. Often, these forms of reactive geoengineering view their proposed technologies as a temporary tool to help develop a sustainable socioeconomic system. In Table 1, we outline the differences (and similarities) between proactive geoengineering, and reactive intensification and reactive risk-reduction respectively.

6 | CONCLUSION: GEOENGINEERING RE-THOUGHT AND RE-IMAGINED

Geoengineering interventions have fundamentally shaped today's world. Through dams, canals, tunnels, and land reclamation, they have altered the physical appearance of the lithosphere—including many of its ecosystems. Attempts to alter the weather and climate, regionally and globally, also have a long history. Contemporary, more reactive, geoengineering proposals share a history with these earlier, hubristic forms of geoengineering that have fundamentally altered the face of the globe. Geoengineering, both of the climate and of the lithosphere, will likely play a role in the future governance of the earth and its systems. The increasing complexity and interconnectedness of environmental concerns means that large-scale, interdisciplinary attempts to curb the damages are certain to attract more attention over the coming years. This attention may be turned toward a host of technologies that appear unconnected at first glance; disparate technologies such as tunnel-digging, biogenetic modification, and spraying aerosols into the atmosphere. Likewise, experts in marine biology may offer carbon capture and storage through the use of microalgae, or to provide biofuels (Greene et al., 2017). Lithospheric geoengineers also continue to be at the forefront of interventions that further drive anthropogenic climate change; or that try to tackle its consequences. Their expertise is as central to mining and fracking, as it is to finding waste disposal sites for nuclear waste or carbon storage. In regions where climate change causes increasing erosion or rainfall variations, lithospheric geoengineers might help human settlements to adapt to changing environments (Delgado, 2014). With land-use being a major concern for carbon capture and storage, engineering geologists might soon find themselves in demand for the mining and application of chalk for advanced weathering. The search for and planning of underground storage in the context of CCS is another field in which the different geoengineering communities might intensify their collaboration in the future (Espinoza et al., 2011; Masoudian et al., 2013; Pan et al., 2016). Even expanding and revitalizing public transportation systems, as part mitigation and adaptation will involve lithospheric geoengineering expertise. Expanding the European railway system, for example, required several new base tunnels to be constructed, such as at the Gotthard or the Mont Cenis. In the field of climate engineering, research projects to limit the consequences of a warming climate using geoengineering technology have already started regionally, in the use of marine cloud brightening technologies to safeguard the Great Barrier reef (Readfearn, 2020). Fierce debates on whether *global* climate geoengineering through SRM can ever be defensible are also underway.

Across the board, geoengineering requires invasive, large-scale interventions in the planetary environment. This means that geoengineering inevitably raises concerns about questions about the legitimacy, desirability, and technical feasibility of such proposals. Reactive geoengineering is not necessarily *less problematic* than pro-active geoengineering was, nor is it necessarily less hubristic. Reactive climate geoengineering might limit and hinder comprehensive climate mitigation, in favor of speculative promises about “negative emissions,” “overshoot,” and “shaving the peak” of global

TABLE 1 Typology of proactive and reactive geoengineering

		Reactive geoengineering	
Proactive geoengineering		Type I: reactive intensification	Type II: reactive risk-reduction
Aim	Subjugating a wilful nature to the dominion of human activity and mastery.	Partially reacting to environmental degradation caused by human activity; permanent application with the aim of extracting resources.	Mainly reacting to environmental degradation caused by human activity; often a temporary application to gain time to organize structural change.
Preferred metaphors	<i>Military</i> : war, conquest, control	<i>Systematic</i> : harmony, balance, equilibrium	<i>Techno-fix</i> : medicinal, plan B, repair, care, restoration
Paradigmatic carriers	<p><i>Lithospheric geoengineering</i>: Land reclamation projects (Prussia, Netherlands); Sea Canal projects (Panama Canal, Kiel Canal, Suez Canal); Alpine Tunnel projects (Mont-Cenis, Gotthard, Simplon). <i>Climate (and weather) geoengineering</i>: Early suggestions of climate control, most notably in USSR. Project Stormfury trying to control storm and cyclones; Cloud seeding in Project Popeye in Vietnam War; Cloud seeding Beijing Olympic Games 2008.</p>	<p><i>Lithospheric geoengineering</i>: Integrated regional planning projects: (Tennessee Valley Authority, India Rivers Inter-link project); Exploration for renewable energy transition (geothermal energy, lithium, etc.); exploration of waste sites for (as safe as possible) storage (e.g. nuclear waste, CCS). <i>Climate geoengineering</i>: CDR, where imagined around carbon capture and storage projects that require large-scale land-use transformations; Use of carbon capture technologies to be able to either (a) postpone steep emissions cuts, or (b) continue carbon emissions indefinitely. A combination of SRM and CDR as imagined mechanism to mask temporary “overshoot” of carbon budget/concentrations.</p>	<p><i>Lithospheric geoengineering</i>: Infrastructure projects changing geomorphological formations in order to support public transportation rather than individual mobility or short-distance flights, e.g., expansion of European Railway System; <i>Climate (and weather) geoengineering</i>: Cloud seeding after 1986 Chernobyl disaster in an attempt to control the location of radioactive fallout; Solar radiation management proposals as insurance against catastrophic climate risk; Regional Marine Cloud Brightening to protect Great Barrier Reef.</p>
Ideas about complexity	Nature can ultimately be understood and controlled.	Active, adaptive management of projects; tech-optimism regarding understanding and controlling complexity, often downplays potential dangers.	Systems as complex and chaotic: management only possible to a certain degree. Not-intervening is <i>also</i> chaotic and complex. Public recognition of potential dangers.
Conception of uncertainty	Uncertainty is a feature of a <i>lack</i> of knowledge. Nature, however, is <i>knowable</i> in principle, so better science and technology can control for risks.	Risks can be reduced to a manageable minimum by close monitoring of environment, technology and society and maintenance and repair has to be kept up indefinitely.	Uncertainty can never fully be reduced. Awareness that reducing uncertainty happens through a <i>selective</i> reduction of complexity.

warming. As such, appearing as a reactive solution to environmental problems, reactive climate geoengineering might actually *exacerbate* climate risks. Reactive climate geoengineering might also turn out to be form of *reactive intensification*—like the TVA—in which ostensible “fixes” of environmental degradation are instead used to expand the environment’s exploitation. It is important, then, to be clear about what types of geoengineering are present in the various fields, as interdisciplinary collaboration around complexity and uncertainty becomes increasingly common. This includes careful study of the “lessons learned” in older branches of geoengineering, as well as the warnings that can be drawn from those lessons. *How* geoengineering interventions are conceptualized, and with what aims, should be of central concern. This includes the histories of specific interventions, but it also includes investigating where different technological proposals intersect, or share common histories. An awareness of the checkered history of proactive and

reactive geoengineering helps us to foreground that debate. One step towards understanding the implications and future of climate geoengineering better is a recognition of its wider history, of the multiplicity of disciplines involved and their impacts on nature and society in the past.

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Jeroen Oomen: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; writing - original draft; writing-review & editing. **Martin Meiske:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; writing - original draft; writing-review & editing.

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