

1 Introduction

you scientists, you're absolutely nuts. You didn't just do this without asking anybody for authorisation or without inquiring about the procedure that has to be followed before this.

(researcher O)

Dreams and nightmares

On 7 January 2009, the German research vessel *Polarstern* left Cape Town, South Africa, for the Southwest Atlantic Sector of the Southern Ocean. It carried 48 scientists on a journey to fertilise 300 square kilometres of ocean with six tons of dissolved iron (Alfred Wegener Institute, 2009). Planning an experiment designed to find out how much extra carbon dioxide could be stored in the oceans, these scientists intended to fertilise the sections of the Southern Ocean with small iron filings. Specifically, they wondered about the effects of iron fertilisation on the local ecology of the ocean and how iron fertilisation would affect the capacity of oceans to store carbon. To the naïve surprise of the researchers, this Indo-German research project called LOHAFEX (Loha being the Hindi word for iron, and FEX the acronym for Fertilisation EXperiment) attracted fierce international criticism. They were accused of 'major tinkering with the marine ecosystem' (Bhattacharya, 2009), disrespecting the national sovereignty of Australia, furthering commercial interests in carbon capture, and conducting ecologically questionable research without sufficient supervision. Some even called the experiment outright illegal, because they thought it contravened the UN Convention on Biodiversity (Paull, 2009). In Germany, the experiment also attracted criticism. The Bundesministerium für Umwelt (the German Ministry of Environment—BMU), not consulted prior to the project, wrote an open letter to the Bundesministerium für Bildung und Forschung (the Ministry of Education and Research—BMBF), demanding that the project be stopped¹ (Schuh, 2009; Stockrahm, 2009). As political tension mounted, an expert committee of external researchers was asked to assess both the legality and the desirability of the research project. Although several of them were highly critical of the project—one assessor described the project as 'absolutely nuts'²—they also

found that ‘it wasn’t prohibited in terms of the law’ (researcher O). Soon after, the project ended. Officially, it found that iron fertilisation wasn’t as promising as it had been imagined to be. Several feedback systems limited the potential to ‘fertilise’ the ocean to store more carbon. Unofficially, it found that iron fertilisation was a politically toxic research topic. To many, ocean iron fertilisation was *geoengineering* or *climate engineering* and, as such, it was anathema. Ironically, this controversy around LOHAFEX became the catalyst for a sustained climate engineering research program in Germany. As a result of the controversy, many people realised that the idea of active climate manipulation ‘was out there’. The group of scientists and scholars asked to assess LOHAFEX formed a ‘cluster of excellence’, a group of scientists dedicated to discussing whether climate engineering technologies—speculative technological ‘solutions’ to climate change—warranted more responsible research. Through several rounds of funding applications, eventually this cluster of excellence yielded one of the biggest sustained research initiatives with public funding in the world: the German Research Foundation’s (DFG) SPP-1689.³ Permanently influenced by the LOHAFEX controversy—and the carefulness of the DFG—this SPP program operated under a specific slogan, ‘assessment, not development’ of climate engineering technologies.

In March 2017, another group of scientists met in Washington, DC. These scientists too wanted to discuss how to manipulate the Earth’s climate systems. Many of them had been intrigued by the possibility for over decade. Like the LOHAFEX experiment, this meeting addressed the possibility of using invasive technological interventions to ‘counteract anthropogenic climate change’. Aimed as an openly political meeting, this *Forum on U.S. Solar Geoengineering Research* was designed to put the possibility of *engineering* the Earth’s climate on the political agenda. The main drivers behind the event, the scientists David Keith and Ted Parsons, were hoping to introduce ‘climate engineering’, a field of research comprising a wide variety of technological responses to the problem of anthropogenic climate change, to the American political world. Keith and Parsons hoped to normalise climate engineering research—and to find some political support. To them, assessment *and* development of climate engineering technologies was the prudent thing to do, given how dire climate change is starting to get. Various emotions were present in that room. Some people were palpably excited. For them, the forum was a minor triumph. Many at the *Forum* had staked careers and reputations on the pursuit of climate engineering research. For years, if not decades, they had been championing climate engineering research. Here they were, in the heart of the American political world, arguing their research was inevitable to avoid catastrophic climate change. Far less conflicted than researchers of the German SPP, these scientists were *excited* by the intellectual challenges of climate engineering. Others, such as myself, felt conflicted about the *Forum*’s aims. We certainly need inventive solutions to climate change. Climate engineering research is timely and important. But the prospect of using invasive technological fixes is deeply worrying—politically, socially, scientifically, and morally.

Between the *Forum on U.S. Solar Geoengineering Research* and its main driver, David Keith's research group at Harvard University, and the SPP-1689, major disagreements existed. Many continue to exist. Yet they all share one interest: doing climate engineering research—and worrying about how to do so responsibly. Describing a wide variety of speculative technologies, climate engineering envisions technological solutions to anthropogenic climate change.⁴ It imagines using invasive and partial 'techno-fixes' to avert the worst dangers of climate change.⁵ To many, climate engineering is a direct reaction to anthropogenic climate change. As a result, the more acute fears about climate change become, the more traction climate engineering research gains. In reality, however, the history of climate engineering is far more convoluted and complicated. Of course, manipulating the Earth's climate is not a new idea. Climate intervention research is both very old and incessantly modern. 'Weather and climate modification, or "rainmaking" (the more popular and also more restricted concept), is not new to our era or our country', a U.S. National Science Foundation committee on weather modification noted in 1965:

Many traditional societies, including the American Indians, have practiced some type of religious or ritualistic rainmaking. The ceremonials and rituals have varied from dousing holy men with water to burying children up to their necks in the ground in the hope that the gods would be sympathetic and drop tears from the heavens. These ceremonies are not only to induce some form of desirable weather but also to reinforce the tribal religious beliefs and opinions which maintain social unity.

(National Science Foundation, 1965, p. 1)

Nearly every culture in history had its own mechanisms to reconcile the uncertainty of climate and weather. Most of these were mystical, and some more practical. Since Francis Bacon declared Nature 'man's dominion', however, Western scientists have tried to control the climate more systematically. Over the past century, the prospect of climate control has been ever-present in both politics and science. In the first few decades after the Second World War, overzealous scientists dreamed of controlling the weather and the climate. When climate change first appeared on the political radar in the 1960s, techno-fixing was the *only* solution that people considered (The White House, 1965). This enthusiasm waned in the 1970s and 1980s as environmental concerns grew. As a result, scepticism about the technical feasibility of climate and weather control partially displaced the technological hubris of the 1950s and 1960s. For several decades, climate modification remained an abstract dream, relegated from the scientific mainstream. By and large, climate engineering, defined by the Royal Society as 'deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change' (Royal Society, 2009, p. ix), remained a minor (but highly controversial) interest of climate politics. According to David Keith, arguably the world's most prominent climate engineering researcher, for decades 'a de-facto taboo

against serious work on geoengineering discouraged quantitative work; little was done' (Keith, 2013, p. 92).⁶ In recent years, however, climate engineering has started to return to the centre of the scientific vision. As climate change grows more dire by the day, more and more scientists are willing to look into these speculative technologies. In this book, I address this growing scientific interest in climate engineering. Through looking at two major research initiatives, the aforementioned SPP-1689 and David Keith Group, I investigate what types of dreams, fears, epistemologies, and histories drive climate engineering research—at least in the Western academies. This is important, because these academies are still main drivers of both the IPCC and the climate change debate as a whole. As such, we would do well to understand how and why scientists imagine climate engineering to be a potentially worthwhile addition to climate change policy—even despite its controversial nature.

Most prominent contemporary 'climate engineers'⁷ are far more apprehensive than their predecessors. For much of the 20th century, imagined climate interventions were militaristic, subjugating the climate and the weather for political, scientific, and military aims.⁸ Where in the early 1960s it seemed obvious to address environmental concerns with active counter-interventions, by the 1990s talk of climate engineering was a curious niche, reserved for a handful of eccentrics and military-industrialists. Climate engineering was unpopular. Only in the mid-2000s it came back into scientific mainstream vision. Paul Crutzen, a Nobel laureate famous for his work on the ozone layer, picked up on several disparate strands of climate engineering research and gave them a platform by calling for more research. In Crutzen's eyes, it was time to take climate engineering seriously as a last-ditch effort to stall climate change. But why was talk of climate intervention such a straightforward option in 1965, and why was it so controversial 30 years on? Why do scientists still think climate engineering research is necessary, despite being afraid it is unreliable and might be appropriated? How and why do they imagine climate engineering might work as a partial approach to climate change?

In this book, I distil those questions into two leading research interests. The first interest is historical, addressing how climate engineering became a conceivable reaction to climate change. The second is more sociological, asking which underlying conceptions of the climate system and the world at large animate and motivate climate engineering research—and how these 'ways of seeing' are historically informed. To address these interests, it is important to first lay out what climate engineering entails in a bit more detail. After a further introduction of climate engineering in the next section, the rest of this chapter is devoted to outlining on how I tackle my research interests and how they fit into the structure of this book.

So *what* is climate engineering?

Climate engineering is not one technology. It is a term describing many different 'deliberate large-scale manipulations of the planet to counteract climate

change'. It consists of a wide variety of speculative technologies. Roughly, these technologies can be subdivided in two types. The first type, carbon dioxide removal (CDR), relies on the simple observation that if humans can cause global warming by adding carbon dioxide to the atmosphere, humans could stop global warming by *removing* that carbon dioxide. Since global average temperatures are correlated to the greenhouse gas concentrations in the atmosphere, what matters are these concentrations. How these concentrations are reached does not matter much in terms of global warming. As long as safe levels of greenhouse gas kept low enough, global average temperatures will stay within safe bounds.⁹ The second category, SRM, in turn, observes that increased greenhouse gas concentrations trap too much solar energy in the climate system. It is this trapped energy that leads to global warming. So, if energy could somehow be prevented from becoming trapped, the climate would not warm as much. Both SRM and CDR are highly controversial. They are often viewed as uncertain, as hubristic, as technocratic, as imperial, even as gendered sets of technologies that will have deeply detrimental effects on our social and natural world. As both sets of technologies approach the problem from a different angle, however, they are controversial for different reasons.

CDR searches for *negative emission technologies* (NETs), technologies that can reduce the carbon concentrations in the atmosphere. Typically, these NETs are imagined to *complement* conventional mitigation—and to treat the root cause of climate change.¹⁰ There are many different ways of absorbing CO₂ from the atmosphere. As such, many different NETs are possible. Because the spread of CDR technologies is much too broad to fully explain them all, I will limit myself to a 'quick and dirty' explanation of the different technologies, focusing not on specific technologies but on forms of intervention. In an imperfect categorisation, I identify three rough forms to explain how CDR might interact with its environment.

The first form of CDR proposes various interventions in natural carbon cycles. The most popular example of this idea is the proposal to grow more forests, afforesting previously non-forested land and reforestation of previously deforested lands. Other options include using iron particles to fertilise oceans for more algae growth and using the rapid weathering of ground limestone. These 'technologies' envision using biospheric processes to store more carbon. In a sense, this means that these proposals are 'natural' options—but they still have significant drawbacks. Ocean iron fertilisation, for example, interferes with the natural cycles of ocean life (Cao and Caldeira, 2010; National Research Council, 2015a). Afforestation needs huge swaths of land, while potentially also wreaking havoc on the hydrological and nutrient cycles (Sonntag *et al.*, 2018). The main objection to this sort of intervention is that it requires major changes in natural systems, changes that are unpredictable. Of course, as this form of CDR raises questions about the appropriate use of ecosystems, there are also political objections to these 'natural' options.

The second CDR form aims to intervene in socioeconomic systems, often where socioeconomic systems meet ecosystems, such as in agricultural

practices. These technologies, more than forestation or ocean fertilisation, intend to make biological systems already utilised by human industry store more carbon. Bio-energy carbon capture and storage (BECCS), for example, proposes to turn corn and other crops into fuel, in order to capture the carbon emissions of these fuels at their source (National Research Council, 2015a). Bio-char or other forms of biological carbon capture might be used to grow plants, store their CO₂, clear pastures, and regrow plants (Lehmann, Gaunt and Rondon, 2006; Lehmann and Joseph, 2015). All these technologies, however, have similar drawbacks to afforestation and reforestation, in that they require vast areas of land. Again, this raises serious concerns about land use, because it may lead to ‘land-grabbing’ by corporations and wealthy countries.¹¹ Additionally, it may also disrupt ecological cycles.

The final set of technologies is the most technologically intensive, using artificial systems rather than biospheric interventions to capture carbon. These technologies are extremely diverse. Heavily patented (Oldham *et al.*, 2014), technologically intensive CDR measures are typically developed commercially. Direct air capture (DAC), which proposes the use of machinery to literally suck carbon dioxide out of the atmosphere, in particular, is often imagined to be a commercial solution. It is still highly expensive but might become commercially viable once accurate carbon prices are introduced (Keith *et al.*, 2018). Obviously, the differences between these three forms of CDR aren’t absolute, and many proposed CDR blend the forms mentioned above.¹²

In principle, CDR is not controversial for its aim: less carbon dioxide in the atmosphere. But CDR is not unproblematic. It is highly unlikely that NETs could be implemented at the scales required to halt climate change (Lawrence *et al.*, 2018). Still, despite this uncertainty, NETs are now deeply embedded in the IPCC scenarios for the 2°C and 1.5°C climate goals (Anderson and Peters, 2016; Beck and Mahony, 2018). The assumption that carbon dioxide can still be captured later might hamper efforts towards conventional ways of mitigation. Effectively, counting on CDR might *exacerbate* the risks of climate change. Even if it *does* work, there are serious political and ethical objections to CDR. Many of its technologies assume the use of large swaths of land and water, possibly displacing and harming many who rely on that land for their livelihoods. Also, relying on future carbon capture shifts mitigation responsibilities of current generations to future generations, on the basis of *speculation* about the technical feasibility and political desirability of carbon capture.

SRM is even more controversial. Not only are the technologies speculative, risky, and uncertain, they also do not lower greenhouse gas concentrations. They are, rather, ‘symptom treatments’ for the adverse consequences of anthropogenic climate change (Lovelock, 2008; Nerlich and Jaspal, 2012). As rising CO₂ concentrations cause more heat to be trapped in the Earth’s climate system, SRM is the term describing various attempts to remove this excess heat. SRM technologies propose to increase the reflectivity of the Earth, its ‘albedo’. Increasing the Earth’s reflectivity creates ‘negative radiative forcing’,

by either reducing the amount of energy that enters the climate system or increasing the amount that leaves it. This counteracts the increasing greenhouse effect, which traps solar energy in the climate system. According to the proponents of SRM research, SRM could prove vital in preventing climate catastrophes. If done right, it could limit global warming to somewhat safe levels. Perhaps, it might even help slow the *rate* of climate change. Because the speed with which the climate is now changing is probably wholly unprecedented, even on geological timescales, ecosystems and humans do not have enough time to adapt. Slowing this rate of change, then, could help reduce ecosystem disruption, prevent mass extinctions, and give humans time to adapt too.

At its most basic, SRM proposes to counter one unprecedented development (rapidly increasing greenhouse gases) with another: the deliberate increase of the Earth's reflectivity. There are many ways in which the Earth's reflectivity fluctuates, but two examples jump out here. The first example is a natural phenomenon—one that provided crucial inspiration for some high-profile SRM proposals. In 1991, Mount Pinatubo in the Philippines erupted, hurling large amounts of sulphur into the troposphere and stratosphere. These sulphuric aerosols cooled the Earth for the subsequent 18 months, leading many scientists to suggest humans could emulate such a cooling process. A second example of fluctuation of the Earth's albedo is human-induced, namely the process of industrialisation that has influenced the Earth's reflectivity in myriad ways (National Research Council, 2015b; Royal Society, 2009). Deforestation for agriculture, for example—while a significant source of CO₂ emissions—makes for a more reflective Earth surface because agriculture is more brightly coloured. Sulphur and other aerosol particles emitted by factories and aviation already mask global warming significantly by refracting sunlight coming into the atmosphere. Dark grey infrastructure (such as cities), on the other hand, *absorbs* heat.¹³ Proponents of SRM imagine they could further expand this influence on the Earth's climate system *deliberately*. Again, there are many different proposals for this, ranging from fairly innocuous to deeply invasive.

The most basic form of deliberate albedo modification is relatively uncontroversial. Related to climate adaption, these technologies envision making human infrastructure more brightly coloured. The effects of such interventions would be primarily be felt locally. Adapting urban infrastructure to retain less heat, for example, can reduce heat and improve air quality in cities. For climate change globally, however, it would do little. It would simply not change the overall reflectivity of the Earth enough. In order to influence climate on a global scale, SRM technologies have to be far more invasive than infrastructure adaptations. Apart from the occasional outlandish, sci-fi-esque proposal (e.g. Ming *et al.*, 2014), two types of SRM technologies currently attract most attention. On the one hand, there is (marine) cloud brightening. According to this idea, clouds could be made brighter and reflect more sunlight. These technologies can be aimed at regional or local cooling (often around the (Ant) arctic to reduce sea ice melt) or, if implemented at sufficient scales, to cool the

Earth as a whole. The other major technology is stratospheric aerosol injection (SAI). It proposes to *mirror* the effects of a volcanic eruption by injecting tiny particles into the stratosphere. This speculative technology attracted attention as a possible solution to climate change as early as the 1960s (The White House, 1965). It remained a peripheral scientific interest throughout the 1990s and early 2000s, to return to full view in 2006, when Paul Crutzen championed it in his call for climate engineering research.¹⁴

Technically, many of these technologies may be feasible. They may, in a narrow sense, limit warming. They may even prevent a lot of the damage that global warming will do in the future. But like CDR, these technologies are deeply controversial. Like CDR, they might limit the conviction of people and politicians to mitigate greenhouse gas emissions—concerns I treat more extensively in Chapters 3–5. The exact effects of their implementation would be deeply uncertain (McLaren, 2018). Because they require specialist knowledge and complex sociotechnical systems, they may exist in tension with democratic systems and values (Szerszynski *et al.*, 2013). Global implementation of these technologies will certainly be objected to by many communities because it conflicts with their values and beliefs (Emmett and Nye, 2017).

In short, the climate engineering research field is diverse and highly controversial. The concerns around climate engineering are not uniform. Not all concerns apply equally to all forms of climate engineering. Adding to the complexity is the fact that, although CDR and SRM are often imagined in conjunction, some of these technologies may work in direct opposition. Reforestation and afforestation, for example, would be most effective using trees with dark leaves. As these absorb the most energy, these leaves facilitate the most rapid photosynthesis and therefore absorb the most the CO₂.¹⁵ Yet this also means that these forests are darker than the land used to be, therefore *reducing* the albedo. Roughly, objections to climate engineering fall in three distinct domains: the physical or technical, the political, and the normative. Can it be done? Can it be politically organised in a just way? Can it be governed at all? Should it be done? All these questions are virtually unsolvable. Whether or not ‘it can be done’ deeply depends on how one defines technical success. Whether it can be governed democratically depends not only on how one imagines democracy but also on what sociotechnical systems will be needed to make these technologies work technically. In all discussions, even the technical, normative, and value-loaded discussion loom large. And in all political and normative discussions, there is the ever-presence of technical questions.

Constructing the imaginary: theory of knowledge and futures

Climate engineering inevitably raises questions about the shape of a desirable future. Who gets to make decisions about the global climate future? What will the role of sociotechnical systems be in that future? How would this be organised? How can different concerns, convictions, and cultures be

weighed against each other? As Levin *et al.* (2012) point out, climate change is a ‘super-wicked problem’. Time is running out, the socioeconomic systems causing climate change are simultaneously trying to find the solution, there is no strong central authority, and policy options do not give the future its proper weight.¹⁶ Because climate change is such a wicked problem, climate engineering research as a proposed (partial) solution is necessarily a ‘post-normal science’ where ‘facts are uncertain, values in dispute, stakes high, and decisions urgent’ (Funtowicz and Ravetz, 1993). In post-normal science, in contrast to ‘normal science’ as an authoritative fact-finding enterprise—providing expert opinion for policy—where to locate ‘truth’ is problematic.¹⁷ Because values are in dispute, many different visions of science and truth coexist. In essence, climate engineering is a discussion about what climate futures are desirable, who should have the authority to chart such desirable futures, and what the role of science is in charting such futures.¹⁸ According to Sebastian Pfotenhauer and Sheila Jasanoff, ‘charting a desirable future... inevitably presupposes an undesirable present as the backdrop’ (Pfotenhauer and Jasanoff, 2017, p. 789). For climate engineering, in a way, the inverse is true. The central premise of climate engineering is the prospect of an *undesirable* climatic future.¹⁹ In this undesirable future, severe climatic change wreaks havoc on social, economic, political, and sociotechnical systems of the coming century and beyond. Correspondingly, *retaining* the present state of the climate system is the desirable future that is charted.²⁰ In a sense, this means contemporary climate engineering research, in its own controversial way, searches for a form climate maintenance or climate restoration, asking one basic question: How can the climate sweet spot of the Holocene be maintained despite industrialisation and its corresponding carbon emissions?

The question of how societies construct their futures, based on what types of knowledge, authority, and visions, is not particular to climate engineering. The study of this question has been a point of convergence for many academic disciplines, particularly disciplines focused on the convergence of human and non-human systems. Two bodies of work are particularly important here. Science and technology studies (STS), mixing historical, sociological, philosophical, and anthropological research on the role of science and technology in contemporary societies, helps to understand how knowledge-making processes co-produce political order and particular imaginations of what society should look like. It also helps to understand how visions of desirable futures motivate actions in the present. Second, the environmental humanities, an interdisciplinary recombination of humanist scholarship questioning human-nature relations, can help to interrogate the visions of nature and the human that underlie climate engineering. As Noel Castree and his co-authors observe, global sustainability science (also including climate engineering) still operates under what they call a ‘stunted conception’ of human dimensions. Humanist scholarship might help solve this problem by engendering more ‘plural representations of Earth’s present and future that are reflective of divergent human values and aspirations’ (Castree *et al.*, 2014, p. 763).

In climate engineering, questions about the formation of knowledge and technology meet questions about human-nature relationship and questions about the future. Who gets to decide what knowledge is relevant for climate engineering assessments? Could SRM ever be implemented fairly equitably, even democratically (Szerszynski *et al.*, 2013)? How do imaginations, discourses, and metaphors about climate engineering affect the people's judgement of its viability and desirability (Baskin, 2019; Nerlich and Jaspal, 2012)? What is the role of 'non-scientific' concerns, such as morality, culture, and values (Emmett and Nye, 2017; Hulme, 2014; Preston, 2013)? Can the complex sociotechnical systems of climate engineering, including negative emissions and albedo enhancement, be designed and governed in fair, equitable, and politically and environmentally sustainable ways (Hulme, 2014; Rayner *et al.*, 2013; Stilgoe, 2015)? What is the relationship between social forces and cultural developments and the ways climate engineering technologies are imagined and developed (Beck and Mahony, 2018; Bellamy, 2016; Geden, 2016; Oomen, 2019)? And how do imagined climate futures shape climate engineering development (Baskin, 2019)?

Imagining the place of climate engineering

In this book, I ask how climate engineering is imagined *by the researchers themselves*. Specifically, I investigate how climate engineering came to be imagined as an approach to global warming, as well as how climate engineers imagine the place of climate engineering in climate policy. This means that I question not only how climate engineers decide upon the relevant facts but also how they imagine climate engineering as part of a possible approach to anthropogenic climate change. Specifically, I interrogate how values and convictions about human-nature relationships influence imaginations of what climate engineering can and should do. In doing so, I draw from co-productionist STS research. Co-productionist scholarship analyses how science, technology, and social order co-produce one another by shaping social processes and values. In turn, those values and processes shape the development of science and technology (Jasanoff, 2004; Latour, 1993). Like the environmental humanities, co-productionist research stresses the importance of collective (self-)imaginings and identities—based on visions of futures, pasts, and presents as well as value-systems and cultures. Stemming from insights in political science and anthropology about collective imaginations about nationalism (Anderson, 1983), the imaginative force of globalisation (Appadurai, 1996), and the *social imaginary*, the imagined collective basis of social life (Taylor, 2004), humanist research increasingly focuses on the power of collective (self-)imaginings to shape present and futures. Collective imaginations of technological futures and the mobilisation of support and collectives for those imaginations are the explicit focus of work on *sociotechnical imaginaries* (STIs). Defined as 'collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated

by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology' (Jasanoff, 2015, p. 3), STI scholarship explicitly investigates how collectively held imaginations shape sociotechnical futures. Crucially, STI research is premised on the assumption that science and politics are intimately intertwined with the (post-)modern social order. Collective imaginaries facilitate collective actions towards certain imaginations of the future, while they inhibit action towards other possible futures. Tying into earlier calls for less hubristic, more humble understandings of technology and social technologies (Jasanoff, 2003), STI theory ties together traditions in STS research that focus on the formation of scientific fact, fiction, and consensus (Callon, 1984; Latour, 1987, 1993; Shapin and Schaffer, 2017) and on the entanglement of science, technology, and society (Jasanoff, 2004, 2007). It facilitates a theoretical understanding of how social and technological processes co-produce particular futures. STI theory also connects to an older awareness that the cultural history of science, especially in Europe and the United States, has overestimated the predictive capacity of science (Funtowicz and Ravetz, 1993; Jasanoff, 1994, 2003; Ravetz, 1970; Scott, 1998). Importantly, STIs also make room for value-based readings of science and technology, opening up a political debate about the relationships between human understandings of nature, of the future, and of culture influence sociotechnical development.²¹

By opening up the black box of the sociotechnical imagination, STI theory enriches scholarly understanding of the formation of climate engineering considerably. Over the course of the past decade, scholars have written about how climate engineering research fits into the scientific culture of prediction and certainty, and how its history is connected to military interests and modernist hubris (Fleming, 2010). In the early years of climate engineering assessment, most critical scholarship focused on the way certain framings permitted certain conversations about climate engineering (Huttunen and Hildén, 2014; Luokkanen, Huttunen and Hildén, 2014; Nerlich and Jaspal, 2012), followed by calls open up the conversation, including wider frames and participation (Bellamy *et al.*, 2013). Observers have also raised serious questions about the political ramifications of climate engineering, particularly SRM, and the risk of 'locking-in' climate engineering through its development (Cairns, 2014; Szerszynski *et al.*, 2013). In recent years, scholars have increasingly focused on the embedding of particular imaginations and expectations about the climate future into climate engineering research. From 'magical thinking' about the potential of negative emissions technologies (Rayner, 2016) to the effects of new ways of accounting for emissions pathways (Beck and Mahony, 2018), these analyses hinge upon the ways politics and science interact with imaginations of desirable and possible futures. Simultaneously, philosophers, historians, and humanists have criticised climate engineering for its stunted conception of the climate and natural systems (Emmett and Nye, 2017; Hulme, 2014; Preston, 2013). Blending STI theory with anthropological and historical insights from the environmental humanities allows me to

blend together these criticisms into a more comprehensive understanding of how climate engineers relate to their research.

Gaining such a comprehensive understanding means engaging seriously with the history of climate engineering as well as with the sociology of its present. In this book, then, I rely on previous climate engineering scholarship from both history and sociology, supplemented by my own empirical research. Two books deserve special mention. Jim Fleming's *Fixing the Sky* (2010) outlines the entanglement between the history of climate control and militaristic visions of the Cold War. It remains the single most authoritative voice on climate engineering's history. Additionally, Jeremy Baskin's *Geoengineering, the Anthropocene, and the End of Nature* (2019) should be considered an authoritative voice on climate engineering's present. It focuses specifically on the STIs of SRM—many of which can to some extent be used to understand CDR research as well. Both Fleming and Baskin observe climate engineering's history of hubristic technological optimism during the early Cold War. For Baskin and Fleming, climate engineering remains deeply connected to these early roots. As Baskin observes, a wider STI of 'Mastery', in which nature was to be mastered in the geopolitical struggle for dominance, animated early climate modification research in the United States and the USSR. In the 1970s and 1980s, as nature came to be reimagined as fragile (Jasanoff, 2001; Kwa, 2001), climate modification dreams slowly came to be reimagined as climate engineering.²² According to Baskin, contemporary climate engineering is forming competing imaginaries about climate engineering. The first narrative Baskin identifies regards SRM as an 'illicit intervention in the natural world, a plutocratic initiative deploying a dangerous technology of hubris (a techno-fix), a disaster for the world's poorest, and one which should not be allowed to proceed' (Baskin, 2019, p. 123). The second narrative sees SRM 'as part of an elite conspiracy to actively, and secretly, poison the land, air, and water by spraying chemicals—"chemtrails"—from airplanes for a variety of malevolent purposes' (ibid.). The final imaginary, on the other hand, more amenable to climate engineering, 'imagines governing the climate as a component of governing the world and tackling the risks of climate change' (ibid.). In this last view, market considerations, the idea of geo-management, and imaginations of salvation from climate catastrophe are all part of the climate engineering narrative.

I draw heavily on both Baskin and Fleming, because their astute observations are important. All these narratives are discursively battling for the right to imagine the future of climate engineering—and the future of the world. Building on Baskin and Fleming's historical and sociological work, this book specifically asks what these concurrent visions for climate engineering are and on what basis that vision takes shape. Where I differ, however, is by trying to analyse what specific kinds of epistemological and normative disagreements underlie different positions on climate engineering. At the moment, most visions for climate engineering are still insufficiently stabilised, often too inconsistent, to form clear imaginaries. To many, the role that climate

engineering could or should play in the climate debate is unclear. Many, and I include myself, wildly oscillate between different positions. At the same time, there are certainly already groups trying to stabilise particular visions about climate engineering. Several sociotechnical vanguards, ‘relatively small collectives that formulate and act intentionally to realize particular sociotechnical visions of the future’ (Hilgartner, 2015, p. 34), located in Europe and the United States, adopt different discourses at different times. They might intermittently use particular narratives rather than others, but they ultimately try to shape the debate according to *their* visions about climate engineering. This begs the question on what basis these particular visions of the climate future rest. What are the ways of knowing and seeing sociotechnical, natural, socio-economic, and political systems that drive the climate engineering debate?

STIs never arise from a vacuum. A long history of humanist research has shown how scientists and their theories are products of their social environment. Scientists operate in certain paradigms, ways of seeing and understanding their scientific practice that orders and directs their visions (Kuhn, 1962; Polanyi, 1946). They are, moreover, not only influenced by their own training as a scientist but order their reality according to the norms and conceptions of their societies (Foucault, 1994). STIs, in short, are always the product of cultural, historical, social, scientific, and technological traditions. Whether the racialised ideologies of Cecil Rhodes (Storey, 2015), the imagining of post-fossil futures (Hajer and Pelzer, 2018; Pelzer and Versteeg, 2019), or the different ways in which societies relate to genetic technology (Jasanoff, 2007), the development of STIs is always tied to existing collective imaginations and self-understandings. Here we find the need to enrich the view of climate engineering as a sociotechnical development with the environmental humanities. Cultural visions shape the imagined relationship between humans and their environment. As such, they steer climate engineering research in particular directions. Climate engineering imaginaries may develop within specific research communities, they borrow ways of relating to knowledge, the role of science, and particular views of the environment from a larger culture. If we wish to understand how climate engineering develops and will develop, we also need to understand the cultural basis of the sociotechnical conversations around climate engineering.

Constructing an imagination: ways of knowing, ways of seeing

In analysing the ways climate engineers relate to their research, I take a lead from John Pickstone.²³ According to Pickstone (2000), the histories of science, technology, and medicine are characterised by different ways of knowing, different outlooks on what knowledge is and how it can be arrived at. These ways of knowing are natural history, analysis, world readings (hermeneutics), experimentalism, and analysis, all five of which have their own particular ways of doing science and understanding what knowledge is. Natural history is concerned with description and classification, analysis in breaking

things down into constituent elements, experimentation with control and systematically creating novelties and order, hermeneutics with ‘reading’ the world for meaning, and technoscience where making knowledge also makes commodities and technical artefacts. All these ways of knowing play a part in climate engineering, as divergent disciplines meet, and values continue to be in dispute. These different ways of knowing might show up in the different methodologies of academic disciplines or at different times, but they do not necessarily underlie the fundamental differences in climate engineering visions. These fundamental differences instead arise from different ways of ‘seeing’, rather than knowing, respective aspects of climate engineering concerns. These ways of seeing are unconscious effects of culture, widely interpreted, rather than systematised ways of creating knowledge. Inspired by John Berger’s *Ways of Seeing* (1972), I interpret ways of seeing as particular lenses or foci on the issues at stake:

The way we see things is affected by what we know or what we believe. In the Middle Ages when men believed in the physical existence of Hell the sight of fire must have meant something different from what it means today. Nevertheless their idea of Hell owed a lot to the sight of fire consuming and the ashes remaining—as well as to their experience to the pain of burns.

When in love, the sight of the beloved has a completeness which no words and no embrace can match: a completeness which only the act of making love can temporarily accommodate.

Yet this seeing which comes before words, and can never be quite covered by them, is not a question of mechanically reacting to stimuli... We only see what we look at. To look is an act of choice. As a result of this act, what we see is brought within our reach—though not necessarily within arm’s reach.

(Berger, 1972, p. 8)

I use the concept ‘ways of seeing’ as an analytical metaphor, a lens or window through which to analyse how scientific actors make sense of the abstract and debated objects they are studying. Seeing might strike some as too narrow a metaphor. Other mental and sensorial apparatuses, such as intuition, touch, and thought, certainly co-determine the ways climate engineering researchers do research and imagine climate futures. The dominance of sensorial sight for the human species, however, a consequence of becoming a bipedal mammal, particularly in visually minded European societies, has led the English language (like Dutch, German, and other languages) to imbue the word ‘seeing’ with a wide variety of meanings. Vantage points, a different viewpoint, seeing things differently, not seeing eye to eye; none of these expressions necessarily connote the literal act of seeing. Rather, they mobilise the predominance of seeing as a way of making sense of the world

as a means to convey complex ideas and thoughts. Ways of seeing, then, are not meant to express the literal act of viewing, but rather to make sense of complex multidimensional, often abstract, latent, or culturally determined convictions and epistemologies. As John Berger explains, ‘often dialogue is an attempt to verbalize this—an attempt to explain how, either metaphorically or literally, “you see things”, and an attempt to discover how “he sees things”’ (Berger, 1972, p. 9). Ways of seeing, then, I define as explicit or implicit visions, understandings, and foci that facilitate a particular understanding of what is at stake.

Any imaginary is built on a multitude of such ways of seeing, both implicit and explicit. Looking at the ‘ways of seeing’ particular aspects of climate engineering allows me to explain the role of collective imagination and intentionality in shaping particular visions. At the same time, it also allows us to retain the agency of the non-human, which presents itself to the researcher in particular ways depending on the ‘ways of seeing’ that researcher has. According to actor-network theory (ANT), agency in social developments doesn’t just comprise human intentionality. Concepts, ideas, non-human entities, structures, and processes also have agency shaping sociotechnical and socio-scientific developments by acting in networks, taking on different meanings at different times (Latour, 2005; Law and Hassard, 1999). In ANT, anything can be an actor, and the actor holds *radical indeterminacy* in terms of size, shape, or motivations (Callon, 1999). Through the various ways in which a scallop presents itself in a debate between scientists and fishermen, for example, the scallop (and the human visions thereof) has in a very real sense a form of agency over how human networks around it develop (Callon, 1984). By adopting ‘ways of seeing’ as a complementary metaphor to the STI, I retain human intentionality as leading, determining the focal points of visions, while remaining attentive to the surprising agency of non-human networks.²⁴

Research into the sociotechnical imagination has proven potent in understanding how hidden assumptions and collective ways of imagining the future (co-)create particular sociopolitical configurations and particular forms of social order. Ways of seeing builds upon this by inverting the question, focusing on the disparate values, epistemologies, and visions at the heart of STIs rather than on their political effects.²⁵ Imaginaries simultaneously shape and are shaped by ways of seeing. Through their normative and social effects, they can prescribe particular communal visions, but they also depend on particular visions to arise. For climate engineering, this means that commonly held ways of seeing shape how climate engineering can be imagined. It also means that commonly held imaginations shape particular visions because they direct what scientists choose to look at. ‘Seeing’ aspects of climate engineering in a certain way is both social and personal, both collective and individual. Visions of a desirable (political) climate are predicated on scientific histories, collective deliberations, and particular cultures as well as privately held convictions and intuitions.

Negotiating ways of seeing

Ways of seeing are communal as much as they are personal. They result from a constant negotiation over which ways of seeing should be awarded more serious attention than others. These negotiations can take place in trying to find a common tongue to speak with and determine what conceptions of the climate or of a particular ecosystem are relevant. They can also take place during attempts to define how climate engineering should be imagined as part of the portfolio of climate response. They can even concern disagreements over the role of science and technology in climate engineering discussions. Many of these negotiations take place over the so-called epistemic authority, the authority to make claims about the truth and be believed.²⁶ Scientists closely guard this epistemic authority by negotiating boundaries of legitimate scientific visions through ‘boundary work’ (Gieryn, 1999). They continually reiterate the borders of their authority, debating what relevant, reliable, or accurate knowledge is. They also constantly negotiate which sciences should be trusted in the public domain. As science studies have convincingly shown, the authority over truth claims is a social process.²⁷ Epistemic authority is not necessarily dependent on whether something simply is ‘true’ or ‘factual’ but has to be awarded and enacted (Latour, 1987; Shapin and Schaffer, 2017). The establishment and maintenance of this authority is a complex social process. Epistemic authority is often awarded differently in different communities, as it ties into cultural backgrounds and pre-existing beliefs about authority and epistemology (e.g. Douglas and Wildavsky, 1982).²⁸ It is also ‘enacted as people debate (and ultimately decide) where to locate the legitimate jurisdiction over natural facts’ (Gieryn, 1999, p. 15). Such negotiations play out in disciplinary science, but even more intensely in interdisciplinary environments.²⁹ Different academic disciplines come with their own standards for good science, their own methodologies, and their own assumptions about what relevant knowledge is. They enact their own ways of seeing. Reconciling these views can be tricky. To achieve inter- or transdisciplinary research, knowledge and epistemologies must be made to speak to other epistemologies, often beyond academic disciplines.

In inherently interdisciplinary subjects, in wicked problems such as climate engineering, scientific disciplines and scientists are in constant negotiation over which epistemologies and even ontologies are most applicable. Ways of seeing, as I outlined them above, are the result of these negotiations, both on the intimate scales of particular visions of scientific subjects and methodologies and on the societal scales of who should get a say in what. In a way, ways of seeing blend scientific ‘facts’ such as knowledge and cultural ‘fictions’ such as norms and values into visions about how humans should interact with their environment. Through their respective ways of seeing, climate engineers make sense of abstract ideas about the climate, politics, economics, and the Anthropocene. The various ways of seeing in this book provide a lens through which we might make sense of why climate engineering is so contentious, so difficult, and so diverse.

Who dreams the designer climate: questions and methodology

Ways of seeing are convergences of views on particular aspects of research, such as the climate or political configurations and personal convictions. Different ways of seeing take shape in reaction to cultural, political, and scientific histories. They also form through particular framings, interdisciplinary collaboration between researchers, and through the cultural imaginaries in which researchers live and operate. If we want to understand the development of climate engineering, we need to understand the underlying ways of seeing the technical, the political, and the normative that animate its imaginaries. As a set of speculative technologies, climate engineering can only be understood if we understand where the dreams and expectations about these technologies come from—what ways of seeing shape it. The extensive theoretical reflection above now allows us to refine the two central questions of this book:

- How did climate engineering come to be imagined as an approach to anthropogenic climate change? What ways of seeing climate change and climate engineering resulted from that history?
- On what basis do climate engineers form their imaginaries of climate engineering futures? What are the ways of seeing the physical and technical, the social, and the normative that underlie different positions on climate engineering?

This book answers those questions based on a mixed-method interdisciplinary approach. It borrows freely from sociology, history, anthropology, philosophy, and even some critical literary interpretation. To my mind, complex problems such as climate change and climate engineering cannot be understood through a strict disciplinary lens. They challenge our conception of what science is, what nature is, and how society should be organised. In this book, then, I combine the critical methodologies of STS, and their insistence on following the scientific process, with environmental humanities' concerns about human-nature relationships and environmental ideologies. In so doing, I hope to contribute not only to the debate on climate engineering—though there certainly is that—but also to the discussion about how imaginaries and visions of science, technology, and the environment take shape.

In my historical approach, I unabashedly rely on more explicitly historiographical work on the origins of climate engineering. Specifically, I have taken care to recombine the histories of climate engineering and climate change, on cultural, political, *and* epistemological grounds. To be able to do so, I lean heavily on historical work on both climate science and climate engineering. Apart from the books by Jeremy Baskin and James Fleming mentioned above, several other volumes were particularly important to inform my thoughts on climate engineering. Oliver Morton's *The Planet Remade*

(Morton, 2016) provides insights that the informed reader may find throughout this book. His book, comparatively optimistic about the promises of climate engineering—too optimistic in my opinion—provides a broader look at technologies and ideas that may ‘remake our planet’. Jack Stilgoe’s *Experiment Earth* (Stilgoe, 2015) shows that similar historical sourcing can lead to a very different interpretation of climate engineering. For my historical analysis of climate change, several accounts stand out. Jim Fleming’s works (Fleming, 1998, 2016) penned excellent histories about the discovery of climate change.³⁰ Paul Edwards’ *A Vast Machine* (Edwards, 2010) is a masterpiece about the construction of climate knowledge. Mike Hulme’s interdisciplinary attempt to reframe climate change as a *human* problem, rather than a scientific one in *Why We Disagree about Climate Change* (2009) is also one I am deeply indebted to.³¹

My story of climate science, and its corresponding dreams of climate control, is mostly a story of the Western academies. There certainly is a more complex, non-Western centric story to be told here, but unfortunately this is beyond the scope of this book. This story of climate science is a Western story of scientific developments, political power, vested interests, and economic rigidity. For a long time, the dream of manipulating the climate flowed from European, American, and Soviet scientific traditions, in which science was tied to dreams of environmental control. Its research revolved around power, both ideological and imaginative power and cold, hard military power. Later, when anthropogenic climate change came to dominate political and scientific agendas, fear of climate change and despair about political inaction supplemented the initial excitement about climate control. These longer histories continue to influence climate engineering research today—in both expected and surprising ways. In this book, I attempt to understand the confluence of the longer history of climate modification research with the way contemporary climate engineering researchers do their research. Why do climate engineers use particular parameters in their research? On what basis do they believe that the climate could be engineered? Do they even believe such a thing? How do they *feel* about the prospect of actively manipulating the Earth’s climate? How much thought do they give to climate politics? Or to the politics that will inevitably follow from their research? In this book, these are the questions that I attempt to answer.

Meet the climate engineers

This book, the answers it provides and the subsequent questions it raises, is the result of empirical research I conducted as a PhD student (2015–2019) and my reflections on this research since. Specifically, this book relies on comparative case studies of a German climate engineering research program, SPP-1689, and a U.S. climate engineering research group, the David Keith Group, based at Harvard University. Over the course of three years, I immersed myself in the climate engineering debate. Between January and April 2017,

I spent four months with the David Keith Group as a participant observer, attempting to understand their research, their relationships, and how they are related to climate engineering. With the German SPP, I attempted to do the same thing. Because the geographic dispersion of SPP researchers all over Germany made a similarly focused approach unfeasible, I toured Germany, interviewing researchers and attending SPP workshops. To my knowledge, *Imagining Climate Engineering* is the first ethnologically informed assessment of climate engineering research.

I chose to compare the David Keith Group and the SPP for several reasons.³² For one, both research institutions were part of the *sociotechnical vanguard* of climate engineering research. Both were highly visible in the research community, and both had significant influence on public and political debates concerning climate engineering. Despite these similarities, however, the aims and methods of both groups diverged considerably. The first major difference concerned the stance towards climate engineering. Both the German public and its scientific community are deeply sceptical about, even adversarial to, climate engineering. The SPP internalised these attitudes to a significant degree. More cautious about scientific promises and less interventionistic than American researchers, many German researchers conduct their research in an open attempt to disprove the viability and desirability of climate engineering technologies. The Keith Group, on the other hand, is more amenable to climate engineering. To a large degree, it embodies technological optimism. Its research focuses specifically on how one particular SRM method, SAI, *could* work. Second, the institutional set-up of both research groups was fundamentally different. The SPP was a Schwerpunkt Program of the German Research Foundation (DFG). As a federally funded research project, the SPP relied on the DFG to decide which research projects would be funded. As a result of this dependency on a federal agency for funding—an agency that is politically visible and vulnerable—the SPP was cautious, eschewing political controversy as well as they could. Their credo was ‘assessment, not development’.³³ The Keith Group, on the other hand, relied (and continues to rely) predominantly on private donors. Its research focus is decided upon by David Keith himself. As a result, the group can afford, and actually needs, to be far more entrepreneurial and controversial.³⁴

Through these differences, the Keith Group and the SPP provide a window into the climate engineering debate as a whole. The two groups functioned as centres of climate engineering research on their continents and as a reference point for many. David Keith himself is a well-known and controversial advocate for climate engineering research. He arguably remains the most visible climate engineer in the world. The SPP on the other hand was the most significant publicly funded climate engineering research consortium during its time. In analysing their (dis)similarities, then, this book shows what types of considerations are part of the discourse among climate engineering researchers, what they disagree about, and how they construct visions around these disagreements. But by showing what is *in* the scientific

view, it also shows what *isn't*. Specifically, it shows how particular ways of seeing climate engineering bring different types of concerns into view, while obscuring others. Although not all arguments and disagreements about climate engineering can neatly be categorised as a feature of a way of seeing 'climate' or 'politics', most fundamental scientific disagreements arise from different ways of seeing these different aspects.

Chapter set-up

In this book, I set out to create a historically informed view of climate engineering's present, in the hope to inform its future. In order to do so, Chapter 2 and 3 address the history of climate engineering and other dreams of environmental control—a history that, as the subsequent chapters show, never fully disappears. In Chapter 2, I show that the dream to control the climate has deep historical roots, in an entanglement of scientific epistemologies with political and military aims. These entanglements present themselves particularly forcefully in the decades following the Second World War, when climate modification schemes reached their early zenith. I also chronicle how a culturally changing conception of the environment, in conjunction with an increasingly global and model-based epistemology in climate science, led to the (temporary) disappearance of those dreams.

In the subsequent historical chapter, Chapter 3, I address how the climate change debate and the scientific discourse around this discussion coalesced to recreate an institutionalised 'optimism' about climate modification—for dread of climate change rather than dreams of climate control this time. This chapter chronicles how the early climate change debate provided a rather adversarial atmosphere for climate engineering research, while simultaneously already being primed for renormalisation of climate interventions. It shows how despair about anthropogenic climate change led to the re-emergence of technological dreams, often using similar arguments and similar epistemologies but simultaneously more hesitant and uncertain about both the feasibility and the desirability of climate engineering. In short, Chapter 3 outlines how climate change denial, political lethargy, and continued ideological trust in technoscientific solutions for environmental problems all worked together to *renormalise* the thought of actively intervening in the Earth's climate.

Three empirical chapters follow this historical introduction. Themed around 'ways of seeing' climate engineering, these chapters describe the climate engineering debate by way of three domains—the physical, the political, and the moral.

Chapter 4 covers the 'physical'. It discusses the variety of meanings that the term 'climate' holds, both analytically and socially, for climate engineers. Building on the history of climate science, it asks how different climate engineering researchers differ in their views on what aspects of the climate are important. How certain can scientists be, for example, in their (predictive) knowledge of the climate? This chapter outlines how different conceptions

of the ‘knowability’ and predictability create different views on how feasible climate engineering could be. Climate engineering imagination drives on selectively incorporating or excluding certain layers of complexity. In this chapter, I show that different types of climate engineer prefer particular selections and reductions of complexity. As a result of these preferences, they hold different views not only on the feasibility but also on the desirability of climate engineering.

Chapter 5 deals with the ‘political’ and the social. It builds on observations made in other parts of the book by asking how particular conceptions of power and authority influence researchers’ view on the political feasibility and governability of climate engineering. Like the other empirical chapters in this book, this chapter addresses what lenses climate engineering researchers adopt in researching the politics of climate engineering, and how they selectively reduce the complexity of the political issues at hand in climate engineering. This chapter describes how certain political concerns arise from particular views on the climate, and how these concerns coincide with specific visions on (global) politics and economic systems. Furthermore, it shows a debate within the climate engineering research community about what role they should play in the public debate as scientists. Crucially, that debate revolves around disagreements about what the role of knowledge and knowledge-makers should be in politics.

The final empirical chapter, Chapter 6, connects the debates in Chapters 3 and 4 to what are essentially contested worldviews on morality. In Chapter 6, we see climate engineers grapple with ontological and metaphysical questions about the relationship between humans and their environment. This chapter zooms in on existentially troubling nature of questions around deliberate climate control. Dreaming of a designer climate—even falling short of actual design and control—raises many questions about morality, including questions of justice, metaphysics, and the ontological status of ‘the human’. In Chapter 6, I address how certain conceptions of human–nature relationships influence positions on the desirability of climate engineering—as well as how particular views of the climate and politics create certain conceptions of ‘the human’ and justice and vice versa.

In the final chapter, Chapter 7, finally I weave these threads together. Being able to entertain the thought of climate engineering requires particular imaginative and epistemological frameworks that are structurally embedded through epistemological, cultural, and political traditions. Specifically, this chapter shows how it requires a clear field of vision that relies on specific reductions of the social and geophysical complexity of the climate, climate change, and climate engineering. As such, it ties together the epistemological debates in Chapter 4, the political debates in Chapter 5, and the normative disagreements in Chapter 6. It addresses different assumptions about the understanding of climate systems, following assessments of technological prowess. Most importantly, it not only teases out historical (dis)continuities around climate engineering practice also shows how ‘seeing’ different continuities

and ruptures leads to fundamentally different positions on climate engineering. Rather than answer what it means to consider climate engineering, it reverts to asking the question: what sort of belief systems is most prominent in climate engineering research? And what does that mean for the future (political and scientific) development of climate engineering?

Concluding remarks

In the introduction to her seminal work *Designs on Nature*, Sheila Jasanoff (2005) describes her book in Weberian terms—as a work of understanding (*Verstehung*) rather than a work of causal explanation (*Erklärung*). So is this. Born from a conviction that qualitative understanding might help the troubled environmental and sociotechnical futures of the postmodern world, this form of *Verstehen* creates a form of care, an intimacy between the subject matter and its interlocutor. Qualitative interviews and ethnographic observations are interpretative work, infused by the worldview and the expectations of the conducting researcher themselves. Who I am, as a male, Caucasian, highly educated, and comparatively young man from the Netherlands; how I have gained access to the subjects; and my particular relationships to my research subjects have influenced my results and analyses. Because of this, my analyses here should always be treated with scepticism. They may be enlightening, and they may shed a new perspective on climate engineering imaginaries, but they remain personal reflections. Between my conversations and my writing, much time has passed. The passage of time is a curious thing. It can bring the perspective of time, allowing one to see things more clearly, more fully, and more surely than one could embroiled in the thick of the proceedings. But the passage of time also shapes and re-makes one's image of the past. Memory is not perfect. Neural pathways are thread and rethread, reforming one's memory of the past always to suit some version of the present. One is always forming a coherent narrative of self, of one's life. As a chronicler and observer, it was my job to ascribe meaning to the narratives of others, finding myself perennially speculating about why people act and think the way they do. I too had to construct a narrative over time. While I have notes and recordings, my images, the coherent and cogent narrative that forms itself in my neurons and my set of associations and assumptions change their flavour over time. Interactions in my intellectual communities do not merely form my methodological and intellectual outlook, but they also continually reshape my view climate engineering. As I continue to mature academically, my thoughts continue to change. So, while I offer this book confidently believing that it can enrich the debate on climate engineering, it remains a work of subjectivity. Those reading this book should treat my interpretation with as much critical scepticism as I have done my subjects.

I wrote this book because I am torn about climate engineering. To me, climate engineering represents one of the hardest sociotechnical questions of

our time. I remain sceptical about the central premise of climate engineering research, the premise that catastrophic climate change is inevitable without its research, which seems to take for granted many current socioeconomic, political, and cultural configurations. STS and the environmental humanities, my intellectual and academic homes, implore me take the social and the discursive seriously. The world can change immeasurably more quickly than most of us can imagine. Visions of speculative technologies always have social effects, serving to either maintain or change certain sociopolitical configurations. This book, then, is my interrogation of the predominant visions for the future of climate engineering. It paints a complex picture of climate engineering's history, a history of both scientific hubris *and* climate change fears. In doing so, it asks how contemporary visions on the (knowability of) the climate system, the politics of climate change and engineering, and human-nature relationships influence climate engineering research. Rather than provide a clear answer for or imaginary of climate engineering, I wanted to show the incredible complexity that goes into any one position on climate engineering—as well as how such positions both draw on and enact particular epistemological, cultural, and political imaginations. Specifically, I have attempted to draw out how particular ideologies and scientific epistemologies *code* for more or less coherent imaginations of what climate engineering can and should do.

Notes

- 1 This wasn't merely a disagreement between ministries. It was also *political*. At the time, the DMU was run by Sigmar Gabriel of the SPD, the German social-democrat party, while the BMBF was run by Annette Schavan, from the Christian-democrat party. With the German federal elections slated for later in the year, the SPD saw an opportunity to attack a political opponent (even though operating in a political coalition) for their support of an unpopular research project.
- 2 See epigraph.
- 3 It ran from 2013 to 2019 in two phases. It consisted of roughly ten loosely connected but independent research projects on climate engineering technologies, politics, and ethics. Between the first phase (2013–2016) the project leadership remained almost unchanged, and most projects continued with similar lines of investigation in the second phase (2016–2019).
- 4 People also refer to climate engineering as geoengineering, climate intervention, climate manipulation, or by way of its specific technologies. In this book, I prefer 'climate engineering', except where I quote people directly.
- 5 None of these technofixes could perfectly 'reverse' climate change, and all of them are highly contentious. They might bring dangerous side effects and have vastly unequal effects both politically and environmentally, and many worry they detract from conventional climate change mitigation.
- 6 At the same time, however, even in the 1990s powerful voices always called for climate engineering as the preferred response to climate change. As we shall see in this book, ever since climate change became a public worry in the late 1980s, climate engineering has been considered as a possible response.
- 7 It is important to note that climate engineering researchers themselves would not be too appreciative of the term 'climate engineer'. For one, climate engineering

is still very controversial. And second, climate engineering is still in its infancy, and no one is actually engineering the climate *yet*. I chose to use ‘climate engineer’ nonetheless, for reasons of brevity and clarity. Here it connotes: people engaging seriously in climate engineering research.

- 8 According to Jim Fleming (2010), the foremost historian of climate engineering, we should never forget the ‘checkered history of weather and climate modification’. We should remain aware of this deeply militaristic history, he says, because it continues to shape climate engineering dreams in the present. Climate engineering will almost inevitably remain a hubristic and militarist affair. Although Fleming certainly has a point, this view does not do current climate engineering research or its researchers justice.
- 9 Although it has to be noted that if concentrations linger above ‘safe’ levels for too long, certain irreversible processes may have begun that could lock the Earth into a permanent ‘hothouse state’ (Steffen *et al.*, 2018).
- 10 As many have shown (Anderson and Peters, 2016; Beck and Mahony, 2018), however, NETs are now so deeply embedded in IPCC projections and political agreements that ‘partial displacement/replacement of’ conventional mitigation would probably be the more accurate description.
- 11 Typically imagined as a bottom-up approach to climate change, bio-char, as yet, does not seem in direct contradiction to empowerment. There is not enough scientific knowledge, however, to assess the real promise of bio-char.
- 12 See National Research Council (2015a) for a more extensive overview of CDR technologies.
- 13 On the whole, human systems have increased the Earth’s reflectivity. This means global temperatures would have already risen more in response to carbon emissions if other processes of industrialisation hadn’t increased the Earth’s albedo!
- 14 See National Research Council (2015b) for a more extensive overview of SRM technologies.
- 15 In some scientific communities, people have even started to speculate about genetically engineering trees and shrubs in order to make them absorb CO₂ more efficiently (Schwander *et al.*, 2016).
- 16 Levin *et al.*’s super wicked problem plays of the term ‘wicked problem’ to describe problems that resist easy solutions because of their social complexity (Churchman, 1967; Rittel and Webber, 1973).
- 17 I want to stress here that the difference is not necessarily that ‘facts’ in post-normal science *are* more uncertain than those in normal science, but rather that they are more *contested*. Scientific facts are always uncertain, as they are complex findings relying on specific epistemologies and ontologies. In post-normal science, however, that uncertainty is more contested, as values are in dispute and facts typically seen as highly consequential.
- 18 As well as, of course, a discussion about the amount of certainty and predictability technoscientific interventions could bring.
- 19 As Jeremy Baskin (2019) astutely observes, this lack of an inherently desirable imaginary for climate engineering, specifically SRM, limits the extent to which climate engineering gains traction as an attractive policy options.
- 20 Still, of course, climate engineering also presupposes an undesirable present as the backdrop. Lacklustre political and economic commitment to mitigation is juxtaposed with a more desirable future, in which successful international collaboration on climate change is the norm.
- 21 As Jeremy Baskin (2019) adds, there is no explicit mention of environmental understandings in Jasanoff’s definition of STIs. As such, he expands the definition in his usage ‘to include not only how people imagine they fit with other people and with social structures, but also how they fit with the more-than-human-world’ (Baskin, 2019, p. 8), adding that ‘it is hard to conceive a social order which

lacks at least an implicit understanding of the environment' (ibid.). I wholeheartedly agree with Baskin, and therefore follow him in this.

- 22 According to Jim Fleming, the hubristic view of mastering the climate has never fully disappeared. Current climate engineering research is an outflow of this scientific history.
- 23 Who, in turn, borrowed much of his inspiration for Michel Foucault in his analysis of how certain ways of *knowing* are imbedded in scientific practice.
- 24 In this attention to the agency of the non-human, ways of seeing marry the more focused theoretical depth of STIs with the analytic focus of ANT. Whereas ANT looked at the agency of actors in their networks, actors that can be human or non-human, material or non-material, STIs looks at collective imaginations of futures and how these are brought into existence by collective action. So, where ANT flattens humans' intentionality and performance, STIs tend to privilege a politically coherent view over the detailed, nuanced, and often self-contradictory networks of agency and visions that motivate human-non-human networks.
- 25 This does not mean, of course, that such an analysis is apolitical. Instead, it argues that to understand the politics of climate engineering visions, it is important to break them down to their constituent parts.
- 26 In contemporary (Western) societies, science, scientists, and experts typically hold significant epistemic authority. This authority is the result of a long cultural history that privileged scientific knowledge as an important source of authority, often even political authority (Ezrahi, 1990, 2012; Porter, 1996). At the same time, this authority constantly has to be maintained and reiterated socially. Epistemic authority is allocated and defended through a host of social processes (Gieryn, 1999; Hajer, 2009; Hilgartner, 2000).
- 27 Ironically, this renders the question what 'science', 'technology', 'expertise', and 'knowledge' are exactly both immensely relevant and completely irrelevant at the same time. What is accepted as expertise or knowledge acquires epistemic authority, but this allotment is a *social* process, so this can be awarded to a wide variety of visions and knowledges.
- 28 As research around climate change denial shows, such denial at least in part connects to competing notions of epistemic authority—and the acceptance of only particular figures as epistemically authoritative (Dunlap, 2013; Kahan *et al.*, 2012; McCright and Dunlap, 2011).
- 29 Interdisciplinarity, defined by Erik Jantsch as 'the synthesis between two or more disciplines which establishes a new level of discourse' (Jantsch, 1980, p. 304), relies on sustained interactions between several academic disciplines.
- 30 A worthwhile early history of the American dream to influence (and control) climate is also *The Rainmakers* by Clarke Spence, written during a comparative lull in enthusiasm for weather modification schemes (1980). Although mostly concerned with the notions of weather control, Spence does an excellent job in outlining the early dreams of weather masters.
- 31 Other notable influences were the volume *Changing the Atmosphere* (Edwards and Miller, 2001) and the monograph *Behind the Curve* (Howe, 2014).
- 32 The reader might notice that throughout this book, it may seem that climate engineering is a Western-centric project. In many ways it is. While I was designing my research, non-Western visibility in the predominantly Western climate engineering debate was still limited. If at points in this book it appears as if Germany, the United Kingdom, and the United States are the only places where relevant research occurred, however, this is a fault of the writing, not a factual reality. The very nature of this research, however, with its focus on a European research project and an American one, limits the text in a particular way. Be aware, while reading, that increasingly there are other locales, such as India, China, Russia, and the Philippines, relevant for climate engineering research.

- 33 The research consortium consisted of ten independent research projects that could define their research aims themselves, as long as they stuck to ‘assessment, not development’. This led to widely divergent research projects focusing on, for example, liability issues for SRM, the comparison of different climate engineering technologies (both SRM and CDR), or the politics and ethic of climate engineering technologies.
- 34 They can, for example, propose to launch a balloon into the stratosphere as part of the development of workable SRM technology—to much discontent among activists (Hanley, 2020; Lukacs, 2017).

References

- Alfred Wegener Institute (2009) ‘LOHAFEX: An Indo-German Iron Fertilization Experiment – What Are the Effects on the Ecology and Carbon Uptake Potential of the Southern Ocean?’, 13 January. Available at: <https://www.awi.de/en/about-us/service/press/archive/lohafex-an-indo-german-iron-fertilization-experiment-what-are-the-effects-on-the-ecology-and-carb.html> (Accessed: 16 August 2020).
- Anderson, B. R. O. (1983) *Imagined Communities: Reflections on the Origin and Spread of Nationalism*. London, UK: Verso.
- Anderson, K. and Peters, G. (2016) ‘The Trouble with Negative Emissions’, *Science*, 354(6309), pp. 182–183. doi: 10.1126/science.aah4567.
- Appadurai, A. (1996) *Modernity at Large: Cultural Dimensions of Globalization*. Minneapolis: University of Minnesota Press (Public Worlds, v. 1).
- Baskin, J. (2019) *Geoengineering, the Anthropocene and the End of Nature*. Cham, Switzerland: Springer International Publishing. doi: 10.1007/978-3-030-17359-3.
- Beck, S. and Mahony, M. (2018) ‘The Politics of Anticipation: The IPCC and the Negative Emissions Technologies Experience’, *Global Sustainability*, 1, p. e8. doi: 10.1017/sus.2018.7.
- Bellamy, R. *et al.* (2013) ‘“Opening Up” Geoengineering Appraisal: Multi-Criteria Mapping of Options for Tackling Climate Change’, *Global Environmental Change*, 23(5), pp. 926–937. doi: 10.1016/j.gloenvcha.2013.07.011.
- Bellamy, R. (2016) ‘A Sociotechnical Framework for Governing Climate Engineering’, *Science, Technology, & Human Values*, 41(2), pp. 135–162. doi: 10.1177/0162243915591855.
- Berger, J. (1972) *Ways of Seeing*. London, UK: Penguin Books.
- Bhattacharya, A. (2009) ‘Tossing Iron Powder into Ocean to Fight Global Warming’, *The Times of India*, 6 January. Available at: <https://timesofindia.indiatimes.com/home/environment/global-warming/Tossing-iron-powder-into-ocean-to-fight-global-warming/articleshow/3943779.cms>.
- Cairns, R. C. (2014) ‘Climate Geoengineering: Issues of Path-dependence and Socio-technical Lock-in: Climate Geoengineering Lock-in’, *Wiley Interdisciplinary Reviews: Climate Change*, 5(5), pp. 649–661. doi: 10.1002/wcc.296.
- Callon, M. (1984) ‘Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St Brieuc Bay’, *The Sociological Review*, 32(1_suppl), pp. 196–233. doi: 10.1111/j.1467-954X.1984.tb00113.x.
- Callon, M. (1999) ‘Actor-network Theory – The Market Test’, in Law, J. and Hassard, J. (eds) *Actor Network Theory and After*. Oxford, UK: Blackwell Publishers, pp. 181–199.

- Cao, L. and Caldeira, K. (2010) 'Can Ocean Iron Fertilization Mitigate Ocean Acidification?: A Letter', *Climatic Change*, 99(1–2), pp. 303–311. doi: 10.1007/s10584-010-9799-4.
- Castree, N. *et al.* (2014) 'Changing the Intellectual Climate', *Nature Climate Change*, 4(9), pp. 763–768. doi: 10.1038/nclimate2339.
- Churchman, C. W. (1967) 'Wicked Problems', *Management Science*, 14(4), pp. 141–146.
- Douglas, M. and Wildavsky, A. (1982) *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers*. Berkeley; Los Angeles: University of California Press.
- Dunlap, R. E. (2013) 'Climate Change Skepticism and Denial: An Introduction', *American Behavioral Scientist*, 57(6), pp. 691–698. doi: 10.1177/0002764213477097.
- Edwards, P. N. (2010) *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press.
- Edwards, P. N. and Miller, C. C. (eds) (2001) *Changing the Atmosphere: Expert Knowledge and Environmental Governance*. Cambridge, MA: MIT Press.
- Emmett, R. S. and Nye, D. E. (2017) *The Environmental Humanities: A Critical Introduction*. Cambridge, MA: MIT Press.
- Ezrahi, Y. (1990) *The Descent of Icarus: Science and the Transformation of Contemporary Democracy*. Cambridge, MA: Harvard University Press.
- Ezrahi, Y. (2012) *Imagined Democracies: Necessary Political Fictions*. New York, NY: Cambridge University Press. doi: 10.1017/CBO9781139198769.
- Fleming, J. R. (1998) *Historical Perspectives on Climate Change*. Oxford, UK: Oxford University Press.
- Fleming, J. R. (2010) *Fixing the Sky: The Checkered History of Weather and Climate Control*. New York, NY; Chichester, UK: Columbia University Press (Columbia Studies in International and Global History).
- Fleming, J. R. (2016) *Inventing Atmospheric Science: Bjerknes, Rossby, Wexler, and the Foundations of Modern Meteorology*. Cambridge, MA: MIT Press.
- Foucault, M. (1994) *The Order of Things: An Archaeology of the Human Sciences*. Vintage books edition. New York, NY: Vintage Books.
- Funtowicz, S. O. and Ravetz, J. R. (1993) 'Science for the Post-normal Age', *Futures*, 25(7), pp. 739–755. doi: 10.1016/0016-3287(93)90022-L.
- Geden, O. (2016) 'The Paris Agreement and the Inherent Inconsistency of Climate Policymaking', *Wiley Interdisciplinary Reviews: Climate Change*, 7(6), pp. 790–797. doi: 10.1002/wcc.427.
- Gieryn, T. F. (1999) *Cultural Boundaries of Science: Credibility on the Line*. Chicago, IL: University of Chicago Press.
- Hajer, M. A. (2009) *Authoritative Governance: Policy-making in the Age of Mediatization*. Oxford, UK ; New York, NY: Oxford University Press.
- Hajer, M. A. and Pelzer, P. (2018) '2050—An Energetic Odyssey: Understanding "Techniques of Futuring" in the Transition towards Renewable Energy', *Energy Research & Social Science*, 44, pp. 222–231. doi: 10.1016/j.erss.2018.01.013.
- Hanley, S. (2020) *Harvard Profs Plan Geoengineering Experiment, Igniting Ethics Debate*, *Cleantechnica.com*. Available at: <https://cleantechnica.com/2020/07/24/harvard-profs-plan-geoengineering-experiment-igniting-ethics-debate/> (Accessed: 19 August 2020).
- Hilgartner, S. (2000) *Science on Stage: Expert Advice as Public Drama*. Stanford, CA: Stanford University Press (Writing Science).

- Hilgartner, S. (2015) 'Capturing the Imaginary: Vanguards, Visions, and the Synthetic Biology Revolution', in Hilgartner, S., Miller, C. A., and Hagendijk, R. (eds) *Science and Democracy: Making Knowledge and Making Power in the Biosciences and beyond*. New York, NY: Routledge, pp. 33–56.
- Howe, J. P. (2014) *Behind the Curve: Science and the Politics of Global Warming*. Seattle: University of Washington Press.
- Hulme, M. (2009) *Why We Disagree about Climate Change: Understanding Controversy, Inaction and Opportunity*. Cambridge, UK ; New York, NY: Cambridge University Press.
- Hulme, M. (2014) *Can Science Fix Climate Change? A Case against Climate Engineering*. Cambridge, UK: Polity Press (New Human Frontiers Series).
- Huttunen, S. and Hildén, M. (2014) 'Framing the Controversial: Geoengineering in Academic Literature', *Science Communication*, 36(1), pp. 3–29. doi: 10.1177/1075547013492435.
- Jantsch, E. (1980) 'Interdisciplinarity: Dreams and Reality', *Prospects*, 10(3), pp. 304–312. doi: 10.1007/BF02220370.
- Janasoff, S. (1994) *The Fifth Branch: Science Advisers as Policymakers*. 2. print. Cambridge, MA: Harvard University Press [u.a.].
- Janasoff, S. (2001) 'Image and Imagination: The Formation of Global Environmental Consciousness', in Edwards, P. N. and Miller, C. C. (eds) *Changing the Atmosphere: Expert Knowledge and Environmental Governance*. Cambridge, MA: MIT Press, pp. 309–337.
- Janasoff, S. (2003) 'Technologies of Humility: Citizen Participation in Governing Science', *Minerva*, 41(3), pp. 223–244. doi: 10.1023/A:1025557512320.
- Janasoff, S. (ed) (2004) *States of Knowledge: The Co-production of Science and Social Order*. London, UK; New York, NY: Routledge (International Library of Sociology).
- Janasoff, S. (2005) *Designs on Nature: Science and Democracy in Europe and the United States*. Princeton, NJ: Princeton University Press.
- Janasoff, S. (2015) 'Future Imperfect: Science, Technology, and the Imaginations of Modernity', in Janasoff, S. and Kim, S. H. (eds) *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*. Chicago, IL; London, UK: The University of Chicago Press.
- Kahan, D. M. et al. (2012) 'The Polarizing Impact of Science Literacy and Numeracy on Perceived Climate Change Risks', *Nature Climate Change*, 2(10), pp. 732–735. doi: 10.1038/nclimate1547.
- Keith, D. W. (2013) *A Case for Climate Engineering*. Cambridge, MA: The MIT Press (Boston Review Books).
- Keith, D. W. et al. (2018) 'A Process for Capturing CO₂ from the Atmosphere', *Joule*, 2(8), pp. 1573–1594. doi: 10.1016/j.joule.2018.05.006.
- Kuhn, T. S. (1962) *The Structure of Scientific Revolutions*. Chicago, IL: University of Chicago Press.
- Kwa, C. (2001) 'The Rise and Fall of Weather Modification: Changes in American Attitudes toward Technology, Nature, and Society', in Edwards, P. N. and Miller, C. C. (eds) *Changing the Atmosphere: Expert Knowledge and Environmental Governance*. Cambridge, MA: MIT Press, pp. 135–164.
- Latour, B. (1987) *Science in Action*. Cambridge, MA: Harvard University Press.
- Latour, B. (1993) *We Have Never Been Modern*. Cambridge, MA: Harvard University Press.

- Latour, B. (2005) *Reassembling the Social: An Introduction to Actor Network Theory*. Oxford, UK: Oxford University Press.
- Law, J. and Hassard, J. (1999) *Actor Network Theory and After*. Oxford, UK: Blackwell Publishers.
- Lawrence, M. G. *et al.* (2018) ‘Evaluating Climate Geoengineering Proposals in the Context of the Paris Agreement Temperature Goals’, *Nature Communications*, 9(1), p. 3734. doi: 10.1038/s41467-018-05938-3.
- Lehmann, J., Gaunt, J. and Rondon, M. (2006) ‘Bio-char Sequestration in Terrestrial Ecosystems – A Review’, *Mitigation and Adaptation Strategies for Global Change*, 11(2), pp. 403–427. doi: 10.1007/s11027-005-9006-5.
- Lehmann, J. and Joseph, S. (2015) *Biochar for Environmental Management: Science, Technology and Implementation*. 2nd edn. London, UK: Routledge.
- Levin, K. *et al.* (2012) ‘Overcoming the Tragedy of Super Wicked Problems: Constraining Our Future Selves to Ameliorate Global Climate Change’, *Policy Sciences*, 45(2), pp. 123–152. doi: 10.1007/s11077-012-9151-0.
- Lovelock, J. (2008) ‘A Geophysicist’s Thoughts on Geoengineering’, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 366(1882), pp. 3883–3890. doi: 10.1098/rsta.2008.0135.
- Lukacs, M. (2017) ‘Trump Presidency “Opens Door” to Climate-hacking Geo-engineer Experiments’, *The Guardian*, 27 March. Available at: https://www.theguardian.com/environment/true-north/2017/mar/27/trump-presidency-opens-door-to-planet-hacking-geoengineer-experiments?CMP=share_btn_fb (Accessed: 9 August 2020).
- Luukkanen, M., Huttunen, S. and Hildén, M. (2014) ‘Geoengineering, News Media and Metaphors: Framing the Controversial’, *Public Understanding of Science*, 23(8), pp. 966–981. doi: 10.1177/0963662513475966.
- McCright, A. M. and Dunlap, R. E. (2011) ‘Cool Dudes: The Denial of Climate Change among Conservative White Males in the United States’, *Global Environmental Change*, 21(4), pp. 1163–1172. doi: 10.1016/j.gloenvcha.2011.06.003.
- McLaren, D. P. (2018) ‘Whose Climate and Whose Ethics? Conceptions of Justice in Solar Geoengineering Modelling’, *Energy Research & Social Science*, 44, pp. 209–221. doi: 10.1016/j.erss.2018.05.021.
- Ming, T. *et al.* (2014) ‘Fighting Global Warming by Climate Engineering: Is the Earth Radiation Management and the Solar Radiation Management Any Option for Fighting Climate Change?’, *Renewable and Sustainable Energy Reviews*, 31, pp. 792–834. doi: 10.1016/j.rser.2013.12.032.
- Morton, O. (2016) *The Planet Remade: How Geoengineering Could Change the World*. Princeton, NJ: Princeton University Press.
- National Research Council (2015a) *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, DC: National Academies Press, p. 18805. doi: 10.17226/18805.
- National Research Council (2015b) *Climate Intervention: Reflecting Sunlight to Cool Earth*. Washington, DC: National Academies Press, p. 18988. doi: 10.17226/18988.
- National Science Foundation (1965) *Weather and Climate Modification: Report of the Special Commission on Weather Modification*. Washington, DC: National Science Foundation.
- Nerlich, B. and Jaspal, R. (2012) ‘Metaphors We Die By? Geoengineering, Metaphors, and the Argument from Catastrophe’, *Metaphor and Symbol*, 27(2), pp. 131–147. doi: 10.1080/10926488.2012.665795.

- Oldham, P. et al. (2014) 'Mapping the Landscape of Climate Engineering', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031), p. 20140065. doi: 10.1098/rsta.2014.0065.
- Oomen, J. (2019) 'Anthropocenic Limitations to Climate Engineering', *Humanities*, 8(4), p. 186. doi: 10.3390/h8040186.
- Paull, J. (2009) 'Geo-engineering in the Southern Ocean', *Elementals: Journal of Bio-Dynamics Tasmania*, 93, pp. 16–20.
- Pelzer, P. and Versteeg, W. (2019) 'Imagination for Change: The Post-Fossil City Contest', *Futures*, 108, pp. 12–26. doi: 10.1016/j.futures.2019.01.005.
- Pfotenhauer, S. and Jasanoff, S. (2017) 'Panacea or Diagnosis? Imaginaries of Innovation and the "MIT Model" in Three Political Cultures', *Social Studies of Science*, 47(6), pp. 783–810. doi: 10.1177/0306312717706110.
- Pickstone, J.V. (2000). *Ways of Knowing: A New History of Science, Technology, and Medicine*. Chicago, IL: University of Chicago Press.
- Polanyi, M. (1946) *Science, Faith, and Society*. Chicago, IL: University of Chicago Press.
- Porter, T. M. (1996) *Trust in Numbers: The Pursuit of Objectivity in Science and Public Life*. 2. print., and 1. paperback printing. Princeton, NJ: Princeton University Press (History and Philosophy of Science).
- Preston, C. J. (2013) 'Ethics and Geoengineering: Reviewing the Moral Issues Raised by Solar Radiation Management and Carbon Dioxide Removal: Ethics & Geoengineering', *Wiley Interdisciplinary Reviews: Climate Change*, 4(1), pp. 23–37. doi: 10.1002/wcc.198.
- Ravetz, J. R. (1970) *Scientific Knowledge and Its Social Problems*. Piscataway, NJ: Transaction Publishers.
- Rayner, S. et al. (2013) 'The Oxford Principles', *Climatic Change*, 121(3), pp. 499–512. doi: 10.1007/s10584-012-0675-2.
- Rayner, S. (2016) 'What Might Evans-Pritchard Have Made of Two Degrees?', *Anthropology Today*, 32(4), pp. 1–2. doi: 10.1111/1467-8322.12263.
- Rittel, H. W. J. and Webber, M. M. (1973) 'Dilemmas in a General Theory of Planning', *Policy Sciences*, 4(2), pp. 155–169. doi: 10.1007/BF01405730.
- Royal Society (2009) *Geoengineering the Climate: Science, Governance and Uncertainty*. London, UK: Royal Society.
- Schuh, H. (2009) 'Düngerwirbel', *Die Zeit*, 22 January. Available at: <https://www.zeit.de/2009/05/Glosse> (Accessed: 16 August 2020).
- Schwander, T. et al. (2016) 'A Synthetic Pathway for the Fixation of Carbon Dioxide in Vitro', *Science*, 354(6314), pp. 900–904. doi: 10.1126/science.aah5237.
- Scott, J. C. (1998) *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed*. Nachdr. New Haven, CT: Yale University Press (Yale Agrarian Studies).
- Shapin, S. and Schaffer, S. (2017) *Leviathan and the Air-pump: Hobbes, Boyle, and the Experimental Life*. Princeton, NJ: Princeton University Press (Princeton Classics).
- Sonntag, S. et al. (2018) 'Quantifying and Comparing Effects of Climate Engineering Methods on the Earth System', *Earth's Future*, 6(2), pp. 149–168. doi: 10.1002/2017EF000620.
- Spence, C. C. (1980) *The Rainmakers: American "Pluviculture" to World War II*. Lincoln: University of Nebraska Press.

- Steffen, W. *et al.* (2018) 'Trajectories of the Earth System in the Anthropocene', *Proceedings of the National Academy of Sciences*, 115(33), pp. 8252–8259. doi: 10.1073/pnas.1810141115.
- Stilgoe, J. (2015) *Experiment Earth: Responsible Innovation in Geoengineering*. London, UK; New York, NY: Routledge, Taylor & Francis Group.
- Stockrahm, S. (2009) 'Algenexperiment im Atlantik: Eisendüngung hilft nicht gegen Treibhausgase', *Die Zeit*, 23 March. Available at: <https://www.zeit.de/online/2009/13/lohafex-beendet> (Accessed: 16 August 2020).
- Storey, W. K. (2015) 'Cecil Rhodes and the Making of a Sociotechnical Imaginary for South Africa', in Jasanoff, S. and Kim, S. H. (eds) *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*. Chicago, IL; London, UK: The University of Chicago Press.
- Szerszynski, B. *et al.* (2013) 'Why Solar Radiation Management Geoengineering and Democracy Won't Mix', *Environment and Planning A: Economy and Space*, 45(12), pp. 2809–2816. doi: 10.1068/a45649.
- Taylor, C. (2004) *Modern social Imaginaries*. Durham, NC: Duke University Press (Public Planet Books).
- The White House (1965) *Restoring the Quality of Our Environment*. Washington, DC: The White House.