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Speculative promise as a driver in climate engineering research: The case of Paul Crutzen's back-of-the-envelope calculation on solar dimming with sulfate aerosols

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ABSTRACT

In this paper, I study the generative role of speculative promise in climate engineering research. My analysis operationalizes Alfred Nordmann's call for a 'forensics of wishing', a variety of technology assessment which scrutinizes the politics of anticipation in technoscience. Using scientific articles and reports as primary sources I trace the uptake and contestation of bold claims made by atmospheric scientist Paul Crutzen a decade ago. In 2006, Crutzen called for dedicated research on stratospheric albedo enhancement as a method to cool the planet. A back-of-the-envelope calculation invoking the eruption of the Mount Pinatubo volcano as a case to be mimicked served to illustrate the method. In the paper, I concentrate on the reception of this idea by fellow climate scientists. Besides fundamental objections being made to Crutzen's climate paradigm, less idealized models appeared to produce much less promising calculations. The initial claims however kept re-appearing as well and continue to exert influence as idealized models take the idea further. Speculation thus continues to be an important driver of the research. In the conclusion, I discuss aspects of the worldview underlying the proposal, drawing on environmental humanities literature on the human condition in the Anthropocene.

1. Introduction

In 2002, in an article in *Nature* discussing the concept of a new geological era called 'Anthropocene', atmospheric chemist Paul Crutzen suggested that engineering the climate might well become a widely supported, scientifically underpinned policy response to global warming (Crutzen, 2002). The concept of the Anthropocene soon made its way into the agenda of global change scholars, while the climate engineering scenario did not attract much attention. This changed drastically

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when Crutzen wrote an editorial essay titled "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" for *Climatic Change* in 2006. In this essay the atmospheric scientist and Nobel laureate called for substantial research and development on climate engineering. Crutzen had in mind a climate fix introduced in the 1970s which revolved around adding aerosols to the stratosphere to reflect sunlight back to space, a kind of 'solar dimming'.[3] By way of a back-of-the-envelope calculation, invoking the eruption of Mount Pinatubo in 1991 as a case to be mimicked, Crutzen estimated the amount of sulfur to be injected in the stratosphere at 1–2 million tons per year.

The enormous impact of Crutzen's essay has been widely acknowledged. It seems plausible that Crutzen's stature as a Nobel laureate on the chemistry of the ozone layer, his unambiguous stance on the importance of emission reduction and a widespread feeling that climate policy had failed contributed to the quick rise of climate engineering on the climate policy agenda. Yet it certainly took more than that for fellow atmospheric scientists to consider solar dimming with aerosols a credible and legitimate subject of research. In this paper, I focus on the argumentative means that Crutzen used to make his case and I provide an account of how atmospheric scientists responded to his proposal. The back-of-the-envelope calculation which invokes the eruption of Mount Pinatubo forms the central core of Crutzen's proposal. Viewing the back-of-the-envelope calculation as an instance of speculative promise, I attempt to trace how it performs a politics of anticipation characteristic of technoscience. The lens that I use to scrutinize the performative force of speculative promise is Alfred Nordmann's concept of 'forensics of wishing' (Nordmann, 2010). I understand 'forensics of wishing' to be a way of scrutinizing the normative outlook implictly contained in speculative schemes. Scientists may wish whatever they like, but they should present wishes as wishes, instead of claiming that in the future some device is going to work as they wish. The analyst's normative outlook is to hold it untruthful, in a moral sense, to claim the fulfillment of a potential at some point in the future merely on the basis of a theoretical possibility. When scientists couch intentions to work towards the fullfilment of a hypothesized potential in a 'can-do' rhetoric, something is going awry. Unpacking the rhetorics and detailing the who, where and when of such claims and their effects is, in my understanding, the 'forensics of wishing' that Nordmann calls for.

The politics of anticipation around the climate engineering idea forcefully put on the agenda again by Paul Crutzen in 2006 has many dimensions. The proposal itself anticipates the future in several ways. Firstly, it imagines a – not too distant – future in which climate engineering with sulfate aerosols will be a technique ready to be deployed. Here, speaking matter-of-factly about a technique which does not exist as yet is a well-rehearsed way of making it look real. Secondly, it imagines a path up to that future in which the technique is being developed through dedicated research, made possible through the deployment of R&D resources. This is the way in which technoscientific research agendas anticipate the near future. Thirdly, it imagines a mode of decision making in which expert advice serves as a basis for legitimacy, counting on an unproblematic unfolding of decisions and their implementation. This assemblage of imaginaries constitutes a very specific worldview involving centralised technocratic decision making and control over the atmosphere. It is being contested by scientists and citizens who call for the articulation of alternative futures (see e.g., Hulme, 2014). This contestation is another dimension of the politics of anticipation around climate engineering. It connects with the wider cosmopolitics of what it means to anticipate the future of the Earth and its inhabitants, now debated in the context of the Anthropocene as a new era.

I begin by introducing my theoretical perspective, which comes in two parts. First, I introduce Nordmann's outlook on technoscience and his take on technology assessment as a 'forensics of wishing'. Nordmann approaches technology assessment in a way that differs subtly but importantly from the general literature on technology assessment. Nordmann's reflexive stance vis-à-vis mainstream technology assessment is that it risks taking the same hold on the future as technoscience itself. In his view, technology assessment needs to scrutinize what is unfolding before our eyes, in the present, instead of focusing on scenarios of the future. The second part of my theoretical perspective discusses the back-of-the-envelope calculation as a special rhetorical device. It offers an explanation of why the back-of-the-envelope calculation may lure scientists and publics to consider speculative promise as credible science, using insights from science and technology studies and the sociology of expectations. In the empirical part I operationalize both theoretical perspectives. This historical account firstly shows how Crutzen's calculation assembled, by conflating theoretical possibility and technical feasibility, the promise of an effective climate fix. The last part traces the reception, further uptake and assessment of this promise among fellow atmospheric scientists. Here I show how the mainstreaming of Crutzen's idea as a subject of research and development involves modeling efforts that both undermine and continue the promise of an effective fix. The promise is being undermined by modelling efforts which introduce complicating physical and chemical processes and which emphasize further unknowns, while highly idealized models that are seen as more do-able continue to play a central role. I conclude that idealized models embodying the kind of speculative promise mainstreamed through Crutzen's intervention continue to drive research on the climate fix of solar dimming with aerosols, even while 'disappointment' has followed 'hype' in dedicated research (cf. Brown, 2003). In the overall conclusion, I discuss the underlying assumption that climate engineering offers a calculable, controllable option to cool the planet for the benefit of its human inhabitants.

[3] Crutzen revived an idea suggested by his colleague Mikhail Budyko in the early 1970s. Budyko had suggested adding sulfate aerosols to the stratosphere to backscatter sunlight as a means to attenuate global warming, which he saw as inevitable. Imagining ways to reflect sunlight rather than lowering CO_2 emissions had also been the first response of US science advisors in the 1960s (Fleming, 2010, 238–241).

2. A science studies perspective on calculating climate engineering futures

2.1. Alfred Nordmann's outlook on technoscience and speculative promise

Politics of anticipation are a central concern in philosopher Alfred Nordmann's outlook on technoscience. "It is the very idea of taking hold of the future that characterizes the transgressive hubris of the technosciences", Nordmann asserts in an article in which he sets out his approach to technology assessment (Nordmann, 2010, 10). How do the technosciences take hold of the future? To answer this question, one first needs to define what technoscience is. According to Nordmann, the main characteristic of technoscience is that it does not distinguish between theoretical representation of the world and technical intervention into the world. While representing and intervening may have been going together throughout the history of science, the ideal to purify representation, to work towards truthful representation apart from potential application, has been demoted since, roughly, the 1980s. Pressures on scientists to become more entrepreneurial has caused a shift in research practice towards anticipated application and commercialization. The US Bayh-Dole Act of 1980, is a marker of that shift (see e.g. Kwa, 2011, 270). The distinction between theoretical representation and technical intervention has lost its relevance, thus making technoscience seem the normal way of doing research in the current era.

An effect of the lack of distinction between theoretical representation and technical intervention, its proclaimed irrelevance, is the prominence of speculative schemes on research agendas and the difficulty to assess what may be a plausible trajectory. Theoretical possibility and technical feasibility are often conflated. This conflation arguably amounts to a fallacy. A hypothesis which needs to be confirmed through a process of inquiry is different from a device which is made to work without having to obtain special knowledge. The way in which technoscience takes hold of the future is by claiming a certain future function of a potential working device by speculating that it works as hypothesized, thus negating the hypothetical nature of the claim. Technoscience's driving ideal is thus wish fulfillment, Nordmann asserts. This rather grandiose attitude to intervening in the world is what constitutes the transgressive hubris of the technosciences.

Nordmann's approach to technology assessment takes technoscience's way of shaping the future as its entry point. In what he calls a 'forensics of wishing', technology assessment focuses on how in specific technoscientific research practices potentials, promises, wishes and the like are formulated and how these imaginaries shape trajectories. This kind of technology assessment does not concern itself with imaginary futures, as this would amount to endorsing the technoscientific attitude. It concentrates on 'what is happening' rather than drawing scenarios, since "trying too hard to imagine possible or plausible futures may diminish an ability to see what is happening" (Nordmann, 2014, 88). It is the process by which a compelling vision of a technological future is produced, which forms the focus of inquiry. This 'visioneering assessment' unpacks how technoscientific research agendas present technological trajectories as both a necessary means to fullfill the wish and as an innovation challenge (Nordmann, 2013).

Nordmann's concern with 'what is happening' should not be seen as a kind of 'presentism'. His engagement with the present intends to make intellectual space for a historical conception of technological and human development, and to act responsibly out of an obligation towards the future (Nordmann, 2014). For Nordmann, anticipation means being prepared for the future without pretending to be able to steer towards it out of an illusion of control. Accepting contingency means that we can only truly envision alternatives to the world as it is now, which is not the same as envisioning futures. Acting out of an obligation towards the future means assessing technologies in the present, considering how they do or do not align with our conceptions of the good life. Analyzing instances of hypothetical reasoning cloaked as fulfillable potential and unravelling the force of speculative promise in unfolding technoscientific trajectories functions to make space for an obligation towards the future. In this way, Nordmann's forensics of wishing open up the politics of anticipation. His metaphor of forensics, which makes one view the formulation of hubristic wishes in technoscience as akin to a crime, functions as a strong reminder to take very seriously the role of technology assessment to engage in a critical, analytical dissection of what is happening before our eyes in everyday technoscientific practice.

2.2. A science studies perspective on the performative force of the back-of-the-envelope calculation

The speculative promise that drives technoscientific research can take a variety of forms, including narrative, image, formulas and numbers. It has been noted by analysts that a certain form of quantified speculation, the back-of-the-envelope calculation, has a prominent role in proposals of climate engineering (Fleming, 2010, xii ff; Kintisch, 2010, 4). Such calculations mobilize physical or chemical formula to show how, theoretically, climate variables like radiation or CO_2 could be controlled. The calculations are called back-of-the-envelope calculations not because they are literally jotted down on a scrap of paper in a creative act of imagination, but because they are rough calculations that suggest a working method. By suggesting a working method, even if this method is still non-existent and only works theoretically (e.g. hypothesized on the basis of an analogy with a natural process), such back-of-the-envelope calculations are instances of speculative promise.

According to insights from Science and Technology Studies and the sociology of expectations, instances of speculative promise and other kinds of expectations are generative of research trajectories as they 'guide activities, provide structure and legitimation, attract interest and foster investment' (Borup et al., 2006, 285–286). The generation of research trajectories requires the speculative promise to be both credible and legitimate (Joly, 2010).

Specific forms of speculative promise like the back-of-the-envelope calculation thus have a performative dimension alongside their representational qualities. The performative dimension is what the promise brings about, what it effectively communicates, while the representational dimension concerns the truthfulness or adequacy of representation. In social studies of science the two dimensions are regarded inseparable as scientific authors use 'literary technologies' to convince readers of the trustworthiness of their claims and there is no ultimate, objective arbiter to judge truthfulness (Shapin & Schaffer, 1985). Quantification is a particular form of rhetoric and literary technology associated with objectivity which continues to be an important cultural ideal in the sciences (Porter, 1992). In this sense, an aspect of the performative force of quantified statements in contemporary scientific literature is that they convey objectivity. One aspect of the performative dimension of the back-of-the-envelope calculation thus hinges on its association with objectivity. The association with objectivity constitutes part of the credibility of the speculative promise.

Back-of-the-envelope calculations furthermore have a sketch-like quality, which invites elaboration. Sketch-like drawings have been analyzed for their cognitive and social roles (Pacey, 1999). They function as heuristics, guiding the search for a solution to a concrete problem, or helping to grasp the working of a device which still only exists on paper. Back-of-the-envelope calculations can play a heuristic role as mathematical formula are checked for their adequacy in solving physical problems by inserting rough numbers (Collins, 2007), or rules of thumb are used to get an order of magnitude solution to a engineering problem (Vincenti, 1990). Since back-of-the-envelope calculations concern concrete, case-specific solutions, they resemble the Kuhnian exemplar in their generative heuristic quality. The exemplar has been noted for its heuristic quality leading to the generation of a research trajectory as it involves a 'direct modeling of one's own research problems and solutions on exemplary concrete problem solutions' (Nickles, 2009, 448). Another aspect of the performative dimension of the back-of-the-envelope calculation thus hinges on its generative heuristic quality, its potential to generate a new trajectory of research based on a specific theoretical outlook and, in case of a design problem, the building of design solutions. This heuristic quality constitutes part of the legitimacy of the further inquiry into the speculative promise, it legitimises its speculative character.

3. Paul Crutzen's proposal on climate engineering, its pedigree and its reception among peers

In his essay titled "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" (Crutzen, 2006) atmospheric scientist Paul Crutzen argued for climate engineering as a second-best response to global warming, the best option in his view being a substantial lowering of emissions of greenhouse gases. As the latter policy response showed no sign of being realized at a global level – emissions were going up rather than down – Crutzen argued that an alternative involving climate engineering should be looked into. Not only were emissions going up, the aerosol pollution in the lower atmosphere which had masked global warming to some extent by way of dimming the incoming solar radiation, was going down. This was good news in terms of pollution abatement, but bad news for the solar dimming which helped to mask global warming. In Crutzen's reasoning the solar dimming capacity of aerosols however also held the key to a way of cooling the climate which had been proposed three decades before by fellow atmospheric scientist Mikhail Budyko. I will first briefly sketch these earlier proposals and their reception before going to the details of Crutzen's proposal.

In the early 1970s, the atmospheric scientist Mikhail Budyko had suggested adding sulfate aerosol to the stratosphere to counter global warming, by means of aircraft or rockets. Budyko presented a back-of-the-envelope calculation of how much sulfur would be needed to cool the planet by a few degrees. Reducing solar radiation by 2 percent would require burning some 100,000 tons of sulfur per year (Fleming, 2010, 241). At the time, the idea of controlling weather and climate was hotly debated. The optimism of the earlier post-war decades about a complete prediction and control of atmospheric flows made possible by rapidly developing computational science had given way to doubts about effectivity, concerns about environmental side effects and public outrage over the use of weather modification as a weapon of war in Indochina (Fleming, 2010; Kwa, 2001). Expressing the rather more cautionary *Zeitgeist* of the 1970s, atmospheric scientists William Kellogg and Stephen Schneider argued that "it is nearly impossible at present to establish conclusively cause and effect linkages (let alone magnitudes) in any single weather or climate modification experiment" and that engaging in global experiments would be "the height of irresponsibility if we could not adequately foresee the outcome" (Kellogg & Schneider, 1974, 1170). On the other hand, Budyko's idea remained an interesting perspective for those putting faith in computation, planetary engineering and the emerging paradigm of Earth System Science. Some of these scientists were to be found at the US Lawrence Livermore National Laboratory and they were going to play a central role in reviving climate engineering. At the lab, the climatic effect of stratospheric aerosols had become a central concern, entangling research lines on stratospheric pollution from supersonic flight, climatic impacts of volcanic aerosols and 'nuclear winter' scenarios (Dörries, 2006; Edwards, 2012). The group engaged in an Atmospheric Model Intercomparison Project shortly after the IPCC was founded, an effort to standardize climate models which, as we will see, also played a central role in the mainstreaming of climate engineering.

With the rising concern about global warming, speculative ideas about climate engineering, including Budyko's proposal, were taken from the shelf. In 1991, atmospheric scientist Michael MacCracken issued a report at Lawrence Livermore in which he discussed the option of the 'human volcano'. While mentioning adverse effects for solar energy, astronomy and ozone, MacCracken asserted that "the amount of sulfur to be injected would be well less than that now causing 'acid rain' and would be dispersed rather than concentrated, and thus would not create problems when rained out" (MacCracken, 1991, 6). The next year, the option also figured in a US National Academy of Sciences assessment, mobilizing back-of-the-envelope calculations to argue for its cost-effectiveness. An amount of "2×10^7 kg of dust" would be needed "to mitigate the 1989 US input of CO_2" (NAS, 1992, 450). The next in line to review and recalculate the option was atmospheric scientist Robert

Dickinson, who in 1996 published a NASA funded review of the injection of stratospheric aerosols as one of two “promising approaches” to climate engineering, which might “well be of lower economical cost than would be global reductions in fossil fuel use” (Dickinson, 1996, 279). “The effect of adding aerosols to the stratosphere can be quantified rather well because of studies of the effects of past volcanoes, which do this same thing naturally”, Dickinson asserted (Dickinson, 1996, 284). He estimated the amount of sulfate aerosols to be added to the stratosphere at 10 million tons per year for a cooling of nearly 2 W/m^2 (Dickinson, 1996, 286).

In 2006, Crutzen offered his own back-of-the-envelope calculation, invoking the eruption of Mount Pinatubo as a natural analog like Dickinson did a decade before:

> “... we adopt a simple approach based on the experience gained from the Mount Pinatubo volcanic eruption. For the Mount Pinatubo eruption, Hansen et al. (1992) calculated a radiative cooling of 4.5 W/m^2 caused by 6 Tg S,[4] the amount of S that remained in the stratosphere as sulfate six months after the eruption from initially 10 Tg S (Bluth et al., 1992). Linear downscaling results in a sulfate climate cooling efficiency of 0.75 W/m^2 per Tg S in the stratosphere. The estimated annual cost to put 1 Tg S in the stratosphere, based on information by the NAS (1992), at that time would have been US $25 billion (NAS, 1992; Ron Nielsen, personal communication). Thus, in order to compensate for enhanced climate warming by the removal of anthropogenic aerosol (an uncertain mean value of 1.4 W/m^2, according to Crutzen and Ramanathan (2003)), a stratospheric sulfate loading of 1.9 Tg S would be required, producing an optical depth of 1.3%. This can be achieved by a continuous deployment of about 1–2 Tg S per year for a total price of US $25–50 billion, or about $25–50 per capita in the affluent world, for stratospheric residence times of 2–1 year, respectively” (Crutzen, 2006, 212–213).

What Crutzen did by way of this mixed narrative-quantitative argumentation for the do-ability of stratospheric climate engineering is taking the eruption of Mount Pinatubo as proof-of-concept for a working climate engineering fix. A decade before, fellow atmospheric scientist Robert Dickinson had also suggested to take Mount Pinatubo as an example, however adding the caveat that “serious miscalculations could occur as a result of our lack of understanding of the climate system” (Dickinson, 1996, 281). Caveats were absent in Crutzen’s argument, giving the impression that taking Mount Pinatubo as an exemplar of climate engineering would not need further scrutiny. Crutzen thus conflated theoretical possibility and technical feasibility, a conflation characteristic of technoscientific speculative promise as analyzed by Nordmann. Crutzen’s insistence to take the eruption of the volcano as proof-of-concept also came in narrative form in a further argument about the advantage of the climate fix as an intervention that works at short notice:

> “In contrast to the slowly developing effects of greenhouse warming associated with anthropogenic CO_2 emissions, the climatic response of the albedo enhancement experiment would start taking effect within about half a year, as demonstrated by the Mount Pinatubo eruption (Hansen et al. 1992)” (Crutzen, 2006, 216).

The introduction of a ‘climate engineering experiment’ introduces some ambiguity as to whether the method would still need a proof of demonstration or could perhaps fail. The narrative as a whole, including the back-of-the-envelope calculation however conveys an optimistic ‘can-do’ mentality, with very little space for caveats, second thoughts or the possibility of failure. The overall message is that the method’s effectivity could be safely assumed since it has been ‘demonstrated’ by the volcanic eruption. Crutzen’s assessment of the effectivity of climate engineering thus appears to be based on a proof-of-concept, a concrete demonstration, albeit one that is not of human making. Quite crucially, Crutzen presented the idea as if an analogy between natural process and technical intervention was not hypothetical, but a proven correspondence even before technical intervention had been undertaken.

The reception of Crutzen’s proposal among fellow climate scientists was mixed and included fundamental objections. Notwithstanding the reluctance of climate scientists to engage in research on climate engineering, however, specialist contributions soon started to assume the logic of an unfolding program of research and development, as called for by Crutzen. First of all, editorial comments of five fellow atmospheric scientists were joined with Crutzen’s essay in *Climatic Change*. Epistemic doubts and ethical concerns made up an important part of these commentaries, while they all endorsed Crutzen’s call for more research. Crutzen’s calculations figured in three of the five comments, all of them critical about the assumptions which underpinned the core calculation in which the eruption of Mount Pinatubo was taken as an exemplar. Both Jeffrey Kiehl and Michael MacCracken took issue with Crutzen’s calculation for its global averaging of the effects of the eruption. Crutzen had cited Hansen et al. (1992) as a source for the cooling effects, referring to one simulated number: a peak in solar dimming of 4.5 W/m^2 early 1992. Hanssen and co-workers had offered a simulated prediction of the global cooling effects of the Mt Pinatubo eruption shortly after it took place. In the meantime, a growing body of literature had come to offer details of the actual effects of the eruption on regional climates, integrating swathes of data in the modeling. The eruption had caused *winter warming* in the Northern Hemisphere instead of cooling, MacCracken and Kiehl noted, thus criticizing Crutzen on the drift of his argument. Asserting that “simple counter-balancing may not be the actual consequence of stratospheric injection” (MacCracken, 2006, 240), MacCracken quoted a contribution in *Science* by Alan Robock which detailed regional effects of volcanic eruptions:

> “During the NH [Northern Hemisphere] winter of 1991–92, the temperature in the troposphere over North America, Europe, and Siberia was much higher than normal, whereas over Alaska, Greenland, the Middle East, and China, it was lower than normal . . . The unusual cold in the Middle East produced a rare snowstorm in Jerusalem and led to the death

[4] 1 Tg = 1 Teragram = 1 million tons.

of coral at the bottom of the Red Sea (*12*). The same pattern was observed during the winter of 1992–93. Climate reconstructions show that this pattern has followed every large, sulfate-rich tropical explosive eruption of the past century and a half (*13*, *14)*" (Robock, 2002, 1243).

While MacCracken countered Crutzen's suggestion of a simple and effective solution by providing details of the regional climatic effects of volcanic eruptions, Jeffrey Kiehl objected on more fundamental grounds. For Kiehl, the climate paradigm on which Crutzen relied was defective. The effect of winter warming in the Northern Hemisphere instead of a globalized cooling as suggested by Crutzen called for a fundamental reflection on epistemic issues, involving reducible and irreducible ignorance:

"As pointed out by Crutzen, the Earth does cool due to this experiment [the eruption of Mt Pinatubo], but this experiment also provides ample evidence of the non-local and non-linear response of Earth's climate system, e.g. winter NH [Northern Hemisphere] warming. This example exhibits how Earth's climate system is far more complex than a simple energy balance picture. For this reason, I support Crutzen's argument that more detailed and comprehensive modeling studies be carried out with regards to experiments. But my concern is that all models have their limitations (e.g. note the inability of models to predict the appearance of the Antarctic ozone hole before it was observed). When will we know a model is 'good enough' to go out and perform a real experiment?" (Kiehl, 2006, 227).

The epistemic issues raised by Kiehl were echoed by another climate scientist, Lennart Bengtsson. Like Kiehl, Bengtsson argued that the climate paradigm on which Crutzen relied to make his calculations, was defective in several respects (Bengtsson, 2006). The climate system should be seen as essentially chaotic due to internal variations, its complexity only partly understood and its future states of limited predictability. As an example of the climate system's complexity being only partly represented in models Bengtsson mentioned climate feedbacks, to which models are hugely sensitive. If climate engineering along the lines proposed by Crutzen would be undertaken, evaluating its climatic impact against the background of natural variability would take several decades, Bengtsson concluded.

A much less critical reception, or rather an outright endorsement of Crutzen's proposal soon came from atmospheric scientist Tom Wigley by way of a short article in *Science* published in October 2006 (Wigley 2006). Wigley had been involved in modeling the impact of volcanic eruptions on climate at the National Center for Atmospheric Research. In an article published in 2005, he and co-workers had concluded that "there are still substantial discrepancies between different estimates of the forcing [of the Mt Pinatubo eruption]" (Wigley, Ammann, Santer, & Raper, 2005). Such epistemic issues were absent in the high-profile, optimistic response to Crutzen's proposal. Proposing to combine mitigation with stratospheric climate engineering as suggested by Crutzen, Wigley presented the option as a way to buy time. As an authority in the field of volcanic impacts on climate, Wigley put weight on Crutzen's idea by extending his reasoning about Mount Pinatubo as an exemplar of climate engineering. He joined the game by taking the eruption of Mount Pinatubo as a 'standard eruption'. Mount Pinatubo henceforth came to represent a numerical standard for global cooling to be used in simulating climate engineering. The results of modeling a "standard eruption every year, every two years and every four years" were shown, assuming the analogy between volcanic eruptions and climate engineering to be perfect. Mimicking Mount Pinatubo, besides being straightforward in its effectivity, would "present minimal climate risks", Wigley asserted. Wigley thus embraced Crutzen's suggestion to view the eruption of Mount Pinatubo as 'proof of concept' for climate engineering while also echoing the tenor of his argument that it would be a simple and effective cooling method. His main contribution to the unfolding research and development trajectory was to introduce the volcanic eruption as a numerical standard for global cooling and using this standard to sketch scenarios of climate engineering.

For Ken Caldeira's climate modeling group at Lawrence Livermore, Crutzen's intervention and Wigley's follow-up by way of standardized simulation appear to have opened a window of opportunity.[5] The group had been working on climate engineering by simulating the effects of a reduction in the solar constant, concluding in 2000 that "geoengineering may be a promising strategy for counteracting climate change" (Govindasamy and Caldeira, 2000). By 2007, their modeling work had become highly relevant in the light of Crutzen's and Wigley's contributions, since "only a handful of model simulations have addressed the climatic consequences of such geoengineering proposals" (Matthews & Caldeira, 2007, 9949). In this way, simulations which took the technical feasibility of cooling the planet for granted were getting entangled with simulations of the climatic consequences of volcanic eruptions, as if they shared the same research object.

Climate scientists concentrating on the effects of volcanic eruptions and the adequacy of volcanic eruption as an analogy for climate engineering however started to tone down the optimism. If the eruption of Mt Pinatubo is taken as an analogy for climate engineering, climate science needs to look beyond its effects on temperature as the global cycle of water and its associated latent heat energy form a vital link in the climate system, Kevin Trenberth and Aiguo Dai argued. The year following the eruption of Mt Pinatubo was not only cooler on the whole, it was also considerably drier in many regions. "Creating a risk of widespread drought and reduced freshwater resources for the world to cut down on global warming does not seem like an appropriate fix", the authors concluded (Trenberth & Dai, 2007, 4). In the same vein, Alan Robock argued in a

[5] Bibliometric research has shown the importance of Caldeira's work in exploring the solar dimming idea. He is the top-ranking author in terms of number of publications on the subject (Oldham et al., 2014). Caldeira has received both public funding (Lawrence Livermore is funded by the US Department of Energy) and private funding (from Bill Gates, 1,000,0000 $/yr to David Keith and Ken Caldeira according to Robock, 2012). The main sources of public funding of solar dimming research are the US National Science Foundation, the European Commission and NASA (Oldham et al., 2014).

short contribution in *Science* that volcanic eruptions should be taken as a warning rather than as “an innocuous model for what humans could do by creating a permanent stratospheric aerosol layer” (Robock, 2008, 1166).

The credibility of Crutzen’s proposal as a simple and effective solution received further blows as microphysical processes associated with delivering sulfur in the stratosphere began to be discussed in depth. Other than assumed in back-of-the-envelope approaches such as Crutzen’s calculation and the idealized[6] simulations of Wigley and Caldeira’s team, the cluttering of sulfur particles would complicate the calculation of the amount of sulfur needed. This is one nonlinear process among other uncertain microphysical and chemical processes that could be expected to play a role, reviewers concluded (Rasch et al., 2008; Rasch, Tilmes et al., 2008). While Crutzen produced an estimate of 1–2 million tons of sulfur to counteract a doubling of CO_2 (Rasch, Crutzen & Coleman, 2008) the reviewers came to an estimate double and possibly up to 10 times this amount:

> “Our studies have shown that the delivery of aerosols or their precursors, at least using our hypothetical aircraft, is a formidable task. For the conservative scenarios we have explored, it would take of the order of a million flights of 4-h duration (2500 km) per year to deliver the nominal amount of aerosol (10 Tg particles/yr = 2.5 Tg S/yr) needed to balance the warming associated with increasing greenhouse gas emissions. These numbers are still quite rough, and it is possible that up to four times as much sulphur might be required” (Rasch, Tilmes et al., 2008, 4030–4031).

As the work of modeling the microphysical processes progressed up to ‘third-generation approaches’, the estimated amounts escalated further. Based on these approaches a US National Academy of Sciences committee took 10 million tons of sulfur per year, hence 5–10 times the amount calculated by Crutzen, as a *lower limit* of what might be needed:

> “The more comprehensive treatments [of aerosol microphysics] indicated that at least 10 MtS/yr (approximately the amount of sulfur injected by the Mount Pinatubo eruption) would be needed annually to maintain a radiative forcing of $-4\,W/m^2$, roughly equal to but opposite that associated with a doubling of atmospheric carbon dioxide” (NAS, 2015, 81).

To this once further revised estimate the reviewers added numerous uncertainties and caveats to simulating the evolution of aerosols blown in the atmosphere during volcanic eruptions. They also dismissed a direct correspondence between volcanic eruptions and injecting aerosols. According to them, the analogy should be viewed as hypothetical: it is useful as a heuristic, but it should not be taken literally. The less idealized the modeling approaches become, the less simple and effective stratospheric climate engineering thus appears to be. What started as a straightforward and scientifically sound looking back-of-the-envelope calculation promising an effective climate fix is becoming a growing pool of ‘real challenges to models’ (NAS, 2015, 76).

Notwithstanding the revised, much less promising looking estimates and the continued objections by climate scientists to taking the volcano analogy literally, an important driver of the research and development trajectory on stratospheric climate engineering has been the speculative promise with which it started. Over the last five years, performing simulations with idealized models saw major efforts under the umbrella of the Geoengineering Model Intercomparison Project (GeoMIP). Being a project under an ongoing program of comparing climate models from different institutions around the globe, GeoMIP effectively mainstreamed the modeling of climate engineering. Comparing outcomes of different climate models had become standard practice in the climate modeling community, geared towards producing robust results for IPCC climate assessments.[7] Such comparisons had included the effects of historical volcanic eruptions on climate, but not of potential climate engineering. In this program, scenarios of climate engineering were introduced in 2010 by an international group of atmospheric scientists who had been doing work on stratospheric albedo enhancement within their institutes (Kravitz et al., 2011). They proposed to the climate modeling community to engage in simulating four standard climate engineering scenarios so as to be able to compare the results. Two of these scenarios involved reducing the solar constant to represent globally uniform stratospheric albedo enhancement. An advantage of these highly idealized climate engineering model experiments which had been introduced a decade ago by Ken Caldeira and co-workers at Lawrence Livermore was that they were very do-able: “The idealized specification of forcing also makes it especially easy to implement” (Kravitz et al., 2011, 163). By 2013, the results of these model experiments performed by 12 mainstream climate models involving efforts of 24 atmospheric scientists affiliated to institutes around the world were published. Again the highly idealized character of the model experiments was noted to be advantageous, as it “has allowed broad participation and facilitates intercomparison”, while at the same time making it possible “to address robust features of the impact of solar geoengineering” (Kravitz et al., 2013, 8321). While the concluding section introduced caveats, including that “the results should neither be mistaken as an evaluation of geoengineering proposals or issues surrounding their implementation” and that more work needed to be done with less idealized models (Kravitz et al., 2013, 8330), it also maintained an overall promise of control as “careful planning of optimal geoengineering strategies might be required to produce desired climate changes while avoiding side effects” (Kravitz et al., 2013, 8331). It is the interlacing of this kind of speculative promise of engineering control with confident statements such as “[simulated climate engineering intervention] G1 is effective at preventing the Arctic sea ice loss that

[6] The term ‘idealized’ is used by the climate modelers themselves. The simulations are called idealized because they represent stratospheric aerosol injection by decreasing solar radiation in the models. The models are otherwise called complex, coupled atmosphere-ocean general circulation models (AOGCMs). These AOGCMs have become complex machines, integrating enormous amounts of data (see Edwards, 2010).

[7] GeoMIP forms a continuation of the Program for Climate Model Diagnosis and Intercomparison (PCMDI) conceived by Lawrence Livermore modelers around 1990 (Edwards, 2012, 37).

occurs in [climate scenario] *abrupt4xCO2*" (Kravitz et al., 2013, 8330) which make caveats and uncertainties look like hurdles that will be taken in the near future if only climate modelers invest enough effort. The overall thrust of the GeoMIP efforts as portrayed by the climate modelers is that effective climate control, involving the fine-tuning of the amount and timing of stratospheric aerosol injection, is a potential to be realized. This promise is made to look even more realistic by such statements as "2020 . . . is a reasonable estimate of when the delivery systems needed to inject the aerosols might be ready" (Kravitz et al., 2011, 164). There is no reference or any underpinning of this speculation about delivery systems, which thus functions as a wish to be fulfilled.

To conclude this summarizing account of the reception and assessment of Crutzen's climate engineering proposal by fellow climate scientists, I would like to recall analyses in science studies of how 'disappointment' invariably follows 'hype' when grandiose technoscientific promises get scrutinized by peers and publics (Brown, 2003). The above account shows these dynamics, yet adds another, rather more surreptitious dynamics. It is the surreptitious dynamics of the mainstreaming of speculative promise as back-of-the-envelope simulations predicated on an assumed analogy which I have attempted to bring to light. Using Nordmann's lens of a 'forensics of wishing', I have attempted to show how a conflation of theoretical possibility and technical feasibility not only characterized Crutzen's proposal itself, but how this form of speculative promise continues to drive the unfolding research and development trajectory. Paul Crutzen's proposal to launch a program of research and development on the climate engineering idea of cooling Earth by mimicking Mount Pinatubo has shown to be a persuasive way of anticipating the future. While some of his colleagues have contested the underlying climate paradigm, the idea is being taken further through collective modeling exercises on the assumption that unknowns will be reduced sufficiently in the future and that tuning interventions at planetary scale is a possibility.

4. Concluding remarks

How has Crutzen's back-of-the-envelope calculation on emulating Mount Pinatubo convinced atmospheric scientists and their funders to conduct and support research on stratospheric climate engineering with sulfate aerosols? As my account shows, the reception of his idea was mixed, with some atmospheric scientists immediately pointing to fundamental flaws in Crutzen's broad brush, smooth picture of how to emulate a volcano to cool the planet. Yet even these scientists supported the setting up of a research program to elaborate and assess Crutzen's speculative idea, and thereby provided crucial support. The back-of-the-envelope calculation formed only the heuristic seed of an idea, but it effected enough credibility and legitimacy to be explored further. Crutzen's conflation of theoretical possibility and technical feasibility was exposed in critical contributions, yet it formed no fundamental hindrance to further elaboration. Put differently, the technoscientific novelty in his calculation as compared to those of forerunners was that it presented a particular, much studied volcanic eruption as a proof-of-concept.

The mainstreaming of Crutzen's idea happened almost 'overnight' as other renowned atmospheric scientists like Tom Wigley fully endorsed the idea of taking the Mount Pinatubo eruption as an exemplar, making it a standard in modeling exercises. Seizing the moment, Ken Caldeira's modeling group at Lawrence Livermore could present their strand of idealized modeling involving a reduction of the solar constant as a timely and relevant line of research in the emerging research program.

What is even more remarkable, and disconcerting because of its surreptitious dynamics, is that over the years speculation has continued to be a strong driver of climate engineering research. Predicated on the technoscientific and visioneering stance that speculation will at some point yield a working technology, idealized modeling has come to function as regular science. As other analysts have argued, climate engineering research has become regular 'science for policy' (Dilling and Hauser, 2013) and a necessary preparation for an uncertain future (Markusson, Ginn, Ghaleigh, & Scott, 2014). The sobering results of models which introduce complicating mechanisms do not appear to put a reign on speculation, while a strong impulse for working with idealized models is that they are most 'doable'. Speculation thus appears to be the normal way of doing climate engineering research.

While my account of the reception of Crutzen's climate engineering proposal has focused on driving dynamics and contestations 'internal' to climate science, it has given rise to a public controversy which is being played out on many planes and which has been studied from many angles. The environmental humanities literature offers insights about which worldviews, hence ontological commitments, underlie positions in the various entangled debates on climate engineering. As these ontological commitments also underlie the politics of anticipation 'internal' to climate science, they deserve scrutiny from the point of view of a 'forensics of wishing' which has been central to my approach. What kind of world is being imagined, speculated about and anticipated, hence to some extent wished? As noted in the introduction, Paul Crutzen first mentioned the possibility of climate engineering in a piece in which he elaborated the notion of Anthropocene (Crutzen, 2002). Here he expounded the view that scientists should aspire to become planetary managers, which he later detailed in his essay focused on stratospheric climate engineering: humanity had played the volcano unintentionally and, having realized the damage, should now play the volcano in a more thoughtful, controlled manner. This kind of 'magical thinking' characteristic of Western cosmic ordering (Walker, 2013) perceives the planet as an object amenable to calculation and over which humans have control. As Galarraga and Szerszynski observed:

> "This is the picture of the maker of climate which currently dominates the contemporary discourse of geoengineering, one which involves, firstly, forming a predefined idea of a possible climate to be achieved and, secondly, actualising that form by somehow impressing it onto the matter of climate. The climate architect is an idealised, imagined figure who

knows in advance the form that they want the climate to take; who can identify the process whereby they can provoke the climate to take it; and who can carry out that process and bring the matter of climate into the desired form. If uncertainties are acknowledged in this way of thinking about making the climate, they are seen as factors that are exogenous to the process of production itself, and as in principle capable of being ironed out by future technical refinements" (Galarraga & Szerszynski, 2012, 228).

The ontological commitments underlying the wish of a controllable climate stand in stark contrast to stances which do not take humans to be masters of a calculable cosmos. The climate scientists who have been objecting to Crutzen's climate paradigm, invoking complex feedbacks and hinting at irreducible unknowns, appear to be committed to a rather more humble spectrum of stances. Such humble stances are being articulated more in depth by environmental humanities scholars focusing on the human condition in the Anthropocene. In his book *Inhuman Nature*, Nigel Clark foregrounds a profound asymmetry in the relationship between humans and the Earth. Rather than being manipulable object or symmetrical materiality amenable to co-constitution, the latter provides volatile ground for the former, basically being vulnerable bodies and minds in search of stability (Clark, 2011). In this context we may wonder what to make of Anthropocenic entanglements suggested by studies which indicate that melting glaciers have increased volcanic activity in the Arctic (Palsson et al., 2013, 9). How much does our knowledge of the Earth protect us against its volatility, apparently partly provoked by humans speeding up earthly metabolisms? Such musings may put us back on our feet and inspire a politics of anticipation which does away with grandiose wishes and engages in discussing and altering 'what is happening', given that we are historically situated, vulnerable but not politically powerless humans (cf. Bonneuil and Fressoz, 2013).

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