Introduction

Unite behind the science.
Greta Thunberg[1]

September 20, 2019. At the very moment I am writing these lines, millions of people are gathering worldwide for a climate strike to pressure governments to take action on climate change. Counting participants distributed around the globe, it is one of the biggest protest demonstrations in human history. The event is closely linked to the youth movement #fridaysforfuture and its lead figure Greta Thunberg, who has haunted selected leaders of Western democracies since the hot summer of 2018. Climate change now sits at our kitchen table, stares at us from our social media timeline and makes our political representatives tremble. Earlier, concern about global warming was linked essentially to certain jobs (environmental sciences, non-governmental organizations [NGOs], journalism), political views (leftist, progressive, ecologist), and ethical considerations (religiosity, protection of God's creation). Now, by contrast, it takes considerable effort *not* to be confronted with the climate issue. Whether one likes it or not, climate change requires active positioning within our daily life, our personal networks and our (analog and digital) filter bubbles. People have tended to take the future with climate change into account within their daily lives only since very recently but now with striking force.

1 https://youtu.be/bz8jSJAkFRM, retrieved on April 3, 2019.

What were the reasons for this changing perception of the urgency of climate change? How did climate change evolve from a scientific fact into a global matter of social, economic and political concern? Attempts at explaining these questions fill many books. Perhaps the new scientific insights about the severe impacts of climate change have convinced the public of its urgency; or humans just needed time to make sense of climate change and figure out ways of dealing with it in a concerted manner; or scientists and activists have learned how to communicate climate change better and beat the argumentation of climate skeptics and deniers. Probably all these explanations have their share of truth. It is, however, undebated that global warming requires new scientific ways of thinking about the world, its past, present and futures.

Figure 1: "Unite behind the Science," tweet by Greta Thunberg following her speech at the French National Assembly on July 23, 2019. Source: Twitter[2]

2 https://twitter.com/gretathunberg/status/1153693427487387648, retrieved on September 3, 2019.

As a matter of fact, there has arguably never been an issue of global concern so intimately linked to the sciences. This relationship is reflected in Greta's call to "unite behind the science" and the central role scientists play in mediating, negotiating, regulating and governing the issue at various levels. Equally important but more controversial is the role of technology in climate change. On the one hand, climate change has literally been caused by technology, namely the massive release of carbon dioxide (CO_2) and other greenhouse gases (GHGs) by multiple industries since the middle of the 19^{th} century. On the other hand, technology also plays a central role in the mitigation of climate change, be it renewable energies, energy efficiency measures or more recent and controversial approaches subsumed under the term of negative emissions.

In this book, however, the focus lies on another technology intimately linked to the climate issue: Computer models. As media scholar Julie Doyle puts it, "climate change has been reliant upon science and technology for its detection, and for predicting the various scenarios of its future development and impacts" (Doyle 2011: 16). Computer modeling has become the fundamental organizing principle for the global epistemic community surrounding the climate change issue (Edwards 2001: 34; Sundberg 2007: 473). This crucial role of computer models and simulations in climate research have also made them a recurrent theme in the social sciences and humanities. Scholars have discussed epistemic and representational issues widely and characterized the way simulations represent the world or aspects of it (Gramelsberger 2008b; Pias 2008; Winsberg 2010). Other works discussed the historical development of climate modeling technology and infrastructure (Edwards 2010) and considered it a lead discipline for the dawning age of simulation-driven science (Gramelsberger 2008a: 105). There has also been considerable academic work addressing the relationships between model-driven climate research and climate policy (Gramelsberger/Feichter 2011), with the exemplary role of the Intergovernmental Panel on Climate Change (IPCC) in this regard (Hulme/Mahony

2010). Scholars have discussed the transformation of climate models from heuristic tools into political instruments (Heymann/Hundebøl 2017) and the sociotechnical frictions created in the course of downscaling global models to the regional level (Mahony 2017; Mahony/Hulme 2012).

Another line of research has specifically considered the role of visual media in the translation of scientific knowledge emanating from computer simulations. Notably, diagrams and maps are popular devices to communicate insights from computer experiments to the broader public (Doyle 2009 2011; Manzo 2009 2010; Schneider 2012, 2017). Climate images gain political status in the process of socialization: "[…] climate science is the paradigmatic field in which images take on a role as political agents" (Schneider 2012)

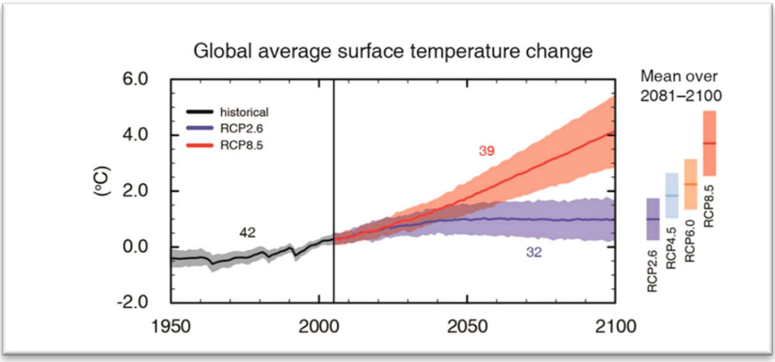

Figure 2: possibility space of the future, drawn as Representative Concentration Pathways (RCPs). Source: IPCC 2013, 21

This is especially true for the visualizations featured in the IPCC assessment reports, notably the "hockey stick" (Montford 2010; Walsh 2014), the "burning worlds" (Schneider 2012, 2016, 2017) and the "burning embers" (Mahony/Hulme 2012). Figure 2 featured in the fifth assessment report of the IPCC (2013), for example, represents the numeric results of comprehensive computer simulations. Nevertheless, they are strategically framed and publicly understood as choices between two pathways of the future – a detrimental scenario (red), with severe warming of the global atmosphere, and a more sustainable scenario (blue), which requires a massive transformation of our ways to produce, consume and live.

As Birgit Schneider has highlighted, these graphs have become mobile across contexts and social worlds. As *immutable mobiles* with considerable semantic flexibility (Latour 1988), they offer various interpretations and fulfill many functions for multiple actors (Schneider 2012).

Mobilization and stabilization

Drawing on this idea of graphs and maps as immutable mobiles for climate change mediation, research for this book started with an ethnographic study of scientific modeling work at the Potsdam Institute for Climate Impact Research (PIK). The PIK is one of the major institutes running comprehensive computer simulations calculating scenarios of the future with climate change. In my interviews, observations and interventions at the institute, I learned a lot about the mobilities and immobilities of visual artefacts within scientific modeling practice. However, I also discovered that images are not by far the only artefacts in climate modeling practice that began to travel. As a matter of fact, many elements in scientific modeling practice have become increasingly mobile, fluid and permeable across social worlds and application contexts. Accordingly, my study also increasingly turned into a multi-sited ethnography (Marcus 1995), involving equally analog, digital and hybrid fields and places of investigation.

In the book, I will document and discuss mobilization and stabilization within scientific modeling practices, which are both linked to new role models in research ('open science') and to the imbrication of modeling practice within digital, networked infrastructures. I argue that these new sociotechnical constellations change the way scientific modeling and climate prediction works considerably. Moreover, these transformations of scientific modeling practice may also provide some explanations for the way climate change has currently 'kicked in' within current debates and various publics.

Technographic ordering of elements

Methodologically, this investigation started with the belief that more qualitative research is needed to understand the practices, artefacts and infrastructures of contemporary data collection, processing, analysis, representation and dissemination. Rather than testing the theories available, the aim of this study was to root theoretical considerations within empirical observations of practice, material and symbolic representation. Barney Glaser and Anselm Strauss have formalized this position in their conceptualization of *Grounded Theory* thinking, which should enable the systematic discovery of theory from data:

> We believe that the discovery of theory from data – which we call *grounded theory* – is a major task confronting sociology today, for, as we shall try to show, such a theory fits empirical situations, and is understandable to sociologists and layman alike. Most important, it works provides us with relevant predictions, explanations, interpretations and applications. (1999: 1)

While generally agreeing on the direction of this verdict, sociologist Werner Rammert has highlighted that there is no such thing as theory-free empiricism in science. Indeed, empirical observations are always focused, put into perspective and mediated. For Rammert, the task is then to document and reflect thoroughly on the selection processes in play, the points of view taken, and the optics or instruments in use (2007: 16). The methodological considerations around *technography* provided some directions and terminological ordering for this study. Werner Rammert and Cornelius Schubert argue against meta-narratives about the ontology of 'the technical' and 'technology' in philosophical and sociological theory in their conceptualization of the approach

(2006). According to them, such meta-narratives may be interesting from the science-historical perspective but fail to grasp the practical discourse with technology, as it is conducted by laboratory researchers, inventors, engineers, workers, entrepreneurs and users (ibid.: 12). This oscillates with my field, where (digital) technology was virtually omnipresent but did not provide a useful category to be 'observed.' General characterizations of 'simulation modeling technology' were not helpful for understanding how actors actually construct computer models, carry out simulations and deal with predictions of the future with climate change. Against this backdrop, technography as a micro-sociological approach aims at investigating the "practical production and installation of techno-social orders in strategically relevant situations, in view of discovering exemplary practices and mechanisms for the development of new institutions and global regimes" (ibid.: 13, translated by the author). Technography may begin with interactions among humans and interactivities with objects and explores patterns of hybrid micro-orders. In conflict and coalition with others, these micro-orders may lead into powerful macro-constellations. Rammert characterizes three types of technology-related practices, namely, *making technology*, *using technology* and *participation of technology* (2007: 4). However, in the case of technological practice in simulation modeling, the boundaries between these categories are blurry or sometimes nonexistent. The technological devices distributed described within this study rarely have distinct 'producers' or 'users' but are mutually constructed and operationalized ('used') by communities of 'contributors.' Then again, such contribution cannot be understood independently from technological participation, which is increasingly automated within digital platforms and infrastructures. In the context of this study, a general categorization of elements regarding the categories of humans, things and symbols has been conducive for identifying interactional relationships.[3] While connections are always drawn between different 'families' of elements, the chapters of the book each have a particular focus – Chapter I explores physical elements, such as architecture, telescopes, computers and forests, Chapter II focuses on the practices of human scientists, chapter III on visual inscriptions, chapter IV on models and software, chapter V on numerical data, and chapter VI on digital platforms, which built relationships between multiple elements.

Technographic interventions

In terms of its methodology and procedural ways forward, technography draws mainly on ethnographic methods of observation, inscription and description. Going beyond classic field studies, these methods include approaches such as videography, webnography and interactivity experiments (Rammert/Schubert 2006: 13f). Compared to these approaches, the present study particularly highlights the inventive capacities of theories, methods and artefacts. In combination, they can be seen as heuristic devices that trigger new questions, draw out new aspects and help to co-create our research fields. Lury and Wakeford (2014) have reiterated the relevance of method to the empirical investigation of the contemporary and suggested the development and operationalization of *inventive methods* to investigate the happening of the social. For them,

> an inventive method addresses a specific problem, and is adapted in use in relation to that specificity; its use may be repeated, but the method is always oriented to making a difference. (Lury/Wakeford 2014: 11)

The authors stress that inventiveness is not to be equated to new. Inventive methods may include well established devices, such as

3 Werner Rammert puts it similarly as "wetware, hardware, and software" (2007: 19).

experiments, patterns or populations, marginal(ized) ones, such as anecdotes, screens or speculations, or relatively new ones, such as the probe or phrase: "What unites them, however, is that they are methods or means by which the social world is not only investigated, but may also be engaged" (ibid.: 6). In so doing, they open up the question of how methods contribute to the framing of change, understood "not only as complex, contradictory and uncertain, but also as everyday, routine and ongoing" (ibid.). Lury and Wakeford are drawn to the term *device,* a word with multiple everyday meanings (object, method, bomb), to conceptualize and operationalize inventive methods further.

> […] the notion of the device not only admits that object and methods are mutually constitutive, but also acknowledges that it is their relation that forces us to confront the new. (ibid.: 8)

For Lury and Wakeford, devices never operate in isolation but in relation to an apparatus and complex ensemble of practices. This relational and situational quality is a source of permanent destabilization, which prevents the device from becoming "a mere tool, which could be used always and everywhere in the same way" (ibid.: 9). This embedding in the apparatus also highlights the ability of devices to be powerful agents that not only represent reality but co-create it.

I engaged in a number of activities in my fieldwork that oscillate with the idea of inventive methods and devices. This includes a methodological operationalization of maps, interventions such as workshops, and interdisciplinary collaboration. Considering that these devices are embedded in the technographic interventions, they are discussed in the course of the chapters.

Plan of the book

The six chapters of the book are structured around particular elements and field sites. The different scales and ontologies of these sites have evoked different questions, foci, and research tactics. Understanding theory, method, and research phenomena as interrelated categories, which are mutually elaborated within the research process (Bender/Zillinger 2015: XI), conceptual approaches are discussed within the chapters in a dialogue with the empirical material. Accordingly, the chapters aim equally at characterizing distinctive constellations of elements relevant to scientific practice in climate impact research, but also discuss the situated methodological tactics and devices that have been used for investigation.

Chapter I describes the making and consolidation of Telegrafenberg as a place to do spatial, Earth and climate research. In the 19th century, a forested hill near the Prussian residential city of Potsdam was increasingly connected with telegraphic communication networks and put on the map of the German Kaiserreich. In the 1860s, Wilhelm Foerster and other astronomers proposed transforming the hill into a research infrastructure for a prospective new scientific discipline – astrophysics. Potsdam appeared to be a perfect location for this endeavor, due to its position within proximity but also a healthy distance from the Prussian capital Berlin. Building on the work of Susan Star, Karen Ruhleder and Geoffrey Bowker (Bowker 2005; Star 1999; Star/Ruhleder 1996), I will address these aspects of proximity and distance as essential qualities for the making of new infrastructures for technoscientific innovation. This involves diverse forms of infrastructural elements, including physical particles, architectures, rail tracks and telegraph masts, telescopes and spectrometers, scientists and machinists, scientific disciplines and governmental entities. At the beginning of the 20th century, Telegrafenberg had become a veritable place to do astrophysics, meteorology and geodesy. An identification of the elements and their relationships of this achievement is probed through a temporal layering of spatialities (i.e. infrastructure maps) enabling infrastructural inversion (Bowker 2005). Building on Geoffrey Bowker's (2015) comments on the temporality of infrastructures, I also challenge linear representations of time within infrastructural analysis and highlight parallel and repetitive (re)constructions of pasts, presents and futures. The astonishing monument of the Einstein Tower, for example, provides an opportunity to reflect on (dis-)connections from traditions and the promise of futures in architecture and infrastructure. In this context, I also challenge the idea of a master narrative in infrastructure (Star 1999) and propose instead to focus on heterogeneous promises, functionalities and representations that infrastructure provides for different people at different times. Finally, I introduce the newest contributions to the science park and the PIK in particular.

Chapter II is a collage of the idioculture (Fine 1979, 2007) at the PIK. I discuss Hans Joachim Schellnhuber's conceptualizations of Earth System Science (Schellnhuber 1998) and geo-cybernetics (Schellnhuber/Kropp 1998) as the conceptual lines for work at the institute. I propose the entanglement of different dimensions that are specific to the idioculture at the PIK. Firstly, the integration of science for sustainability opens a Pandora's Box multiplying the number of issues and perspectives to be taken into account in research endeavors at the institute. Research at the PIK goes well beyond the calculation of GHGs or temperature increases. It embraces a cybernetic understanding of the world, where everything is connected to everything. Secondly, this multiplication of research objects requires the operationalization of inter- and transdisciplinary collaboration. To be able to make statements about everything, one has to hire experts of heterogeneous scientific disciplines and bring them together to collaborate with each other. Thirdly, the heterogeneity of the scientific disciplines participating in this project has to be stabilized through the use of common scientific methods, namely, those of simulation modeling and computational science. Computer models, code and digital infrastructure are omnipresent elements in the scientific practices at the PIK. Fourthly, I will argue that the PIK should not only be grasped as a center of calculation (Latour 1987), but also as a center of accountability (Rottenburg 2009). Prediction through computers cannot be understood solely as a matter of calculation and epistemic representation but rather as a matter of political representation, translation and accountability. There are different views at the institute how to handle relationships to the world outside the scientific community. As I will argue, these different views are not so much linked to the extent of openness but rather to the question of its timeliness. The principal question is whether one should engage in openness after the stabilization of the facts (i.e. a project cycle) or from the beginning of ongoing experimentation. I introduce the discourse of *open science* and its infrastructural reading as the perspective currently gaining momentum at the PIK. The remaining chapters describe different ways of dealing with openness, mobilizing visualizations (III), software (IV), data (V) and multiple elements (VI).

Chapter III describes the making, operationalization and use of the online geoplatform ClimateImpactsOnline (CIO) as a device for science mediation. Being part of the project team of CIO for one year, I was able to observe and participate in activities of science mediation during the Long Night of the Sciences and educational work within German schools. While the PIK scientists had a clear picture of the 'end users' of the online platform, I argue that the practices within the frame of science communication cannot actually be grasped through categories such as 'users' or 'user interfaces.' In fact, the 'user interface' may have been the one standing in the way of true engagement with the climate issue. Following the further development of the platform and accompanying activities with teachers and pupils, I will show how actors managed to *infrastructure* (Star/Bowker 2006) practices of debate around climate impacts in German schools. This entailed a parallel and continuous configuration of new artifacts and practices. I would argue that the role of the geoplatform in this context was one of an *anchoring device,* enabling open but also channeled debates about climate change and its future.

Chapter IV deals with the mobilization of computer models as a strategy to bring climate change to new territories, communities and infrastructures. Supplementing existing work on the regional downscaling of climate models and its migration to multiple geographic places (Mahony/Hulme 2012; Mahony 2017), I propose to discard representational concerns about traveling computer models and focus instead on technological considerations in model and knowledge mobilization. Discussing the example of the climate impact model CLIMADA, I will show that scientific programming in climate impact research is currently in a state of massive reconfiguration. I will discuss aspects of this reconfiguration, such as Pythonization, coding openness, software packaging, and organization within digital communities and platforms. Furthermore, I introduce the Jupyter Notebook as a methodological device to stabilize such practices of mobilization. Taken together, these configurations can be characterized as *mobile modeling*. The latter, as a practice, generally privileges technologies that optimize performance through the distributiveness of functionalities and elements, while mutually instating devices for overview and control. Mobile modeling is a forward-looking practice aiming at the future amplification of artifacts and knowledge.

Chapter V sheds a light on the related perspective of digital knowledge mobilization, such as open datasets, infrastructures and services. Addressing the making and infrastructuring of a specific open dataset of GDP[4] time series by the PIK scientists (Geiger et al. 2017), I will discuss the conceptualizations of traveling data, information and knowledge in science within existing literature (Latour 1999a; Leonelli 2015; Rheinberger 2011). My observations and infrastructure analysis suggest a shift of attention within computational science from the production of evidence to that of open, linked and reusable datasets. Similar to the production of open software discussed in Chapter IV, open data practices introduce a forward-looking perspective into scientific practice, producing artifacts for prospective reuse. These tendencies of a *datafication of science* are supported by the increasing prominence of the data publication (Costello 2009), which enables researchers to

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make 'opening data' accountable within dominant gratification schemes in science (i.e. scientometrics, impact factors).

Chapter VI aims at drawing together several of the aspects discussed so far. It introduces the sea level rise (SLR) mapping project *Surging Seas* as an example of a harbinger of things to come. This includes data-driven predictions of climate change impacts, an increasing permeability of social worlds within the public engagement with science and technology, and the importance of a forward-looking impression within digital platforms and infrastructures. Branching from the concept of fluid technology (De Laet/Mol 2000), I propose a new terminology for a socio-technical understanding and investigation of digital science and technology. Digital technology may seem essentially fluid. However, rather than focusing on fluidity and fluid objects, I propose an attentive shift towards its *viscous elements*. Fluidity and viscosity are different sides of the same coin in fluid dynamics. Viscous liquids may be subject to changes of shape, but they are more persistent than other (more fluid or less viscous) liquids. Viscous elements affect the course of other elements, sometimes even organizing the fluidity of these others. In the context of this study, software libraries, packages and frameworks can be characterized as *viscous elements.* This will be illustrated by the case of the Leaflet Library, which enables the mobilization of interactive maps within the infrastructures and platforms of the web.

The conclusive chapter of the book summarizes the findings of the investigations and discusses permeability and digital openness as new boundary conditions of today's scientific modeling practice.