

**INTRODUCTION TO
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Special Section:

Historical, Philosophical and Sociological Perspectives on Earth System Modeling

Key Points:

- With the advent of climate change as a major challenge of our time, Earth system modeling has become highly policy relevant
- In this situation, the social mechanisms that play a role in any scientific endeavor become particularly exposed
- This paper introduces perspectives on “science as culture” and highlights relevant ideas from the three subsequent commentaries

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**Historical, Philosophical, and Sociological Perspectives
on Earth System Modeling**

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Abstract With the advent of climate change as a major challenge of our time, Earth system modeling has become highly policy-relevant regulatory science. In this situation, the social mechanisms that play a role in any scientific endeavor become particularly exposed. By discussing historical, philosophical, and sociological (HPS) aspects of the field’s current “cultures of prediction” together with the physical science community in a physical science journal, we aim to provide an entry point into HPS reasoning for climate scientists interested in reflecting on their field and science in general. This paper, first, introduces our perspective on “science as culture” and climate modeling as “regulatory science” and, second, highlights and connects relevant ideas from the three commentaries that follow it. In so doing, we hope to give a fuller picture of climate science, the interplay it engenders between HPS and the physical sciences, the distinctions that it gives rise to as compared to some of the more traditional, exact, sciences in which it is rooted and its place in society including its role in scientific policy advice.

1. Why Do Historical, Philosophical, and Sociological Perspectives Matter for Climate Scientists?

Some 360 years ago, Thomas Hobbes, natural philosopher and author of the political treatise *Leviathan*, and Robert Boyle, mechanical philosopher and inventor of the air pump, engaged in controversial debates over Boyle’s air-pump experiments. In their seminal study of the controversy, historians of science Steven Shapin and Simon Schaffer explore how acceptable methods of knowledge production were negotiated and how material technologies (the air-pump itself), literary technologies (the experimental report), and social technologies (Gentlemen witnesses) were mobilized to establish the cultural authority of scientific experimentalism. Shapin and Schaffer (1985) conclude the following: “As we come to recognize the conventional and artifactual status of our forms of knowing, we put ourselves in a position to realize that it is ourselves and not reality that is responsible for what we know.” (p. 344). In discussing the role of social factors in the production of knowledge, Shapin and Schaffer (1985) place particular relevance on what they call “technologies of trust” (p. 60). The (virtual) witnessing of a public assured that things had been done in the way claimed and served to “secure the assent of skeptics and bind communities together” (Hilgartner, 2000, p. 11).

In much the same way, what historian of science Paul Edwards has called the “climate knowledge infrastructure” (Edwards, 2010, p. 19) has worked as a “technology of trust” in successfully establishing anthropogenic climate change as a scientific fact. At its heart is the “vast machine” (Edwards, 2010) of climate modeling as material technology. The models’ ability to integrate the practical cosmos in ways that endeavor to remain faithful to known natural laws—and in so doing approximately reconstruct many features of the observed climate—makes climate models seductive surrogates for reality (Lahsen, 2005). The “truth-like” quality of their simulations, their integrative capacity, and the lack of better alternatives for a global society grappling with its influence on the trajectory of the climate system have given comprehensive climate modeling a hegemonic status, despite the concern that their simulations have well known, “pervasive and systematic errors when compared with observations” (Palmer, 2016, p. 2). Based on model simulations, the literary technology of regular Assessment Reports produced by the Intergovernmental Panel on Climate Change (IPCC) uses scientific consensus as a social technology for scientific policy advice. Since its inception in 1988, the panel has framed a stable climate as a common good and has become the role model of scientific policy advice on a global scale (Beck, Borie, Chilvers, et al., 2014; Beck, Borie, Esguerra, et al., 2014).

In the tradition of Shapin and Schaffer, this paper and the three commentaries that follow it present perspectives on “science as culture” and climate modeling as “regulatory science” that draw on the analytic repertoire of the history, philosophy, and sociology of science (HPS). The inherently complex nature of the climate system, the interaction between diverse scientific fields of inquiry as well as between science, politics, and the public sphere, and the different and often unquantifiable degrees of imperfection of simulations give relevance to these perspectives.

Boyle’s experimental culture in seventeenth-century England and the “cultures of prediction” of today’s climate modelers share many basic features, yet what distinguishes them is the temporality of their claims. While Boyle was concerned with establishing matters of fact by way of pneumatic experiments, climate modelers have moved beyond that scope and engage in what sociologist Gary Alan Fine has called “futurework” (Fine, 2010, p. 102; Heymann et al., 2017a). Based on an analysis of operational meteorology as an occupation between science and service, Fine argues that a public prediction is composed of four elements: gathered data, disciplinary theory, historicized experience, and institutional legitimation (Fine, 2010, Chapter 3). While the first three affect the ability to make a prediction, the fourth “speaks to whether the prediction will be taken as valid” (ibid.).

So Fine comes back to the relevance of social factors in the acceptance of matters of fact. This recognition is now commonplace in science studies, yet it deserves broader consideration among climate scientists because with the advent of climate change as one of the major challenges of our time, their field has become highly policy relevant. The aim of futurework is to give public and policy recommendations, and in this situation, perspectives from HPS crucially matter. This HPS standpoint does not deny, nor contradict, that individual researchers have all sorts of motivations for working in climate science, including advancing basic research and solving academic puzzles. Rather, it shifts the focus from the individual person to the field and its institutions and argues that a social position as “regulatory science” is consequential for any research field, including the field’s legitimation, funding, production, and presentation of knowledge (Eyal, 2019; see also Jasanoff, 1990). HPS scholars ask for these implications and study in how far being policy relevant impacts research agendas, funding structures, publication strategies, and knowledge practices in climate science.

Sociologist Gil Eyal has used the analogy of a three-lane highway to explain the implications of being “regulatory science” or “science for policy” for any scientific field (Eyal, 2019, p. 7f). On Eyal’s three-lane highway, the left, fast lane belongs to law and policy, those social worlds where decisions about how to act need to be taken here and now, at times one and for all, but certainly not too easily revisable. Eyal therefore calls legal and political decisions “closed facts.” The right, slow lane on the highway belongs to pure scientific research. Eyal calls it slow not only because of its own long-term temporality (including the potential to replicate, revise, and outright omit previous facts) but also because there is no rush to arrive at decisions about how to act. For both these reasons, Eyal calls scientific facts “open-forward” facts. On the middle lane, eventually, “the fast and the slow must adjust to one another” (Eyal, 2019, p. 7). This middle lane is the space of regulatory and policy science: “While the methods used in regulatory science may seem superficially similar to the methods used in pure research, they operate within a distinct temporal frame. To bridge open-forward scientific facts with closed, actionable legal and policy facts, regulatory facts take the form of cutoffs, thresholds, guidelines, surrogate end points, acceptable risk levels, consensus documents, expert assessments, simulations, stress tests” (Eyal, 2019, p. 8). The middle lane is where much of today’s climate research is now situated, a zone which is “contentious and crisis-prone precisely because it serves as the interface between scientific research, law and policy” (Eyal, 2019, p. 8).

Social mechanisms play a role in any scientific endeavor as the analysis of Boyle’s fundamental research shows. Yet the usual defense—that collective scrutiny may purify knowledge of any social bias in the long term—“falls completely flat when it comes to regulatory science, where one cannot wait for the long term, and where, therefore, the social mechanisms stand exposed in the glaring light of a decision taken in the here and now” (Eyal, 2019, p. 8).

It is the aim of this collection of historical, philosophical, and sociological perspectives on climate science to address some implications of the policy relevance of Earth system modeling. So far and despite the ability of the different fields of inquiry—HPS and climate science—to enrich one another, the lack of parity among the disciplines limits the bandwidth of their discourse. While newcomers from HPS perceive the need to

“study up” when they scrutinize their natural science colleagues (Hulme, 2011; Victor, 2015), this perception is usually not reciprocated. By addressing these questions together with the physical science community in a physical science journal, this introduction and the three commentaries that follow it aim to provide an entry point into HPS reasoning (and literature) for physical scientists interested in “studying up.” In so doing, we hope to give a fuller picture of climate science, the interplay it engenders between HPS and the physical sciences, the distinctions that it gives rise to as compared to some of the more traditional, exact, sciences in which it is rooted and its place in society including its role in scientific policy advice. Before we introduce the individual commentaries, let us briefly recall how this came about.

2. HPS on Stage

Events such as the Fourth International Conference on Earth System Modeling (4ICESM) in 2017 reflect the expansion of the climate modeling community, its professionalization, sophistication, differentiation, and specialization. Behind the large numbers of accomplished individual contributions, it also reveals—though less visibly—deep questions looming and unsettling limits of scientific wisdom. How well have climate modelers satisfied scientific expectations and brought clarity to impending questions? What is the role of climate models, what are their limitations, and what should they be? Why has the community and the evidence it produces proved less effective than some might have hoped in communicating its messages and fueling political action? Where shall the community steer in future years and what should be the guiding values and norms for the decisions needed? Exposed to these challenges for many years, climate modelers (at least a fair amount of them) have taken an interest in broader reflections and, at 4ICESM in Hamburg, for the first time at this conference, received contributions by a few strangers from disciplines such as HPS with openness, interest, and lively discussion.

It was with great curiosity that we as historians, philosophers, and sociologists of science entered the stage of 4ICESM. In his opening speech, the head of conference told an audience of nearly 250 international participants that the idea of cross-cutting presentations on the HPS of Earth System Science was to “nudge us out of our comfort zone” and to “make us uncomfortable.” Assigned with this task and trying to live up to expectations of being provocative, the six HPS speakers were taken with the openness with which the audience expressed approving comments as well as “amicable disagreements” (Stevens, 2017). It was especially practical issues of communicating the science in public and policy debates that attracted the attention of the audience, while some of the more conceptual considerations met with skepticism or dissent.

One of the talks introduced a model of society which suggests that there is no “global we” actor position in society, that is, no global political subject who could govern the planet, and—informed by scientific evidence—centrally understand, tackle, or even solve “the climate problem” (Grundmann & Rödder, 2019). During discussion time, a younger scientist asked in doubting disbelief: “Did you mean to suggest that we *cannot solve the climate problem?*” (authors’ emphasis). The answer given was that the aim of this conceptual consideration was to make the audience think about how “the climate problem” looks different from different positions and places in society and what “solving the climate problem” in our multiperspective society might actually mean, for instance, by which metric(s) one would measure its “solution”? This answer may not sit easily especially with junior scientists who have been socialized in a society in which “evidence-based” decision-making is a major quality seal and in which political appeals to “global solutions to climate change” oftentimes ignore social heterogeneity.

Another instance of dissent was a philosopher’s argument that satellite-based observations are interpretations rather than measurements. Such disagreement reveals different conceptual traditions. What is a measurement and what an interpretation? HPS disciplines’ central emphasis on the human construction character of practices, concepts, and knowledge in general is less familiar to most scientists. Terms such as “reality,” “fact,” “measurement,” or “faithful to natural laws” (which we have used in this introduction) appear self-evident but bear deep complexities that make students of HPS use them with caution. Decades of discourse in HPS show that concepts are simplifications obscuring their ambiguous, context-dependent meanings and human-constructed character (Restivo & Croissant, 2008). The multitude of individual human perceptions and shared social constructions suggests, for example, that there are many different conceptions of what is referred to as being “reality” (Paul-Choudhury, 2012).

Admittedly, HPS perspectives and research do not make problems (such as climate change)—and problem solving for that matter—look any simpler. Quite to the contrary, through the eyes of HPS, problems and problem solving look much more complicated compared to common conceptions of scientists and engineers. HPS scholars put emphasis on conceiving climate change as a social problem and thus suggest reassessing the reach and role of the natural sciences (Castree et al., 2014; Grundmann, 2016; Hulme, 2011; Jasanoff, 2010; Rödder, 2017). All the more surprising was the mostly positive resonance to the talks including requests to reread the presentations in print. We are happy to comply with this request with this collection of commentaries. To invite readers to the three further commentaries in this series, we will now briefly present some arguments and conclusions with regard to the topics “science as culture” and “regulatory science.” For the “science as culture” topic, we synthesize ideas from HPS for discussions of modeling practice (section 3.1) and epistemic challenges (section 3.2), and for the third topic, the science-policy relation, we present a sociological perspective (section 3.3).

3. Earth System Modeling in Historical, Philosophical, and Sociological Perspectives

3.1. Modeling Practice

Climate modeling emerged as a discipline in the shadow of the cold war, when military interests prioritized the use of the first digital computers for solving equations systems describing the atmosphere and its weather. Weather and climate modeling quickly emerged as powerful tools to investigate the atmosphere and to understand and predict the evolution of its state (Edwards, 2010, 2011; Harper, 2008). Numerical methods and computer technology facilitated a revolution in meteorology and climatology and the rise of a new research domain (Aubin & Dahan, 2002; Heymann, 2010b; Schellnhuber, 1999). Scientists invented specific practices such as model building, parameterization, validation, and numerical simulation and experimentation. They developed a specialized language to describe and communicate their endeavors and adopted appropriate norms as well as shared codes of practice in their everyday academic work (Gramelsberger & Feichter, 2011; Heymann, 2020). Researchers in HPS refer to this material, intellectual, and social backdrop of a scientific community with the term culture. Scientific fields and disciplines, just like social groups in broader society, represent and form specific cultures. This perspective is common and well accepted when we refer to national cultures but less common in the world of scientists. Still, it is important to understand the historical and social conditions of scientific practice and its performative functions. As for any social group, the decisions of scientists are informed, their interests are guided, and their interpretations are shaped by the culture of which they are part (Knorr-Cetina, 1999). In the tradition of Boyle’s experimentalism, climate scientists learn to see the world in specific ways—and tend to forget or do not learn to see it in other ways. In what the sociology commentary calls a “multiple worlds” society, this is the norm, not an exception (Grundmann & Rödder, 2019). Science is a specific way of reality making and world construction, one among several others.

Philosopher of science Gabriele Gramelsberger has referred to this characteristic of science as the normativity of science (Gramelsberger et al., 2019). Science produces perspectives and worldviews, which shape understanding and guide practice, and, hence, carry normative meaning (Sarewitz, 2004). Historian of science Matthias Heymann has explained this feature by describing the historical emergence of specific cultural codes in weather and climate modeling, which become self-evident elements of modeling practice embodying normativity (Heymann & Dahan Dalmedico, 2019). Cultural codes in science comprise all kinds of representations, which carry meaning, inform behavior, align practice, and contribute to create coherence. Climate modeling makes no exception.

The salience of cultural codes is usually not visible, because scientists have learned to share and comply with them largely unconsciously. Such cultural codes become visible only once they clash with others, meet with resistance, and cause conflict, as is typically the case in policy contexts. By the mid-1960s, climate modeling had become a small but well-established research culture, which shared cultural codes such as theory-based mathematical modeling, numerical approximation, parameterization, model experimentation, and a great pragmatism in dealing with the many shortcomings modelers have to live with. Likewise, since the 1990s, the simulation of future projections has become a cultural code in the climate modeling community, which thus has been epitomized a “culture of prediction” (Fine, 2010; Heymann

et al., 2017a). One example of the normativity of projections is its use for assessing geoengineering scenarios, even if many modelers feel uncomfortable with it (Feichter & Quante, 2017; Keith, 2000).

Philosophers and historians of science have shown that simulation, in the sense that climate science uses it, is an epistemic, social, political, and cultural machine that “changes our experience, our sciences, our very minds” (Keller, 2003, p. 201). One way in which simulation changes our scientific culture is through the tension it introduces between prediction and understanding (Held, 2005). Another way, paradoxically enough, is through its ability to merge descriptive and predictive cultures. Consider how the old discipline of comparative climatology is now happily practiced on model universes made available through exercises such as the World Climate Research Programme’s Coupled Model Intercomparison Project—although informed by different interests, concepts, and questions (Heymann, 2010a; Heymann & Achermann, 2018). Given the abundance of soft factors in climate projections (and many other domains in the Earth sciences) and the fact that uncertainty ranges of climate projections have not significantly narrowed in the past 40 years (Palmer, 2016), HPS researchers provocatively labeled Earth science a social science (Oreskes, 2015) and climate knowledge a “weak” type of knowledge (Heymann, 2020).

3.2. Epistemic Challenges

The complexities of the climate system, as well as the complexities of models, cause many epistemic challenges. Even the fact that there is no analytic way to solve the primitive equations with realistic initial and boundary conditions forces practitioners to accept compromise. The limited amount and quality of observational data and the limits of testing complex models have likewise been a matter of concern, both among modelers (McWilliams, 2007; Stevens & Lenschow, 2001) and HPS scholars (Guillemot, 2010; Oreskes et al., 1994). In addition, the need to base models on necessarily imperfect parameterizations gives rise to significant frustration (Randall et al., 2003). Climate models call for pragmatism and compromise, which allow impressive progress but also raise unpleasant questions. Is compromising with physical theory and understanding one deeper reason that model improvement appears increasingly difficult? Is there a limit to what future climate models can achieve? Which, then, is the best strategy to take for future climate modeling science (Bony et al., 2013; Guillemot, 2017; Held, 2005; Stevens & Bony, 2013)?

Climate models represent an impressively successful research paradigm in spite of disadvantages such as the condition of including unrealistic constructions (parameterizations) and demanding tedious efforts of iterative trimming and tuning. They helped to expand climatic knowledge significantly. Historian of science Amy Dahan Dalmedico along with others has emphasized the integrating character of climate models, calling them “unifiers” of a disunified science. She referred to this characteristic as “antireductionism” (Dahan, 2010; Heymann & Dahan Dalmedico, 2019). Still, the antireductionism of climate models coincides (or correlates?) with unsurmountable imperfection (McWilliams, 2007). Modelers need to accept many types of uncertainties. They are left without final proof or certainty that their models perform well for the right or the wrong reasons. They can neither be certain that their models would work in worlds with different physical circumstances compared to those scientists have met so far and learned to master (but these worlds may emerge in the future). The “holistic grasp” of Earth system models creates an epistemic opacity that makes analytic understanding of complex models of climate either extremely difficult or even impossible (Humphreys, 2004; Lenhard & Winsberg, 2010).

Uncertainty has become a particularly sensitive issue with rising public and political interest in climate science and its results. Within the IPCC, for example, scientists have attempted to domesticate uncertainty by carefully defining procedures, protocols, and terminologies for dealing with it (Heymann et al., 2017b). A virtual science of uncertainty itself has emerged (Landström, 2017). On the other hand, model diversity and the spread of model results have been conflated with uncertainty, a pragmatic but misleading trick, because all models could be wrong in similar ways (Masson & Knutti, 2011; Parker, 2010).

Philosopher of science Johannes Lenhard, accounting for the inescapable limitations of climate modeling, suggested describing the scientific understanding climate modelers offer as pragmatic understanding—obviously not a type of understanding that fulfills most scientists’ ambition for realism (Gramelsberger et al., 2019; Lenhard et al., 2007). Climate modelers have learned to be modest in this regard and to deal with (or get used to and ignore) critique that this condition repeatedly has elicited, although with a fair deal of annoyance and frustration, given many harsh treatments they had to bear, and with significant tensions

emerging within the climate modeling community (Bray, 2010; Grundmann, 2011; Hourdin et al., 2017; Mauritsen et al., 2012; Randall & Wielicki, 1997).

Given climate models undisputed importance for making sense of climate change and the fierce disputes surrounding the claims based on models, philosopher of science Wendy Parker proposes a radical remedy to seek relief from the goal of realism. Models, she argues, should be treated as tools that are only aimed at specific, well-defined, and clearly restricted purposes (Gramelsberger et al., 2019). The realism of models, hence, is an irrelevant objective, as long as the models work adequately for the envisaged purpose. Parker calls this the Adequacy-for-Purpose principle. It is open, however, whether this strategy would be accepted in the climate modeling community and serve as a shield against undue assaults.

3.3. Modeling as Regulatory Science

The complexities of the climate system pose continuous challenges to the climate modeling community, yet these are dwarfed by the complexities of driving on the middle lane, “at the seam of inevitable friction” (Eyal, 2019, p. 8). Many would have expected, not the least climate scientists themselves, that with the accelerated pace of both normal and regulatory science on the right and middle lane, traffic on the left lane, the world of politics and law, would have adapted to the middle lane speed recommendation. This reliance might be traced back to the cultural authority of science and technology in our society in general (Jasanoff, 1990, 2004), as well as to the successful agenda setting of the IPCC in the climate debate in particular (Beck, 2009; Gupta, 2010). Yet sociological reasoning suggests that such a linear model of policymaking looks at social problems with an engineering logic and overestimates the role and relevance of scientists and scientific evidence in navigating traffic on the fast lane.

Based on general social theory, sociologists of science Reiner Grundmann and Simone Rödder in their commentary critically engage with what they call an “evidence first” model of the science-policy interface, namely, the assumption that better scientific evidence will be more policy relevant or even lead to better climate policies (Grundmann & Rödder, 2019). The question is, can we envisage that there is a direction in which information flows between the social worlds, or traffic lanes, of science and policy, through the middle lane of regulatory science? Who is in the driving seat on the middle lane? Based on what they call a “multiple-worlds model of society,” Grundmann and Rödder argue that the policy relevance of the IPCC can only go as far as to where it encounters the logics of the political system, where scientific knowledge alone is rarely effective in compelling public policies. In conclusion, it is more appropriate to think of evidence and assessment reports as serving a political function such as the legitimation of certain (a priori) policy preferences (Geden, 2015). The “evidence-first credo” is a case in point of the depoliticization of the political world, as it assumes that political progress in dealing with climate change requires convincing people about the science (Sarewitz, 2011). The result of this depoliticization is a lack of progress in climate policy as science has taken center stage but is unable to offer political solutions (Grundmann, 2018).

Simultaneously, the literary and social technologies of the IPCC politicize climate science. With the establishment of the panel, governments wanted to control scientific statements on “an issue which was accelerating on the policy agenda more rapidly than most leaders in the North were comfortable with” (Haas, 2014, p. 580). Especially the emphasis on consensus seems misplaced and the scientific agreement (as documented in IPCC reports) has not been policy effective (Grundmann & Rödder, 2019). Grundmann (2018) has argued that “the consensus pertains to minimalist statements such as those that observed temperature increases are most likely the result of human activities” (p. 437). At the cutting edges of climate research, more—and more specialized—research usually produces contradictory evidence and hence complicates the knowledge base (to name but three issues: climate sensitivity, extreme weather events, and negative emissions and geoengineering; cf. Marotzke et al., 2017). More research usually provides resources for many different policy options (Grundmann & Rödder, 2019). Acknowledging scientific controversy in these matters is not the same as rejecting climate change as a global policy problem. Yet it raises questions about the “rightful place of science” (Sarewitz, 2009) in political decision-making as well as about implications of the politicization of climate science. For example, the social technology of scientific consensus has proven vulnerable to the exposure of exclusionary practices and active “consensus-making” such as in Climategate (Hulme, 2013, p. 146; see also Grundmann, 2011).

4. Concluding Remark

As practitioners drawn from the slow lane and overpasses of Eyal's highway, we found the experiment of confronting scientists with the cultural assumptions of their trade to be an enriching one. To discuss how the field employs climate models as material technology, assessment reports as literary technology, and scientific consensus as social technology in scientific policy advice, hopefully helps scientists better appreciate the ways in which understanding develops, is accepted as such and influences—or not—the flow of human history. We are convinced that it crucially matters to reflect on the implications of being regulatory science for the field itself, including its credibility, research agendas, and knowledge practices. We very much hope climate scientists interested in these broader aspects will find new perspectives and worlds opened to them by this brief pit stop into the historical, philosophical, and sociological aspects of climate science.

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