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Epistemology and Politics in Earth System Modeling: Historical Perspectives

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Key Points:
- Earth system modeling initially thrived in a Cold War environment emphasizing prediction and control of the atmosphere
- The environmental era introduced a new massive challenge to Earth system modeling: its politicization and demands for long-term climate prediction
- More recently, Earth system models have become political agents and led to a problematic convergence of Earth system science and climate governance

Abstract This commentary provides a critical account of Earth system modeling history. It argues that Earth system modeling is not simply a domain of science but also a form of politics. Earth system science carries the ideas and social and cultural norms of the peculiar historical eras in which it emerged and grew. Systems thinking and a strong belief in the power of modeling have its roots in the early Cold War era. When the Cold War era gave way to a time characterized by economic stagnation, social unrest, and rising environmentalism, climate science absorbed the new cultural trend of environmental concern, while retaining an optimism and enthusiasm in the modeling paradigm. The post-1990s era reveals particularly clearly the political power that climate scientists unleashed. The modeling paradigm assumed hegemonic status, seized economic and social processes, and created not only scientific knowledge but also conceptions of political management of the Earth. The modeling paradigm, once a scientific strategy largely in the hands of scientists, has turned into a political agent in its own right, beyond the full control of the scientific community.

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1. Introduction

What does the history of science have to contribute to the understanding of climate modeling? Historians have shown that science is not an autonomous and independent space but dependent on and in many ways interacting with politics and culture. Likewise, science does not simply produce scientific knowledge, which can be used or not—even though this is what most scientists believe. Science constructs concepts, understandings, and worldviews, which in complex ways interact with and shape science and society. Social scientists often speak of a coproduction of science and social order (Jasanoff, 2004).

Earth system modeling is no exception. The modelers are part of a scientific culture, which determines standards of practice and social interaction, shared values and norms, specialized language and forms of communication, and disciplined ways of looking at the world and engaging with it. Like any other scientific domain, Earth system modeling bears the imprint of its history and of the politics and culture in which it emerges and operates. Earth system modelers today are faced not only with the task of solving complex scientific problems but also with coping with the traces of the Cold War and the post 1970s environmental era. In addition, Earth system modelers must deal with the current social, political, and cultural obsessions ranging from climate catastrophism to lack of interest about and denial of climate change.

Climate and Earth system modeling have experienced impressive advances and can boast of significant accomplishments. Weather and climate modeling found its birthplace and its early identity in the intellectual atmosphere of the Cold War. Climate modeling rose from a tiny research field of a few dozen people in the late 1950s to a huge research domain comprising several thousand scientists at the close of the previous century (Edwards, 2010; Weart, 2018). On this path, deep transformations in politics and culture, such as environmentalism, globalization and postmodern values, shaped and changed scientific ambitions, social roles, and the self-understanding of climate modelers (Edwards, 2010; Henderson, 2014; Heymann, 2019a).

Climate and Earth system modelers constructed increasingly complex representations of processes in the atmosphere and, later, the whole Earth system. Climate modeling emerged from a specialty garnering little attention outside the climate modeling community to a prime example of powerful science with great public relevance, having a huge impact on perceptions, discourse, and politics. Climate modeling "survived" immense epistemic challenges, such as dealing with uncertainties and with the limits of knowledge (as, e.g., about cloud processes and aerosols). It managed tremendous social expectations, such as the demand for long-term projections of climate change. And it weathered malicious political attacks, such as attempts to undermine the authority of climate science by interest groups during the 1990s (Oreskes et al., 1994; Oreskes & Conway, 2010). Since its beginnings, climate modeling has struggled continuously for the assurance, serenity, and certainty of a well-established and powerful research domain (Marotzke et al., 2017; Palmer, 2016).

Despite the notable accomplishments of climate modeling, frustrations persist in the Earth system modeling community. Some modelers feel as if they are prisoners caught within the confines of unsurmountable barriers. For example, restrictions in mathematics and computer power limit the extent to which scientists can fully grasp the complexities of climate and the impacts of its change. Tireless efforts to improve models and the knowledge based on them appear partly corrupted in recent years by the lack of decisive progress (Bony et al., 2013; Randall et al., 2003). Unsettling questions need to be raised: How well do Earth system modelers really understand atmospheric, climatic, and Earth system processes and their interaction? And how well do they understand the models devised to represent them? Why do the models not improve in the ways that scientists expect or hope they will?

Just as unsettling are the complexities of politics. An ethos of serving society with knowledge about climate change, an ethos shared by many modelers, and one in which they have invested so much for almost three decades, appears foiled by disagreement over effective climate politics (Beck & Mahony, 2018; Schellnhuber, 1999). Why have the messages of climate scientists apparently failed to facilitate and fuel purposeful political action? What are the barriers to appropriate climate policies? After many years of political demand for climate projections, Earth system modelers have recently raised fundamental questions about scientific priorities and future directions. Should the modeling community continue to focus on climate prediction? Or should it readjust priorities with stronger focus on a better understanding of basic climatic processes (Bony et al., 2013; Held, 2005)?

These are big questions. Historical research will not answer these questions but can contribute to placing these questions in a broader perspective. This article will provide an account of the stages of historical development to which the science of climate and Earth system modeling owes many of its strengths and peculiarities. It attempts to convey the argument that climate modeling experienced not only significant changes in its scientific mission and social and political roles but also became an active element in the shaping of climate politics. In recent years, however, climate modelers gradually lost ownership and control of the political use of their epistemic tools. The following sections offer an interpretation that seeks to explain how these changes came about. The future, however, is open. Historical knowledge and sensitivity may offer some additional guidance for decisions ahead.

2. 1945–1970: The Cold War and the "Ontology of the Enemy"

Hardly anybody today would see modern climate science as driven by geopolitical tension and the idea of global competition and war. This, however, was the breeding ground of new scientific ideas and practices from which climate modeling and deep transformations in the culture of climate science emerged (Edwards, 2010; Hart & Victor, 1993). A look back to climatology in the 19th and early 20th centuries helps to make the novel peculiarities of this culture visible. Climatology, as conceived in the 19th century by Alexander von Humboldt and others, was a very different endeavor, before World War II and the Cold War ushered in a new era of atmospheric and climate science. This, often called, "classical climatology" was a geographical, descriptive discipline, invested in the collection and analysis of vast amounts of meteorological data from which climatologists hoped to derive patterns and knowledge of climate. In addition, it was a science dedicated to serving human affairs ranging from agriculture and forestry to transport and industry. Climate was associated with a specific geographical location and directly linked to human experience and needs (Heymann, 2010, 2009).

Classical climatology thrived in the age of imperialism with its population growth, burgeoning colonial aspirations and new demands for climatic knowledge (Morgan, 2018; Livingstone, 1993, pp. 216–293). Bjerknes's path-breaking primitive equations, first formulated in 1904, represented a foreign approach to classical climatologists, who were not well versed in mathematical physics and working with differential equations. In the eyes of dynamic meteorologists, these equations bore the promise of a comprehensive physical understanding of the atmosphere. For most climatologists, however, they clashed with established priorities, values, and norms. The primitive equations implied a physical reductionism, which was foreign to the holistic ideal of climatological detail and comprehensiveness, and effectively canceled human affairs out of the equation. Many climatologists neither paid attention to nor understood or trusted the high-flying theoretical ambitions, approximations, and mathematical manipulations involved in using these equations but rather relied on established empirical evidence (Endfield et al., 2015; Heymann, 2010, 2009; Martin Nielsen, 2015; Martin-Nielsen, 2017; Sörlin, 2011).

After World War II, traditional climatological wisdom persevered, though it was much less visible as a research field. An example was United Nations Educational, Scientific and Cultural Organization (UNESCO)'s Arid Zone Program, which aimed at investigating regional climatic extremes and problems of drought and desertification (UNESCO, 1963). This program entailed a Humboldtian type of holism: the extensive and detailed, empirical investigation of specific regions' climatic conditions with the help of knowledge and expertise from a large diversity of disciplines including meteorology, climatology, geography, hydrology, geology, plant ecology, and vegetation history (Wallén, 1963, p. 469). The UNESCO program was an exception, however. The climatological research culture it represented lost significance and support after World War II (Heymann, 2019b). The Cold War era and its politics of science strongly privileged other directions and ambitions.

The conditions of World War II and the early Cold War furnished science and technology with new tools, such as computers, rockets, and systems science, and hitherto unseen authority, resources, and expectations. Erickson et al. (2013) coined the term "Cold War rationality," which describes the deep belief pervading this era that all systems, natural and social, could be understood, modeled, and controlled, provided sufficient resources were made available. Science acquired a central place in the heart of American society, guided by key concepts such as internationalization, colonization, extension of inhabited spaces such as the Arctic and Antarctica, conquest of space, and fully mastering the physical environment of the Earth. The expertise regime of this period was guided by a simplified conception of a linear pattern: Scientific research and knowledge had to guide political decisions. This proved a very profitable system for researchers, who were clever enough to offer scientific endeavors and goals aligned with the Cold War obsession with science that focused strongly on the physical and Earth sciences.

The Cold War was a peculiar historical era characterized by a cultural hegemony of war. Cold War thinking pervaded scientific conceptualizations and practices. An "ontology of the enemy" constituted the epistemology of this time (Galison, 1994); that is, the antagonism of the superpowers constituted a basic category of the understanding of reality. Military competition on a global scale infused all layers of culture and determined the new and expanded roles of science and technology. Historians of science have amply shown the pervasiveness of this Cold War epistemology for disciplines ranging from physics and the environmental sciences to molecular biology and psychology.[1] At the same time, the sciences took a pragmatic turn during and after World War II. A focus on operative, predictive results, and application succeeded a predominance of the ideal of expanding fundamental, coherent knowledge of natural phenomena, and laws of nature.

Meteorology, profiting from the links between scientists and the military, was firmly rooted in this tradition. Cold War interests resonated particularly well with the promises of meteorologists. The development of computers, a product of the war, helped make nonlinear differential equations tractable and allowed for the possibility of applying many complex equations at once. The development of computers also fueled enthusiasm and allowed for far-reaching political promises. These included practical applications of great value such as controlling the atmosphere through science-based weather prediction and weather and climate modification—strong arguments in an era of geopolitical ambitions and military rivalry (Fleming, 2012; Harper, 2017). These promises reflected the obsession of gaining and maintaining control of foreign powers as well as of the powers of nature and the environment. In hindsight, the new Cold War ambitions caused a "phase change" (Agar, 2006) in the investigation of climate that paved the way for a new emerging culture of climate modeling.

[1]Authors such as Daniel J. Kevles, 1995, writing on physics; Amy Dahan Dalmedico, 1996, on mathematics; Peter Galison, 1994, on cybernetics; Lily Kay, 2000, on genetic coding; Robert Leonard, 2010, on game theory and experimental psychology; Ronald E. Doel & Heymann, 2016, and Jacob D. Hamblin, 2005, on geophysics; and Paul N. Edwards, 1996, 2010, and Erik Conway, 2008, on computer and atmospheric science unanimously made this point. For an overview of Cold War science see Needell, 2000; Dahan Dalmedico & Pestre, 2003; Dahan Dalmedico & Pestre, 2004; and Heymann & Martin Nielsen, 2013.

The atmospheric sciences soon occupied a comfortable seat in the new state-driven funding carousel. It helped leading meteorologists such as Carl-Gustav Rossby, Jule Charney, Norman Phillips, and Syukuro Manabe in developing the practices and standards of new modeling communities. Only in this time did the study of climate fully emerge as a physical science, which shifted focus from geographical detail to causal understanding. While weather prediction was the focus, by the 1960s, climate modeling had become a small, but well-established research culture. This research culture was characterized by particular practices, such as theory-based mathematical modeling, grid-based numerical approximation, radical simplification to make nonlinear differential equations numerically solvable, the development of model hierarchies from simple, unrealistic to more comprehensive and realistic models, strategies of parameterization, tweaking and tuning, model experimentation, and validation (Dahan Dalmedico, 2001b). The small climate modeling community enthusiastically embraced these epistemic practices, which, however, remained controversial in the broader climatological discipline.

Not all scientists shared the new directions and conceptions of science during the Cold War, which emerged most powerfully in the United States but also in many other countries. Physicists were divided between those approving (and profiting from) applied military research and those objecting to the influence of the military-industrial complex and in favor of theoretical research of the laws of nature (Kevles, 1995). Mathematicians debated the rise of applied mathematics dedicated to serving practical interests and solving technical problems, with some being in favor of a pure form of mathematics “in the honor of the human spirit” (Dahan Dalmedico, 2001a). Many meteorologists viewed ambitions of weather and climate modification with much more reluctance than enthusiastic politicians and hopeful farmers (Harper, 2017). Likewise, many climatologists did not easily accept the new practices and standards of computer-based and theory-driven modeling, which reduced climate to a purely physical phenomenon, neglected historical and geographical knowledge about climate, and increasingly marginalized traditional values of empirical comprehensiveness, detail, and rigor (Heymann, 2009, 2010; Martin Nielsen, 2015; Martin-Nielsen, 2017).

3. 1970–1990: Perceptions of Chaos, Social Unrest and the Emergence of a New Zeitgeist

In the post-1970s era, further significant cultural transformations proved to be of foundational importance to perceptions of climate and climatic problems and the development of climate modeling. Historians have described the 1970s as a time of deep social, political, and cultural transformation (e.g., Ferguson et al., 2010; Jarausch, 2008). This time is marked by the two oil crises and the transition between the growth regime of the “Trente Glorieuses” (Fourastié, 1979) or “Golden Age” (Hobsbawm, 1994) of economic growth to the resulting new regime of stagflation with social unrest, environmentalism, globalization, and neoliberalism on the rise. The techno-optimistic drive of Cold War rationality faltered in favor of more pessimistic perceptions of a complex and chaotic world (Beck, 1992). Among others, new, politically engaged forms of applied science emerged as a response to new perceptions of conflict and crisis such as in the environmental sciences (see Egan, 2017; Graf, 2017; Heymann, 2017).

This period also saw the emergence of a broad interest in chaos and disorder in disciplines such as mathematics, physics, environmental science, computer science, and engineering. Physicists, to take one example, aspired to a more down-to-Earth science and a return to the concrete and macroscopic character of phenomena. They increasingly opposed highly theoretical, abstract particle physics and the rigid forms of organization in hierarchical institutions of big science such as huge high-energy physics laboratories—a typical product of Cold War science (Kaiser, 2011; Kevles, 1995). James E. Lovelock, likewise, exemplified this turn. Starting his career in the early Cold War, he began his work infused with the epistemological priority of physics, mathematics, and information theory, before he moved on to an epistemological regime of environmental sciences inspired by biological systems thinking (Dutreuil, 2018; Ruse, 2013).

The vogue of change spread far beyond scientific communities and reached many spheres, intellectual, managerial, political, artistic, and so forth, which contributed to the “making of new worlds,” where concepts such as instability, branching, uncertainty, emergence, or scenario attracted increased attention. The logic of scientific reasoning, the relation between causes and effects, had changed and become more complex: Many important features of the world proved nonlinear, a small detail could bring forth a catastrophe.

Complexity, which scientists formerly held to be reducible into elementary units, turned out to be irreducible. A comprehensive, global approach in dealing with complex problems became important. The immensely successful scientific strategy of reductionism seemed to have reached its limits. Some authors even announced its end in the near future (Dahan Dalmedico, 2004).

These changes of perception and representation of the world also upset the hierarchy of the disciplines. Mathematics and theoretical physics lost their dominant position, whereas the life, Earth, and environmental sciences conquered the new Pantheon of science. Research across disciplines became a primary objective (Gibbons et al., 1994). A joint physical, biological, and social approach to the investigation of human beings and nature, such as was common in many domains of the environmental sciences, turned widespread, together with such notions as risk society, precaution, and sustainable development.

This era strongly affected the development of the atmospheric and climate sciences. In particular, the rise of the environmental movement and the perceptions and cultural values it brought with it had a deep impact on the culture of climate science. Environmentalism established a new environmental paradigm, which shifted the perspective from the Earth as a resource for human purposes to the Earth as a planet endangered by human activity (Caldwell, 1996). Enthusiasm for weather and climate modification in the Cold War era gave way to opposite perspectives on climate: concern about inadvertent climate change due to human emissions of greenhouse gases. A new style and language of concern characterized scientific assessments of the environment and atmosphere and put climate change on the scientific agenda (SCEP, 1970; SMIC, 1971).

Climate modelers, who had operated largely ignorant of and undisturbed by environmental concerns during the 1950s and 1960s, experienced a deep cultural shift during the 1970s. The idea of impending risks about future changes of climate—though believed to occur potentially decades ahead—introduced a new massive challenge: the politicization of climate science with increasing demands to investigate climate change and serve politics with long-term climate prediction. This was not an insignificant charge. The first generation of modelers of atmospheric circulation and climate, such as Norman Phillips, Joseph Smagorinsky, Syukuro Manabe, and Akio Arakawa, primarily pursued the goal of improving the physical understanding of the atmosphere, even though the possibility of global warming due to carbon dioxide emissions had been known for some time.

A new and younger generation of modelers, such as Stephen H. Schneider and James E. Hansen, propagated a strong language of concern about future climate change since the early 1970s. They helped move the art and science of climate modeling toward the goal of prediction, in order to inform society about the potential threats of future warming (Heymann, 2012; Heymann & Hundebøl, 2017). Hansen explained the objective in plain words: "We're taking the model and using it for climate applications" (Weart, 2000). In 1981, he and his team published the results of the first simulated climate projections with a one-dimensional climate model in *Science* (Hansen et al., 1981).

This work met with strong criticism. Many scientists deemed the understanding of the mechanisms and causes of climatic trends and fluctuations far from sufficient for such projections. Models were still very simple and coarse. They ignored important processes and suffered from immense uncertainties. More than half of the *Science* article by Hansen and his coworkers was dedicated to the discussion of uncertainties such as the lack of knowledge about vegetation albedo feedback, ocean processes, tropospheric aerosols, and "the nature and causes of variability of cloud cover" (Hansen et al., 1981, pp. 958–960). Still, Hansen and his group put trust in their climate model and its projections. They concluded "*improved confidence* in the ability of models to predict future CO_2 climate effects" (Hansen et al., 1981, p. 964; emphasis in the original).

With the work of Hansen and others, climate projection was in the world—and it was to remain so, becoming a core exercise of climate modelers for the Intergovernmental Panel on Climate Change (IPCC) assessments since the early 1990s. The decision to pursue predictive modeling was a significant one, because it involved new priorities as well as adjusted practices, standards, and research strategies. It demanded channeling scientific and institutional resources from the development and testing of models to model application, from struggling for better understanding to full-scale simulation of climate projections (Held, 2005). It called for further radical pragmatism and an adjustment or softening (some regarded it an erosion) of scientific standards and ideas of what represented good and bad science. Doubts about deterministic climate modeling, as raised by Edward Lorenz since the late 1960s, subsided rather than being addressed. Many

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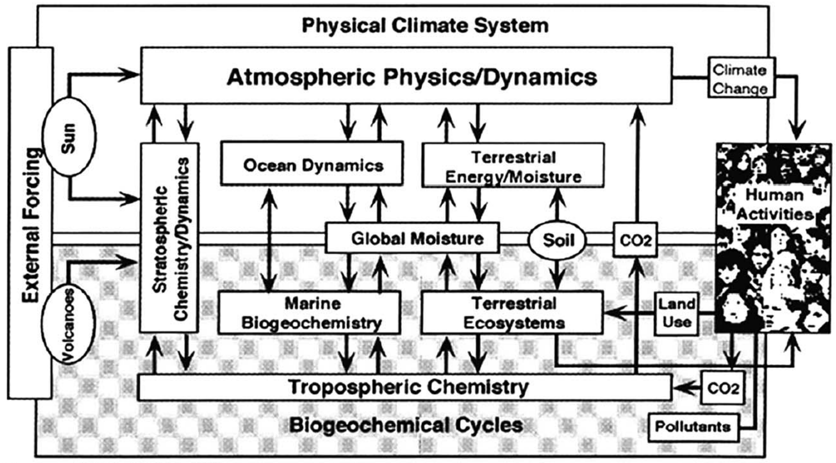

Figure 1. The Bretherton Diagram of the Earth system (Source: National Research Council, 1986, p. 19).

uncertainties persisted. Parameterizations, in spite of improvements, remained a weak point and matter of debate (Guillemot, 2017a; Heymann, 2012; Heymann & Hundebøl, 2017).

The politicization of climate modeling went along with still another deep cultural change: climate science went public. Schneider and Hansen proved also pioneers in addressing public audiences with alarming claims to raise political attention. Schneider published in 1976 the influential popular book *The Genesis Strategy: Climate and Global Survival*, which made him a celebrated public figure, and led to his appearance on the popular Johnny Carson TV show, as well as other venues (Henderson, 2014). Hansen leaked his 1981 article to the *New York Times*, which featured a front-page article "Study finds warming trend that could raise sea levels," just a few days before the *Science* paper came out (Heymann & Hundebøl, 2017).

These attempts to maximize public attention, in spite of the uncertainties of the science, represented a strong offense against the norm of scientific reticence, a norm that still the majority of climate scientists subscribed to, particularly in the cases of uncertain science. The approach of maximizing public attention in regards to climate science resulted in criticism, debate, and rejection (Hansen, e.g., lost funds from the Department of Energy). Only a few years later, however, public communication of uncertain science became a standard exercise with the mission of the IPCC.

4. Post-1990s: Earth System Modeling and the Climatization of Politics

Climate modeling inherited Cold War system thinking. Comprehensive reports of the early 1970s clearly show climate scientists' appreciation of the systemic character of climate and its dependence on the interactions and feedbacks of atmosphere, hydrosphere, cryosphere, biosphere, and so forth (SCEP, 1970; SMIC, 1971). Since the 1980s, quickly expanding knowledge and computer power facilitated giant leaps forward in transforming the system idea into computer code. Reflecting the Gaia vision of an Earth as a complex system of interacting entities, Francis P. Bretherton, director of the National Center for Atmospheric Research from 1974 to 1980, coined the term Earth System Science (Bretherton, 1985). In 1986, he led the way to Earth System Modeling with his famous diagram (Figure 1)—along with similar conceptions of like-minded allies (Schellnhuber, 1998; Uhrqvist, 2015; Lax, 2016, 2018; Edwards, 2010, ch. 7).

This systemic approach advanced progressively. Climate modelers, first, coupled representations of atmospheric processes on different scales. They added crucial couplings with ocean models; generalizations of couplings with ice and soil models; and, later, with chemical and biological models. Since about 2000, the carbon cycle and its feedbacks have become a prominent component of climate modeling. The stronger focus on the carbon cycle led to a profound change in the modeling of the climate with its center of gravity shifting from the atmosphere to the soils and biogeochemical cycles. A modular conception of couplings enabled progressive system integration. With its simulation and validation procedures, its comparison protocols, and its interfacing projects, this methodology seemed able, at least in theory, to allow limitless scientific progress (Uhrqvist, 2015).

The "one model to fit all" strategy (Uhrqvist, 2015) fueled great intellectual and institutional enthusiasm among scientists. First, Earth system models (ESMs) bore the deeper promise to integrate all relevant knowledge and unite a dis-unified science that had fallen apart in autonomous and little connected disciplines and research domains (Galison & Stump, 1996). While the rhetoric of a unity of science, associated with the logical positivism of the 1930s, had long been abandoned, ESMs offered compensation as unified representations of the (geo-)physical world. German climate scientist Hans Joachim Schellnhuber judged this holistic grasp of Earth system modeling a "second Copernican revolution" (Schellnhuber, 1999).

Second, Earth system modeling gathered and connected a large number of disciplines and research domains in a collective venture. It involved a progressive process of networking and the reconfiguration of the scientific communities, which had to grow together to contribute to comprehensive models. Formerly, scientists regarded the language and grammar of mathematics as a major unifying force in science. Now, fast computation and numerical modeling had become the next big thing. The Humboldtian holism of classical climatology—assembling empirical knowledge from all relevant disciplines—was elevated to the level of model holism in Earth system science (Heymann & Achermann, 2018; Uhrqvist, 2015).

Third, the amalgamation of models and disciplines paralleled the amalgamation of scientists, institutions, and nations in large programs of international collaboration, a development that had started already since the late 1950s. Efforts such as the Global Atmospheric Research Program, the World Climate Research Program, the International Geosphere-Biosphere Program, and the IPCC facilitated and supported the systemic approach. In this context, the climate and Earth system modeling community had grown from minor beginnings to a powerful, international force.

4.1. Politics and Economics Seize Modeling Practices

Since the 1990s, modelers had to accept what a decade earlier many deemed highly contentious: Modeling the Earth system had become political. The notion of model appeared as an essential tool in binding science and political action. The IPCC manifested the emergence of a new regime of expertise in which the community of scientists was conditioned and formalized by issues on the political agenda. The model as such lost attention as a goal in its own right. Instead, modeling as a projection activity for political purposes, the generation of possible or desirable climate futures decades ahead, gained predominance. So the evolution of models toward taking a better account of ecosystems and their interaction with the climate paralleled the rise of the political theme of adaptation in the negotiations of the climate regime and the political stakes associated with it (Dahan Dalmedico, 2007).

This culturally and scientifically significant shift yielded a multiplication of resources, work force, and public attention. Hosts of scientists advanced from dealing with scientifically important tasks to dealing with politically important tasks in the framework of the IPCC's mission. Scientific work became dressed with a considerable ethical task and responsibility (some may have felt it an ethical bind). Fittingly, Schellnhuber likened the climate scientist of the late 20th century to a physician of the Earth, one who sought knowledge with the purposes of healing the Earth. The idea of the Hippocratic Oath and the social role and status it brought to physicians appeared to have been expanded to Earth system scientists (Schellnhuber, 1999).

Predictive modeling as a political venture did not only affect conditions and tasks of climate modeling. It fueled an expansion of the holistic aspiration, which in turn further affected the status and role of climate modelers. First, scenario, rather than model, became a key concept and depended on social and economic competence. Scenarios expressed the spatial and temporal coherence of assumptions about climate forcing by anthropogenic disturbance through numerical forecasts and story lines. Scenario building, thus, opened doors to further scientific communities—engineers, economists, sociologists, and biologists (interested in the interactions between carbon cycles and vegetation and forest cover)—to contribute to developing scenarios. The IPCC established scenarios based on variable criteria of openness and resilience of contemporary economies and provided a coherent framework for all simulations carried out for the first four IPCC reports.

Second, the modeling paradigm expanded in the realm of the social and economic sciences. Researchers in these disciplines developed so-called integrated assessment models (IAMs), which made use of the data produced by ESMs to evaluate the effect of economic and environmental policies on environmental and climate change and its social and economic impacts. IAMs are not geophysical but socioeconomic models integrating several modules (demography, economy, climate, land use, energy use, etc.) that, taken together, aim at describing how different parameters change over time under different constraints (such as a temperature target). IAMs served for generating knowledge about impacts and the consequences of mitigation and adaptation policies. They could be combined with economic cost-benefit calculation tools, as illustrated by the Stern (2007) report (Armatte, 2007; Dahan Dalmedico, 2010).

With the development of IAMs, the modeling strategy became an aggregator of epistemic cultures more than ever—and a more or less shared tool of government. Obviously, ESMs and IAMs belonged to entirely different classes of models subject to different scientific practices and standards. Taken together, however, they represented a powerful knowledge regime. By linking ESMs and IAMs and using them, scientists constructed a new world. This knowledge regime bore performative agency in its own right. It disciplined scientists to see the world in certain ways and act according to the standards of practice it imposed. It shaped interests, perceptions and worldviews, and the transformative agendas they propelled. Models fabricated a shared understanding and vision of the world. What models, simulations, and the ways to make sense of them did not reveal remained outside this world.

For Earth system modelers, this meant to be socialized with and immersed in specific norms, values, and epistemic practices and standards, which defined their scientific culture. It included accepting (or getting used to) imperfection, pragmatism, and uncertainty, from which reliable knowledge had to be derived. The construction and integration of submodels under conditions of complexity and limited computer power required compromise, approximation, and workaround strategies along with extended efforts of tweaking and tuning (Edwards, 2010, ch. 13; Heymann & Achermann, 2018).

ESMs also became increasingly loaded with complexity and uncertainty; computational processes in turn became increasingly inscrutable (Lenhard & Winsberg, 2010). Francis Bretherton put it concisely: "the more complex the model, the messier the garbage" (quoted in Fisher, 1988, p. 55). Modelers conscientiously adjusted their practices and norms to these conditions, even if not all felt comfortable with these practices in the same way (Shackley, 2001). The long silence and secrecy about the black box of model tuning, which modelers opened only very recently, reveals the uncertainty and ambiguity surrounding it and the fears about charges of model manipulation (Hourdain et al., 2017; Mauritsen et al., 2012; Voosen, 2016).

The hegemony of models in this knowledge regime also provoked critique. The integration of reductionist quantitative models does not overcome reductionism (Hulme, 2011). A quantitative, equation-based logic of ESMs and IAMs does hardly represent the complexities of social processes and society-environment interactions sufficiently. Furthermore, the modeling paradigm "has served to marginalize other, less reductionist ways of understanding global climate change," by largely excluding, for example, historical and sociological perspectives and local and indigenous types of knowledge from climate research and discourse (Cohen et al., 1998, p. 345). The global grasp of models, along with its limited spatial resolution and reduced attention for local detail and complexity, made Earth system science "a microcosm of the globalization syndrome" (Clifford, 2009, p. 359) and an agent "of globalizing reductionism" (Heymann & Achermann, 2018).

Researchers in the humanities, who investigate human-environment relations, have in recent years criticized the neglect of the human dimension in climate research and demanded climate scientists pay more attention to it. Earth system modeling, obviously, puts natural processes in the center, whereas human activities and affairs only represent a boundary condition (as in the Bretherton diagram that depicts human activity at the margin). Though humans are a key factor in climate change "as a driving force, a subject of impacts, or an agent in mitigating impacts and adapting to change" (Holm et al., 2012, p. 25), the IPCC never included expertise about the complexity of human action and behavior.

4.2. The New Ontology of Earth Management and the Failure of Climatization

The outstanding feature of integrated modeling is less the nature of the models and of modeling practices itself than its societal uses. These include the simulation of projections of future climate, the assessment of costs or policies, and the negotiation of political strategies and protocols. Sebastien Dutreuil (2016) suggested that Earth system science ushered in a new ontology. The "Earth system" as a new ontological category involved the connection and conflation of science and governance. Scientists, the builders of the Earth system, fabricated two things at the same time, a system of knowledge production and a system of management of the Earth. The Nobel Prize awarded to the IPCC in 2007 can be taken as evidence for this convergence of Earth system science and environmental and climate governance.

The new Earth system ontology drove effectively a twofold development in the last decade or so, which the U.N. Framework Convention on Climate Change Conference of the Parties (COP 21) in Paris in December 2015 even amplified. On the one hand, it effected a *globalization* of the climate problem through the inclusion of new issues such as development, energy, forests, biodiversity, global inequality, and urban planning into the climate regime (Aykut & Dahan, 2015). On the other hand, it caused a kind of *climatization* of the world by actors who presented issues, which were formerly unrelated to the climate regime, through a climatic lens (Aykut et al., 2017; Dahan Dalmedico, 2016). Recent climate conferences attract actors from very different backgrounds and sectors (oceans, fisheries, forests, agriculture, food security, etc.), who are affected by the climate problem and want to be stakeholders of the negotiations in order to defend their interests. These actors advocate their own interpretations of the climate problem, its causes, and possible solutions.

Globalization and climatization have made the climate regime an important public and political issue but have not contributed to achieving effective climate policies. To the contrary, these developments have caused a multiple schism of reality. One schism is the deep gap between the managerial vision of the climate problem in the UN arenas, on the one side, and the real world of politics as it works, on the other. The former world deals with scientific knowledge and the conclusions to be drawn from it. The latter world is marked by the violence of geopolitical power relations, unrestrained economic competition, domination by wasteful modes of capitalist production and consumption, and the destructive inertia of the ecological crisis. In addition, this schism fueled effects of selectivity. Debates on energy, particularly regarding fossil fuels, for instance, were in many ways hyperclimatized but surprisingly absent from the discussions and negotiations under the U.N. Framework Convention on Climate Change. The analysis of this "energy paradox" reveals that institutional interests and deliberate strategies of major actors in climate governance conspired historically to keep energy issues out of negotiation texts, not the least to avoid further complications and conflict (Aykut & Castro, 2017).

Another schism is the gap between the abstract, statistically and computationally constructed space of a global climate and the large temporal and spatial scales of environmental prediction, on the one side, and the embodied, visceral experience of weather and the horizons of everyday decision-making and meaningful engagement with climate, on the other (Heymann, 2018; Hulme, 2010; Jasanoff, 2010). Timothy Morton (2013, p. 58) calls climate change a "hyperobject"—something that is so vast, spatially and temporally, that it becomes "almost impossible to hold in the mind." A whole communication industry aims to translate the predictions of Earth system science for a variety of publics, bridging scales of space and time in a bid to manufacture engagement and political will (Callison, 2014). Yet, as a number of scholars have argued (e.g. Hulme, 2009; Latour, 2015), it is futile to expect that findings established by scientific observations or the power of scientific predictions motivate on their own a turn against the driving structural forces of global climate change such as against environmentally damaging capitalistic production and consumption.

4.3. A New Time of Fake Truths

Further setbacks occurred recently. U.S. President Donald Trump and right-wing elites in American society have brought an ignorant nationalist agenda to power, denied climate change, destroyed environmental regulation, and denounced the ideal of a common world that the post-WWII liberal dream and multilateralism have shared. With Trump, fake news, fake truths, and even fake science—deliberate disinformation and manipulation of truth claims and science—become common currency and political tools: The false solutions and the chimeras on which he builds policies introduce further uncertainties and risks in an increasingly disorderly and destabilized world. In the climate arena, questions about the scenarios of decarbonization cause further preoccupation; the epistemology of these scenarios seems to have disturbing parallels with this kind of policy.

Between COP 15 in 2009 in Copenhagen and COP 21 in 2015 in Paris, the 2° target was constantly reaffirmed in climate arenas. The 2° target, which was first proposed by the Commission of the European Union in 1996, described a consensus about the maximum allowable global warming to avoid dangerous anthropogenic interference in the climate, even though its utility and attainability were discussed controversially in scientific journals (Guillemot, 2017b). These disagreements, initially confined to a narrow scientific milieu, emerged publicly at the time of the Paris COP. At the COP 21 conference in Paris in December 2015, countries across the globe adopted an historic international climate agreement: to hold the increase in global average temperature to below 2°C, even to intensify efforts to limit the increase to 1.5°C, and to achieve net zero emissions in the second half of this century. Since Paris, however, notoriously insufficient commitments put us on a trajectory not of 2 °C, but rather of 3 or 3.5 °C (UNEP, 2016, 2017).

Paradoxically, in the same time span between 2010 and 2015, as greenhouse gas emissions continued to grow, a series of increasingly optimistic decarbonization scenarios were published. These 2° scenarios rely mainly on negative emissions technologies (NETs) that remove carbon from the atmosphere on a large scale. These scenarios are produced by IAMs on the basis of warming projections simulated with ESMs. The goal to remain below 2° warming in this century requires a very rapid drop in CO_2 emissions around the world leading to zero emissions within a few decades. As this goal seems to be unachievable, and since it is impossible for politicians to acknowledge that, the alternative is a temporary overshoot of atmospheric CO_2 concentrations, followed by sucking carbon out of the atmosphere in the second half of the 21st century through NETs.

Among these technologies, the most widely invoked in 2° scenarios is bioenergy with carbon capture and storage (BECCS). It consists in growing plants for bioenergy, burning them, capturing the carbon dioxide released in the process, liquefying it under pressure, and storing it underground. In the fifth IPCC report of IPCC Working Group 3 Mitigation of Climate Change (published in 2014), out of the 400 scenarios with a 50% probability of warming below 2° in 2100, 344 assumed large-scale use of BECCS (the others assumed that emissions would peak in 2010 and are thus already obsolete). NETs' "central place in the IPCC scenarios became the Plan A," wrote Kevin Anderson (2015), deputy director of the Tyndall Centre for Climate Science Research, after the Paris Conference. This "plan A" has emerged even though BECCS technologies have only been tested experimentally and pose various problems: They may be very costly, not acceptable by local populations, and they would require an enormous proportion of the Earth's total arable land (on the order of the surface area of India, by some estimates).

Hence, the rhetoric about negative emissions is mostly an intellectual and political deception. The technologies that would allow us to absorb carbon emissions so far do not exist or may function only at unrealistic scales. There have always been distant and abstract objectives of reduction in climate negotiations, without incorporating the concrete (material and social) transformations, the technologies, or the financial instruments that are indispensable to achieve them. So, deceptive rhetoric seems to perpetuate the schism of reality even further. The investigations based on it tend to take on features of what might be called fake science, suggesting troubling parallels with contemporary policy.

5. Conclusions

Earth system modeling and integrated assessment modeling are politics. This, in short, is the message this essay conveys. From the perspective of scientists, the integrated modeling paradigm appears as an immensely powerful and successful strategy for grasping and controlling the complexity of the natural and social world and producing scientific knowledge as well as politically relevant information about climate change. From the perspective of the historian (and, more generally, researchers in the social sciences and humanities), who aims to set the modeling paradigm in a broader historical perspective, a different picture emerges. Tools such as ESMs and IAMs actively interfere with and shape understandings, negotiation processes, and outcomes of political discourse and action (or nonaction). Knowledge tools become effective political agents. This is what we refer to by using the term politics, even though this perspective (or interpretation) is unfamiliar and foreign to most scientists.

Earth system science inherited and ESMs carried ideas and social and cultural norms of the peculiar historical eras in which they emerged and grew. Systems thinking and the idea that the Earth system is a complex, but principally understandable mechanistic machine, have their roots in the early Cold War era. This era also implanted a strong belief in the power of science; its privileged status for knowledge production; and, hence, ability and responsibility to serve politics and practice in the postwar society. When this era gave way to a time characterized by economic stagnation, social unrest, and rising environmentalism, climate science absorbed environmental concern as a new cultural trend but retained the optimism and enthusiasm in the modeling paradigm. A new level of politicization of climate science increasingly defined norms, directions, and practice and shaped its self-identity and social status.

The IPCC era since about 1990 brought integrated modeling, ESMs and IAMs, and its new political roles to full bloom. The climate knowledge regime they constituted turned into a true culture of prediction (Heymann et al., 2017), determined by the privileged task of providing predictive knowledge about climate change and its impacts in the form of future scenarios and projections.

The post-1990s era reveals particularly clearly the political power climate scientists unleashed. The modeling paradigm assumed hegemonic status, seized economic and social processes (IAMs), shaped perspectives and understanding, and created a new ontology of governance by conflating the use of knowledge tools and the creation of political meaning or, in this case, knowledge production and political management of the Earth. The modeling paradigm, once a scientific strategy largely in the hands of scientists, had turned into an agent of change in its own right. It resembled a strong seed nourished from and acting on a conducive environment, geared toward growth, and ingrained with developmental vigor pushing it from the scientific role of improving understanding to the social task of producing policy-relevant predictive knowledge. Politics evolved from models, as models created opportunities and normative pressures, and were mobilized and activated by networks of actors pursuing their different scientific, social, and political agendas.

Recent developments such as model application for the support of geoengineering (Feichter & Quante, 2017) or the deceptive political rhetoric of the 2° and 1.5° targets lay open a dangerous political dynamic putting model application on the verge of fake science. The political implications of models show the complexity of coproduction, which is not a democratic or balanced process, but dependent on social power and subject to negotiation and appropriation. In the climate arena, scientists increasingly feel dispossessed of their tools and their use in the making of meaning. Hélène Guillemot (2017b) suggested that coproduction in this arena increasingly turned from science-driven coproduction to policy-driven coproduction (see also Beck & Mahony, 2018; Figueres et al., 2017).

Stagnating progress with complex ESMs, the loss of autonomy and control due to political interests and growing concerns about fake science create significant frustrations among Earth system scientists. This frustration may help to think afresh, review the status of Earth system science and its historical and political binds and champion, and toil for alternative routes. History is done and its binds are not eternal. The future is open.

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