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Philosophy of climate science

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Abstract

There are two interrelated fundamental motivations at the heart of climate science. On the one hand, climate science is about understanding the complex physical system that is the climate system. At the same time, climate science is expected to provide tools that could help societies to understand and address the challenges raised by (anthropogenic) climate change. In this double perspective, climate science faces a number of fundamental epistemic issues that have started to attract the attention of the philosophy of science community in the last two decades or so (philosophy of climate science is thus a very young sub-discipline of philosophy of science). In particular, the social relevance of climate science leads to fundamental questions related to the role of what are often called non-epistemic values—that is, social, ethical, economic, political, … values—in climate science and climate modelling. Through their many ramifications, these questions partly shape the development of the philosophy of climate science; this chapter aims to highlight important steps in this shaping by reviewing some of the central issues in philosophy of climate science. More broadly, this chapter illustrates how philosophy of climate science is contributing to move (parts of) philosophy of science closer to issues that are relevant to society, as well as to a 'realignment' of science and society in the face of the deep challenges raised not only by climate change but, more generally, by the drastic, planetary-scale human-induced environmental changes that characterize the Anthropocene.

Biographical Note

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Introduction

There are two interrelated fundamental motivations at the heart of climate science. On the one hand, climate science is about understanding the complex physical system that is the climate system. At the same time, climate science is expected to provide tools that could help societies to understand and address the challenges raised by (anthropogenic) climate change, which the United Nations characterize as the "defining issue of our time". In this double perspective, climate science faces a number of fundamental epistemic issues that have started to attract the attention of the philosophy of science community in the last two decades or so; philosophy of climate science is therefore a very young sub-discipline of philosophy of science (for overviews, see Frigg et al. 2015a and 2015b, Bradley and Steele 2015, Winsberg 2018, Bradley et al. 2023, Parker 2023).

Since climate models (relying on computer simulations) play a central role in climate science, an important part of philosophy of climate science has accordingly focused on epistemic issues connected to climate modelling—even if the theoretical foundations of climate science also raise a number of important conceptual issues (e.g. about the very definitions of climate and climate change, see Werndl 2016; see also Katzav and Parker 2018). More specifically, central issues in the epistemology of climate modelling concern model evaluation and uncertainty quantification, which, in the light of inductive risk and given their importance for climate decision-making, lead to fundamental questions related to the role of what is often called non-epistemic values – that is, social, ethical, economic, political, etc. values – in climate science. Through their many ramifications, issues related to values in climate science – together with, more largely, the very social relevance of climate science – partly shape the development of the philosophy of climate science. This chapter aims to highlight important steps in this shaping by reviewing some of the central issues in the philosophy of climate science (the approach here is deliberately selective, and there hence is no attempt at being exhaustive).

Epistemology of climate modelling

Climate models are representations of relevant physical aspects of the climate system. They rely on physical laws (e.g. energy conservation) that are encoded in mathematical equations (e.g. Navier-Stokes equations), which need to be solved by discretizing the Earth into finite grid cells (whose size defines the resolution of the model) and applying numerical methods (computer simulations). Once initial and boundary conditions are specified, climate models can then simulate the evolution of the climate system, towards both the past and the future, thus allowing to make a range of numerical experiments for different purposes. There is a variety of climate models, notably depending on the number and type of processes and subsystems of the climate system they include; the current most complex models, such as the global or general circulation models (GCMs) and the Earth system models (ESMs), typically include the main atmospheric and oceanic processes, representations of the land surface, sea ice and elements of the biogeochemical cycles, as well as interactions among these components. Relevant subgrid processes (such as, e.g., certain cloud processes) are accounted for in an effective (and simplified) way via a variety of procedures generically labelled 'parameterization'.

This modelling framework and the complexity of the climate system raise a number of fundamental epistemic and conceptual issues, which are related to central philosophy of science topics. What it means for a climate model to be confirmed – a crucial issue for both understanding the climate system and addressing climate change – has given rise to important discussions highlighting a number of difficulties. Lenhard and Winsberg (2010) argue that the high complexity of climate models (such GCMs) makes it very difficult to identify the precise reasons behind their empirical success (or failure), thus leading to a form of confirmation holism. The role of observational data in model confirmation has attracted some attention (Lloyd 2009), in particular in the subtle context of climate model calibration or tuning, which is a crucial aspect of the parameterization procedure (Steel and Werndl 2013, 2016 and 2018, Frisch 2015). As a consequence, there is a growing consensus in the literature that climate models themselves should not be evaluated in terms of confirmation (or truth), but rather in terms of fitness- or adequacy-for-purpose (Parker 2009, Knutti 2018, Parker 2020).

Now, assessing the extent to which a given climate model is adequate for a certain purpose can be quite challenging (Katzav 2014), and in particular it requires some understanding of the uncertainties that are involved in climate modelling. The uncertainties in this context are of various types, some of which are related to the complex and chaotic nature of the climate system. Accordingly, a standard way to address these uncertainties is to build different types of climate model ensembles in order to probe the various types of uncertainties, such as multi-model ensembles (models with different structures, thus probing structural uncertainty), perturbed parameter/physics ensemble (multiple runs of a single model with different parameter values, thus probing parameter uncertainty) and initial condition ensemble (multiple runs of a single model with different initial conditions, thus probing initial condition uncertainty). These ensemble methods raise a number of foundational epistemic issues, about their justification and the appropriate use and interpretation of probabilistic tools in this context. Various forms of robustness analysis lie at the heart of most of the justificatory moves for the epistemic power of the ensemble methods in climate modelling (Lloyd 2010 and 2015, Vezér 2016, Dethier 2024). However, features of the concrete ensembles that are being built in practice – in particular the fact that they are 'ensembles of opportunity', i.e. that in many ways they are constrained much more by pragmatic considerations such as the availability of models and resources rather than by the ambition of systematically investigating uncertainties (Tebaldi and Knutti 2007) – as well as features of the climate models themselves – such as their lack of independence from one another and the existence of shared biases – raise a number of difficulties for the robustness strategy, as well as for the probabilistic quantification of uncertainty in this context (Stainforth et al 2007, Parker 2011 and 2013, Katzav et al. 2021). Despite recent attempts to improve the original robustness analyses (see Winsberg 2018, ch. 11-12 elaborating on Schupbach 2018's explanatory robustness analysis), there are still many important open issues, which tend to weaken the confidence one might have in some of the (probabilistic) uncertainty assessments relying on a robustness analysis of model ensembles (Harris 2021, O'Loughlin 2021, Harris and Frigg 2023a, b).

More fundamentally, a debate has emerged in the last decade in the philosophy of climate science literature about the epistemic implications of certain mathematical features of climate models – such as lack of structural stability, understood in a precise topological sense – that may constraint the policy relevance of certain modelling endeavours, such as certain types of model projections; some of these implications have been referred to as the hawkmoth effect in the literature, in reference but also in contrast to the (in)famous butterfly effect (Frigg et al. 2013 and 2015, Frigg et al. 2014, Mayo-Wilson 2015, Goodwin and Winsberg 2016, Winsberg and Goodwin 2016, Nabergall et al. 2019, Dethier 2021, Lam 2021, Frigg and Smith 2022). These are part of a family of considerations (e.g. about structural model inadequacies) possibly pointing to some fundamental epistemic constraints (and limitations) to climate modelling, which may be in tension with certain aspects of the (dominant) strategy in climate science of developing more complex, higher resolution (e.g. kilometre-scale) climate models, relying on increasing – most recently: exascale – computational power. When it comes to the decision-relevance of this modelling strategy (or modelling paradigm), these epistemic constraints highlight the crucial role of physical understanding or what is sometimes referred to as "process understanding" in the climate science literature (see Knutti 2018), background knowledge (Baumberger et al. 2017), and expert judgement more generally (Thompson et al. 2016, Katzav et al. 2021, Majszak and Jebeile 2023; see Lam and Majszak 2022 on the central role of expert judgement in the context of climate tipping points, which involve deep uncertainties). The recent integration of machine learning techniques into climate modelling further strengthens the epistemic relevance of expert judgement in this context (Jebeile et al. 2021, 2023).

Values in climate science

The central role of expert judgement in climate science is at the roots of the influence of non-epistemic (e.g. social, ethical, economic, political, etc.) values in climate science. In particular, within the framework of climate modelling, non-epistemic values have been convincingly argued to enter the picture at different stages, in the very development of individual models, in the construction of model ensembles, as well as in the model and uncertainties assessments. For instance, parameterization and tuning procedures typically involve epistemic trade-offs, e.g. concerning the climate variables and phenomena to prioritize (optimize), and such choices can be influenced by values. Hourdin et al. (2017, 592) give an example of a possible choice to be decided by the modelling centres between optimizing the ocean heat transport in the North Atlantic and optimizing tropical convection choice that can be influenced by the non-epistemic values and interests represented in the modelling centres (the ocean heat transport in the North Atlantic is important for the European climate). More generally, model development involves numerous choices that are not fully constrained by theory or observation, thus leaving ample room for the influence of non-epistemic values, not only in shaping model purposes and priorities, but also in selecting the entities and processes to be represented as well as the way to represent them. The same holds true for building model ensembles and assessing uncertainties on this basis (e.g. using probabilistic tools): the selection and weighting of models may implicitly or explicitly involve value-laden dimensions, e.g. favouring certain spatial scales or certain regions, and the probabilistic quantification of model uncertainties may also be influenced by non-epistemic values in various ways, such as through inductive risk considerations (i.e. related to the consequences of making an error) or through the role of background knowledge in a Bayesian approach (Biddle and Winsberg 2009, Winsberg 2012, Parker 2014, Parker and Winsberg 2018). The influence of non-epistemic values in (the making of) climate science has started to be explicitly acknowledged not only in the philosophical literature, but also recently in the climate science literature itself (Pulkkinen et al. 2022; the role of non-epistemic values has also been explicitly discussed in the latest report of the Intergovernmental Panel on Climate Change, see IPCC 2021), and there is a broad consensus that avoiding the influence of non-epistemic values altogether in climate science is extremely difficult, if not impossible in practice (and maybe not even desirable).

This situation raises the crucial question of how to integrate and manage non-epistemic values in climate science in a legitimate way, in particular in view of fair and just climate decision-making. There is a growing body of research in philosophy of climate science in recent years on this pressing issue, and this research gets part of its inspiration from the general philosophy of science work on values in science (see Elliott 2022 for a recent overview). There are various proposals and case studies in the literature, which all tend to agree that identifying necessary and sufficient conditions for legitimate value management in science in general is extremely difficult (akin to a 'new demarcation problem', see Resnik and Elliott 2023), especially given the myriad of ways in which non-epistemic values can be entangled with science and scientific reasoning, in all the different fields of science. Nevertheless, a number of crucial features have been convincingly put forward for managing values in science, which are nicely captured by three conditions highlighted in Elliott (2017):

(1) Transparency: "scientists should be as *transparent* as possible about their data, methods, models, and assumptions so that others can identify the ways in which their work supports or is influenced by particular values" (2017, 14).
(2) Representativeness: "scientists and policymakers should strive to incorporate values that are *representative* of major social and ethical priorities" (2017, 14).
(3) Engagement: "scientists, citizens, and policymakers should encourage appropriate forms of *engagement* between scientists and other stakeholders" (2017, 15), in particular those affected by the implications of the science under

consideration. Such an engagement aims to promote diversity (within both the scientific and stakeholders' communities), as well as a "critical reflection on values in science" (Elliott 2022, 47).

Slight variations of the conditions (1)-(3) have been argued for as legitimate ways to integrate and manage values in climate science (Intemann 2015, Parker and Lusk 2019, Jebeile and Crucifix 2021, Pulkkinen et al. 2022). However, implementing these conditions in the global context of climate science may face serious difficulties, especially in the perspective of addressing the climate challenge. The conditions of representativeness and engagement may be particularly difficult to implement: indeed, depending on the purpose and scale under consideration, it may be extremely challenging to genuinely identify the relevant priorities and values, as well as the relevant stakeholders to engage with. Moreover, and crucially, the proposed conditions for value management offer little guidance for navigating value conflicts and trade-offs. These considerations raise fundamental ethical and political philosophy issues (e.g. related to power relations structuring the engagement with stakeholders, for instance in the Global South), and their entanglement with fundamental epistemic issues and values is getting increasing attention in the philosophy of (climate) science. Accordingly, this latter scholarship has started to consider ethical and political reasoning as well as the tools of political philosophy as important resources for value management in science, and in climate science in particular (calling for the development of a 'political philosophy of science', see Schroeder 2022 and Lusk 2021). For instance, democratic tools – especially in terms of deliberative democracy – have been put forward to ensure the representativeness and legitimacy of values in science. In the context of climate science, recent work has highlighted the relevance of incorporating the values of the climate change information users along such (deliberative) democratic lines, but up to now mainly in cases where the inductive risk and the stakeholders can be clearly identified (for instance, in the context of climate services, see Parker and Lusk 2019, Lusk 2020).

More generally, the very production and framing of (physical) climate change information have also been subject to increasing attention recently, at the intersection of climate science and philosophy of science.

Regional climate change information and physical climate storylines

The epistemic constraints and the value-laden aspects of climate modelling discussed above are of course far from making climate modelling irrelevant or epistemically problematic as a whole. Climate modelling is crucial to contemporary climate science and the central and global climate science claims about climate change are widely acknowledged to possess a very strong epistemic status, such as those concerning the attribution of global warming to greenhouse gas emissions associated with (certain) human activities, as well as those concerning future global trends such as increasing global mean surface temperature under various emissions scenarios.[1] However, the epistemic constraints and limitations, as well as the value dimensions of climate modelling and climate science highlight the importance of the 'framing' of climate change information, especially at the regional and local scales, which are the relevant scales where people get affected, in particular through extreme events. Building decision-making relevant climate change information has thus been a crucial topic in climate (change) science in recent years, and this issue illustrates how close to its field of study and its developments philosophy of climate science tends to evolve. The recent climate science subfield of extreme event attribution – which can be seen as a type of (regional) climate change information, the decision-making relevance of which (e.g. for adaptation) is disputed tough – is an illustration of this tendency.

Extreme event attribution investigates the possible links between extreme climate or weather events and anthropogenic climate change. There are several approaches to extreme event attribution, involving different methodologies. Given a particular extreme climate (weather) event, the standard probabilistic approach to attribution typically focuses on the change in likelihood of the occurrence of the type of climate (weather) extremes to which the event under consideration belongs, comparing the probability of occurrence under actual anthropogenic forcing (p_1) with the counterfactual probability of occurrence without anthropogenic forcing (p_0). Within this approach, one can then define the fraction of attributable risk $FAR = 1 – p_0/p_1$, which is usually understood as the fraction of the likelihood of the type of extreme event that is attributable to anthropogenic forcing.

Alternatively, the storyline approach to extreme event attribution proposes a causal and conditional strategy, which does not focus on making probabilistic assessments, but rather aims to investigate how the event under consideration unfolded and how climate change influenced the different contributing causes (or 'driving factors' in the climate science jargon). Exploiting the distinction between dynamical and thermodynamic aspects of climate change, the storyline approach can typically provide (conditional) attribution statements about the thermodynamic contribution of climate change to the intensity of a specific extreme event (conditional on the dynamical aspects leading to the event) – in particular in cases where probabilistic attribution statements may not be available or meaningful (e.g. because involving too many uncertainties).

Philosophers of science have started to investigate these different methodologies in extreme event attribution, soon after they were discussed in the climate science literature. An important philosophy of science contribution in this context is to clarify that the different approaches to extreme event attribution encode different research questions, specifically involving different attitudes towards inductive risk (Lloyd and Oreskes 2018, Winsberg et al. 2020, Lloyd and Shepherd 2023): the standard probabilistic approach tends to be more focused on avoiding 'type I' errors (false positives), whereas the storyline approach tends to focus more on avoiding 'type II' errors (false negative). Privileging one risk attitude over another is – implicitly or explicitly – typically motivated by (epistemic and non-epistemic) value considerations. Since extreme event attribution has potential implications in the legal and policy-making (e.g. adaptation) contexts, it has contributed in recent years to draw philosophy of climate science closer to the science-society (science-policy) boundary. Indeed, a (small) number of philosophers of science are taking part in the current debates about the implications of (the various methodologies in) extreme event attribution for climate change litigation, as well as loss and damages, often in a way involving interdisciplinary collaborations with climate scientists (Lusk, 2017, Pfrommer et al. 2019, Lloyd and Shepherd 2021, Lloyd et al. 2021).

The use of physical climate storylines, which can be defined as "self-consistent and plausible physical trajectory[ies] of the climate system, or a weather or climate event, on time scales from hours to multiple decades" (IPCC 2021, §1.4.4.2), is in no way restricted to the attribution context and actually constitutes a distinctive and novel approach to (regional) climate change information more broadly (Shepherd et al. 2018, Shepherd 2019). There are different varieties to the storyline approach in climate science (Baldissera Pacchetti et al. 2023), but they all share a common emphasis on causal understanding and conditional statements, typically exploiting causal networks. The flexibility of the latter allows for conditional and counterfactual statements that can provide a better control of uncertainties and can thus be more relevant for decision-making than the standard probabilistic (ensemble) approach, especially in contexts involving high or deep uncertainties such at the regional and local scales. Of course, physical climate storylines do involve climate models (including high-resolution ones), but current work on storylines also aims to ‘contextualize’ the model outputs using different, interdisciplinary resources (for instance, possibly involving relevant social, historical, political, economic, etc. aspects) – notably fostering engagement with relevant stakeholders and their values – in order to build more “meaningful” climate change information (Shepherd and Lloyd 2021; this is also connected to a reflection on the usability of climate information, see Jebeile and Roussos 2023). By taking seriously the entanglement of epistemic and non-epistemic dimensions, the storyline approach embodies the intertwining of climate science with philosophy of climate science (as well as neighbouring disciplines such as science studies and social science) on a number of issues in recent years – an intertwining that we expect will further increase in the future in the light of a growing awareness of the multidimensional nature of the climate challenge.

Conclusion

Because of the social relevance of its field of study, philosophy of climate science – despite being very young – is contributing to move philosophy of science closer to issues that are relevant to society. This move can be seen as part of a reconnection of (parts of) philosophy of science not only with social concerns but also with its own pre-World War II history. Indeed, it is generally understood that it is only in the post-war context that philosophy of science became disconnected from any sort of social concerns (see Reisch 2005). In this sense, philosophy of climate science naturally shares some common ground with feminist approaches to philosophy of science, and also participates to the development a ‘socially relevant philosophy of science’ (Plaisance and Fehr 2010; see also the contributions on ‘Feminist philosophy of science’, ‘Socially engaged philosophy of science’ and on ‘Science and Values’ in this volume).

Furthermore, the recent evolution of the philosophy of climate science – e.g. in relation to non-epistemic values – is contributing to a broader reflexion on “a realignment of the relations between science and society” (Ludwig forthcoming), in the face of the deep challenges raised not only by climate change but, more generally, by the drastic, planetary-scale human-induced environmental changes that characterize what has been called the Anthropocene. In this perspective, climate change needs ultimately to be considered within the larger context of the anthropogenic disruptive interferences to the fundamental processes of the entire Earth system itself. The magnitude and possible existential dimensions of these challenges may require novel perspectives on values in science that integrate foundational epistemic considerations with interdisciplinary insights on knowledge production (e.g. involving dimensions related to justice, power structures, etc.). Philosophy of climate science – and, increasingly, of Earth system science – has a fundamental role to play in the development of such novel, epistemically sound, interdisciplinary perspectives on knowledge production for the Anthropocene (see Lam and Rousselot 2024 for preliminary steps).

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[1] The very strong epistemic status of these global climate science claims comes from a variety of lines of evidence, centrally involving a robust understanding of the relevant physical processes at a global scale (and specifically for thermodynamic aspects of climate

change). The epistemic reliability of model projections at regional and local scales (as well as those more tightly connected to dynamical aspects of climate change) is in general weaker.