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Introduction

> "Of course not every single adherent of the scientific world-conception will be a fighter. Some glad of solitude, will lead a withdrawn existence on the icy slopes of logic." From the Vienna Circle's manifesto, *Wissenschaftliche Weltauffassung*
>
> (Hahn, Neurath and Carnap 1929)[1]

2016 was the warmest year on record.[2] It broke the record of 2015, which broke the record of 2014. The nine consecutive months from December 2015 to August 2016 were all record-breakingly warm. This was the fifth time in the twenty-first century that a new record had been set. All 16 of the years that have passed in the twenty-first century are among the 17 warmest on record (with 1998 rounding out the lot.) All five of the five warmest have been since 2010.

Regionally, the patterns have been a bit more complicated but reflect the underlying trend. Ocean surface temperatures had their warmest year; all six continents experienced one of their top five warmest years on record, and Arctic sea ice experienced its smallest seasonal maximum ever and its second smallest seasonal minimum.[3] The 13 smallest seasonal maximums have all been in the last 13 years. The melting of Arctic ice is an especially significant change in the global climate because of its feedback effect: as the temperature rises, ice melts, and melting ice reduces the amount of sunlight reflected back into space, which makes the temperature rise

[1] Translated in Neurath and Cohen (1973), p. 317, quoted in Reisch (2007), p. 58

[2] The average global surface temperature for 2016 was 0.94°C above the twentieth-century average, 0.83° celsius above the long-term average (14°C) of the World Meteorological Organization (WMO) 1961–1990 reference period, and about 0.07°C warmer than the previous record set in 2015. This is approximately 1.1°C higher than the pre-industrial period.

[3] Peak ice in the Arctic in 2016 was reached on March 24 at 5.607 million square miles (14.522 million square kilometers) – the smallest peak ever. 2012 still barely holds the record for the lowest summer minimum area of the Arctic Ocean covered by ice with a low of 1.58 million square miles (4.1 million square kilometers).

even more. The melting of the Arctic permafrost, moreover, could release billions of tons more carbon and methane into the atmosphere – also accelerating warming.

Precipitation patterns continued to get more extreme, with some regions experiencing record drought (especially southern Africa and Australia) and some experiencing record flooding (especially China and Argentina). Some regions experienced both.[4] Understanding and predicting the impact of warming temperatures on regional precipitation remains a serious challenge.

Climate change is real, and it is happening in front of our eyes. And while Americans are almost evenly split with regard to whether or not they believe that human activities are the cause of these changes, the scientific community is not. The relevant experts on the climate system are virtually unanimous in their acceptance of anthropogenesis: the proposition that human activities (primarily in the form of the combustion of fossil fuels, but also the extraction of those fuels, deforestation, livestock farming, and the manufacture of concrete) are responsible for at least the bulk of those changes. Not only do climate experts unanimously hold these views. So do virtually all the members of neighboring scientific disciplines and their scientific societies.

Still, well-meaning people sometimes conflate that unanimity with the idea that anthropogenesis is an obvious truth – that it can be established with ease or simplicity. I was at a public lecture once where the speaker (a journalist) said that the truth of anthropogenesis was like 1+1=2. I do not think this kind of rhetoric is helpful. One obvious danger of overstating the simplicity of the reasoning is that it encourages poorly informed laypersons to think they can evaluate the reasoning themselves, and potentially find simple flaws in it. It's true that the greenhouse effect, which explains why the earth doesn't look like the ice planet of Hoth in *The Empire Strikes Back*, is a simple mechanism involving heat-trapping gasses, and one whose existence is easy to establish. And it's not hard to show that humans have been producing ever-growing quantities of those gases for over 200 years. So, there is some relatively simple reasoning, based on a simple model,[5] that makes the hypothesis of anthropogenesis plausible and perhaps even more likely true than not. But the community of experts believes unanimously in anthropogenesis not merely because of this

[4] The United Kingdom, for example, had record-setting rainfall in December/January 2015–2016 and then a bottom quartile autumn accumulation.
[5] See section 3.2

simple reasoning, or because of anything that should be likened to 1+1=2. They believe it because of decades of painstaking work in collecting and studying data, pursuing multiple independent lines of evidence, building and studying complex models run on clusters of powerful computers, and recruiting into their ranks the expertise of literally dozens of different scientific disciplines: Climatology, Meteorology, Atmospheric physics, Atmospheric chemistry, Solar physics, Historical climatology, Geophysics, Engineering, Geochemistry, Geology, Soil science, Oceanography, Glaciology, Paleoclimatology, Ecology, Synthetic biology, Biochemistry, Biogeography, Human geography, History, Economics, Ecological genetics, Applied mathematics, Mathematical modeling, Computer science, Statistics, and Time series analysis, just to name a few.[6]

In short, the scientific study of the climate and its response to human activities isn't just vitally important to the future of the planet. It's also rich, interesting, complex, and deeply interconnected with almost every area of study that occupies the minds of twenty-first-century scientists. On top of all that, it is literally awash with all the conceptual, methodological, and epistemological issues that perennially preoccupy philosophers of science: the nature of scientific data and its relation to theory; the role of models and the role of computer simulations in the practical application of theory; the nature of probabilities in science and in decision making; how to think about the latter when the probabilities available seem ineliminably imprecise; the methodology of statistical inference; the role of values in science; confirmation theory; the role of robust lines of evidence in confirming hypotheses; social epistemology (the value of consensus in science; group knowers and authors; the value of dissent) and too many others to list.

It's just the kind of scientific practice that you would expect philosophers of science to take an exceptionally keen interest in. But until relatively recently, you would have been pretty disappointed. The reasons for this are complicated. One reason is that philosophers of science tend to cluster around a small group of scientific topics, in which they collectively build expertise, and about which there is collective agreement that they are "philosophically interesting." A Martian, visiting earth, who tried to learn about the range of scientific activities in which humans engage by visiting a meeting of the Philosophy of Science Association, would find us to be very parochial in our interests.

[6] (Brook 2008)

Another reason might have to do with philosophy of science's withdrawal to "the icy slopes of logic" during the post-war McCarthyite period of American academic history, detailed by George Reisch, Don Howard, and others.[7] Reich and Howard remind us of a time when American philosophers of science followed the leadership of the members of the Vienna Circle (who had come to the United States to flee the Nazis), not only with respect to their epistemological and (anti)metaphysical commitments, but also with respect to one of their deepest motivations: that philosophy of science should be engaged with "the life of the present," and pursue the aim of turning the scientific enlightenment toward the project of bettering the social conditions of mankind. But the pre-war association of those same philosophers with workers' parties and democratic socialism put the careers of their followers in peril. In reaction, the general character of philosophy of science in the English-speaking world became politically neutralized: distanced from issues of social concern, and focused on areas of science of little social consequence.[8]

Whether in part because of the warming of the climate or not, and certainly in no small part due to the growing influence of feminist philosophy of science, the icy slopes of logic have been melting of late, and the number of philosophers of science interested in socially relevant philosophy of science has grown in the last decade or two. Socially relevant philosophy of science can mean a variety of different things,[9] but it certainly refers to philosophical work that engages with science that has significant social impact. It is therefore no surprise at all that there is a growing interest in climate science among philosophers of science of late – both as a research topic in its own right, and as a useful case study that is easily adaptable to philosophy of science pedagogy. The topic also complements much of the recent work on climate ethics. Climate ethics is primarily concerned with ethical issues that surround climate change and how issues of justice bear on the duties and responsibilities producers of greenhouse gases have toward those they will affect. This work is best done in the context of a reasonably good understanding of the science of climate change, and thus climate ethicists can certainly benefit from a philosophically informed presentation of the foundations of climate science.

[7] (Reisch 2007, Howard 2003)
[8] The earliest exceptions to this were probably when feminist philosophers of science started (in the 1980s or so) to take an interest in areas of biology and social science that had implications for gender-related social concerns. "Socially relevant philosophy of science" and "feminist philosophy of science" were for a relatively long period virtually synonymous.
[9] See Fehr and Plaisance (2010)

This book was written for the benefit of everyone who wants to come down from the icy slopes, as well as for climate scientists curious about what philosophers think about their work. I hope for it to serve both as an introduction to the major themes of the philosophy of climate science, and as an effort to add to that enterprise – to advance our philosophical understanding of the field. It is written to be as useful as possible, in the first instance, for students and scholars in philosophy of science who are interested in exploring climate science as a topic of philosophical study. But it is also intended to be accessible to a wider general audience, and to be useful as a resource for people studying general philosophy of science who prefer to see that material presented with real, living examples of scientific practice. I certainly hope some climate scientists will be curious to see what philosophers think of their discipline.

The book is not intended to be a polemic in defense of climate science or in defense of anthropogenesis.[10] Almost everywhere, I will be assuming that, with regard to questions about which the community of climate scientists share broad agreement, the answers that climate science delivers are the best answers we can find. I will be primarily interested in interpreting those answers (when it isn't obvious how to do so) and uncovering the logic, methodology, and conceptual foundations of the reasoning used to produce those answers.

The first part of the book is primarily about the methodology of climate science: Chapter 2 is about climate data and the relations between those data and climate hypotheses. Chapter 3 is about climate models in general, with an emphasis on static, equilibrium models of global radiation balance. Chapter 4 is on climate simulations. Chapter 5 is on chaos and its implications for climate science, particularly with regard to the difference between making predictions and making projections, and the nature of a "forcing experiment," which is one of the main ways in which simulations are used in climate science.

The second part of the book is mostly about uncertainty, and about how to interpret climate hypotheses for which we have only probabilistic support: Chapter 6 is on the interpretation of probability in climate science. Chapter 7 is on the related notion of "confidence" in climate projections, and on the nature and origins of climate uncertainties. Chapter 8 is on statistical inference and on decision making under

[10] Readers interested in more polemical defenses of climate science, and in particular in works that are primarily directed at refuting the arguments of climate skeptics and climate deniers, can turn to many good such resources that are already out there.

uncertainty and decision making under risk. It includes a discussion of so-called integrated assessment models, which try to make decision making itself model-based and scientific. Chapter 9 is on the interplay between uncertainty quantification in climate science and the role of social values in climate science.

The last part of the book is mostly on epistemological issues: Chapter 10 is on evaluating model skill, including discussions of "verification and validation" of climate models and of the epistemological impact of the fact that climate models are "tuned." Chapters 11 and 12 are both on the role of "robustness analysis" in climate science: that is, on the epistemological importance of the fact that some climate hypotheses are supported by a variety of lines of evidence, and of the fact that some hypotheses are jointly predicted by a whole ensemble of different models. Chapter 13 is on the application of various themes from "social epistemology" to the epistemology of climate science. Chapter 14 offers some concluding remarks.