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Uncertainties, Plurality, and Robustness in Climate Research and Modeling: On the Reliability of Climate Prognoses

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Abstract The paper addresses the evaluation of climate models and gives an overview of epistemic uncertainties in climate modeling; the uncertainties concern the data situation as well as the causal behavior of the climate system. In order to achieve reasonable results nonetheless, multimodel ensemble studies are employed in which diverse models simulate the future climate under different emission scenarios. The models jointly deliver a robust range of climate prognoses due to a broad plurality of theories, techniques, and methods in climate research; the range reliably indicates the future development of the global climate. Nevertheless, the uncertainties are widely used by skeptics to challenge the IPCC's prognoses. Such skeptical allegations can well be distinguished from points of fruitful epistemological criticism: in spite of the enduring range of prognoses, the epistemic uncertainties should not play a role in finding agreements on climate change mitigation.

Keywords Uncertainties in climate science · Plurality in climate science · Robustness in climate science · Reliability of climate prognoses

1 Introduction

In climate research, statements on climate change, including those by the Intergovernmental Panel on Climate Change (IPCC), are largely based on climate models. This faces many challenges, however, as these models aim to make statements about a very complex system in a huge spatiotemporal span. Climate modeling thus allows for statements about the climate merely under hypothetical emission scenarios:

> they are projections of what would happen if greenhouse gases were to be emitted at particular rates over the course of decades or centuries. [… T]he observational data

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> that is needed in order to assess the quality of their predictions will not be available, even in principle, for quite some time. (Parker 2006, 353)

Climatic prognoses gained from simulation models have, therefore, a specific epistemological status which has recently become an object of investigation by philosophers of science, and this for good reasons regarding the political importance of the matter.

The aim of the paper is to demonstrate that the practical problems climate research has to deal with do not justify climate skepticism. I will discuss what can be considered the currently most relevant arguments philosophers of science and climate researchers have brought forward when methodologically discussing the challenges of climate research. Then, I am going to show that there is comprehensive plurality in climate research which can be found in all areas of climate research: a huge diversity of scientists from all around the world and from different disciplines such as physics, biology and geology as well as from the social sciences and economy jointly explore a huge diversity of facets of the climate system and of factors that it is influenced by. This results in scientific plurality of theoretical approaches, techniques, and methods, additionally advanced by the diversity of cultural backgrounds of a global research community. The diverse results are used to construct, evaluate and improve climate models and, consequently, help to produce a robust range of climate prognoses. On this basis there is good reason to assume that the future temperature trend that climate research outcomes indicate is reliable, although the range of prognoses is not likely to shrink. The variety of methods and theories in connection with the heterogeneity of the global research community contradict the standard objections that are made by climate skeptics against the reliability of the outcomes of climate research, i.e.

(a) The methods (in particular the models) used in climate research are not reliable;
(b) Theory choice in climate research is tainted with biased assumptions;
(c) Climate researchers are biased.

I want to raise awareness of the fact that the uncertainties that concern specific scientific details in climate modeling do not support climate change denial which is usually based on the claim that climate research does not provide reliable policy-relevant information.

The paper is structured as follows: first, I'll give an overview of the state of the methodological discussion. As Biddle and Winsberg (2010) have pointed out, there are three sources of uncertainty in climate modeling regarding the evaluation of climate models, their parameter values, and their basic structure. I'll explore all three of them, starting with the evaluation of climate models in Sect. 2. I will argue that the evaluation of climate models can be protected against biases and circularity by using a diversity of data stemming from a plurality of methods, techniques, and theoretical approaches; this allows for independent and reliable testing of the models. In Sect. 3, the high complexity of climate models is explored, with a focus on how physical uncertainties such as uncertainties about climate feedbacks require tuning of the models and ad hoc adjustments of parameter values. This is handled by employing cross-tabulations and comparison of empirical data; that way, potentially biased assumptions in the models can be tested and either confirmed or undermined. However, even if one agrees so far that the current climate models permit an empirically adequate understanding of the climate system due to the plurality of methods, techniques, and theories in climate research, there are still data uncertainties which lead to a diversity of future emission scenarios, which will be the topic of Sect. 4. Here, I'll show how this is pragmatically handled by the employment of ensemble studies in which all qualified models simulate the climate under diverse emission scenarios. This procedure accounts for a variety of emission scenarios, including experts' diverse assumptions concerning the effects of political greenhouse gas regulation and, thus, socio-economic future trends. The heterogeneity of the global research community renders skeptical allegations of shared biases in climate research untenable. Nevertheless, as I'll point out in Sect. 5, climate skeptics misuse the scientific uncertainties to promote climate change denial challenging the reliability of climate research; this kind of skepticism differs substantially from methodological convergence skepticism which argues with good reason that even an improvement of the data situation is not likely to entail deterministic climatic prognoses. In contrast, climate change denial is finally debunked as politically motivated, used in order to postpone agreements on climate change mitigation. The conclusion is, hence, that decision makers in climate policy should support climate protection measures as climate research provides sufficient and robust results that are confirmed by a broad international scientific community employing a variety of methods and theoretical assumptions.

2 Evaluating Climate Models

Recording of temperature data began sporadically and under insufficient technical conditions in the middle of the nineteenth century. In the course of the twentieth century, observational data were collected on a more and more regular (and representative) basis. But there are still gaps in our knowledge of the global average temperature from 1900 until today, which is problematic as recent general circulation models must qualify for being employed in the IPCC's assessment reports (ARs) by simulating the temperature of this time span. Only if the models are able to approximately reconstruct the temperature data from the past, they are endorsed by the IPCC. The lacking temperature data are hence reconstructed by employing weather models: observational data and so-called reanalysis data from weather models subsequently get aligned with each other: due to the lack of observational data the temperature development that is used to evaluate the models rests to some degree on reanalysis data from weather models.

It might hence be objected that these data might be constructed (consciously or not) in such a way as to lead to specific simulation outputs. Such distortion could emerge, for example, if weather models already include certain assumptions or if data are merely chosen or interpreted to confirm certain assumptions. In particular, Betz (2006, 112) and Parker (2011) have argued that such "model-laden data" could not provide independent testing of the climate models: when data are constructed in order to specifically direct the models, this will result in a circular modeling procedure. Note that this is not a specific problem of reanalysis data but concerns even raw data which are by no means simply given but selective and theory-laden as well; satellite and radiosonde data for example are assumption-laden and contested (Lloyd 2012). But irrespective of this fact, "[t]his raises the worry that the fit between […] data sets and simulations of past climate [… is] artificially inflated" (Parker 2011, 587). Parker is hence concerned about circularity in the testing of climate models as weather models include "assumptions about the physics of the atmosphere that are similar, if not identical, to those included in [climate models]" (Parker 2011, 587; cf. Parker 2006, n5).

There is, however, good reason not to be too worried about this. First, weather models are small-scale models that provide regional forecasts for only a couple of hours or maximally a few days. As such weather models are well testable against the actual weather they provide reliable data. Second, the reanalysis data are only used to fill gaps in (long-term) observations; so they are not arbitrarily chosen but constrained by these observations as they must lie in the range of the gaps. Third, it might not even be a problem if both types of models include some similar or even identical physical assumptions, as such assumptions can be isolated and tested. For example, as Elisabeth Lloyd has pointed out, cloud parametrizations

> are supported by special research groups who study clouds. The scientists involved use empirical data to create small-scale models representing individual cloud elements, from which they develop improved cloud parametrizations for the general circulation models. (Lloyd 2010, 978)

The same can be expected in the relation between weather models and climate models: if an assumption works reliably in a weather model this can well be considered as an indicator for the adequacy of the assumption. In sum, the evaluation of climate models on the basis of reanalyzed weather data does not challenge the climate models' outcomes.[1] Still, Parker is right that this whole issue should be subject to more research. It seems crucial to investigate what assumptions are shared in all climate and weather models, and to scrutinize to what extent these assumptions are independently testable, by experiments[2] or against observations. Lloyd recently came up with an exemplary case-study on the use of satellite data in evaluating climate models: she makes clear that it indicates a wrong understanding of the quality of raw data when they are understood as simply representing the "real world" while they are in fact assumption-laden; to make them useful for climate modeling, Lloyd demonstrates, it is necessary to compare them to and combine them with many other different sources of evidence (Lloyd 2012). In the following, I'll tie in with Lloyd's argumentation by demonstrating how the plurality of theories, techniques, and methods as well as the social diversity in climate research supports the IPCC's claim that the trend the current global climate prognoses indicate is reliable.

3 Model Uncertainties

In particular, uncertainties in climate modeling are deeply rooted in uncertainties regarding the physical behavior of the global climate, i.e. in uncertainties regarding the question of how climate factors are causally linked to each other. For example, climate change feeds back to its causing factors, which can either amplify (positive feedback) or diminish (negative feedback) climate change in turn. Yet the extent of many feedback processes is uncertain. Clouds are a well-known example, as their behavior is hardly understood. It is even controversial whether there is positive or negative cloud feedback, i.e. whether global warming influences clouds in a way that boosts global warming or, on the contrary, has a cooling effect. A similar example is Siberian tundra and submarine permafrost. Thawing permafrost is already releasing huge amounts of methane and CO_2 which will accelerate global warming. However, it is unknown how the release of additional carbon will at the same time stimulate the growth of new plants which are consumers of carbon dioxide. A less controversial feedback is caused by the melting polar ice caps: as a result of the

[1] In paleoclimatological modeling where climate proxies play a decisive role the situation is similar. Such paleo data are obtained from tree rings and ice cores. Here, reconstruction is independent of models as raw data are extracted from samples, analyzed by chemical and physical procedures and calibrated on the basis of present measurements.

[2] The behavior of aerosols, for example, is successfully explored in laboratory experiments in which different layers of the Earth's atmosphere can be artificially generated (cf. KIT 2012).

reduction of polar ice, less sunlight gets reflected; the less ice covers the Earth's surface, the faster global warming proceeds and the faster the ice sheets vanish.

Experts now disagree about the extent and the strength of these feedback processes (Bony et al. 2006). Accordingly, the representation of feedback factors varies in the models, and the exact extent of global warming must stay uncertain despite the improvement of observational data and computer capacities and increasingly complex models.

Because of physical uncertainties like these, tuning of the climate models is necessary: if the model outputs deviate too much from observations, ad hoc adjustments of parameter values are used to achieve alignment (IPCC 2007a, 8.1.3.1; Parker 2011, 587f.; Lenhard and Winsberg 2010, 257). The very first climate models yielded prognoses that appeared so absurd that the models had to be adjusted *ad hoc* without any empirically based evidence for such an adjustment (Betz 2006, 74).

This becomes particularly problematic as all components that are included in current climate models (such as aerosols and clouds, ocean–atmosphere circulation, sea ice, winds etc.) are modeled and then coupled in order to constitute general circulation models; the simulated process is dynamic: all modules are in permanent interaction, exchanging data during the simulation. Lenhard and Winsberg (2010) identify this complex process which they call "fuzzy modularity" as a key feature of climate models that can both strengthen or weaken the modules' effects. Biddle and Winsberg explain this very well:

> if module *X* is good at predicting phenomenon *Y*, and if module *W* is good at predicting phenomenon *Z*, it will not, at least in general, be the case that the model consisting of *X* and *W* will be good at predicting both *Y* and *Z*. (Biddle and Winsberg 2010, 182)

Thus, it is often stressed that climate models function as black boxes, their outputs stemming from an opaque complexity. The IPCC admits that while the results can be aligned with observations, "[…] their source is often hidden by the model's complexity" (IPCC 2007a, 8.1.2).

That way, ad hoc adjustments in a specific model pose the risk not only of merely shifting errors but, even worse, of creating new and even bigger ones. Such errors might not even be discovered when the results now better fit with the observations—though the accuracy of the model's structure has changed for the worse. This risk can only be minimized if ad hoc changes are aligned with a variety of observational data from as many different sources as possible: such diversity of methods warrants that ad hoc adjustments of specific models stay within a realistic range; it provides independent confirmation of the modified module.

But there is another serious problem climate modelers have to face: all current climate models could merely imply the same omissions, simplifications or idealizations, as pointed out by Parker with reference to Cartwright (1991): "[… I]n general, the possibility should be taken seriously that a given instance of robustness in ensemble climate prediction is, as Nancy Cartwright once put it, 'an artifact of the kind of assumptions we are in the habit of employing'" (Parker 2011, 591). This is indeed a problem climate modeling is faced with, not least because all current climate models evolved from a few models from the 1950s: there might just be inherited biases shared by all today's models. But then, what could be done to protect the value of robustness against Cartwright's objection?

The only way to handle this problem seems to make use of a plurality of techniques again: "shared theoretical presuppositions […] can be eliminated by using a number of techniques, each of which is theory-dependent in a different way, to produce a robust body of data" (Culp 1995, 441). Note, however, that "elimination of biases" can only mean a reduction of biased assumptions in model ensembles: we have some methods for reducing incorrect and empirically flawed assumptions, but we cannot be sure that we don't have biased assumptions in the models. This would assume a standard of certainty that is inappropriate in a scientific setting. But the plurality involved gives good reason to rely on the prognoses the models generate, and I, just as Lloyd, hold it a promising endeavor to scrutinize to what extent this also indicates the models' accuracy (i.e. empirical adequacy).

Climate models are fed with and tested against a body of data that is confirmed by observations from many different sources including ships, satellites, radiosondes, and ground stations, experiments, and reanalyses. Paleoclimatological proxies are an important source, too, as they deliver strong evidence for the correctness of the prognoses that the models produce: ice cores, for example, provide evidence of the temperature and of the CO_2 and methane concentrations in the atmosphere during the last 400,000 years (Rahmstorf and Schellnhuber 2006, 10–11; cf. n1). Thus, possibly biased assumptions about atmospheric composition may be compared to actual empirical measurements from ocean buoys or weather balloons, and possibly biased assumptions in the models about other details can be cross-compared to other detailed empirical measurements.[3] It is precisely through this thorough cross-tabulation and comparison of empirical data that potentially biased assumptions in the robust models are either confirmed or undermined. This testing and confirmation of models is pursued by many of the top modelers in the world, e.g. by Ben Santer, who runs the international center at Berkeley for the intercomparison of climate models.[4] Lloyd is, therefore, right to put this pluralistic emphasis on climate modeling. Moreover, the general risk that the models indicate an unrealistic development of climate change is minimized by the cultivation of theoretical plurality in multimodel ensemble studies.

4 Employing Ensemble Studies

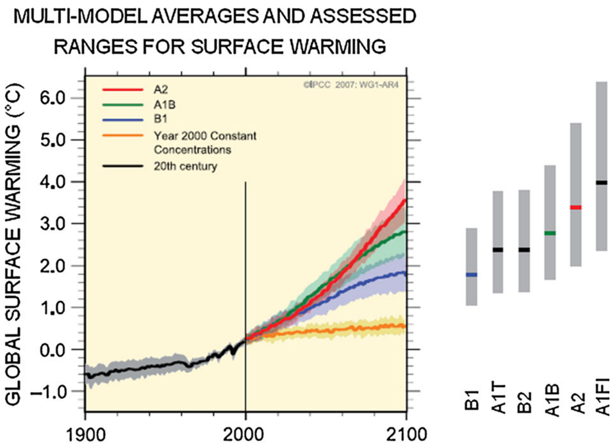
Global climate models must qualify to find entrance into the IPCC assessment reports by reconstructing the temperature data from the past. There is a variety of models that are able to reconstruct the observational and reanalysis temperature data from 1900 until today. In the third AR, 2001, 31 models, in the fourth AR, 2007, 23 models were involved (IPCC 2001, 8.5; IPCC 2007a, 8.2).

Next to this plurality of models there is a diversity of expertises regarding socio-economic future trends. Apart from the fact that, of course, nobody can foresee the future but has to estimate trends, even our knowledge of current local greenhouse gas emissions is doubtful due to a lack of direct atmospheric measurements. Methane, for example, is emitted in large quantities by animal farming or waste deposits. Its exact concentration can only be detected by direct measurements. Such measurements are complex and expensive; accordingly, the values currently assumed rely mostly on assessments reported to the United Nations Framework Convention on Climate Change by governments and industries.

[3] I am very grateful to Elisabeth Lloyd for explaining this to me in detail.

[4] Lloyd names this "complex empiricism"; in contrast, "direct empiricists" assume in a Popperian sense that any raw data gotten from measurements directly represent the "real world" and can be, thus, used in the modeling process. Using specific series of selected raw data in fact allowed a group of skeptics to deny the well-confirmed outcomes of the current climate models built by Santer and colleagues. For more details see Lloyd (2012).

There are significant differences between the reported values and the observational data from control measurements, though, which means that actual local quantities of methane emissions have remained unknown (Levin et al. 2011; Weiss and Prinn 2011).[5] As a consequence, experts differ about local economic developments, too. Yet, it is experts that decide which particular socio-economic trends are to be assumed (Oppenheimer and Yohe 2011). This is handled in a pragmatic way: according to the different expertises, a variety of emission scenarios is defined, including experts' diverse assumptions concerning not only current greenhouse gas concentrations but also the effects of political greenhouse gas regulation and, thus, socio-economic future trends. All emission scenarios that expert groups consider plausible are taken into account within so-called ensemble studies in which the entire set of qualified models is employed. Well-known figures from the ARs visualize this:



IPCC 2007b, 14

The figure shows the models' ability to approximately reconstruct the temperature between the years 1900 and 2000. It shows different possible future temperature trends under different socio-economic scenarios (until 2100). The square shows the IPCC's best estimations of temperature trends in three different possible scenarios by graphs (bottom-up: B1, A1B, and A2). The scenario illustrated by the bottom line indicates the warming in case the annual emissions do not change from the average of 2000, which is of course unrealistic and just serves as a benchmark. The other three lines indicate one environmentally friendly scenario, B1, in which clean, resource-efficient technologies have been introduced, and two economically oriented scenarios, A1B and A2. In B1, the "emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives" (IPCC 2007b, 18). In A1B, all energy sources are used in a balanced way; it "describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies" (Ibid.). A2 "describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local

[5] An improvement of data regarding the local concentration of greenhouse gases in the atmosphere could be achieved only by enhanced control measurements. This, of course, requires investments, which would be worthwhile, though, not least in terms of emission policy as "the investment would not be great compared to the economic cost of failed regulation" (Nisbet and Weiss 2010, 1242).

identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented" (Ibid.).

The six vertical bars in the right part of the figure indicate the range of possible temperature developments until 2100 which all 23 models jointly yield in six different scenarios (including the three scenarios the development of which is pictured by the graphs in the square). The small horizontal lines within the bars again depict the IPCC's best estimations.

Model intercomparisons regarding a specific scenario are known as multimodel ensemble studies. The figure shows a superensemble which combines several, in this case six, ensembles (thus forming an ensemble of ensembles). The combined models

> differ in a number of ways—in the form of some of their equations, in some of their parameter values, and often in their spatiotemporal resolution, their solution algorithms, and their computing platforms as well. A typical multimodel study requires the participation of research groups at various modeling centers around the world, each running its 'in-house' models on local supercomputers, and delivers a total of a few dozen simulations of future climate under a given emission scenario. (Parker 2011, 582)

That way, a broad variety of theoretical assumptions is included in the modeling procedures. This theoretical plurality admits to an overview of global climate trends considered plausible under the diversity of current expert opinions. Though we cannot gain deterministic prognoses, this method at least provides us with a range of hypothetical prognoses that are considered likely, given our present knowledge. Hence, the knowledge that a global warming within the range of 1.1 to 6.4 °C will take place until 2100 is claimed to be robust, and a warming of at least 1.8 °C is considered very likely (IPCC 2007c, 70).

However, it largely depends on the judgments of experts which development is considered particularly likely or the best estimation. Such expertise depends on contextual values and preferences, at least to a certain degree; it might be

> made not because emphasizing one prediction task over another has significant epistemic benefits, but rather because one set of prediction tasks is thought to be more important, in terms of its social, political, or economic consequences, than another. (Biddle and Winsberg 2010, 180)

This, however, does not mean that theoretical assumptions in climate modeling are optional, as is often argued by climate skeptics, i.e. that experts can arbitrarily pick out scenarios, data, or parameter values that fit their personal preferences. As Longino (1990, 2002) has pointed out, non-epistemic values can be held in check by social diversity. Due to underdetermination, Longino argues, empirical science is inevitably influenced by non-epistemic values, even in its context of justification. However, if many points of criticism from different social, moral, and political perspectives are included in the scientific discussion, arbitrary idiosyncratic influences as well as unconscious value influences through background assumptions are revealed and, accordingly, prevented. This way, different perspectives function as control instances: personal preferences are considered as epistemic resources rather than obstacles. Scientific hypotheses should, for epistemic reasons, hence be exposed to as many different points of criticism as possible, this criticism increasing the probability that distortions stemming from idiosyncratic preferences become visible and making the respective science reliable.

In fact, the IPCC is "an organization that encompasses the views and work of thousands of climate scientists around the globe—men and women of diverse nationality, temperament, and political persuasion" (Oreskes and Conway 2010, 268; cf. Leuschner 2012, 196). It is the task of the IPCC to summarize the international state of knowledge on climate change in a transparent and comprehensive way. Hundreds of scientists from all around the world are appointed to work on the assessment reports due to their expertise and next to their normal scientific work on a voluntary basis. The reports then are evaluated in a three-level review process in which again hundreds of scientists are involved. As an intergovernmental body the IPCC is open to all member countries of the UN and WMO. Currently 195 countries are members of the IPCC.[6] The *Summaries for Policymakers* are passed in a plenary session that sees political representatives even from countries looking askance at climate change mitigation measures or even reject them, e.g. Saudi Arabia and the US (cf. Rahmstorf and Schellnhuber 2006, 87–88).

Finding this cultivation of social diversity in the IPCC doesn't mean to contradict Biddle's and Windberg's conclusion that "more attention should be paid to the spaces within climate modeling where values play a role" (Biddle and Winsberg 2010, 193). I totally agree with them on this. I merely want to emphasize that climate modeling is not as much an arbitrary enterprise as certain people wants us to believe. The methodological discussion on uncertainties and values in climate modeling does not support such a claim. This is finally to be pointed out in more detail.

5 Convergence Skepticism Versus Climate Change Denial

It is highly unlikely that further research will allow for definite prognoses of the global climate, particularly due to the uncertainties regarding the climate system's causal behavior, but also for technical reasons:

> [… M]any important small-scale processes cannot be represented explicitly in models, and so must be included in approximate form as they interact with larger-scale features. This is partly due to limitations in computing power, but also results from limitations in scientific understanding or in the availability of detailed observations of some physical processes. Significant uncertainties, in particular, are associated with the representation of clouds. (IPCC 2007a, FAQ 8.1)

It is likely that the behavior of aerosols and of clouds, the exploration of which needs small-scale resolution, will never be adequately included in large-scale global climate models for systematic reasons, even if it were fully understood. Problems like this provide strong reason to argue for convergence skepticism (Lenhard and Winsberg 2010). Convergence skepticism doubts that a convergence of climate models can realistically be expected. This skepticism neither concerns climate modeling as such, nor does it deny progress in climate research (Lenhard 2011, 189). What is regarded as unrealistic is that the plurality of climate models will eventually converge and bring out the one exact model that provides definite prognoses. Instead, the "plurality of different forecasts of future climate is likely to be a persistent feature of global climate science" (Lenhard and Winsberg 2010, 253). This convergence skepticism is justified. It is true that the range of prognoses is not likely to shrink in the future and that the robustness of climate prognoses does not imply

[6] Cf. IPCC organization on http://www.ipcc.ch/organization/organization.shtml#.UIvjr2c9anA. Accessed 3 December 2012.

the predictive accuracy of the range of prognoses. Though climate research provides us with a robust range of prognoses, it can be objected that this robustness cannot guarantee truth, i.e. that the real temperature development will actually lie within that very range of prognoses. But this is trivial to some extent: any empirically based scientific theory is always in danger to be proven false by the occurrence of new evidence, and even if one scenario were considered correct, and all employed models converged to one prognosis, this wouldn't prove this prognosis as true. Elisabeth Lloyd puts it in a nutshell:

> Climate models should not be judged primarily or solely on the basis of what they are weak at; if we approached other scientific theories or models this way, we would never accept any of them. (Lloyd 2010, 982)[7]

Climate models seem to be especially useful in two areas: epistemically, they help to understand the climate system. Instead of just stressing that the models are failed if they produce unrealistic outcomes, we could also argue that this helps to spot the weak points in the respective representation of the climate system and our understanding of it:

> When the results don't correlate with reality, modellers use their knowledge of the climate system to try to identify the likely culprits within the model and then correct them. And occasionally what starts as a problem can lead to insights. (Heffernan 2010, 1015)

This heuristic value reveals an important epistemic task of the models. Next to this epistemic value, climate models provide policy-relevant prognoses as they indicate future trends of the global climate under specific socio-economic scenarios. And even though these prognoses are "only possible" and not certain, they are at least in accordance with the current state of knowledge and evidence which is produced and confirmed by a huge diversity of methods and theoretical assumptions employed by a global scientific community. Thus, it seems important to drop the demand on climate models to provide definite prognoses. The range of prognoses that is endorsed under all plausible emission scenarios by all evaluated models can be claimed to be robust, and although this robustness cannot *guarantee* that the actual temperature development will lie within this range it definitely *indicates* that the development will lie within that range, which means it can be considered as certain that global warming takes place despite the uncertainties in scientific details.

Note finally, that Daniel Sarewitz points to the important fact that the term "uncertainty" is used ambiguously in the climate debates:

> [… T]he 'condensation' of uncertainty's many meanings […] into 'one undifferentiated category' […] allows broad claims to be made about how the key to a given problem is more research and more time. (Sarewitz 2004, 396)

It is therefore important to explicate what "uncertainty" in a specific context means. My usage of the term here relates to the repeated confirmation of certain outcomes through a diversity of methods, techniques, and theoretical approaches to reduce epistemic uncertainty regarding these outcomes. This way, climate research provides a robust frame of scientific knowledge for political decisions. It is true that one cannot derive definite

[7] Lloyd (ibid.) further suggests to rather focus on "the models' fundamental strengths" by exploring "the relationships between evidence and climate models". Global climate models then "appear to be much better supported than previously considered". This also concerns the models' outcomes that appear much better supported, too, when the theoretical, methodological, and social plurality that is cultivated in climate research is taken into account.

guidelines for action from this frame. But at least a course of action is clearly indicated. It is not convincing that climate skepticism, too, can find scientific justification, as Sarewitz (2000, 2004) further argues. In contrast, climate skeptics misuse the uncertainties in scientific details to doubt the reality of anthropogenic global warming. But this does in fact not find any scientific support, which was well illuminated by two studies by Oreskes (2004) and Boykoff and Boykoff (2004) showing that of 928 scientific articles, not a single one doubted anthropogenic global warming, whereas 53 percent of 636 surveyed articles in US newspapers were climate skeptical. The strategic employment of pseudo experts through political and industrial stakeholders was also well documented by Oreskes and Conway (2010).

In light of this, it is important to finally distinguish fruitful epistemological criticism from economically motivated campaigns that attempt to undermine the public trust in science and to obstruct the scientific progress in order to defer agreements on climate change mitigation. Climate skeptics assert that scientific knowledge about climate change is influenced by non-epistemic (i.e. political, social or moral) values; they claim that this influence is consistently distorting the results which are inevitably tainted with the scientists' personal preferences. As mentioned above, this argument basically rests on the thesis of the underdetermination of theories. Thus, climate skeptics use an argument which is actually well-known and approved in the philosophy of science (e.g. by Rudner 1953; Douglas 2000, 2009; Wilholt 2009, 2013): the skeptics claim that data evaluations, auxiliary assumptions, estimations, and parametrization in climate modeling will vary, depending on the modelers' background assumptions. Again, this is basically not wrong. However, climate skeptics stress this point further, arguing that climate data, scenarios and models are constructed *in a specific way* to make the outcomes fit the climate researchers' (left-wing) interests. As Philip Kitcher ironically writes, "[according to the skeptics, g]lobal warming is a device used by Birkenstock-wearing, tree-hugging, business-hating, liberal intellectuals for advancing their political aims" (Kitcher 2010, 1233; cf. also Kitcher 2011, 162). This may sound funny, but the problem is serious. In an open letter published in *Science*, 250 scientists from national academies protested against the

> McCarthy-like threats of criminal prosecution against our colleagues based in innuendo and guilt by association, the harassment of scientists by politicians seeking distractions to avoid taking actions, and the outright lies being spread about them. (Sills 2010, 689)

The underlying problem of this denial is that the scientific consensus about anthropogenic global warming is not acknowledged as a scientific outcome but dismissed as a solely political belief.[8] If this assumption is accepted, then anthropogenic global warming can also be doubted on a political basis (Oreskes and Conway 2010, 63). While it is hard scientific work to prove assumptions true and discard wrong ones when scientists are engaged in complex and expensive, laborious and time-consuming projects, be it in modeling, experimenting or observing and data collecting, skeptics, supported by industrial and

[8] Sarewitz (2004, in particular on 392 and in n30) also represents the debate between climate researchers and climate skeptics as if it was a debate between ecologists and environmentalists on the one side and economists on the other. While it is true that there is a high percentage of economists among the skeptics, the climate researchers' community is much more heterogeneously structured and includes physicists and geologists, meteorologists and oceanographists. Most scientists who work in these research fields are to a large extent not politically motivated but they *do* in fact basic research. And this makes the controversy about global warming even stranger because politically motivated skeptics impute scientists to be politically motivated just because the outcomes of their research have political consequences.

political stakeholders, shape the public opinion by simply claiming that all of the scientists' findings are a hoax. Climate research is under great pressure as its credibility has constantly been doubted that way, and scientists have a strenuous time rejecting charges of their work being biased and part of a red conspiracy. They have to discuss the same objections over and over again and must constantly reflect and discuss their theoretical and methodological assumptions. This costs time, money, and nerves, and hinders the epistemic progress.

6 Conclusion

It was the key issue of this paper to analyze and localize problems in climate modeling by giving a critical overview of the current methodological debate. I addressed problems of the evaluation of climate models as well as data and physical uncertainties. It is important to see that fundamental uncertainties of the functional and causal behavior of climatic parameters are likely to remain. While data uncertainties are absorbed by a diversity of emission scenarios, uncertainties regarding the physical behavior of the climate system lead to a diversity of climate models. The plurality of scenarios and models is handled pragmatically in scientific practice by employing ensemble studies in which all qualified models simulate the climate under diverse emission scenarios. This deliberate employment of theoretical plurality provides a robust range of climate trends, and this range is confirmed by many independent sources of evidence nourished by a variety of research projects from all over the world and an ample diversity of scientific methods. Thus, we are given strongest reason to believe that a global warming of at least 1.8 °C will take place until 2100. This has been continuously confirmed by the epistemic progress of a scientific field that cultivates plurality in its theoretical approaches, techniques, and methods, as well as in the social and political relations of its community. The uncertainties in scientific details do not equal uncertainties about anthropogenic global warming and its negative impacts.

What I argued for in this paper is that, despite scientific uncertainties in details, climate research provides policy-makers with robust knowledge that definitely calls for action.

Pielke Jr. (2007) argues that more knowledge cannot solve moral and political problems. Scientists who claim otherwise can act as "stealth issue advocates" misusing their scientific authority to support certain political interests; such behavior undermines the public trust in science.[9] What Pielke neglects, however, is that scientific knowledge is at

[9] Due to this view, Pielke (2009) deplores for example realclimate.org, a weblog that is run by a group of renowned international climate scientists as e.g. Stefan Rahmstorf (Potsdam Institute for Climate Impact Research) and Michael Mann (Penn State University). Pielke criticizes that here the debate on climate change which in his view is exclusively a political debate is treated as if it were a scientific one. The scientists, he says, act as stealth issue advocates because they take a political stand without making this explicit; instead, they claim that the blog solely focuses on scientific issues and doesn't aim to support any political or economic position. However, Pielke objects, the scientists do in fact support a specific position, namely by claiming scientific consensus: according to Pielke this blog's only purpose is to attack climate skeptics such as George Will, Senator James Inhofe, Michael Crichton, McIntyre and McKitrick, Fox News, and Myron Ebell. I do not consider Pielke's argumentation convincing as it seems not plausible that there is no scientific consensus in the scientific community. Obviously, there is scientific consensus on many basic climate issues and in particular on anthropogenic global warming and its impacts (sea level rise, glacier melting, local floodings and droughts), and the weblog's focus is indeed on these facts exclusively, and even discusses scientific uncertainties in the recent state of research. This of course affects political interests as the issues in discussion unavoidably *concern* political interests, namely those represented by people or institutions such as George Will, Senator James Inhofe, Michael Crichton, McIntyre and McKitrick, Fox News, and Myron Ebell. However, this doesn't make the issues as such political.

any rate *relevant* for political decision making. I agree with Mark Brown who criticized that

> Pielke sometimes seems to want to insulate politics from science. […] Pielke is right that scientific knowledge is unlikely to provide conclusive answers to moral dilemmas, but such knowledge is often relevant to those dilemmas. (Brown 2008, 487)

The huge diversity in climate science doesn't mean there's no consensus at all, as Pielke claims, or that, as Sarewitz argues, skepticism finds scientific support.[10] Of course,

> political acts [… are] not taken on the basis of predictive accuracy or scientific justifications about what the future *would* look like, but on the basis of convictions about what the future *should* look like, informed by plausible expectations of what the future *could* look like. (Sarewitz 2004, 398, emphasis in original)

It is true that climate policy cannot act without making normative assumptions. However, convictions and plausible expectations are not as independent of each other as they appear to be here: the scientific outcomes and the scenarios deriving from them should reasonably limit the normative impact in political debates. But climate skeptics ignore or deny the state of scientific knowledge just because their aims and values cannot be realized within the frame of these outcomes. In contrast to Sarewitz and Pielke, who claim that research cannot tell us what to do, I would, therefore, rather say that research cannot tell us what to do *exactly*; yet it provides a robust frame of knowledge that indicates an unambiguous direction for appropriate political decisions, and any discussion, as normative as it will get, is pointless if not held within this frame.

Still, it is important to drop the expectation that climate research will one fine day provide deterministic prognoses. The range of climate prognoses provided by the models has not significantly changed in the last 30 years, and it is not likely to shrink in the near or distant future (Roe and Baker 2007). Epistemically, climate models should hence be particularly valued for their heuristic value, i.e. the part they take in our endeavor to understand the climate system. Politically, their outputs should be valued as a clear indicator for the importance and urgency of global climate protection: "[the] implication for climate policy is obvious: it should not wait for convergence, rather take the pluralistic picture as a given" (Lenhard and Winsberg 2010, 253). Therefore, the scientific uncertainties, with regard to the precautionary principle, must not be used as a reason for postponing climate change mitigation measures.

The plurality of methods, techniques, and theories in climate research and modeling provides reliable results. It is correct that we do not know if political climate change mitigation measures can avoid damages like floodings and droughts, ocean acidification or contamination of water supplies. But what we know is that not to reduce emissions will certainly cause severe problems. It is a fact that the global climate has significantly warmed during the last century and that this is due to a rising concentration of anthropogenic greenhouse gases in the atmosphere. It is also certain that anthropogenic global warming will continue during the twenty-first century. What is unknown is to what *exact* extent and how fast *exactly* the warming will proceed.

Still, as a final thought experiment, let's think about this: what if climate research has indeed failed? What if, in a 100 years from now, we have reason to believe that there

[10] Sarewitz gave special mention to Bjørn Lomborg as a skeptic with a scientific background, which he hasn't, as has been made plain particularly by Fog (2012).

hasn't been a thing like anthropogenic global warming? What if this global warming has indeed proven to be a hoax? In the worst case, we'll look back on a century in which we developed a renewable energy system and preserved our rainforests, fertile soils, drinkwater resources and oceans, a century in which we created a better world—for nothing.

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