Climate Change, Uncertainty, and Policy

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Contents

Abstract

While the foundations of climate science and ethics are well established, fine-grained climate predictions, as well as policy-decisions, are beset with uncertainties. This chapter maps climate uncertainties and classifies them as to their

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ground, extent, and location. A typology of uncertainty is presented, centered along the axes of scientific and moral uncertainty. This typology is illustrated with paradigmatic examples of uncertainty in climate science, climate ethics, and climate economics. The chapter discusses the IPCC's preferred way of representing uncertainties and evaluates its strengths and weaknesses from a risk management perspective. Three general strategies for decision-makers to cope with climate uncertainty are outlined, the usefulness of which largely depends on whether decision-makers find themselves in a context of "deep uncertainty." The chapter concludes that various uncertainties engrained in climate discourse cannot be overcome. It offers two recommendations to ease the work of policymakers, given this predicament.

Keywords

Climate change · Scientific uncertainty · Moral uncertainty · Deep uncertainty · Risk · IPCC · Storylines · Probability · Expected utility

Introduction

The issue of uncertainty in climate change discourse is complex and thorny. Its complexity is due to the fact that there are different kinds of climate uncertainties, which interact with each other, and manifest themselves at various locations in climate science, economics, and ethics. Its thorniness stems from the track record of interest groups who have appropriated – and manufactured – climate uncertainties for political and ideological purposes, typically to downplay the importance of climate action (Oreskes & Conway, 2010).

This chapter focuses on the former issue: the genuine uncertainties that beset climate discourse and that are relevant for policymakers. To preclude misappropriation, however, let me preface the discussion by highlighting some of the issues over which *very little* uncertainty exists within communities of relevant experts (IPCC, 2021):

(i) The main physical mechanism that gives rise to global warming is the greenhouse effect, which has been known for a long time and is scientifically well understood. The accumulation of greenhouse gas molecules in the atmosphere causes ever more heat to be retained on Earth, resulting in rising temperature levels, as well as other changes to the Earth's climate.
(ii) Anthropogenic emissions of greenhouse gases, specifically of CO_2, are the major driver of the climate change we are currently experiencing. Unless global greenhouse gas emissions are rapidly curtailed, the impacts of climate change are very likely to become more severe over the next decades.
(iii) Anthropogenic climate change is associated with several risks and hazards, including an increase of weather extremes, droughts, floods, rising sea levels, biodiversity loss, and associated risks to food security, human health, water supply, liveability, and economic growth.

(iv) While some countries might benefit, at least in the short run, from global warming, and while some animal species may thrive in warmer climates, there are clear indications that the overall consequences of climate change on human well-being and animal welfare should be negatively evaluated. Populations in the Global South and future generations are specifically vulnerable to the negative impacts of climate change.

These findings, and the hard-won scholarly consensus that pertains to them, should suffice to undercut the challenge of climate skeptics and denialists, who question that anthropogenic climate change is real or should be regarded as a ground for concern. But with that said, when it comes to assessing the regional impacts of climate change, or evaluating the desirability of different mitigation and adaptation policies, various scientific and moral uncertainties do come into play. This chapter overviews the sources of these climate uncertainties, as well as various strategies for coping with them.

Conceptualizing Uncertainty

The term uncertainty is infused with meanings. Uncertainty is typically associated with lack of knowledge and therefore negatively appraised: It is a deficit that should be overcome. This is only one face of uncertainty, however. Apart from what is unknown, uncertainty might also refer to what is unstable, indefinite, or indeterminate. Not all species of uncertainty can be overcome by retrieving further information. In fact, sometimes new information serves to increase, rather than reduce, the complexity of a problem, thereby adding a new layer of uncertainty.

Uncertainty may refer both to states of knowledge and to states of the world. It has been regarded as a measure of ignorance and as a hallmark of complexity. Hence, there are various kinds of uncertainty, and the term is conceptualized somewhat differently in different fields of inquiry. For instance, a standard definition in the study of measurement (metrology) is the following:

- *Metrological definition*: The word “uncertainty” means doubt, and thus in its broadest sense “uncertainty of measurement” means doubt about the validity of the result of a measurement (JCGM, 2008).

A rather different definition is found in the fields of economics and standard decision theory, where a distinction is commonly drawn between decision-making under *risk* and decision-making under *uncertainty* (Luce & Raiffa, 1957). This distinction goes back to the work of the economist Frank Knight (1921), who treated risk as calculable and uncertainty as incalculable. Knight’s distinction is sometimes complemented with the further category of decision-making under *ignorance*. If we understand probabilities in evidential terms, i.e., as the degree of evidence that pertains to a given proposition, then this leads to the following tripartite structure:

- *Economical / decision-theoretical conceptualization*:
  - Decisions under risk involve the availability of precise evidential probabilities with high epistemic credentials.
  - Decisions under uncertainty involve imprecise evidential probabilities, or evidential probabilities with low epistemic credentials.
  - Decisions under ignorance involve a complete absence of decision-relevant evidence.

A Typology of Uncertainty

Various proposals have been advanced to articulate a typology of uncertainty which disentangles its multiple dimensions (e.g., Kwakkel et al., 2010; Smith & Stern, 2011; Petersen, 2012; Walker et al., 2013; van der Bles et al., 2019). Perhaps unsurprisingly, given the divergent conceptualizations of uncertainty in different fields of inquiry, no single framework is endorsed across disciplines. The variety of typologies need not be regarded as an embarrassment of riches, however; uncertainty typologies can serve different purposes, and it may be helpful to tailor typologies to specific contexts. Moreover, the typologies that have been articulated in the scholarly literature do involve clear commonalities. For instance, in one way or another, all of them distinguish between (1) uncertainty due to lack of knowledge; (2) uncertainty due to variability in the phenomenon of interest; and (3) uncertainty due to ambiguity. This threefold distinction, one might say, pertains to the *grounds* of uncertainty: It articulates *what makes it the case* that we are not fully certain.

Below I outline a typology that elaborates on the grounds of uncertainty in climate policy. It does so by introducing an orthogonal distinction between uncertainty in the scientific and in the moral domain. *Scientific uncertainty* pertains to states of the world, as well as our knowledge and understanding of it. *Moral uncertainty* pertains to judgments of how the world ought to be, and the associated norms, obligations, and values. In practice, the distinction may be blurred. Policy-decisions about climate mitigation and adaptation are typically beset with both types of uncertainty, and sometimes they are difficult to disentangle (see **B1**). Nonetheless, it is useful to clarify what types of uncertainty are involved in a policy-decision. Doing so can help decision-makers to figure out to whom to turn for expert advice – a scientist, an ethicist, or both? – and to determine whether uncertainty can be reduced, and how so (Fig. 1).

A1. Scientific Uncertainty Grounded in Lack of Evidence

Scientific uncertainties about climate change can be grounded in a lack of solid evidence. Instruments of measurement may be deficient, resulting in incomplete or biased observations. Sampling errors can lead to unrepresentative data. The models into which data are fed can be overly simplistic. The initial conditions from which computer simulations that project future climate change are run, maybe unknown. These and other deficits yield imperfections in our body of evidence and lead to

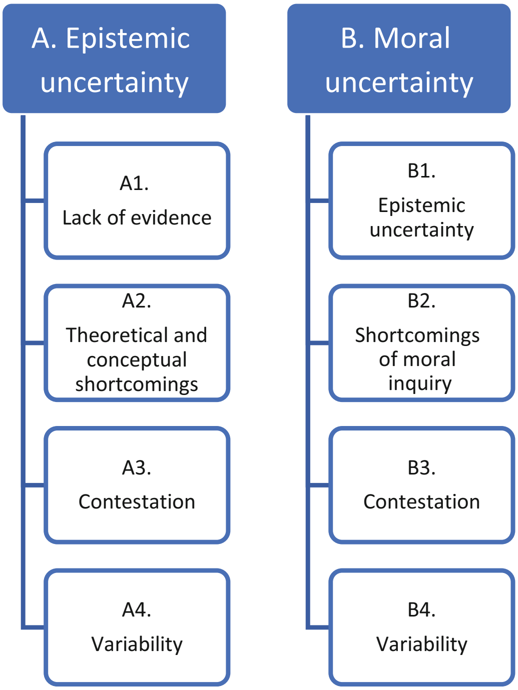

Fig. 1 Grounds of scientific and moral uncertainty

scientific uncertainty (see section "Locating Uncertainties in Climate Science" for more detail). Importantly, evidential uncertainty transpires in virtue of impaired observations, skewed data, and inadequate scientific models, but not in virtue of the phenomena under observation. At least in principle, evidential uncertainty can be overcome, for instance, with better measurements.

A2. Scientific Uncertainty Grounded in Theoretical and Conceptual Shortcomings

Scientific uncertainty can also be grounded in conceptual or theoretical deficits. Uncertainty of this kind is sometimes referred to as "ambiguity." Like uncertainty, ambiguity is a term infused with meanings. In the context of the present typology, A2 refers to unclarities of conceptualization and theoretical interpretation. In such contexts of ambiguity, even when an appropriate amount of information is provided, it remains unclear how this information should be understood. Hence, contrary to A1-type uncertainty, A2-type uncertainty does not stem from a paucity of good evidence, but from deficits in the conceptual and theoretical frameworks for interpreting the evidence, or from a lack of clarity about the problem structure and the variables involved. Uncertainty of this kind may be overcome by improving our conceptual and theoretical toolkit. Note that in the economics literature, ambiguity is often contrasted with the notion of risk, and taken to be synonymous with uncertainty in the decision-theoretical sense outlined at the opening of this section, i.e., as referring to situations in which probabilities cannot be determined (also known as deep uncertainty). Indeed, contexts of ambiguity often preclude probabilistic assessment. For purposes of the present typology, however, the question of whether uncertainty can be represented in probabilistic terms had best be regarded as an orthogonal issue, which has to do with the representation of uncertainty (see section "Representing Uncertainty"). What grounds uncertainty is not the absence of probabilities per se, but the absence of an adequate theoretical or conceptual framework of interpretation.

A3. Scientific Uncertainty Grounded in Contestation

Some uncertainties are consensus-based: The community of experts agrees there is uncertainty regarding a given issue. Other uncertainties are based on disagreement and conflict (Hansson, 2018). Scientists can have a different take on an issue, and there may be good arguments on either side. Rather than a shortage of theoretical frameworks, an issue may be theoretically overdetermined, with different scientists adhering to different theoretical frameworks. Peer disagreement can itself be a source of uncertainty: Sometimes we do not know *what* to believe, because we do not know *who* to believe. Importantly, in discussing contested facts it is important to make a further distinction: Are the facts contested among scientific experts, or are they contested by interest groups or among the general public, with no specific expertise? These types of contestation have different epistemic implications. While expert disagreement can be a justifiable reason to lower one's credence in a scientific proposition, the same does not hold for *any* kind of disagreement regarding a scientific proposition.

A4. Scientific Uncertainty Grounded in Variability

Not all scientific uncertainty transpires in virtue of human ignorance, or theoretical deficits. Uncertainty may also transpire in virtue of the variability that is inherent to the system under study. Natural variability is common in climate science. The Earth's climate is a complex system, which changes over time. Similarly, the evolution of human societies, whose emissions and technological capacities are key determinants of future climate change, is unpredictable in many respects. Absolute certainty about the state of the Earth's climate in the year 2100 will not be achieved until the year 2100. Causal chains to the future are still open, rendering future states of the system indeterminate. The resulting uncertainty – sometimes called *aleatory uncertainty* – cannot be fully eliminated. The variability of the system and the forces that influence it preclude full predictability. As an aside, it might be noted that there has been a long philosophical tradition, inspired by the work of Laplace, of questioning whether not all uncertainty is ultimately due to human ignorance. Hard determinists following Laplace's cue maintain that if scientists would be equipped with better epistemic capabilities, they could eliminate the uncertainty due to variability. Philosophers should bear in mind, however, that this stylized metaphysical doctrine is detached from modern-day scientific practice. In actual climate science, there is no indication that aleatory uncertainty can be eliminated – not even with superior tools and models.

In practice, the distinction between uncertainty due to knowledge gaps and ambiguity (A1–3) versus uncertainty due to variability (A4) cannot always be clearly drawn. Climate change frequently confronts scientists with mixed cases, in which uncertainty results both from limited knowledge and from system variability (see section "Simulation Uncertainties"). Furthermore, scientists may not be able to tell whether knowledge gaps can be overcome by further observation and better theorizing, or whether variability is a fundamental property of the system under scrutiny. Such metauncertainty – uncertainty about the species of uncertainty one is dealing with – is itself an example of conceptual ambiguity (A2).

B1. Moral Uncertainty Grounded in Epistemic Uncertainty

In recent years, normative and moral uncertainty have become topics of scholarly interest. Like scientific uncertainties, normative uncertainties can be grouped in different types (cf. Taebi et al., 2020). One ground are the scientific uncertainties previously discussed. To the extent that essential factual matters are unsettled, we may be uncertain over which course of moral action to pursue. Consider the question of how much of our mitigation resources should be devoted to Carbon Capture and Storage (CCS). One area of ethical contention is the worry that money spent on CCS diverts investments away from green energy solutions, thus posing a moral hazard for climate mitigation. This worry is grounded in a factual claim, but the factual claim is itself contested; the resultant epistemic uncertainty can be a ground for moral uncertainty. Note, however, that greater epistemic uncertainty does not *necessarily* translate to greater moral uncertainty. For instance, with regard to a very risky undertaking (e.g., solar geo-engineering; see section "Future Technologies"), substantial epistemic uncertainty about associated impacts arguably provides strong support to the moral judgment that this undertaking should not be pursued lightheartedly. Hence, epistemic uncertainty can foster moral uncertainty, but it may also breed moral certainty.

B2. Moral Uncertainty Grounded in Shortcomings of Moral Inquiry

As noted in A2, our scientific theories and conceptual frameworks may be deficient. The same holds for our moral theories and concepts. There may be moral uncertainty as to who should be the recipients of moral duties and how concepts of moral evaluation should be explicated. There may be uncertainty about the ontological and moral status of entities to which moral theorizing pertains (e.g., Żuradzki, 2019). Moral values might be vague, imprecise, and may turn out to be incommensurable when spelled out. Vagueness also pertains to what is precisely entailed by moral theories and normative principles, and how they should be combined (MacAskill et al., 2020). Indeed, moral theory may turn out to be underdeveloped in relevant respects. This may be particularly true for climate ethics, as leading scholars in the field have argued (see Gardiner, 2011 on the "theoretical storm").

B3. Moral Uncertainty Grounded in Contestation

Moral uncertainty and ambiguity can come along with – and can be grounded in – moral disagreement. Consider decisions that rely on expected utility maximization versus decisions that rely on the precautionary principle (section "Decision Strategies in the Face of Uncertainty"), or person-affecting versus nonperson affecting views in population ethics. Serious arguments have been articulated on both sides of these debates, which are subject to ongoing academic dispute. Indeed, reasonable disagreement is widespread in ethical scholarship. Conflict might also be felt at an individual level: A moral decision-maker can feel torn about how to weigh the interests of future people against the interests of presently living people and be at loss in formulating an overall moral judgment. Arguably, there simply is no truth to the matter as to how this should be done. Some moral claims are inherently contestable.

B4. Moral Uncertainty Grounded in Variability

Moral inquiry is not static: Over time, new values might emerge and existing values can be conceptualized anew (van de Poel, 2021; Hopster, 2022). The moral desirability of a given course of action might change over time, for instance, because of a different prioritization of values, or because of shifts in our circle of moral concern. Conceivably, in the future we may come to regard all mammals as our moral equals, or we may come to think differently about the perils of existential risk. This insight, in turn, casts some degree of moral uncertainty over policy decisions, as these might have unexpected moral ramifications. For instance, our current decisions might put future groups at risk, of which we were not able to foresee their existence as morally significant entities (Hayenhjelm, 2018). These kinds of unknown unknowns are most prevalent with regard to decisions that have long-term implications, as climate mitigation and adaptation decisions often do (section "Future Populations").

Ground Versus Extent of Uncertainty

The typology outlined in this section captures several faces of uncertainty, but not all of them. Further distinctions could be made, some along orthogonal dimensions. For instance, a further category frequently invoked in classifying uncertainty is "deep uncertainty." According to the Society for Decision-Making under Deep Uncertainty (DMDU) "deep uncertainty exists when parties to a decision do not know, or cannot agree on, the system model that relates action to consequences, the probability distributions to place over the inputs to these models, which consequences to consider and their relative importance" (cf. Lempert et al., 2003). While deep uncertainty, thus understood, cuts across some of the aforementioned categories, the term is typically used to emphasize the *extent* of uncertainty, rather than the *ground* of uncertainty. More specifically, deep uncertainties cannot be expressed in meaningful probabilistic terms; as a result, they require "non-standard" approaches to decision-making. In contexts of climate change decision-making, deep uncertainty is actually quite common, however, and nonstandard approaches are becoming increasingly prevalent (section "Decision Strategies in the Face of Uncertainty").

Policy Implications

I have illustrated that uncertainty can be broken down in many different parts. Yet in policymaking, these different parts are often entangled. Consider the question of whether a government should invest in nuclear energy to realize its CO_2 reduction targets, while guaranteeing energy security. This question has both a scientific and a moral component and is subject to uncertainties on both sides, such as scientific uncertainty regarding the feasibility of satisfying energy needs with other energy resources (A1), or moral contestation over the harms of nuclear waste (B3). Hence, it is important to bear in mind that the presence of one type of uncertainty does not preclude the presence of others. Furthermore, it merits emphasis that different kinds of uncertainty may warrant different kinds of response. As a result, the exercise of identifying which type or types of uncertainty are at stake with regard to a given policy issue can help in formulating adequate responses. For instance, the typology can help policymakers to ascertain whether uncertainty can be reduced by stimulating further research, whether a probabilistic or a nonprobabilistic model of decision-making is warranted in the face of uncertainty, and whether policy measures are sufficiently flexible to cope with unknown unknowns.

Locating Uncertainties in Climate Science

Apart from their *grounds* and *extent,* we can also categorize uncertainties by their *location* (Petersen, 2012). Uncertainties are located at various stages of scientific enquiry and normative decision-making. This section discusses important locations of uncertainty in climate science. Since the climate sciences span many disciplines, each of which comes along its own uncertainties, a comprehensive treatment is beyond the chapter's scope (▶ "Climate Change and Scientific Uncertainty"). Instead, in what follows, I will focus on three locations of scientific uncertainty in particular: observation, simulation, and impact. These respective locations are not associated with specific policy implications. Nonetheless, it will be useful for climate policymakers to have some grasp of the different ways in which uncertainties feed into climate science. This can help in building the right kind of sensitivity to judge the strengths and limitations of scientific policy-advice.

I. Observational Uncertainties

In the 1940s controversy arose over historical measurements of the sea temperature. The controversy was resolved when researchers realized that the bucket that had been used to measure the water's temperature had at some point been replaced, and that the new bucket gave rise to different measurements (Schmidt, 2008). Measurement errors like these are common to practices of data collection. The quality of observed data depends on the reliability of measurements. If equipment is ill-calibrated, measurement errors may creep in. Unfortunately, for some instruments used in climate measurements, calibration is difficult. For instance, satellites that are inaccessible once deployed cannot easily be recalibrated (Baumberger et al., 2017).

There are various other ways in which measurements can be unreliable and may give rise to biased data. Observations are typically sparse in space and short in time: A sample that is obtained through observations may not be representative of large-scale trends. Historical measurements may be absent altogether, in which case scientists typically gather proxy data, which are less reliable than direct measurements. Incompleteness, potential bias, and the possibility of error all add to scientific uncertainty about the quality of observed climate data (e.g., Winsberg, 2018).

Observational uncertainties can sometimes be reduced. For instance, it may sometimes be possible to compare datasets, which have been obtained by independent measurement devices. Following the insight of Pierre Duhem, however, it should be kept in mind that data are theory-laden: The calibration of measurement devices, as well as the regimentation, restructuring, and subsequent interpretation of data, are influenced by auxiliary hypotheses (idem). The theory-ladenness of observations, and the accompanying possibility of theoretical error, constitutes a further source of uncertainty in measurement, which cannot be eliminated entirely.

II. Simulation Uncertainties

One major endeavor in climate science – especially the physical climate sciences – is to simulate future temperature changes and their impact on the climate system (e.g., Petersen, 2012; Winsberg, 2018). Computerized simulations are based on climate models, which pertain to ocean circulations, atmospheric circulations, or couplings thereof. Several global climate models (GCMs) have been designed by teams of scientists around the globe. These models can be compared and integrated, resulting in complex “multimodel climate ensembles” that simulate climate change for this century and beyond. These multimodel ensembles provide key inputs for reports of the Intergovernmental Panel on Climate Change (IPCC).

To generate projections of future climate change, these models require input about indeterminate variables, such as future human greenhouse gas emissions. Hence, the projections of climate models are conditional on emission scenarios. These *projections* should not be conflated with *predictions* about what is going to happen in the future: Climate projections merely show how climate models respond to external forcing scenarios, and the IPCC is explicit not to attach any likelihood to these scenarios. This caveat notwithstanding, projections are important instruments for policymakers, as they provide some indication of what might plausibly happen in the future, depending on future human greenhouse gas emissions. Indeed, the different emission pathways outlined by the IPCC are frequently used as a basis to assess different mitigation options.

There are several kinds of uncertainties that pertain to climate simulations, which can be partitioned in different ways. Here I discuss three subclasses, following

Hawkins and Sutton (2009): uncertainty due to the internal variability of the climate system, uncertainty regarding the external forcings of the climate system, and uncertainty about climate models.

Natural Variability

The Earth's climate system exhibits substantial natural variability. Fluctuations occur even in the absence of external forcings and transpire naturally from the system's nonlinear interactions. An example is the El Niño-Southern Oscillation, which results from the interaction between atmosphere and ocean in the tropical Pacific. Natural variability generates aleatory uncertainty (A4), which is unlikely to be reduced even if climate models improve (Deser et al., 2012).

External Forcings

External forcings are influences on the climate system that shift the equilibrium between how much energy the Earth receives from sunlight and how much energy is radiated out. Several external forcings influence the climate system, including forcings that are anthropogenically induced. While part of the carbon dioxide humans emit remains in the atmosphere for a long time, the majority of the warming response is due to emissions caused within people's own lifetime (Ricke & Caldeira, 2014). By implication, how climate change will evolve over the next decades and centuries crucially depends on the actions of current and future generations. Yet there is substantial uncertainty with regard to the amount of greenhouse gases humans will emit over the next decades and the rate with which emissions will be curtailed. Hence, there is uncertainty regarding future emissions scenarios – a type of uncertainty sometimes called "scenario uncertainty." This uncertainty, in turn, is bound up with questions about the future of human technology, political institutions, and demography, to which we will return in section "Uncertainties in Climate Economics and Ethics". The further we look in time, the greater scenario uncertainty becomes.

Apart from uncertainty about anthropogenic forcings, there is also uncertainty about the natural forcings that will influence future climates. Massive volcanic eruptions, for instance, are difficult to predict, but historical and geological evidence shows that they can be game changers in episodes of global warming and cooling. Solar intensity, too, can vary over time. In climate science, such effects are not described as being internal to the natural variability of the climate system (section "Natural Variability"), but as external forcings that act on the system. Hence, apart from "internal variability" the climate system also exhibits "external variability."

Model Response

Even in response to the same emission scenarios, different models simulate different climate futures. This variability points to uncertainty about the accuracy of these models. Our knowledge of the climate system is limited, for instance, with regard to the question of how sensitive the climate is to increased concentrations of greenhouse gases in the atmosphere. Note, however, that in recent years scientists' understanding of “climate sensitivity” has become increasingly refined, and that the associated uncertainty margins have narrowed down (Sherwood et al., 2020).

Model uncertainty stems from various sources. Aerosols and processes of cloud formation are notoriously difficult to represent in spatial and temporal detail; their parametrization is a substantial source of uncertainty in climate models (McFarlane, 2011). Another source of uncertainty is incompleteness: by representing some phenomena and neglecting others, modelers may overlook relevant processes, such as various positive and negative feedback cycles that are currently not well understood. Current models tend to assume – perhaps naively – that atmospheric feedbacks scale linearly with surface warming. Thresholds effects that are uncertain but nonetheless deemed possible by many experts, such as the collapse of the West Antartic Ice Sheet, are typically not incorporated in simulation models.

Simplification is inherent in making models; no model perfectly emulates reality. While this holds true for models in general, there are some characteristics that make existing climate models specifically problematic – more so, for instance, than weather models. For instance, a crucial test for validating climate models is to evaluate them against present observations and to predict the historical record (hindcasting). The shortness of the observational record, however, constitutes an obstacle in doing so (Parker, 2010). Furthermore, to the extent that validation is possible at all, it appears that none of today’s climate models has a perfect fit with the observed record. In fact, all extant models give rise to many results that do not come close to matching observed data, beyond margins of statistical error (Baumberger et al., 2017).

One might hope that using an ensemble of models serves to balance the biases that stem from the reliance on any particular model and can help to infer which simulations are more well-founded than others. Prima facie, it seems plausible to think that *robust* projections – i.e., projections that are replicated in a majority of models in the ensemble – are likely to be true. However, when it comes to model ensembles, an inference from the robustness of projections to their likely truth is problematic (Baumberger et al., 2017). The models in multimodel ensembles rely on similar assumptions and might have similar flaws, which could lead to similar projections. The combination of uncertainties at play in model ensembles, and the imperfections of bias correction measures, makes our epistemic position with regard to the resulting climate simulations somewhat opaque and suggests that surprises are to be expected.

III. Impact Uncertainties

While computerized simulations constitute an important component of climate science, the climate sciences span a much wider field. Various environmental, social, and medical sciences study the environmental and public health impacts of rising temperatures and atmospheric CO_2 levels. Each of these disciplines brings along its own set of uncertainties regarding observed data and anticipated impacts. When it comes to adaptation planning in the face of anticipated environmental impacts, policymakers often find themselves in situations of even greater uncertainty than when presented with uncertainties regarding mitigation decisions. This is because uncertainties are additive: They cascade from one level to the next, leading to an ever-broadening "envelope of uncertainty" (Wilby & Dessai, 2010).

Even though substantial confidence may pertain to assessments of the *kinds* of environmental consequences that are to be expected in the face of rising temperatures, sea levels, and ocean acidification, the precise details of these consequences, such as the magnitude of storms caused by sea-level rise, may be impossible to predict. The same holds for the regional distribution of climate change impacts, which is a source of substantial uncertainty. Merely focusing on changing global average temperatures conceals substantial regional variation. Techniques to downscale global climate models to regional levels are fraught with difficulties (Hewitson et al., 2014). This is unfortunate, since from the perspective of risk assessment and for purposes of adaptation planning, regional differences and associated climate hazards are of distinct importance. Special mention should be made of compound risk events (e.g., heavy rain on saturated soils, or globally synchronized heatwaves affecting global food production), which amplify environmental and human impacts (Zscheischler et al., 2020). While compound events are impossible to predict in detail, the increased frequency of this *type* of event due to climate change is of great importance for adaptation planning.

Uncertainties in Climate Economics and Ethics

There is some overlap between the key uncertainties that pertain to the climate sciences, on the one hand, and uncertainties in climate economics and ethics, on the other. For instance, as discussed in section "External Forcings", climate simulations crucially depend on assumptions about future greenhouse gas emissions. Future emissions, in turn, depend on variables such as the development of human technologies for reducing carbon emissions and carbon uptake (Negative Emissions Technologies), the pace of the energy transition and associated political challenges, and the future of demography as well as economic growth. These topics are also of great importance in climate ethics and economics. Economists, in particular, have played an important role in the development of so-called Integrated Assessment Models (IAMs) (Fleurbaey et al., 2019). These are models which incorporate the interactions between climatic changes and social developments, and which are meant to assist policymakers in making good decisions regarding climate mitigation. But they are also controversial: IAMs inevitably rely on normative assumptions, some of which are contested.

In this section, I single out three topics which are couched in substantial factual as well as moral uncertainty: future technologies, future institutions, and future populations. I highlight these topics as they constitute important variables which may tilt the overall balance of decision-making, for instance, in the context of IAMs.

It should be borne in mind, however, that uncertainties in climate ethics and economics are not limited to these three issues.

Future Technologies

Emerging technologies will play a crucial role in the transition toward a nonfossil economy. Examples include decarbonization technologies in transportation, CCS-technologies in heavy industry, and advanced energy storage technologies that stimulate the deployment of renewable energy. Each of these have a clear potential to help curtailing greenhouse gas emissions, but the pace at which they will be deployed is uncertain. Various other technological developments might serve to accelerate CO_2 mitigation, although some innovations can also have mixed or opposite effects. For instance, the development of cultured meat has potential to reduce agricultural emissions. On the other hand, growing cultured meat is energy intensive; its potential effect on climate mitigation will depend on broader developments in the energy sector. Similarly, future use of artificial intelligence and blockchain might serve to exacerbate energy demands. Whatever new affordances and constraints emerging technologies generate, it is plausible that they will have a major – yet partly unpredictable – influence on climate change mitigation and adaptation.

Somewhat more speculative, but of substantial interest to ethicists, is the emergence of geo-engineering technologies, such as carbon dioxide removal (CDR) and solar radiation management (SRM). There are various kinds of CDR-technologies, some of which are unconventional and risky, such as the iron fertilization of the oceans. The idea behind SRM is to block incoming sunlight, for instance by increasing the concentration of atmospheric aerosols. While this will not reduce the amount of CO_2 in the Earth's atmosphere and its uptake in the oceans (as a result, it will not stop the acidification of the oceans), it could serve to revert global temperature rise. Both SRM and some of the more invasive forms of CDR come along with substantial amounts of recognized uncertainty and risk. Many ethicists think that – at least at present – they are much too risky to be deployed (e.g., Gardiner, 2011). Notice, in this case, that the substantial amount of *scientific* uncertainty that pertains to the effects of geo-engineering does not serve to increase *moral* uncertainty. In fact, the opposite is the case: The amount of scientific uncertainty that comes along with deploying invasive geo-engineering technologies is part of what fosters the present ethical consensus to refrain from deployment (Pamplany et al., 2020).

Future Institutions

The future of political institutions is another source of substantial uncertainty with regard to long-term economic models. Societal ambitions regarding climate mitigation are unpredictable, and democratic elections may yield surprising results. Of specific importance in the context of climate mitigation will be the ambitions of economic and demographic centers of gravity like China, India, and the United

States. For each of them, mitigation ambitions over the next decades are somewhat unpredictable. Moreover, the political and societal dynamics can be disrupted by unforeseen events. Examples are the Covid-19 pandemic and the war between Russia and Ukraine, which have had a notorious impact on efforts at on reducing global greenhouse gas emissions in the early 2020s (Liu et al., 2020). The institutional response to such disruptions, and the institutional changes that might occur in their wake, cannot be predicted but could be of great importance with regard to socioeconomic pathways and future emissions.

Turning to normative questions of ethics and political theory, there is some uncertainty over the question of how future institutions should be designed. Does an effective global response to climate change require new forms of global governance, and if so, under what conditions would these be legitimate? Furthermore, there is uncertainty over the question of how future people should be institutionally represented, which is related to foundational questions regarding the status of future people in moral theory (Gonzalez-Ricoy & Gosseries, 2016).

Future Populations

Future populations are a further variable with major impact on long-term economic models. How will population growth proceed in different parts of the world, and affect global energy demands? Scientific uncertainty on this question is constrained: Predictions about twentieth century population growth have been fairly stable over time. However, future populations are also a source of moral uncertainty. Specifically, the discount rate that economic models apply to the goods of future people has been a source of contention among climate economists (Scovronick et al., 2017). Such contention is entangled with the question of how the risks and benefits of climate mitigation should be distributed across generations, and with assumptions about the future of human welfare. Given the complexity of these issues, moral ambiguity cannot easily be resolved.

Debates about discounting have a salient ethical dimension (Mintz-Woo, 2021). If people will be better off in the future, then it may be morally justified to prioritize the interests of the present generation and to discount the interests of future people. But by what degree, if any? Is the assumption that people will be better off in the future plausible to begin with? These questions are beset with different species of scientific and moral uncertainty. Since policy decisions are sensitive to these uncertainties, an important task in normative theory is to assess how decision-making in the face of uncertainty should proceed.

Representing Uncertainty

Before turning to the topic of decision-making under uncertainty, it is worthwhile to reflect on the different ways in which uncertainties can be represented. Such reflection has conceptual priority: The merits of different decision-procedures under uncertainty depend, in part, on the conceptual framework used to represent uncertainty.

Quantifying Uncertainty

A common way to represent uncertainties is by quantifying them and expressing them probabilistically. Probability statements admit of different degrees of precision. Some statements can be framed in terms of precise probabilities, e.g., "the probability that a given climate expert endorses the scientific consensus that global warming is human caused is 97%" (Cook et al., 2013). A greater range of uncertainty can be attached to statements couched in terms of a probability interval, e.g., "the scientific consensus on anthropogenic global warming is in the range of 90%–100%" (Cook et al., 2016).

Probability statements are conditional on the assumption that the underlying argument, method, or model on which they are based is correct (Ord et al., 2010). First-order probability statements can themselves be qualified, if there is uncertainty regarding the accuracy of the underlying model. Such second-order epistemic qualification – which, too, may be expressed in probabilistic terms – is often desirable when scientific predictions derive from a particular model, the reliability of which should itself be assessed. For instance, the assertion that "the probability that a given domain expert endorses the scientific consensus that global warming is human caused is 97%" is conditional on the soundness of the method employed by Cook et al. (2013). We might conceive of a climate skeptic whose confidence that this method is sound is quite low – say only 10% – in which case the climate skeptic might still feel entitled to question whether a majority of scientists endorse the view that global warming is human caused. Judged by standards of probabilistic rationality, nothing is at fault with such reasoning.

There are definite upsides to quantifying probabilities. Qualitative terms such as "likely" or "improbable" can be interpreted in many different ways and may give rise to misunderstandings or conflicting interpretations. In order to rank risks and to reason precisely about degrees of evidence, numbers are indispensable (Ord, 2020).

That said, the language of probabilities is not the only one that can be used to represent uncertainty. Furthermore, qualitative terms can have certain advantages. While qualitative representation often comes at a loss of precision, it may lead to a gain in faithfulness, if the uncertainty is such that probability estimates cannot be reliably made. Also, in some instances, natural language might actually convey more clearly whether or not a probability is decision-relevant ("this chance is non-negligible"), whereas probabilistic language is more open to interpretation (is a chance of 1 in 100 non-negligible? 1 in 1000? 1 in 10,000?).

Moreover, not all kinds of uncertainty lend themselves for probabilistic representation. For instance, there is no straightforward method to cast uncertainties due to ambiguity in probabilistic terms. This puts some pressure on efforts to rank contexts of knowledge in terms of the extent of uncertainty they involve, going from complete certainty, uncertainty that involves precise probabilities, uncertainty that involves vague probabilities, and deep uncertainty in which probabilities are inherently contested, all the way down to total ignorance (Walker et al., 2013). Such a ranking of uncertainty can be misleading, as it identifies the *extent of ignorance* with the *precision* that probabilistic statements allow for. Yet some uncertainties are genuinely different in kind, which precludes any straightforward ranking. Which means of representing uncertainty – probabilistic or not – is most suitable depends not only on the extent of uncertainty, but also on the type of uncertainty in question (see section "Conceptualizing Uncertainty").

Apart from conceptual reflection, when it comes to the effectiveness of different kinds of uncertainty representations, psychological research can be of great importance. Recent work suggests that in communicating climate uncertainty there is a delicate balance to be struck between being too precise and overly vague (Ho & Budescu, 2019). While decision-relevant details should not be left out in uncertainty communication, efforts to be too comprehensive may backfire. Moreover, it is important to use terminology that puts clear bounds on the uncertainties being communicated (e.g., by specifying a specific range of sea-level rise, rather than specifying that the range is unknown). Bounded uncertainty statements are more easily accepted among the public, whereas uncertainty statements that admit to a lack of resolution decrease confidence in these statements (Howe et al., 2019).

The IPCC's Treatment of Uncertainty

The IPCC employs a standardized vocabulary to represent uncertainties, meant to communicate uncertainty in a clear and consistent manner. The framework that has been in place since the fifth assessment cycle is outlined in Mastrandrea et al. (2010). The IPCC's "calibrated language" contains two key metrics for communicating the degree of uncertainty of a statement: confidence and likelihood. Confidence is expressed in qualitative terms (e.g., "high confidence"). Levels of confidence are a function of the type and quality of evidence, on the one hand, and degree of agreement, on the other. Hence, if an assertion is qualified with "high confidence," then we can infer that there is solid evidence and substantial scientific consensus regarding its truth.

The IPCC's likelihood scale contains quantified measures of uncertainty presented in terms of likelihood intervals for relevant variables. Likelihoods are based on statistical analysis of observations or model results, or on expert judgment. For instance, the fifth assessment report states that it is "extremely likely" that more than half of the late twentieth century warming was human caused (IPCC, 2013). Since the IPCC uses the term "extremely likely" to express a probability interval of 95–100%, we can infer that climate models paired with expert judgment give us a

95–100% likelihood that a majority of the temperature rise that occurred during the last century has been human induced.

Scenarios, Narratives, and Storylines

In the wake of AR5, increasing criticisms regarding the IPCC's representation of uncertainty have been voiced, as it seems to underplay the severity of the risks of global warming. (e.g., Stoerk et al., 2018; Herrando-Pérez et al., 2019). For one, it has been questioned whether the terminological conventions the IPCC employs convey the right message to the public and to decision-makers. Arguably, the IPCC's terminology has been too conservative and occasionally vague: Reliability is achieved at the cost of informativeness (Løhre et al., 2019). Moreover, it has been questioned whether the IPCC's treatment of uncertainty is not too probability oriented. Arguably, given the range of uncertainties that pertain to climate science (see section "Locating Uncertainties in Climate Science"), for many statements about the magnitude of global warming, let alone for statements about its regional impacts, it is questionable whether meaningful probability statements – and even vague probability estimates – can be attached to them (Sutton, 2019). This is not to say, however, that we do not have any relevant information with regard to these magnitudes and impacts, or that such information is not relevant for decision-makers. To the contrary, in the context of risk assessment and adaptation planning "low likelihood high impact events" are of the utmost importance. Hence, the general tenor of the criticism is that the IPCC's approach should be better aligned with key principles of risk assessment (King et al., 2015). In its most recent Assessment Report (AR6), the IPCC has begun to shift its approach accordingly, incorporating a "disaster risk reduction" framework that puts emphasis on low likelihood, high-impact events (IPCC, 2021).

Another notable development is that in recent years increasingly scholarly attention has focused on qualitative climate scenarios, which are advanced as explorative tools that aim to sketch realistic possibilities of what might happen. Shepherd et al. (2018) call this the storyline approach. A storyline is a physically self-consistent unfolding of past events or of plausible future events, to which no specific probability is attached. Storylines are intended to provide information that is particularly well suited for decision-makers. At a psychological level, their built-in narrative enhances emotional engagement. From a risk perspective, they help to focus attention on compound risks which could have major impact, but are not captured in global climate models (see section "Impact Uncertainties"). Furthermore, the logic of research questions that guides the storyline approach implies that it tends to safeguard against false negatives. That is to say, it tends to avoid missed warnings and to ensure that significant impacts of climate change are not overlooked. Arguably this is justified: Climate science should become more like medicine or public health in its assessments of risk, where false alarms (false positives) tend to be preferred over failures to prevent (Lloyd & Oreskes, 2018).

Decision Strategies in the Face of Uncertainty

It is commonly assumed that decision-makers should seek to eliminate or maximally reduce uncertainty. This is not always feasible, however, as some uncertainties simply cannot be eliminated. Moreover, the aspiration to maximally reduce uncertainty may not be desirable. Uncertainty can be an indicator of the complexity of an issue; disregarding this complexity might have the unwanted consequence of impoverishing decision-making. But there are other ways of coping with uncertainty, apart from seeking to reduce it. Idealized frameworks for decision-making in the face of uncertainty are increasingly giving way to "non-standard" frameworks and approaches, such as adaptive decision-making, which are better suited for contexts of deep uncertainty.

In this section, I single out three general strategies of decision-making in the face of uncertainty (cf. Hinkel et al., 2019). These need not be looked at as rivalling strategies, at least not in all contexts. Instead, they can be regarded as strategies that might be suitable in different decision-context, depending on the nature and the degree of uncertainty that confronts decision-makers.

Expected Utility Maximization

Proponents of expected utility theory, or expected value theory, counsel to take decisions by conducting a consequentialist risk-benefit analysis. The expected utility for an action is the sum of the probability-adjusted utility of possible consequences. Maximizing expected utility is the default approach to "decision-making under risk" – i.e., in contexts where decision-makers can assign high-credential probabilities to different outcomes (section "Conceptualizing Uncertainty"). While such contexts dominate textbook examples, however, clear-cut cases of decision-making under risk are unusual in real-life decision-making (Hansson, 2009). When probabilities are not readily available, or can only be estimated with substantial margins of uncertainty, reliance on expected utility theory is controversial (e.g., Bradley et al., 2020). Some proponents advise to stick with the expected utility approach and try to estimate probabilities as well as possible (Broome, 2012). Critics might argue that in contexts of deep uncertainty this either invites false precision, or leads to paralysis in decision-making, as there is no expert consensus regarding the appropriate probability estimates (Hopster, 2021).

Robust Decision-Making

The aim of robust decision making is to define policies that yield acceptable outcomes across a wide range of plausible future states of the world (Walker et al., 2013). Hence, in the case of climate change, acceptable outcomes should be robust to the range of different scenarios that might transpire in virtue of the various scientific uncertainties we face (section "Locating Uncertainties in Climate Science"). This strategy might conflict with the strategy of expected utility maximization, which is generally biased in favor of realizing (or preventing) outcomes that are particularly likely to occur.

There are different types of robustness strategies. One of them is to outline a static policy that will perform well in practically all conceivable situations. A weakness of this strategy is the potential mismatch between what is conceivable and what is realistically possible: Human imagination is limited and likely to be tainted by various cognitive biases. A second robustness strategy is to seek resilience, which may be defined as a system's ability to recover from external disturbances. Resilient decision-making counsels to follow a policy such that whatever happens in the future, a given system will be able to quickly recover. A third type of robustness approach is to plan specifically for the worst possible case. This approach is sometimes associated with the precautionary principle, although it should be kept in mind that the precautionary principle has been operationalized in many different ways, not all of which are specifically geared at avoiding the worst outcome. An element that many operationalizations have in common is their reliance on a decision tripod, which consists of a damage condition, an epistemic condition and a proposed remedy (Steel, 2014). Precautionary decisions may be defensible if the envisioned damage is great, its occurrence constitutes a realistic possibility, and the remedy is effective in preventing this possibility from actualizing (Hopster, 2021).

Adaptive Decision-Making

A third family of decision-making strategies counsels to come up with dynamic policies that can change over time and are adaptive to the challenges at hand. Given that the rate of future climate change is couched in substantial uncertainty, and given that human societies and technologies may evolve in unforeseen directions (section "Uncertainties in Climate Economics and Ethics"), it seems desirable to design policies that can easily be updated when new information becomes available and that allow for flexible maneuvering in the face of novel affordances and constraints. Adaptive planning policies are designed from the outset to respond to how the future unfolds, how the risk landscape changes and how societal values evolve (Taebi et al., 2020).

The adaptive planning framework is partly compatible with expected utility maximization. Yet, it involves something of a paradigm shift from planning based on expectations to planning conditional on observed developments (Kwakkel & Haasnoot, 2019). Decision-making is regarded as an experimental learning process. Especially in contexts with clear potential for unrecognized ignorance, the flexibility that adaptive decision-making nurtures is beneficial.

Conclusion

In the face of the uncertainties that beset climate science, ethics, and economics, it might appear that taking climate policy-decisions, which holistically incorporate considerations from each of these domains, is extremely daunting. This is certainly true. But as I will underline in conclusion, there are two ways in which scientists, ethicists, and economists can ease the task of decision-makers: by filtering uncertainty information that is policy-relevant, and by adequately communicating uncertainties.

First, not all uncertainties that matter to scientists are equally relevant for policymakers (Hansson, 2018). Climate experts involved in policy-advice have a moral responsibility to be selective in their reporting of uncertainty and to emphasize those uncertainties that are specifically relevant in tilting the overall balance of evidence. Apart from recognized ignorance (known unknowns), special attention should thereby be paid also to include unrecognized ignorance (unknown unknowns). For instance, given the natural variability of the climate system, as well as the limitations of our understanding of this system (section "Locating Uncertainties in Climate Science"), we know that in climate science – more so than in many other scientific disciplines – surprises are to be expected (Parker & Risbey, 2015). Indeed, in virtue of the possibility of surprises, greater epistemic humility is warranted than a mere focus on recognized ignorance suggests.

Second, the question of how uncertainty is represented and communicated is of great importance. Uncertainty communication should be adequate for the purpose it is meant to serve (Keohane et al., 2014). Since much climate decision-making is an exercise in risk management, uncertainty reports should be sensitive to the requirements of risk analysis (King et al., 2015). This includes filing complete reports: taking into account all the relevant sources of uncertainty and the available evidence. For instance, returning to a distinction made in section "Representing Uncertainty", it would be misleading to report only on first-order probabilities, if the second-order credentials of these probabilities are rather low. Instead, it is more expedient to highlight the all-things-considered balance of evidence. If there is not much we can positively assert regarding the prospect of a given catastrophe, but the catastrophe cannot be excluded as a realistic possibility, then this should be the key message of the uncertainty report.

There are various further avenues for philosophical work on the topic of climate uncertainty. At a conceptual level, progress can be made by further teasing apart the different dimensions of uncertainty, and by articulating a more fine-grained uncertainty vocabulary, especially at the levels of deep uncertainty and ambiguity. At a normative level, there is ample room to further develop and refine decision-strategies in the face of deep uncertainty. Conceptual and normative work might also be combined, for instance, in attempts to conceptually ameliorate the IPCC's uncertainty terminology. Last but not least, moral uncertainty has only recently been taken up as a standalone topic of philosophical inquiry. Future work on this topic, and the theoretical insights it might induce, are likely to benefit policymakers.

Cross-References

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