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Introduction

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Uncertainty as knowledge

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This issue of *Philosophical Transactions* examines the relationship between scientific uncertainty about climate change and knowledge. Uncertainty is an inherent feature of the climate system. Considerable effort has therefore been devoted to understanding how to effectively respond to a changing, yet uncertain climate. Politicians and the public often appeal to uncertainty as an argument to delay mitigative action. We argue that the appropriate response to uncertainty is exactly the opposite: uncertainty provides an impetus to be concerned about climate change, because greater uncertainty increases the risks associated with climate change. We therefore suggest that uncertainty can be a source of actionable knowledge. We survey the papers in this issue, which address the relationship between uncertainty and knowledge from physical, economic and social perspectives. We also summarize the pervasive psychological effects of uncertainty, some of which may militate against a meaningful response to climate change, and we provide pointers to how those difficulties may be ameliorated.

1. The challenge of uncertainty

Uncertainty is an unavoidable aspect of any scientific endeavour, and climate change is no exception. The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) of 2013 used the word 'uncertain' or its derivatives (e.g. 'uncertainty') more

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than 2200 times in the report of Working Group I alone—around 1.5 times per printed page. In the case of climate change, uncertainty suffuses all aspects of the problem: there is uncertainty about the physics: how much warming can we expect with a doubling of CO_2 from preindustrial levels? There is uncertainty about the economics: how much will it cost to mitigate (or not)? There is even uncertainty about ourselves: how likely is it that humanity will act to control the risk from climate change?

Although the climate community has sought to develop ways of dealing with the various forms of uncertainty (e.g. [1,2]), uncertainty has often been highlighted in public debates to preclude or delay political action (e.g. [3,4]). Appeals to uncertainty are so pervasive in political and lobbying circles that they have attracted scholarly attention under the name 'scientific certainty argumentation methods', or 'SCAMs' for short [3]. SCAMs have been identified as contributing to the delay of regulatory action on many health and environmental problems, including climate change [3]. SCAMs are politically effective because they asymmetrically draw attention to the possibility that because a problem is uncertain, it may be less serious than anticipated.

In fact, in many instances—including with climate change—the reverse is true: mathematical analyses of the risk associated with climate change have revealed that as uncertainty increases, so often does the risk [5,6]. Similarly, potential surprises are more likely to be calamitous than benign, because the probability of extreme climate events (such as sea-level rise) increases with increasing uncertainty, all other factors being equal [5]. Uncertainty can therefore be a source of actionable knowledge rather than an indicator of ignorance.

This issue of *Philosophical Transactions* is dedicated to examining the role of uncertainty in climate change. Given the inherent nature of uncertainty in climate science and especially in the probabilistic forecasting of future climate change (e.g. temperature, rainfall or sea-level change), this topic has received much attention and in fact is deeply embedded in the existing literature in multiple disciplines, from climate science to economics to cognitive science (e.g. [7–10]). This issue of *Philosophical Transactions* does not review that embedded literature, but instead explores the relationship between uncertainty and actionable knowledge. As we show later, the articles in this issue draw a wide arc that touch on many aspects of this complex question, from physical, economic and social perspectives.

The notion that uncertainty might be a source of actionable knowledge may appear counterintuitive. Consider the prediction of floods or other extreme events. Much that is known about the statistical properties of extreme values, such as floods, is based on the extreme values for a distribution of water levels over time. Based on knowledge of extreme-value statistics, we can compute return times of specific flood levels, thereby identifying an event as a '1 in 1000 years' or 'once in a century' flood. This provides an indication of future risks, and insurance companies and property owners are well served to rely on such statistics. However, predictions that rest on extreme value statistics assume that the environment is stationary, i.e. that the statistical properties do not change over time. If the environment is not stationary, and variables, such as total precipitation, its seasonal or episodic character, or soil infiltration capacity, are changing then return times will also likely change although prediction of that change is beset with difficulties, in particular for rare events [11]. As a result, some projections, such as for regional precipitation, are profoundly uncertain [12,13].

In some cases, these changes can be mathematically constrained by a wider probability distribution, as for example in a multi-step assessment of attributable risk that has been applied to the floods in the UK in the autumn of 2000 [14]. In others, deep uncertainty makes it difficult to assign any meaningful probabilities [15]. In yet other cases, we cannot even preclude completely unexpected consequences that are sufficiently surprising to sit outside conventional frameworks for expectation [16]. For millennia, humans have looked at the past to make predictions about the future, with considerable success. This ability is now under threat, and it is reversing a trend towards increased predictive capacity arising from increased knowledge, whether that be more sophisticated models or longer time series, that humans have strived to expand for thousands of years.

Since their appearance some 5000 years ago [17], human civilizations (i.e. state-level societies) have sought to control or manage environmental risk and uncertainty: from agriculture to flood control to industrialization and immunization, humans have become safer and their interactions with the environment more certain. Most of us now are not risking sudden death from a cold snap or starvation from a local crop failure. This trend has been reversed with the onset of the Anthropocene, a new geologic epoch defined by our role in shaping and disrupting the Earth [18].

The human impact on the Earth system has been sufficient for some scientists to suggest that we have already transgressed safe operating boundaries of humanity along at least two dimensions, namely biosphere integrity and climate change [19–21]. One consequence of these transgressions is that we may be about to enter a new climate regime for which we have gathered no experience or data during the first 5000 years of civilization. This growing uncertainty reduces our knowledge about the future.

However, this growing uncertainty also generates its own form of knowledge; namely, the knowledge that to escape likely adverse outcomes in the future, we are well advised to ensure that civilizations return to live within the operating boundaries that have been identified as safe for the Earth's planetary system [19–21]. As noted by Steffen *et al.* [21, p. 2], 'respecting these boundaries would greatly reduce the risk that anthropogenic activities could inadvertently drive the Earth System to a much less hospitable state'. Although even ostensibly 'safe' parameters may entail unknown risks and are thus less than safe [22], they are likely to be saf*er* than climate regimes that arise by continued exceedance of those boundaries. Growing uncertainty about the future therefore ironically imbues us with the knowledge of what we can do to escape that uncertain future.

2. Building knowledge about uncertainty as knowledge: an overview of the articles

Several articles in this issue expand on the relationship between uncertainty and knowledge. Perhaps the most formal and counterintuitive treatment is provided by Freeman *et al.* [23] whose article extends an initial analysis provided by Lewandowsky *et al.* [5,6]. Freeman *et al.* challenge the notion that it might be good news that the IPCC slightly lowered its lower estimate (to 1.5°C from 2°C) of climate sensitivity in its latest report in 2015, compared to the previous report of 2007. Climate sensitivity is a quantity that describes the expected amount of global warming in response to a doubling of atmospheric CO_2 levels from preindustrial times. Estimates of this crucial quantity have been both invariant and elusive for over three decades: there is widespread and long-standing agreement that the value falls within a likely range of 1.5–4.5°C, but it has proved elusive to narrow this range of estimates. On the contrary, although the 2007 IPCC report narrowed the range to 2–4.5°C, in 2015 the IPCC reverted to the earlier range of 1.5–4.5°C. Freeman *et al.* consider the implications of this reassessment of the range of estimates: at first glance, it seems reasonable to conclude that if a doubling of CO_2 levels (which may happen as early as mid-century; e.g. [24]) may yield only 1.5°C warming, as opposed to 2°C, this would be good news indeed. Freeman *et al.* show that the reverse is true: the lowering of the lower bound has increased uncertainty, and it is a mathematical implication of that increased uncertainty that under many reasonable assumptions, the expected risk from climate change also increases.

The article by Kennett & Marwan [25] provides a rather stark illustration that the analysis of Freeman *et al.* [23,26], and the earlier analyses by Lewandowsky *et al.* [5,6], are not simply abstract mathematical games but have a known history of fostering sociopolitical instability. Kennett & Marwan examine the historical dynamics of state formation and decline in the Mexican and Andean highlands within the last 2000 years. They conclude that the formation and consolidation of states and empires are facilitated during stable climatic regimes and disrupted by highly volatile climatic conditions. As they note, 'under conditions of extreme uncertainty it is impossible for people to evaluate the costs and benefits of one strategy or another' (p. xx), thereby preventing adaptation to changing conditions and leading to 'abrupt changes or tipping points in preindustrial states' (p. xx). Climatic uncertainty, in other words, has demonstrably contributed to the collapse of past complex societies.

Contemporary civilizations are clearly more advanced than the regional polities of Andean highlands several millennia ago. Nonetheless, our advanced technology does not immunize our civilizations against the effects of environmental uncertainty, as Bentley & O'Brien [27] show in their article on collective behaviour. Bentley & O'Brien depart from the uncontroversial observation that prior to the twenty-first century, societies' adaptation to environmental change typically happened gradually over multiple human generations, through a combination of individual and social learning. Children learned from their parents and slightly tweaked their skills before passing them on to their own offspring. In our century, by contrast, major changes occur within a fraction of a human generation and on a vastly greater range of geographical scales. Bentley & O'Brien argue that although multi-generational adaptations yielded a generally resilient and sustainable population in the past, it is far less clear how human groups can adapt to the rapid and uncertain transformations of the twenty-first century. Although the environment is changing faster than ever before, multiple layers of technology prevent people from sensing those changes directly. In consequence, direct observation is largely replaced by social learning in advanced societies. We do not directly observe floods or bush fires but follow the discussion of those events on Twitter or Internet-based media. This lack of direct experience increases the likelihood that people will be following a small but determined minority of (mis-)information brokers, in particular, if their messages are culturally consonant with one's belief system.

This process is already visibly occurring with climate change, which has become a highly contested issue (at least in some countries [28–30]) in which misinformation abounds and polarization based on political orientation is rampant [31–34]. We should therefore not take for granted that our advanced and complex civilizations will respond to global challenges in the most appropriate manner. In fact, it is the very complexity of our technological civilizations that should concern us because of the potential for surprises it entails, as Parker & Risbey [35] show in their article on the role of surprises in uncertainty assessments. Parker & Risbey nominate two criteria that scientific assessments should fulfil when reporting the uncertainty associated with projections: they must be faithful and they must be complete. The latter requirement turns out to be rather more involved than might first meet the eye. In order for an assessment of uncertainty to be complete, it must also note the possibility of surprises—that is, the famed 'unknown unknowns'. Parker & Risbey show that although surprises, by definition, cannot be anticipated in the particular, the likelihood that one or the other surprise may arise can be anticipated. As they note, 'it is true that we cannot specify what the unknown unknowns are, else they wouldn't be unknown unknowns; but it doesn't follow that it is impossible to make reasonable judgments about the relative risk of there existing some or other unknown unknown that results in a surprising outcome or behaviour' (p. xx). Complex systems, such as the climate system or global civilization, are known to be prone to surprises, such as unexpectedly large effects of small changes to seemingly insignificant variables on system behaviour. The potential for future surprise is particularly large in systems in which surprises have arisen in the past. Both the climate system (e.g. Dansgaard–Oeschger events revealing profound instability in the climate of the Last Glacial period [36]) and civilizations [25] are complex systems that are known for their history of surprises. Finally, the risk of surprises increases if complex systems are driven outside the conditions in which they have been operating in the past. As Bentley & O'Brien [27] showed, current civilizations are changing more rapidly than ever before. Current climate change is putting the Earth system outside the parameters of the last two millennia (e.g. [37]). Two mutually interacting complex systems are driven beyond their traditional operating parameters. The risk of discovering some of the unknown unknowns in those complex systems therefore cannot be ignored—and the fact that we can recognize that risk attests to the fact that even unknown unknowns need not be entirely unknowable.

In summary, the articles by Freeman *et al.*, Kennett & Marwan, Bentley & O'Brien and Parker & Risbey show how various forms of uncertainty can nonetheless provide constraints on recommended future actions—and hence how actionable knowledge can arise from uncertainty. We find it particularly notable that a more compelling case for climate mitigation can be made based on an increase in uncertainty (Freeman *et al.*), and even based on the recognition of unknown unknowns (Parker & Risbey).

Two other articles provide a detailed quantitative analysis of the implications of uncertainty surrounding climate change. Risbey *et al.* [38] analyse the historical odds of winning various bets on the evolution of global temperatures and examine how those odds are likely to change in the future. Risbey *et al.* find that since 1970, the two successful betting strategies are (i) extrapolating the observed trend and (ii) cherry-picking the warmest trend that has occurred in the last 15 years. No other strategy has been successful during the period of modern global warming, and any climate 'sceptic' would have lost virtually all bets since 1970. Risbey *et al.* also examine the likelihood of winning bets based on future trends predicted by the CMIP5 ensemble of model runs under an intermediate emissions scenario (RCP4.5). They again find that the warming bets win almost 100% of the time until late century, when warming begins to stabilize in response to emission cuts. The certainty of ongoing greenhouse warming, and the fact that it now rivals natural variations on decadal scales, means that bets against greenhouse warming are near certain losers. Furthermore, as noted by Risbey *et al.*, the widespread failure of climate contrarians to bet against greenhouse warming, despite arguing that it must be small, reveals their underlying preferences and shows that they diverge from the public rhetoric.

Finally, the article by Freeman *et al.* [26] recognizes that the world is already on the path to significant expected damages from climate change. The analysis examines the benefits that accrue when uncertainty is reduced through a climate signal—such as recorded global temperatures—that provides a better understanding about the evolution of future temperatures, and thereby permits better adaptation decisions. Such adaptation decisions (e.g. deciding on the height of new sea walls) benefit from improved knowledge of how the climate is evolving. Crucially, this benefit accrues irrespective of whether the signal is for a better or a worse outcome than is currently expected. As a consequence, policy-makers should prioritize investing now in the fundamental science that will better inform us about the extent of future climate change. This is true even if this better information leads to no mitigative action, and hence to no reduction in the final level of climate change damages. Better information allows us to improve our preparation for the eventual outcome, whether that be good or bad, and Freeman *et al.* [26] assess the value that this provides to society.

3. The dragons of uncertainty: human behaviour and the effects of uncertainty

The articles discussed thus far converge on the fairly compelling conclusion that scientific and policy uncertainty need not be a barrier to action—on the contrary, the articles underscore the fact that when the implications of uncertainty are formally analysed, they provide an added impetus for concern and hence for climate mitigation.

We noted at the outset that appeals to uncertainty are often cited as reasons to delay action in political discourse and public debate. The article by Oreskes [39] contributes another historical case study of how uncertainty might lead to inaction. The key point of her article is that uncertainty need not be 'manufactured', as other scholars have claimed in connection with attempts of industry to forestall regulatory action when their products turned out to be harmful, but that scientific uncertainty is unavoidable in most situations. Thus, uncertainty is not manufactured but is exploited to create doubt and thereby undermine knowledge claims that might otherwise compel policy-makers into regulatory action. As Oreskes notes, the key insight of the tobacco industry was that you 'could use normal scientific uncertainty to undermine the status of stabilized scientific knowledge' (p. xx). In this article, she describes how a new case study involving the political battle over electricity generation in the early decades of the twentieth century highlights the efficacy of uncertainty-based messaging and the ideological driver behind those messages. An understanding of the history of those contrarian activities is valuable to understand—and ultimately counteract—similar efforts currently underway with respect to climate change.

Beyond their ability to forestall regulatory actions, uncertainty-based campaigns can have further psychological, cognitive and political implications that have largely escaped notice to date. In fact, we suggest that those largely overlooked consequences of uncertainty may be at least as harmful as the more overt political consequences analysed by Oreskes in this issue and others (e.g. [40,41]).

At a cognitive level, recent research has shown that people's perception of probabilistic information is determined in part by their motivations. Specifically, when people are motivated to arrive at a particular outcome, they detect more variance in probabilistic information. This desirability bias increases when the probability range is wider rather than narrower [42]. In other words, a climate-sensitivity range of 1.5–4°C may elicit more wishful thinking than the range 2–4°C. This human tendency for wishful thinking stands in contrast to the actual implications of the extension of the range of sensitivities as noted earlier [23,26].

The flipside of the wishful thinking coin is that uncertainty increases the response to aversive stimuli if they occur [43]. Specifically, if people are not certain whether the next picture in a long series of events will be aversive (e.g. gory scenes of accidents and injuries), their emotional response is larger than if they know for sure that the picture will be aversive. Uncertainty may thus make us prone to respond emotionally to adverse outcomes, perhaps at the expense of cognitive performance. As we show next, this suggestion has found support in several independent lines of research.

Mueller *et al.* [44] showed that under conditions of uncertainty, people are biased against creativity and prefer mundane functionality instead. This bias expresses itself in a variety of ways, including as an inability to recognize a creative idea when it is presented for evaluation. It follows that the uncertainty that inevitably arises in times of crises may therefore stimulate a bias against creativity that in turn may militate against finding a solution to the crisis. When creativity is most needed, it might be thwarted by people's response to uncertainty.

Similarly, Raihani & Aitken [45], in a survey of some of the relevant evidence, conclude that uncertainty tends to destabilize cooperation. For example, when groups of people are asked to cooperate in a game by investing a certain amount of money into a public good to avoid climate change, then their ability to cooperate declines with increasing uncertainty about the outcome [46]. Specifically, when the probability of an adverse event was only 50%, the groups failed to control climate change, whereas they nearly always succeeded when the probability was near certain (90%). Similar results have recently been reported by Barrett & Dannenberg [47] and Barrett [48]. There is now a considerable body of evidence to suggest that uncertainty is the enemy of cooperation.

Finally, perhaps the gravest potential consequence of uncertainty relates to its potential to trigger, enable or prolong violent conflict. There is a growing body of evidence that reports an association between climate change and the likelihood of warfare and civil conflict [49–53]. In addition to this purely statistical association between climate change and conflict, there are psychological reasons to presume the existence of such a linkage, based on the known role of uncertainty in intergroup threat. Uncertainty can highlight people's needs for safety and security, which they may satisfy by aligning themselves with particular groups, even if they are radical (e.g. [54,55]). Other consequences of perceived uncertainty include enhanced religious zeal [56]. All of those compensatory responses to perceived personal uncertainty have been linked to many forms of intergroup violence (for a review, see [57]).

In summary, perceived uncertainty and a state of personal uncertainty are associated with numerous known psychological responses. At the very least, those responses are unhelpful, and many of them are clearly counterproductive: a bias against creativity when it is needed most is unfortunate, as is the threat to cooperation and, worst of all, the propensity towards violence.

4. Moving beyond the adverse psychological effects of uncertainty: managing information

Although there is a disparity between the actual implications of uncertainty and people's intuitions and behaviours, effective communication can make the implications of uncertainty more easily understood. This was first recognized by Fischhoff [58], who acknowledged the possibility that focusing on uncertainties may discourage action and distract people from decision-making. However, Fischhoff also points out that reframing the debate in terms of 'what gambles we want to take with the natural world' (p. 703) could galvanize decisions.

In this issue, the article by Ballard & Lewandowsky [59] also addresses the notion of how reframing uncertainty can enhance people's responses to climate change. They highlight the fact that projections typically express uncertainty in the outcome itself, but not in the outcome's time of arrival. For example, projections reported by the IPCC generally imply statements along the lines of 'by year X, average global surface temperature will rise by between $Y1$ and $Y2$ degrees'. The authors argue that reporting projections in this manner invites wishful thinking, because it increases the perceived variance in the outcome. Reframing this projection so that the uncertainty is expressed in the time of arrival can reduce the potential for wishful thinking. For example, the projection above can be re-expressed as 'average global surface temperature will rise by Y degrees, and this will occur between years $X1$ and $X2$'. In other words, the projection emphasizes the when rather than the if. Ballard & Lewandowsky demonstrate that when uncertainty is expressed in this manner, people perceive the consequences of climate change to be more serious, and show greater endorsement of mitigative action.

The article by Taylor *et al.* [60] further explores the issue of effective uncertainty communication, by examining the needs of organizations for effectively using climate forecasts. Climate forecasts are starting to outperform historical averages in predicting European winters and are therefore becoming more widely used in organizational decision-making. However, uncertainty arises from the probabilistic nature of the forecasts, and the fact that models do not have perfect reliability. This uncertainty can make forecasts difficult to use, in particular, because people exhibit ambiguity aversion (cf. [61]). Furthermore, there is a lack of empirically supported recommendations for effectively communicating uncertainty. The authors therefore conducted a user-needs survey with representatives from organizations with an interest in seasonal and inter-annual climate forecasting. They find that although users generally perceive forecasts to be useful, they also find them difficult to understand. Users therefore prefer forecasts to be presented in a format that they are familiar with. Moreover, the majority of users preferred to receive information that facilitates yes/no decision-making, but few organizations had clear statistical guidelines for making such decisions.

The article by Lorenz *et al.* [62] also focuses on increasing the usability of climate information. This article focuses particularly on the visual representations of information. The authors conducted an experiment in which local adaptation practitioners were shown climate projections represented in different visual formats. They showed that practitioners differed in their ability to comprehend the visualizations, and in which visualizations they preferred. There was also no clear link between perceived comprehension and actual comprehension. Practitioners tended to prefer the visualization format which they perceived to be most comprehensible, and not necessarily the ones that they actually understood best. This result is consistent with Taylor *et al.*'s [60] finding that users prefer formats with which they are more familiar. These two articles together indicate that tailoring the communication of uncertain climate information to a specific audience is challenging, because the information needs to be communicated in a way that is easily understood, but also in a way that maximizes the ability to make effective decisions.

5. Conclusion

The articles in this issue speak for themselves in their description of the landscape that relates knowledge to uncertainty. Taken together, the body of existing work and these new articles permit three conclusions.

First, the presence of scientific uncertainty does not just reveal a lack of knowledge but is in many cases a mathematical expression of the knowledge we do have. Concerning climate change, our knowledge is extensive and firm indeed: we know that increased concentrations of CO_2 in the atmosphere will cause warming of an absolute minimum of $\approx 1.2^\circ$C per doubling of CO_2 (based on simple blackbody physics with no feedback [63]). The warming is almost certainly bound to be larger due to fast climate feedbacks (e.g. water vapour and albedo), yielding the IPCC-recognized range of climate sensitivities discussed earlier. That range describes and is framed by our recognized knowledge of those processes. However, uncertainty is inevitable, and a reduction of uncertainty regarding climate sensitivity may remain elusive [64], for the simple but mathematically inescapable reason that even if all variables that enter into amplifying feedback loops were known with Gaussian precision, the final estimate of climate sensitivity would nonetheless have a 'fat upper tail'. In addition, there are multiple scales of uncertainty including the deeper, systemic uncertainty about the unexpected responses (unknown unknowns) of complex biological and social systems.

Second, as we have shown earlier, uncertainty is more likely to yield calamitous outcomes than benign consequences. Uncertainty also has a variety of adverse psychological consequences that we reviewed in the foregoing. It follows that uncertainty has far-reaching deleterious impacts on decision-makers in government, security and industry, as well as individual citizens.

Third, several implications follow from the first two conclusions, that uncertainty is unavoidable and that uncertainty has primarily adverse consequences. (i) Scientists have an obligation to better convey uncertainty and to convey it using a range of complementary tools. Decision-makers have an obligation to develop agreed decision pathways to support their yes/no decision-making. Some of the articles in this issue report findings that can assist with those obligations. (ii) Because at least some further climate change is now inevitable, due to the delays in climate system response to emission cuts and due to the fact that even our most ambitious COP21 proposals assume only modest reductions in global CO_2 emissions, we will need to place increasing emphasis on adaptation and building community resilience. This is a vast arena that can benefit from further research. Adaptation will be particularly challenging due to existing scientific uncertainty and especially the propagation of that uncertainty through complex biological, social and political systems. (iii) The adverse impacts of uncertainty, and especially its implications for the costs and nature of adaptation, should empower decision-makers to take mitigative action and to support greater cuts to greenhouse gas emissions.

We know from uncertainty, with near certainty, that climate change is a problem that must be taken seriously.

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