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Uncertainty in science and its role in climate policy

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Policy-making is usually about risk management. Thus, the handling of uncertainty in science is central to its support of sound policy-making. There is value in scientists engaging in a deep conversation with policy-makers and others, not merely ‘delivering’ results or analyses and then playing no further role. Communicating the policy relevance of different varieties of uncertainty, including imprecision, ambiguity, intractability and indeterminism, is an important part of this conversation. Uncertainty is handled better when scientists engage with policy-makers. Climate policy aims both to alter future risks (particularly via mitigation) and to take account of and respond to relevant remaining risks (via adaptation) in the complex causal chain that begins and ends with individuals. Policy-making profits from learning how to shift the distribution of risks towards less dangerous impacts, even if the probability of events remains uncertain. Immediate value lies not only in communicating how risks may change with time and how those risks may be changed by action, but also in projecting how our understanding of those risks may improve with time (via science) and how our ability to influence them may advance (via technology and policy design). Guidance on the most urgent places to gather information and realistic estimates of when to expect more informative answers is of immediate value, as are plausible estimates of the risk of delaying action. Risk assessment requires grappling with probability and ambiguity (uncertainty in the Knightian sense) and assessing the ethical, logical, philosophical and economic underpinnings of whether a target of ‘50 per cent chance of remaining under +2°C’ is either ‘right’ or ‘safe’. How do we better stimulate advances in the difficult analytical and philosophical questions while maintaining foundational scientific work advancing our understanding of the phenomena? And provide immediate help with decisions that must be made now?

Keywords: ambiguity; climate policy; decision support; risk; scientific speculation; uncertainty

1. Introduction

Policy-making, or at least sound policy-making, is often about risk management. Thus, climate science supports sound policy when it informs risk management, informing the selection of climate policy measures that influence key aspects of

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the causal chain of climate change. This chain runs: from humans to emissions and changes in atmospheric concentrations; from changes in concentrations to changes in weather conditions which, with their induced feedbacks, change the climate; and from the weather of this altered climate to changes in risks and the circumstances of individuals. Coherent risk management across such a chain requires input from both the social sciences and the physical sciences, and not only from economics and physics but also from other disciplines, such as ethics. Deep insights and frightening uncertainty in one link may prove either critical or irrelevant, as the implications of a policy option are propagated down the chain to explore their ultimate impact on people [1].

Many different varieties of uncertainty arise in science, and how science handles each depends on the context in which it arises. The focus here is on science in support of policy-making in the context of climate. This restricts the variety of uncertainties touched upon while expanding the importance of effective communication of those most relevant to sound policy-making. Science often focuses on what is known and what is almost known; dwelling on what one is unlikely to know even at the end of one's career may not aid the scientist's career, yet exactly this information can aid the policy-maker. *Scientific speculation*, which is often deprecated within science, can be of value to the policy-maker as long as it is clearly labelled as speculation. Given that we cannot deduce a clear scientific view of what a 5°C warmer world would look like, for example, speculation on what such a world might look like is of value if only because the policy-maker may erroneously conclude that adapting to the impacts of 5°C would be straightforward. Science can be certain that the impacts would be huge even when it cannot quantify those impacts. Communicating this fact by describing what those impacts *might* be can be of value to the policy-maker. Thus, for the scientist supporting policy-making, the immediate aim may not be to reduce uncertainty, but first to better quantify, classify and communicate both the uncertainty and the potential outcomes in the context of policy-making. The immediate decision for policy-makers is whether the risks suggest a strong advantage in immediate action given what is known now.

Climate science itself plays a central role in only three of the links in the causal chain described above, and an inability to determine probabilities from climate science (with or without climate models) does not prevent rational action regarding climate policy. It is true, of course, that the lack of decision-relevant probabilities makes an expected utility analysis unviable [2], but questions of climate policy can be made in a risk-management framework, accepting the ambiguity (Knightian uncertainty) present in today's physical science and in today's economics.

Writing in 1921, Knight [3] noted that economics 'is the only one of the social sciences which has aspired to the distinction of an exact science … it secures a moderate degree of exactness only at the cost of much greater unreality'. A similar competition between *exactness* and *unreality* is present in climate science, where differences between our models of the world and the world itself lead to situations where we cannot usefully place probabilities on outcomes (ambiguity) alongside situations where we can place probabilities on outcomes (imprecision) even if we cannot determine the outcome precisely. Specific scientific details in the 'unreality' of current climate models led Held [4] to note that in the future 'today's global warming simulations will be of historical interest only'. This statement itself may

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be of value to policy-making by stifling overconfidence in the details of today's model output. It does not imply that climate science is of no value in supporting climate policy today, as climate science provides a basis for risk management much deeper and firmer than the latest simulation model. Models can increase our understanding long before they start providing realistic numbers. Sound policy-making can profit from a clear and lively discussion of what we know, what we do not know and what we are likely to soon know significantly better than we know now.

The fact that uncertainties are large cannot be taken to imply that the risks are small, or that policy-makers can act as if the risks were small. Both the magnitude of plausible impacts and the cost of delayed action figure into the risk-management framework, making the claim 'uncertainty in the future climate justifies acting as if the risks were small' completely untenable. Uncertainty in the face of plausible risks can be argued to support immediate action. In a risk-management framework, scientists propose both the physical mechanisms supporting a view and an estimate of the probability that that view is, in fact, incorrect; ideally suggesting some decisive observations to distinguish their position from the alternatives [5]. Focusing applied scientific research on the reduction of risk and public debate on the point at which current science enters ambiguity sidesteps an endless discussion of establishing certainty. In any case, certainty is not on offer for the particular applications being discussed here. Arguably, certainty is an aim even well beyond the goals of science.

Scientific scepticism can embrace a risk-management framework, stimulating honest public debate over truly open questions while reducing the level of artificial (rhetorical) noise and correcting any past over-confidence in current models. Interestingly, in this framework any 'anti-science lobby' is dislodged from the rhetorically comfortable position of merely casting doubt, and challenged to provide evidence that the risks are small. But its members need not be disenfranchized or even distinguished from scientists holding a minority view. One can rationally choose to act under uncertainty; indeed, inaction is in this case a decision of substantial consequence. Even scientific sceptics will agree that action may be called for unless they can establish that the risk is, in fact, very small. Of course, an anti-science lobby might still argue otherwise. A lack of certainty provides no rational argument against action.

How science handles uncertainty, and communicates it to policy-makers, will change the impact achieved. Policy-making asks complicated questions that span many fields: philosophy, computer modelling, decision theory and statistics as well as climate science, physics and economics. As different fields use the same words with somewhat different meaning, §2 discusses how different varieties of uncertainty will be named in this paper. After this attempt at jargon normalization, §3 introduces in more detail the causal chain that drives policy-making, identifying the origins and impacts of the various uncertainties and noting that how science handles the communication of uncertainty can have a non-trivial impact on the efficacy of policy. Section 4 then examines various impacts that uncertainty can have in a particular policy context, namely the case of selecting a stabilization level for an effective concentration of greenhouse gases in the atmosphere. This brief survey suggests that policy might benefit from improvements in the way science handles and communicates ambiguity (Knightian uncertainty), topics which are discussed in §§5 and 6, respectively.

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Section 7 then projects how choices in the manner in which science handles the topic of uncertainty today can influence its ability to inform policy in a few decades' time. Conclusions are summarized in §8.

2. Distinguishing some varieties of uncertainty

Writing in 1862 about the provision of information regarding the likely weather, FitzRoy [6] stressed, '*When in doubt*, distrusting indications, or inferences from them, the words "*Uncertain*", or "*Doubtful*", may be used, without hesitation' (italics in the original). While doubt remains the active state of the working scientist, the public communication of the scepticism scientists hold regarding various details of the science of the day is often surprisingly constrained and confused. In part, this comes from different scientists using common words to mean very different things. Policy-making is often focused on cases where there is confidence that major changes are likely to occur, while there is very limited ability to quantify the impacts of those changes for people. There are at least four relevant varieties of uncertainty in this case (see also Granger-Morgan *et al.* [7], Petersen [8] and Berliner [9] and references therein), and they are not mutually exclusive: imprecision, ambiguity, intractability and indeterminacy.

— **Imprecision** (Knightian risk, conditional probability): related to outcomes which we do not know precisely, but for which we believe robust, decision-relevant probability statements can be provided. This is also called 'statistical uncertainty' [10–12].

— **Ambiguity** (Knightian uncertainty): related to outcomes (be they known, unknown or disputed), for which we are not in a position to make probability statements.[1] Elsewhere called 'recognized ignorance' [11,12] and 'scenario uncertainty' [10]. Ambiguity sometimes reflects uncertainty in an estimated probability, and is then referred to as 'second-order uncertainty'.

— **Intractability**: related to computations known to be relevant to an outcome, but lying beyond the current mathematical or computational capacity to formulate or to execute faithfully; also to situations where we are unable to formulate the relevant computations.

— **Indeterminacy**: related to quantities relevant to policy-making for which no precise value exists. This applies, for instance, with respect to a model parameter that does not correspond to an actual physical quantity. It can also arise from the honest diversity of views among people, regarding the desirability of obtaining or avoiding a given outcome. Noting indeterminacy reminds us of the difference between a situation where no fact of the matter exists from the case in which there is a fact of the matter but it is not known precisely.

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[1] Some argue that a probability can always be assigned to any outcome. We wish to sidestep this argument, and restrict attention to decision-relevant probabilities in discussions of policy. Subjective probabilities may be the best ones available, and yet judged not good enough to quantitatively inform (as probabilities) the kinds of decisions climate policy considers. We return to this point below.

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Traditionally, science aims to discuss possibilities and quantify uncertainty in terms of probability; *imprecision* is expressed quantitatively through a statement of probability. This is a deeply entrenched aspect of science, particularly in empirical measurement and forecasting. Thus, imprecision in a forecast can be quantified and communicated by providing a probability forecast; a scientific forecast is incomplete without a clear quantification of its imprecision (see Tennekes [13]). That said, it is not at all clear how one is to extract probabilities from computer simulations of any kind, much less from those that extrapolate an entire planet to regimes which have never been observed. The diversity of our current climate models, or of any set of models to be developed in the near future, does not reflect the uncertainty in our future, much less provide quantitative probabilities of outcomes [14,15]. Knight [3] used the word 'risk' to reflect uncertainty in commerce where probabilities were available—those are 'business risks'. He argued that they could be accounted for and treated as merely an additional cost of doing business. Imprecision in climate science is less easily dealt with, not just because the plausible impacts are much larger, but also because they reflect largely one-off risks: there is no appeal to analogies with games (or in business) where there are many instances of the same risk or many players. Modern risk management does not restrict itself to considering only Knightian risk. Uncertainty that can be encapsulated in a probability distribution will hereafter be referred to as *imprecision*.

Ambiguity, in contrast, arises when there are impacts whose uncertainty one cannot quantify via probabilities. This may happen, for example, either when projecting far into the future or when predicting impacts that depend on phenomena one cannot simulate realistically; in such cases, today's models are unable to provide a decision-relevant probability distribution, even if today's science can establish that a significant impact is virtually certain. A coffee cup dropped from a great height onto a hard surface will shatter, even if we cannot compute the number of shards or where they will settle. Similarly, a 6°C warmer world will have extreme negative impacts on individuals and societies, even if we have no definitive science-based picture of the details of what that world would look like.

While science aims to quantify imprecision and reduce ambiguity, there is not always a clear division between imprecision and ambiguity. We may know, for instance, that as long as a model remains within a certain regime it can yield decision-relevant probabilities, and that should a given simulation leave that regime it is at best mis-informative. Communicating what fraction of the simulations have left this regime as the simulations are run further and further into the future might aid the use of model output, while providing only the relative frequencies of various simulated outcomes (hereafter model-based probabilities) could hinder sound policy-making. In general, the clear communication of how the policy relevance of current model simulations is believed to change as one looks farther into the future is rare.

It is sometimes not possible to reduce ambiguity today owing to *intractability*. This may result from merely technological constraints, as when a suitable model exists, but runs slower than real time on today's computers. Alternatively, it may reflect a more fundamental difficulty, as when the relevant partial differential equations are not amenable to numerical solution at all, or perhaps even no physically meaningful equations exist (see Fefferman

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[16][2] and Constantin [17]). In this last case, it is not that a specific value is unknown but rather that no such value exists; this fourth variety of uncertainty will be called *indeterminacy*.

Indeterminacy also includes situations where there are variations in personal values, and may reflect an honest diversity between individuals as to what constitutes a reasonable chance to take. Before the first atomic bomb was tested, a calculation was made to estimate the chance of inadvertently destroying the Earth's atmosphere. The result was not zero. Policy-making must take into account the range of varied beliefs about what choice is appropriate with respect to a given outcome. Indeterminacy also arises when a parameter in our model has no empirical counterpart[3] and the 'best' value to use varies with the question asked. Thus indeterminacy can be expected both in the entrainment coefficients of cloud parametrizations and in the discount rates of economic models.

Not every statement of probability is equally relevant for decision-making, any more than every belief regarding the distance to the moon is equally relevant in computing the fuel taken when sending a rocket there. The diversity of views, some strongly held, as to what a probability 'is' leads us to discuss only 'decision-relevant probabilities' below.

For those who believe objective probabilities exist, decision-relevant probabilities for an outcome are those thought to be good approximations of the underlying objective probability of the outcome. For those who hold that only subjective probabilities exist, the case is more complicated. There is sometimes a difference between the subjective probabilities of an informed person and that of an uninformed person. It is not the origin of the probability that is of interest. It is whether the probability is thought to be robust by the person who holds it, or by the decision-maker, that determines its decision relevance. Decision-relevant probabilities are not flimsy, rather they are robust (i.e. stable in the sense of Cox [20]).

Robust in this context simply means sturdy, and capable of serving well under a wide range of conditions [21]; a robust result is not *expected* to change substantially across a range of possible outcomes. An expert may well know that her subjective probability is not robust, and may then rationally refuse to accept bets based on it. In such cases, as when a wide range of subjective probabilities are proposed and each is thought to be robust, the decision relevance of each is in doubt. Bayes' theorem tells one how to correctly manipulate probabilities, but is mute regarding the decision relevance of a given probability, or how one might use a decision-relevant probability if you believe you have one.

For those decision-makers who accept the existence of ambiguity, the foolhardiness of acting as if the best available probabilities were believed to be robust when no human being believes them to be robust is rather obvious. Those

[2] This concludes 'Fluids are important and hard to understand… Since we don't even know whether these solutions exist, our understanding is at a very primitive level. Standard methods from the theory of partial differential equations appear inadequate to settle the problem. Instead, we probably need some deep, new ideas'.

[3] Some model parameters take a numerical value in the model which corresponds to a parameter in the world measured empirically, while other model parameters (for example, numerical viscosity [18]) have no counterpart in the world and exist only within the model. Yet, other model parameters share the same name as a parameter in the world, yet deficiencies in the mathematical structure of the model imply that the value assigned to the model parameter need bear no relation to its real-world counterpart. See Smith [19] for a discussion of this point.

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who deny ambiguity and the concept of second-order uncertainty, and insist on placing bets on flimsy subjective probabilities, might be allowed to do so, but they cannot claim that the Bayesian paradigm supports such action, or argue convincingly that their actions are in any sense more rational owing to the use of Bayes' theorem.

The guidance produced by the Intergovernmental Panel on Climate Change for the consistent treatment of uncertainties [22] offers a valuable calibrated language for communicating 'the degree of certainty', stressing that sound decision-making depends on information about the full range of possible outcomes. Its focus is on the consistent communication of probabilistic information: quantified imprecision. A wider ranging discussion of uncertainty is available in Granger-Morgan & Henrion [23], both papers provide several preconditions to the formation of probabilities, such as being sure to take all plausible sources of uncertainty into account. Guidance on how to better communicate scientific insights when one cannot meet these preconditions would be of value. Section 4.5 of Granger-Morgan & Henrion [23] contains an early discussion of model error, and when it is inappropriate to assign probabilities to models and other knotty problems the resolution of which 'the prudent analyst' will leave to the users of the analysis. Climate change is sufficiently complex that better resolution will result from the actual engagement of scientists in the policy process, leading to refinement of the scientific work and better understanding of the users of that work.

Avoiding the question of what the probability of a given climate outcome is, and asking instead if that outcome has a probability of, say, less than half a percent, would ease many of the difficulties that distinguishing imprecision and ambiguity pose for climate scientists, while potentially retaining much of the information of value to policy-making. The discussion itself might help distinguish scientists with unusual views, who are unlikely to assign zero probability to anything that is not thought physically impossible, from the anti-science lobby, which often professes an unscientific certainty.

3. The causal chain and sound climate policy

Policy connects actions by people to impacts on people. Figure 1 attempts a schematic of this 'causal chain' which, directly and indirectly, drives policy. While nonlinear interactions limit any literal interpretation of this chain, it indicates causal pathways and policy-relevant uncertainties. The idea is taken from Palmer *et al.* [24], who presented a nonlinear perspective in a chain reflecting the physical interactions central to the Earth's climate system. Those phenomena are contained in the third link of figure 1. The chain reflects the end-to-end nature of sound policy-making: uncertainties must be propagated between links, as uncertainties in one link may prove irrelevant (or be magnified) in another link. In this end-to-end sense, the properties of good policy-making are common with good climate science.

Policy generally aims to improve the well-being of individuals by reducing the risks they face, although in many cases there will be gains to some and losses to others, with relative societal valuations cast into the problem. Sometimes there are immediate goals, such as managing the risk of flooding; for many individuals, risks posed by today's climate are not managed effectively. The design of policy

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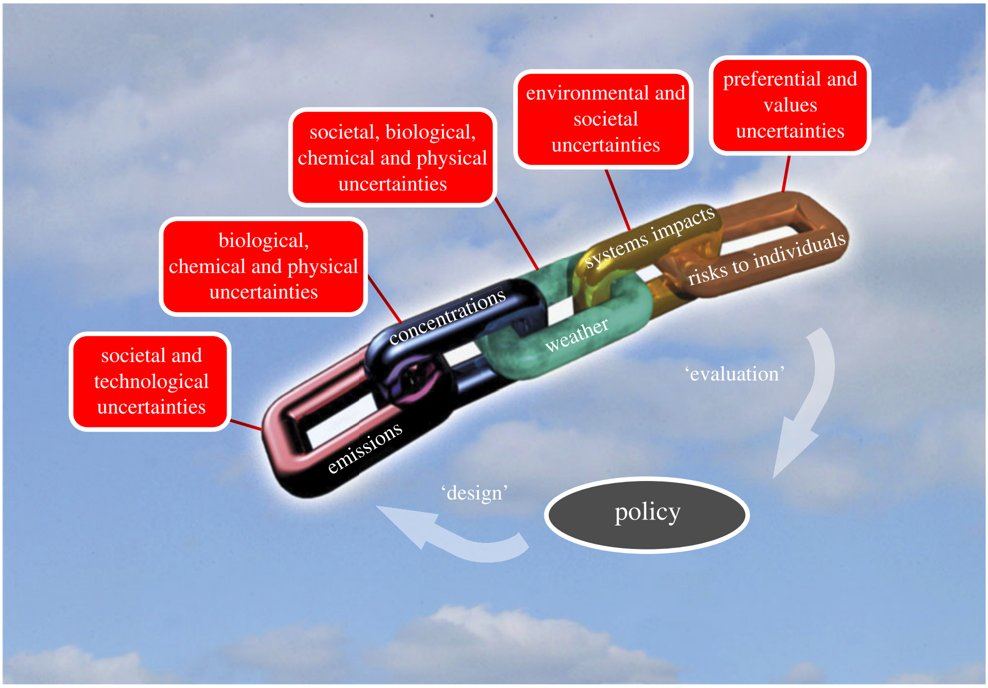

Figure 1. An illustration reflecting the causal chain of climate change from actions by people to impacts on people.

is hampered by a variety of uncertainties, with different sources of uncertainty playing various roles in different links of the chain. Identifying robust strategies, where the desired policy aim is very likely to be achieved under a wide range of uncertainties, is of value. Inasmuch as weaknesses in the science can dramatically reduce robustness, clear communication of the implications of these weaknesses is a great aid to sound policy-making. The overall causal climate chain runs from actions by individuals to risks to individuals. Each link is distinct, and different sources of uncertainty dominate in different links:

Link 1: emissions occur, our quantitative understanding of which is hindered by societal and technological uncertainties.

Link 2: atmospheric concentrations change, our quantitative understanding of which is hindered by biological, chemical and physical uncertainties.

Link 3: weather changes, defining a new global climate, the details of which are obscured by societal, biological, chemical and physical uncertainties.

Link 4: systems impacts alter both political and ecological subsystems, the detailed evolution of which is obscured by environmental and societal uncertainties. It is unclear exactly *which* initial changes will occur, *when* those that do occur will happen and *how* feedback effects owing to these changes propagate, in turn, through the Earth system.

Link 5: risks to individuals change: the desirability or undesirability (the 'value') of which is obscured by uncertainty (valid diversity) in preferences and values, by uncertainties in vulnerability and by uncertainties related to new technologies.

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Even when the uncertainties are high, understanding of the physical systems involved in the three middle links can help identify robust strategies as such. Similarly, the communication of impacts with a relatively low but uncertain probability to policy-makers is critical when policy-makers consider those impacts to pose unacceptable risks. Failure to speculate on the nature of plausible outcomes decreases the value of the science in support of policy-making and leaves the field open to speculation based on far less understanding of the science.

The perceived risks to individuals in the present and the future drive current policy to design and deploy changes to the emission pathway, changes which aim for a more desirable outcome for individuals and societies. Poor handling of uncertainty by science can lead to less effective policy-making. Specifically, encouraging overconfidence in the realism of today's best available simulation or intentionally portraying ambiguity incorrectly as if it was imprecision could lead to undesirable outcomes for individuals and societies, outcomes which could have been avoided by better-informed policy-making today. Alternatively, scientific reflection aided by a realistic analysis of model output can indicate which actions are most likely to reduce the likelihood of undesirable events even amidst imprecision, ambiguity, intractability and indeterminacy. Improving the manner in which science handles uncertainty can aid policy-making in its attempt to shift unspecified 'probability distributions' towards more acceptable outcomes.

It is weather that impacts individuals. Early definitions of 'climate' recognize this; climate reflects the impacts on individuals when it is considered to be the statistical collective of weather however expressed [25]. Under this definition, changes in climate are of direct policy relevance. Modern definitions of climate tend to discuss average weather, say monthly means, and how these average values change in time [26]. Defined in this way, climate does not translate into impacts: in particular, short-lived extreme events [27] are excluded by the definition. This is a result of the simple fact that weather defines the climate, whereas climate, if defined as averages, does not define the weather. And it is weather that impacts individuals.

Weather defines climate, both in the trivial manner that climate is the complete statistical description of weather and in the manner more relevant to climate policy in that weather phenomena induce the changes (in snow cover, vegetation, soil moisture, albedo, precipitation, humidity, cloudiness and so on) that drive feedbacks which magnify climate change. Our inability to predict the weather on a particular day in the far future does not restrict our ability to predict climate change; but our inability to simulate realistic weather limits our ability to drive these feedbacks realistically. And that does limit our ability to predict climate change. Of course, it takes time for these feedbacks to kick in, and simulations at short lead times may not destroy information on continental and larger spatial scales; at longer lead times, however, missing feedbacks on the small scale may well lead to mis-informative model output even at continental scales. Clarifying the expected 'time to failure' (the lead time at which the model output is no longer reliable for guiding policy) of models will aid policy-making. A clear statement of the spatial and temporal scales affected by these feedbacks, and how soon in the future their omission is likely to make the model output an unreliable base for policy-making, is of much greater aid to policy-makers than the statement that these are the 'best available' models.

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Even if, for example, we had near-perfect sub-models of forests and ground water, those sub-models will lead to nonsense if driven for decades by unrealistic rainfall. Today's best climate models have severe shortcomings in simulating rainfall on the spatial scales of large forests. Forest systems play important roles in the climate system, and need to be included for realistic simulation of climate change in the long term; communicating after what point in the future that cannot be done will support good policy-making. More transparent information on the limitations of current models and on how soon the feedbacks that make forests important are likely to be unrealistically simulated, and a timeline on how those missing feedbacks will propagate to larger and larger spatial scales would aid the use of climate model output. Information on how these statistics improve is at least as valuable as statements of which additional processes have been included in the latest models.

As it is the weather that drives the physical feedbacks that contribute to climate change, the nonlinearities of the climate system make attempts to separate 'natural variability' from 'climate change' ill-advised, except perhaps at the largest scales. The physical feedback mechanisms that drive climate change occur locally, on small space and time scales. The system is complicated [28] and employing simplifying linear assumptions to estimate the impacts from highly nonlinear models is somewhat inconsistent. It is important to ask whether or not the 'best available' answer is fit for the policy question it is offered for.

For many scientists, the support of policy-making stops with the communication of the science itself. For policy-makers, there are many other links in the chain. Contrast, for example, the scientific challenges related to defining an emission pathway target which maintains a '50 per cent chance of remaining under +2°C' on the one hand, with the policy-relevant, value-driven challenges of determining whether a given target is 'right' or 'safe' on the other hand. Honest diversity of opinion can lead to indeterminacy in policy targets. Is the better target a 50 per cent chance[4] or a 95 per cent chance? How does one account for differences in the chances that different individuals are willing to take? The ethical challenge of attaching values to outcomes is very deep. Translating aims into outcomes also requires grappling with the uncertainties in economics and international politics. Observing how complex those ethical, economic and social components of the decision chain are, physical scientists might relax and speak a bit more freely about ambiguity in the Earth System, as FitzRoy suggested 150 years ago.

4. The impact of uncertainty in a policy context

The task of determining a target stabilization level for greenhouse gas concentrations was used in fig. 13.3 of Stern [29] to provide concrete examples of how uncertainty impacts policy-making. In this section, the same schematic is used to discuss how imprecision and ambiguity impact the task of selecting a 'simple' policy target. In §5, this schematic is used to illustrate the importance of guidance on the most urgent places to gather new information. These figures

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[4] Indeed, the concept of selecting as a policy target the probability of a one-off event itself raises non-trivial questions of epistemology and meaning. By construction, such a target could never be evaluated, and without a deep faith in the adequacy of today's models it could never be determined.

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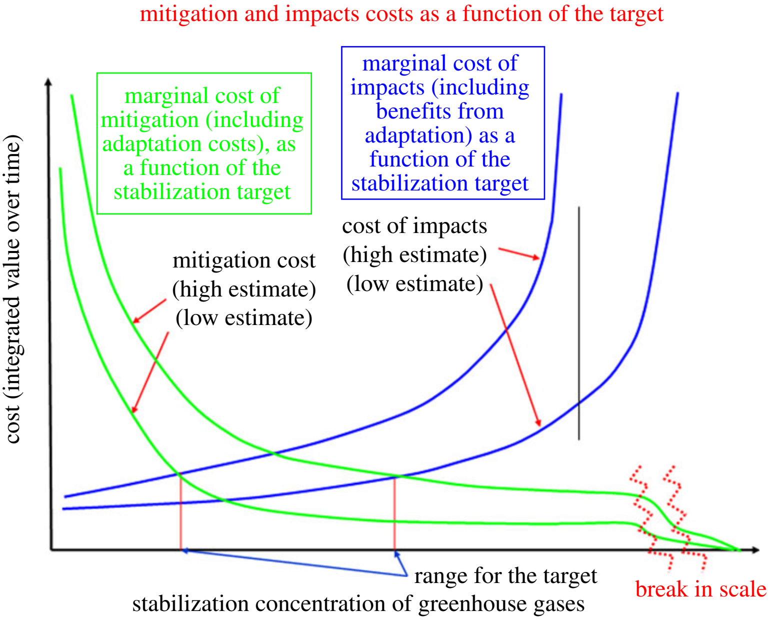

Figure 2. A schematic reflecting the cost curves relevant to selecting a target range for the stabilization of greenhouse gases. The fact that there are two curves both for impacts (blue) and for mitigation (green) reflects the effects of imprecision. Ambiguity implies that even the probabilities reflected by each pair of lines are themselves uncertain.

are intended as a useful guide to thinking about imprecision and ambiguity, a guide which remains useful without making the sweeping assumptions required by most cost–benefit analyses. The context for this discussion is set by ch. 13.4 of the Stern Review [29].

Consider the various costs that are relevant for determining a target value at which to stabilize the concentration of greenhouse gas in the atmosphere. The horizontal axis of figure 2 represents the (effective) stabilization concentration of greenhouse gases in the atmosphere, while the vertical axis reflects marginal costs/benefits (measured at present value and integrated over time). The two green curves running from the upper left to lower right represent the marginal costs of mitigation; they are higher at lower stabilization levels as the costs of mitigation increase for lower concentrations of greenhouse gases.

Of course, the costs of mitigation are not known precisely. Differences between the two green lines reflect the estimated imprecision in the costs of mitigation required to achieve the same target concentration. These two lines represent two isopleths of probable mitigation cost, say the 5 and 95 per cent isopleths of cost. In the absence of ambiguity or indeterminacy there is, for each value of concentration, a corresponding probability density function of associated marginal costs: one green line traces a relatively low cost level, the other a relatively high cost. Similarly, the two blue curves, increasing from lower left to upper right, would denote the marginal cost of impacts as a function of stabilization concentration, and the difference between them reflects the known

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imprecision in those costs. Here, imprecision follows not only from uncertainties in what the impacts will be but also from indeterminacy (due in part to different ethical positions) in how to assign value to various impacts on people. There is also indeterminacy in the impacts a 5°C warmer world would have on people. There are many different ways the world might be 5°C warmer; our inability to place probabilities on the alternatives does not diminish the expectation that each would have immense impacts. In practice, there is ambiguity in what impacts would be generated, which feedbacks activated and the future set of global temperature fields itself.

For very high concentrations, the marginal costs of mitigation go to zero (denoting business as usual) while the marginal costs of impacts become very high. In contrast, the mitigation costs of a low-concentration target tend to be high, while the marginal costs of impacts having achieved a low target tend to be smaller. Given agreement on which two isopleths are acceptable, Stern [29] suggests selecting a target in the range defined between the intersection of the lower green and the upper blue lines and that of the upper green and the lower blue curves. The goal in the present discussion is merely to explore the various factors and complications involved in selecting such a target.

The schematic already reflects imprecision by showing two lines of each colour; how might the effects of ambiguity be illustrated? First, consider the effect of anticipated ambiguity in economic costing or the efficacy of technology. The discovery of a cheap, clean, deployable source of energy would significantly decrease the expected costs of mitigation, lowering the green lines on the left of the graph and extending the viable concentration range to lower target values at an overall lower cost of mitigation. And in evaluating mitigation costs, one must take into account the co-benefits of action, such as energy security, biodiversity and so on. Alternatively, discovering a significant flaw in a planned mitigation technology would raise the lower marginal cost curve (the lower green line), implying higher overall costs and shifting the viable range to higher concentrations. More generally, decreasing the range of imprecision of costs or of benefits would move the corresponding pair of lines closer together. As long as this was achieved without increasing ambiguity, it would aid policy-making by decreasing the viable range while increasing confidence in it.

Second, natural feedbacks imply that some stabilization targets may be unattainable, even if we are uncertain of which target values they are. Exceeding local temperature thresholds will activate natural feedbacks, which release additional greenhouse gases, for example. This may in turn lead to a further increase both in concentrations and in temperatures, effectively making certain target stabilization concentrations unachievable. It is also conceivable that natural feedbacks might exist which would remove greenhouse gases above some concentration threshold, although we know of no proposed mechanism that, once activated, would continue to reduce concentrations in the manner that known positive natural feedbacks would be expected to continue increasing concentrations.

In addition, just as there is hysteresis in the climate system, there are path dependencies in technological discovery. A ‘strong’ mitigation strategy may lead to the rapid discovery of new technologies. Significant difficulties in modelling technological development robustly indicate a clear and important indeterminism in evaluating marginal costs.

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Ambiguity also implies that if achieving required political action requires one simple target emissions pathway, then that target will be several steps removed from the true policy goal. In the setting of figure 2, this would follow from the facts that emissions alone cannot be reliably mapped into atmospheric concentration; and even where such a mapping is available, concentration does not determine global mean temperature. And a specific global mean temperature does not determine local conditions anywhere on the planet, nor the impacts on any individual. In short, embracing the existence of ambiguity suggests focusing on the more robust policy solutions. Identifying robust solutions would be a major contribution to support decision-making. The clearer the implications of gaps in the scientific evidence are made, the more relevant the resiliency of the policy formulated.

5. Handling ambiguity in science

Science is often found to be a reliable guide to action, even if it can never provide true certainty. And just as there is a scientific approach to forecasting what will happen, science can also inform questions of what is believed virtually impossible to happen.[5] Ambiguity covers a third category: things that cannot be ruled out, but to which today's science cannot attach a decision-relevant probability. It is this third category where scientists often prefer not to tread. Progress here can be of significant value for policy-making. When asked intractable questions, the temptation is to change the question, slightly, to a tractable question which can be dealt with in terms of imprecision and probability, rather than face the ambiguity of the original, policy-relevant, question. Science will be of greater service to sound policy-making when it handles ambiguity as well as it now handles imprecision.

Failure to successfully communicate the relevance of imprecision or recognized ambiguity clearly risks the future credibility of science and is widely deprecated. Less straightforward to deal with are simplifications of the science, required for broader communication. Even more complex is the political use of scientific evidence to motivate action, rather than to inform decision-making. The focus here will remain on how science informs policy, encouraging a greater willingness on the part of scientists to openly grapple with ambiguity as they do now with imprecision. Ideally, science engages with the policy discussion and decision-making. Discussing the implications of intractability can also benefit policy-making, as can investigating when indeterminacy might reduce the impact of imprecision or ambiguity in the science on policy-making.

Scientists and statisticians can model anything they can think of. Models then imply probabilities which may or may not reflect the likelihoods of events in the world. Either way, these '*implied probabilities*' are well-defined mathematical concepts that can inform policy as long as they are accompanied by a clear statement of the probability that model is fundamentally flawed, and thus when the implied probabilities will prove misleading. An insufficient understanding of metal fatigue resulted in the catastrophic failure of early passenger jet aircraft. No model, or collection of models, would have provided decision-relevant implied probabilities for the time of failure of these aircraft. Similarly, probabilistic projections from financial models that fail to realistically simulate changes in

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[5] Borel [30] would argue scientists should say 'impossible'.

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liquidity will prove misleading if, in reality, liquidity changes. It is not enough for financial models to 'include' liquidity, or for climate models to 'include' ecosystem models of forests: the policy relevance of their output hinges on sufficiently realistic simulation. For phenomena that are known to be important, informing decision-makers *a priori* as to the limited range (of liquidity, rainfall or metal stress) outside which the model is likely to be mis-informative can lead both to better policy-making for the future and to better real-time decisions when using the model daily. The use of ensembles of models cannot be expected to yield robust implied probabilities when all of the models have similar flaws in their mathematical structure [14]. A simple example of this would be the use of an ensemble of models based upon Newton's Laws to predict the orbit of Mercury. While general relativity can provide accurate prediction of Mercury's orbit Newton's Laws cannot, nor can an ensemble of different models each based on Newton's Laws accurately quantify the imprecision of such a forecast. Difficulties with Mercury's orbit were known long before general relativity was available, yet the most popular attempts to resolve these difficulties assumed that models based on Newton's Laws held, thereby confusing model error with imprecision. This led to the belief in and eventual 'discovery' of the planet Vulcan.

As with Newton's Laws, climate models have a limited range of utility. Attempts to extract postcode-level information across the UK regarding the hottest day of summer in the 2090s, using an ensemble of today's climate models, requires evaluation (http://ukclimateprojections.defra.gov.uk/content/view/868/531/) [31]. Ensembles can be informative, but, at lead times on which shared inadequacies come into play, interpreting them as probabilities is reminiscent of Wittgenstein's [32] remark on someone buying several copies of today's morning paper in order to gain confidence that what the first copy said was true. Even examining different media outlets known to have a shared editorial bias provides only limited assurance.

Given both the exactness and the Knightian unreality of current climate models, one must avoid suggesting spurious relevance by reporting model-based implied probabilities as if they reflected imprecision in our knowledge of the future of the world, just as one avoids reporting spurious accuracy in a calculation. Model-based implied probabilities merely reflect the diversity of our models; the exactness of this reflection should not distract from the unreality of the models from which they are derived. The diversity of our models need not reflect the imprecision with which we know the future. This holds both for our models of physical systems and for those of economic systems. There is no principled method for moving from simulations to decision-relevant probabilities in either case. Models may prove more informative if one aims to understand phenomena and discuss risks than if one attempts to forcibly extract probabilities from models that are far from being able to simulate realistically the things, or drivers of things, which impact people in today's climate.

For phenomena best modelled with nonlinear models, the utility of 'implied probabilities' in traditional decision theory is in doubt [14,33]. Dietz *et al.* [2] discuss alternative approaches to forming policy which embrace scientific ambiguity. Better demarcation of the boundary between where imprecision can be quantified and where ambiguity dominates aids sound policy-making. While some progress has been made in terms of interpreting model diversity to define a

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'non-discountable envelope' of outcomes [34], it appears impossible to translate this diversity into imprecision because of shortcomings in the mathematical structure of climate models [14,26]. When models agree in distribution, one might hope that details of formulation are ignorable; at present, models disagree, implying that the details of formulation do have a significant impact on the simulations [14,35]. Grappling with ambiguity explicitly can clarify how and where these disagreements should impact sound policy-making. Climate science, economics and policy-making might each benefit from a better understanding of the sources and implications of ambiguity.

Fruitful engagement of science with policy-making could yield new forms of model design, and alter the experimental design applied to current climate models. One could debate the probable value of models that offer an interesting perspective with those that aim to give quantitative probabilistic forecasts of outcomes given assumptions that are known *not* to hold, contrasting the scientist's desire to develop a series of models which approach reality (eventually) with the decision-maker's desire for the most relevant information available from science today.

Guidance on the most urgent places to gather information and realistic estimates of when to expect more informative answers from current research are both of immediate value. Even in the presence of ambiguity, today's science may suggest which observations to make in order to aid model improvement, to distinguish competing hypotheses or to provide early warning that our understanding is more limited than we believed (as when things that cannot happen, happen). Observations of the current climate, which can only be taken today, are likely to prove of great value in reducing imprecision and ambiguity in the future. Evaluation of climate models requires longitudinal data. Failure to take that data now, even if today's models cannot assimilate it, will delay the reduction of ambiguity in the future.

To cast this in terms of policy-making more explicitly, recall figure 2 and consider the value of more rapidly reducing the imprecision in the economics of mitigation technology. Reducing imprecision would bring the two green lines closer together, while reducing ambiguity could move either of them up or down. Alternatively, learning more about investment strategy and understanding technological advance could prove very valuable, and might also amplify areas of indeterminacy. While one may aim to reduce imprecision, resolving ambiguity may lead to an understanding that our estimate of imprecision was much too low. It is unhelpful to cast gaining this insight in a negative light by saying it 'increased uncertainty'.

One can expect a time asymmetry in the value of new information regarding different areas in this graph. Rapidly reducing the imprecision in the economics of mitigation technology would show significant value, by reducing the current uncertainty in mitigation costs, while a better understanding of climate response and its likely impacts would reduce our uncertainty in the impacts at concentrations not yet experienced. The questions are then: (i) in terms of supporting decisions to be taken in the next 10 years, is there significantly more value in reducing imprecision in one of these areas than in the other? and (ii) in terms of our current understanding, is the same investment more likely to result in a relevant increase of understanding in one or the other? Such questions point to the fact that the formation of climate policy faces a persistent, long-running,

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evolving process. Section 7 deals with the implications this holds in maintaining the science base and incentivizing science for improved support of policy in the future.

Does the presence of ambiguity in the quantitative outputs of our models suggest that we know nothing? Not at all. Climate science provides a firm understanding of the first-order effects one should expect from increasing the concentration of greenhouse gases. Today's models are the most complicated members of a hierarchy of models [36], ranging down to analytically tractable models from over a century ago. While one must avoid the use of computer graphics to over-interpret these newest models, they have not yet cast doubt on the broad outline established by their predecessors and basic science. And they might have. Given our current ignorance, these models are less likely to lead to decision-relevant numbers than to general insight. The value of insight should not be underestimated.

6. Ambiguity and insight in science

The knowledge base in climate science is much deeper than the latest, most complicated climate model, even if the headlines perpetually focus on the latest model runs. The science base as a whole suggests that the risks of significant impacts of increasing greenhouse gas concentrations are large. There are many models, and the latest model takes its place in this hierarchy [4,36,37]. Thus far, each level of the hierarchy confirms that the risk of significant negative impacts is large. Detailed impacts are not certain, but this uncertainty does not suggest a scientific argument that the risks are small. Incorporating scientific uncertainty into policy can reduce negative impacts due either to an ignorance of uncertainty or to the misuse of a good knowledge of uncertainty.

In an early paper on simulating the effect of doubling the concentration of carbon dioxide in a climate model, Manabe & Wetheral [38] noted that 'because of the various simplifications of the model described above, it is not advisable to take too seriously the quantitative aspect of the results obtained in this study'. They then go on to state that their aim was to understand the processes involved, and in that aim they had some success. Their warning against taking quantitative model outputs too seriously still stands today, although our understanding of the climate system has increased significantly in the 35 years since that warning was issued, and models have played a role in advancing that understanding. One can still argue that our climate models are more useful in increasing our understanding and insight than providing detailed numbers suitable for forward planning; this argument becomes stronger in the second half of this century and beyond. Scientific understanding of the mechanisms of the climate system and their likely responses reinforce the view that the risks are significant and that a delay in action can be very costly.

Inasmuch as all probability forecasts are conditional on something, the distinction in climate modelling between *predictions* and *projections* is artificial if the word projection is intended merely to flag the fact that the forecast will depend on the emission scenario which comes to pass. Under any scenario, the forecast imprecision is reflected by a conditional probability, that is, a probability based on the assumption that (conditioned on) a given emission scenario occurs.

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So, in this case the word 'projection' is used to improve communication of the fact that the choice of emission scenario is subject to substantial uncertainty [39]. Focusing on scenario uncertainty can suggest that, if (when) the emission pathway is known, today's models will be able to produce both (what would have been) a realistic simulation and decision-relevant probabilities. It is unlikely that this is the case [4,14].

Physical science and economics can improve the way they handle imprecision by adopting insights of statistical good practice. Cromwell's rule, for instance, suggests that one avoid assigning a zero probability to an event unless one considers that event truly impossible [40]. Implied probabilities can be reported as a range suggested by the various modelling studies, making it clear whether these models are believed to realistically simulate the target. And the presentation of overly precise values can be avoided, as they imply spurious precision.

One example of excellent progress in this area is provided by Bowen & Ranger [41][6] in the table of their box 1.1 which provides 'implied probabilities' of exceeding a given global mean temperature for various concentrations. A range of implied probabilities is given for each entry in the table. The values are all rounded to a multiple of 5 per cent, and vanishing low probabilities are reflected as less than 5 per cent. Explicitly noting that this is an implied probability can aid in the communication of the relevant information; better still would be to provide a quantitative, if subjective, estimate of the probability that the models employed were likely to be adequate for the particular task in question. A given model is more likely to be informative at concentrations near those observed and at lead times closer to the present; quantifying the growth of this 'second-order' probability would aid policy-making.

Policy can often be agreed on coarse information, much less complete than a full probability distribution over outcomes. Financial regulation, as in Basel II and Solvency III for example, focuses on negative events with a probability of greater than 1 in 200 of happening in a year.[7] The healthy scepticism among scientists regarding the limited realism of today's latest models in projections for 2100 does not prevent agreement that the chance of significant negative impacts in 2100 owing to anthropogenic emissions is significantly greater than 1 in 200. In the context of figure 2, considering the physical impacts with a greater than 1 in 200 chance of occurring on a given emissions pathway would cast in stark relief the high stakes policy-makers must deal with.

Given that (i) model diversity need not constrain (anyone's) subjective probability of events in the world, (ii) climate simulations hold a high-profile position relative to the foundational climate science, and (iii) today's models are not empirically adequate even in simulating today's climate, the drive to extract precise probability projections of very high spatial resolution (http://ukclimateprojections.defra.gov.uk/content/view/868/531/) might be found surprising. The astonishing success of computer simulation at providing useful, if far from perfect, probability forecasts for weather phenomena is reminiscent of how the Newtonian framework first advanced and later retarded

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[6] See also [42,43] for discussion of these probabilities.

[7] A key advantage in using such criteria is that the fixed target is the 1 in 200 threshold, it is not tied to some output of the current simulation model. As models improve and insight deepens, events may cross this threshold and new events may be thought of.

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the advance of scientific understanding. Whitehead [44] referred to the misidentification of model-based entities with their real-world counterparts as the fallacy of misplaced concreteness, writing: 'The advantage of confining attention to a definite group of abstractions is that you confine your thoughts to clear-cut definite things, with clear-cut definite relations.…The disadvantage of exclusive attention to a group of abstractions, however well-founded, is that, by the nature of the case, you have abstracted from the remainder of things. …Sometimes it happens that the service rendered by philosophy is entirely obscured by the astonishing success of a scheme of abstractions in expressing the dominant interests of an epoch'. Computer simulations have achieved astonishing success in weather forecasting. Advances in computational graphic arts and statistical post-processing can create an attractive picture from simulations of an empirically inadequate model. Arguably, the policy-relevant aim of today's climate simulation is neither numbers nor pictures but insight. To interpret model-based probabilities for climate at the end of this century as reflecting some aspect of the world is to commit Whitehead's fallacy of misplaced concreteness.

7. Improving the support science provides climate policy-making

Communication is most effective when scientists carefully consider the processes and levers of policy-making. Without careful communication, policy-makers do not know how to use what they are hearing. Communicating all varieties of uncertainty allows policy-makers to more easily hear early warnings for initiating policy action and more confidently ignore late excuses for delaying action further still. The case against action has to successfully argue that the risks are small, not merely that the outcomes are uncertain. Engaging with the policy process and communicating the current level (and limits) of scientific understanding will lead to more effective policy-making than merely providing clear statements of state of the science in terms familiar to the scientists themselves.

Along with other policy targets which persist for decades if not centuries, the need for scientific support for climate policy will be with us on time scales longer than the professional career of any particular scientist. How do we better stimulate and harvest advances in deep and difficult research questions while maintaining foundational work advancing our understanding of the phenomena [45]? How can we maintain and enhance the ways in which science handles uncertainty in all its forms, so as to improve the support science offers to climate policy-makers? Significant engagement with these questions lies beyond the scope of this paper. Nevertheless, there is some value in opening a discussion of these and related questions.

Even as simulations improve, the need to evaluate ambiguity and intractability implies a need for scientific understanding of the Earth System that surpasses the ability to build (a component of) a good simulation. A level of understanding of the entire physical system is of value here: understanding that allows both insight into the system itself and recognition of the limits of state-of-the-art simulations.

Current incentives in science tend to drive the rising generation of young scientists towards specialization. How would the guidance we offer our graduate students change (or the content of our lecture courses), if the aim were to improve

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the state of climate science in 2030, rather than to secure them a career path in 3 years' time? Since scientists are human beings, the policy relevance of their work, its limitations and its oversell are affected by incentives on the table. Current incentives for research programmes are not tuned to benefit policy support in the long run. A solid piece of important mathematics or physical analysis that advances our understanding, but is of little immediate practical value, may prove of less value in securing a research position than the development and first implementation of some parametrization scheme for some 'penguin effect'-like phenomenon.[8] Do current incentives focus researchers appropriately on the foundational work which will prove of most value to policy-makers in the long run?

This is not to say that fundamental research into biological, physical and societal phenomena are not of importance, but rather that insisting that phenomena be 'included' in an operational model that cannot possibly drive those phenomena realistically hampers both scientific progress and policy support. It is, of course, critical to identify situations where numerical details from the best available model are unlikely to be decision relevant, even if those details play a central role in improving the next generation of models.

Positive contributions can occur even when a detailed calculation is intractable, as in cases where all relevant solutions lead policy-makers to the same decision. On another front, estimating when (if ever) today's intractable problem is likely to become tractable, or merely clarifying whether a problem is intractable owing to technology or owing to a lack of understanding, can assist sound policy-making. Even if technological limitations (computer power) limit the immediate policy value of simulations, there is a need to advance the art of simulation so that both the techniques and the human resources are able to take advantage of the computer power when it arrives.

Arguably, science aims at understanding the phenomena, ideally banishing ambiguity to a negligible role and reducing prediction to the propagation of current imprecision into the future. To oversimplify: advances in pure science reduce ambiguity and clarify questions of intractability, while advances in applied science and simulation increase the relevance of our conditional probabilities for decision-making by quantifying imprecision better. Policy support with regard to long-lived phenomena like climate change will be less effective if either area is neglected.

8. Concluding remarks

Sound policy-making embraces the causal chain connecting actions by people to impacts on people. Many varieties of uncertainty are encountered along this chain, including: imprecision, ambiguity, intractability and indeterminacy. Science regularly handles the first with probability theory; ambiguity and intractability are more often used by scientists to guide the advancement of science rather than being handled within science explicitly [45]. A better understanding by scientists

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[8] The penguin effect occurs when penguins, which have black backs and white bellies, react to the local warming and roll over, altering the Earth's albedo. The effect is apocryphal, and were it to exist current models do not realistically simulate the conditions that would drive it. Nevertheless, were a young researcher to implement this effect in one state-of-the-art climate model, he or she would be all but assured employment doing the same at a competing institution.

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of the roles of uncertainty within policy-making may improve the support science offers policy-making. In particular, an improved understanding of which scientific uncertainties pose the greatest challenges to policy-making when projected along the entire causal chain considered by policy, and informed scientific speculation on the likelihood of reducing those specific uncertainties in the near future, would be of immediate value. Some of these roles have been illustrated in the context of a particular example: selecting a stabilization target for greenhouse gas concentration.

Handling ambiguity in science, and the communication of insights from science, has been discussed. The value of scientific insight to policy-making, particularly in cases where state-of-the-art models are not empirically adequate, is stressed. Specifying the robustness of insights, and ideally quantifying how quickly model simulations are likely to become mis-informative as one moves further into the future, are each of significant value to sound policy-making. No scientific extrapolation is complete without a quantitative estimate of the chance of its own irrelevance. Communicating to policy-makers the level of confidence scientists have that their model-based probabilities are not mis-informative is at least as important as communicating the model-based probabilities themselves. Engagement of scientists in the policy-making process, not merely by presenting the outputs of models but by explaining the insights from science, can significantly improve the formation of policy. This is especially true in climate policy, where the scale of the risk is great even if we cannot provide precise probabilities of specific events, and where many plausible changes are effectively irreversible should they occur. Scientists who merely communicate results within the comfortable area of reliable theory abandon the decision stage to those who often have little engagement with the science. Sound policy-making is then hindered by the lack of sound scientific speculation on high-impact events, which we cannot currently model but may plausibly experience. Failing to engage with the question ‘What might a 6°C warmer world look like, if it were to occur?’ leaves only naive answers on the table for policy-makers to work with.

Complementary to the need for scientific engagement with the policy process is the need for more transparent communication of the limits of current models when presenting model output. Policy-makers are often told that the models ‘have improved’ and that representations of more phenomena ‘have been introduced’. Clear statements of the spatial and temporal scales at which model output is ‘likely’ to be mis-informative, and how these change between 2020, 2050, 2090 and so on, would be of great value in interpreting when the model output is useful for a particular policy purpose. Honesty here enhances credibility and thus effectiveness. Even when technically coherent, failing to lay the limits of today’s insights in plain view, as with the presentation of ‘temperature anomalies’ in summaries for policy-makers [26], hinders communication of large systematic model errors in today’s models, and hence the relevant level of ambiguity. The eventual realization that such figures show weaker evidence than originally thought can be blown dangerously out of proportion by the anti-science lobby, making the use of science in support of policy-making more difficult than it need be. Again, greater engagement of scientists in the policy process, openly explaining the insights of today’s science and limitations of today’s models, is a significant benefit. This may prove especially true in situations where decisions are based upon feelings as much as upon numbers [46].

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The expected utility approach is difficult to apply when one is unable to translate possible outcomes into impacts on people. There is both imprecision and significant ambiguity in predictions of the Earth's global mean temperature, yet even a precise value of that temperature cannot be translated into precise impacts on people. And where we have impacts on people, there remain deep ethical challenges in attaching values to outcomes. This approach also struggles with low-probability events; the vanishingly small probabilities that mathematical modelling may suggest are not actually zero should not distract policy-makers from action either. The mathematician Emile Borel, originator of the infinite number of typing monkeys, argued strongly [30] that one must act as if such phenomena were not merely improbable but impossible, whatever may be their impact. This view may shed interesting light on discussions of expected utility; its relevance here is in the fact that climate change poses significant risks and does not have a vanishingly small probability.

Society might better understand science and benefit from science if science as a whole was more effective at communicating ambiguity and its implications. Policy-making would also benefit from an increased willingness from scientists to speculate on questions like: 'When might significant new insights regarding a particular policy target be expected from our next set of model simulations?' and 'What might 5°C warmer worlds look like?' More broadly, there is a need for science to not merely 'communicate' results to policy-makers, but to engage with the policy process.

In this paper, it has been suggested that the communication of science to policy-makers could be aided by:

- scientific speculation on policy-relevant aspects of plausible, high-impact, scenarios even where we can neither model them realistically nor provide a precise estimate of their probability;
- specifying the spatial and temporal scales at which today's climate models are likely to be mis-informative, and how those scales change as we look farther into the future;
- identifying weaknesses in the science that are likely to reduce the robustness of policy options;
- clarifying where adaptation to current climate is currently lacking;
- identifying observations which, in a few decades, we will wish we had taken today;
- distinguishing the types of uncertainty relevant to a given question, and providing some indication of the extent to which uncertainty will be reduced in the next few years; and
- designing model experiments to meet the needs of policy-making.

Similarly, policy-makers could encourage the engagement of scientists by:

- accepting that the current state of the science may not be able to answer questions as originally posed;
- working with scientists to determine how current knowledge with its uncertainties can best aid policy-making; and
- discrediting the view among some scientists that policy-makers are only interested in 'one number' which must be easy to understand, unchangeable and easily explained in less than 15 min.

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Scientists engaged in the policy process can explain the insights and limitations of climate science and climate simulation, better identify the most urgent places to gather new information of value in policy-making now, improve the design of simulation experiments to addresses pivotal questions, and participate in guiding sustainable research programmes to support decision-making as our understanding and computer power increase.

Clearer distinction between imprecision and ambiguity would also be of value, as would a deeper engagement with ambiguity. It would be better to answer a policy-relevant question directly with ambiguity than to answer a similar sounding approximate but largely irrelevant question precisely. Even with the current level of ambiguity in climate simulations, climate science provides significant support to climate policy-making. Current knowledge of the direction of known (if poorly simulated) physical feedbacks, the presence of poorly quantified probabilities and the suspected sources of ambiguity each suggest limiting the impact imposed upon the Earth's climate system, given the magnitude of plausible adverse impacts on people. Whether, and if so when, to go about this is a question for policy-makers, but large scientific uncertainty is never an argument for acting as if the risks are small. Within a risk-management framework, a lack of confidence in the best available probabilities of the day is no argument for inaction. Risk management also considers the magnitude of plausible impacts, the costs of action and the probable consequences of delay or inaction. The flow-stock nature of the process ensures that delaying action on any grounds will lock us into higher concentrations and the associated risks. Policy-relevant science and economics can communicate the costs of delay as clearly as it does the costs of actions.

The advance of science itself may be delayed by the widespread occurrence of Whitehead's 'fallacy of misplaced concreteness'. In areas of science, far removed from climate science, an insistence on extracting probabilities relevant in the world from the diversity of our model simulations exemplifies misplaced concreteness. Computer simulation both advances and retards science, as did the astonishing successes of the Newtonian model, Whitehead's original target. In any event, better communication of uncertainty in today's science, improved science education in the use of simulation modelling that values scientific understanding of the entire system, and the communication of all (known) varieties of uncertainty will both improve how science handles uncertainty in the future and improve the use of science in support of sound policy-making today. How science handles uncertainty matters.

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