POLICY FORUM: CLIMATE CHANGE

Uncertainty and Climate Change Assessments

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Future emissions of greenhouse gases, their climatic effects, and the resulting environmental and economic consequences are subject to large uncertainties. The task facing the public and their policymakers is to devise strategies of risk reduction, and they need a clear representation of these uncertainties to inform their choices. Absent this information, policy discussion threatens to deteriorate into a shouting match, where analysis results are used both to support calls for urgent action and to justify doing nothing while we wait for more information. The Intergovernmental Panel on Climate Change (IPCC), charged by governments to report on the state of knowledge, took on the issue of uncertainty in its Third Assessment Report (TAR) (*1*–*3*). We applaud the attempt to add this component to an already complex assessment process. However, we believe much remains to be done to adequately treat uncertainty in those conclusions that are most important for policy decision-making. Here, we highlight some of the shortcomings of the uncertainty analysis presented in the TAR in the hope of providing impetus to our research community, governments, and the IPCC to improve this aspect of future assessments.

Projections of future climate change are uncertain. On the basis of the recent IPCC report, Reilly *et al.* and Allen *et al.* discuss approaches to and problems in quantifying uncertainty in future climate assessments. See also the Research Article by Wigley and Raper (p. 451)

The guidance given to authors in all three working groups of the TAR was to identify the most important uncertainties and characterize the distribution of values of key parameters, variables, or outcomes, where possible using formal probabilistic methods (*4*). Seeking consistency across the text, a set of terms was proposed to indicate specific likelihoods: virtually certain (99% or more), very likely (90 to 99%), likely (66 to 90%), medium likelihood (33 to 66%), unlikely (10 to 33%), very unlikely (1 to 10%), and exceptionally unlikely (1% or less). Whatever the application, methods for estimating such likelihoods fall into two categories. One applies an analytical model of the process under study and propagates uncertainty in inputs through the model to generate probability distributions of outcomes. In a second approach, probability distributions of key outputs are elicited directly from experts. Naturally, the two methods overlap. In the model-based approach, it is preferable to derive parameter uncertainty from observations, but the needed data often do not exist. Distributions of input parameters then must be selected by expert elicitation. Supplementing model-based uncertainty analysis with expert elicitation also can be useful because uncertainty may be inherent not just in the inputs (which can be analyzed using the model) but in the model structure (which cannot). Care must be taken in applying expert elicitation to compensate for well-known cognitive biases in human judgment (*5*), and protocols to reduce these biases have been developed (*6*).

Careful documentation of the methods applied is also crucially important. For uncertainty analysis using expert elicitation, this involves identifying the experts, detailing how their judgments were elicited, and specifying how multiple judgments were combined to form the results presented. In this way, the exercise can be repeated to gauge whether real changes in the scientific understanding of climate change have occurred, or if differences are simply an artifact of a different group of experts or variations in the protocol.

Expert judgment was widely used in preparing the TAR, but the organizers were not able to impose a consistent procedure across the various components. The likelihood terms above were variously assigned on the basis of "judgmental estimates" in the discussion of the science of climate (*1*) and on using "collective judgment" when discussing the effects of climate change (*2*). However, little or no documentation is provided for how judgments were reached or whose estimates were reflected. In discussion of mitigation measures (*3*), the TAR did not report any analysis using these concepts. The TAR states that many hundreds of scientists contributed to the report. In the absence of documentation, readers could easily conclude that reported likelihoods represent a consensus among them (*7*). This is not necessarily the case (*8*). Many of the scientists listed as contributors were never consulted about these probability judgments.

One of the difficulties facing the IPCC is its emphasis on consensus coupled with the

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Uncertainty in the IPCC's Third Assessment Report

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Reilly *et al.* (*1*) (this page, above) raise several important points regarding the explanation and presentation of the climate change issue. They criticize the treatment of uncertainty in the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC), citing in particular the lack of an estimate of the probability that human-induced warming over the 1990–2100 period will lie either above or below the projected range of 1.4° to 5.8°C. Wigley and Raper (*2*) provide such an estimate based on an exhaustive perturbation analysis of a simple climate model. Here, we address why the authors of the TAR were not in a position to provide a probabilistic forecast of 2100 temperatures, although a consensus statement could be made about the likelihood of different warming rates on shorter (50-year) time scales.

Reilly *et al.* correctly assert that any method of uncertainty analysis should be both documented and reproducible. It was the unanimous view of the TAR lead authors that no method of assigning probabilities to a 100-year climate forecast is sufficiently widely accepted and documented in the refereed literature to pass the extensive IPCC review process. Three reasons stand out: the difficulty of assigning reliable probabilities to socioeconomic trends (and hence emissions) in the latter half of the 21st century, the difficulty of obtaining consensus ranges for quantities like climate sensitivity, and the possibility of a nonlinear response in the carbon cycle or ocean circulation to very high late-21st-century greenhouse gas concentrations.

We illustrate these points using the Wigley and Raper study: they assume a zero chance of emissions either above or below the range of scenarios considered by the IPCC, while noting that these scenarios range of disciplinary backgrounds and world views among its contributors. Where there are widely divergent views and a consensus cannot be reached, the alternative is to present the judgments of each expert independently (*9*, *10*). Whereas a reader may choose to adopt one view or another from those given, this result is almost always preferable to an interpretation that corresponds to no particular expert's view.

Another feature of the TAR is that many less-important conclusions have attached likelihoods, whereas some crucial ones do not. Policy-makers need guidance on a small but important set of questions: how large will the climate change be; how damaging are its effects; and how expensive might it be to meet emissions goals? Likelihood statements about these important matters are too often poorly supported in the TAR or are missing altogether.

For example, a crucial conclusion of the TAR is the reported range of projected global mean temperature change over the next century, given as a rise of 1.4° to 5.8°C. This finding is not accompanied by any quantification of the probability of those projections or the probability bounded by this range, and the reader is left to guess whether the likelihood of exceeding this range is 1 in 10 or 1 in 1000. An example of such an assessment is one carried out at the Massachusetts Institute of Technology by using formal uncertainty propagation techniques to assess a probability distribution for global mean temperature change. Applying an uncertainty analysis to a model of emissions (*11*) and a climate model (*11*), informed by estimates of the joint probability distribution of key climate variables conditioned by the historical data (*12*), we calculate a 95% confidence interval for temperature change by 2100, with no emissions control, of 0.9° to 5.3°C (*13*). For comparison with the estimate by Wigley and Raper in this issue (*14*), our 90% confidence limits are 1.1° to 4.5°C.

The TAR also reports that the projected range of temperature change has increased since the Second Assessment Report (SAR) in 1995, when the range was from 1.0° to 3.5°C. Both the TAR (*1*) and other analyses (*14*) attribute this difference to various causes, including lower projected sulfur dioxide emissions in the IPCC Special Report on Emissions Scenarios (SRES) (*15*), which was a key input to the TAR. However, given that the probability of the emissions forecasts or of the climate forecasts was not quantified in either the SAR or the TAR, and absent a calibrated methodology for measuring the likelihoods of the ranges in the two assessments, the reader cannot know whether or not the shift in range reflects a new judgment about future climate change.

There are some well-documented statements in the TAR, e.g., to the effect that the rate of temperature increase over the next few decades is likely to be between 0.1° and 0.2°C per decade and that the increase over the past century is likely to be larger than over the past 10,000 years. The difficulty in extending the analysis to longer periods was increased by the procedure for developing the new emissions scenarios. The SRES explicitly avoided assigning probabilities to its scenarios. The Wigley and Raper study has assumed that they were of equal probability (*14*), although most emissions analysts would agree that they have very different likelihoods. Emissions forecasting is, in fact, one area where there is a history of quantitative uncertainty forecasting (*16*–*18*) that could be consulted. The difficulty with refraining from giving any estimate of likelihood is that the public will substitute their own nonexpert judgment about the probability and may assume far more (or far less) likelihood than the scientists involved believe.

On the issue of climate-change effects, the TAR includes a chart describing reasons for concern, indicating generally minor risks from a temperature rise of less than 2°C over the century and gradually increasing risks up to 6°C (*2*). However, no significant global impacts assessments have been completed using

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were not designed to span the full range of possibilities. Likewise, they assume only a 10% chance that the climate sensitivity lies outside the range 1.5° to 4.5°C, while acknowledging that the available surveys of expert opinion (*3*) and observational studies (*4*, *5*) currently suggest a larger range of uncertainty in this quantity. Individual authors can always make assumptions that may be controversial in order to explore their implications, but IPCC reports, which are subject to a long and exhaustive review process, do not have that luxury.

Regarding the third difficulty, substantial qualitative changes in the carbon cycle or ocean circulation cannot be ruled out under high-end scenarios as CO_2 levels approach 1000 ppm, but we are not yet in a position to assign numerical probabilities to such developments. The necessary ensemble prediction experiments with models explicitly representing the relevant processes have not yet been performed (*6*). Analyses of uncertainty in climate change to 2100 (*2*, *7*) have so far relied on simplified climate models that, by construction, assign zero probability to this kind of strongly nonlinear response. They may, therefore, be underestimating the full range of uncertainty by an unquantifiable, but possibly substantial, margin.

If we focus on shorter time scales and the response to specific emissions scenarios, the outlook is considerably brighter. The climate response up to the point of CO_2-doubling around the mid–21st century has now been documented with a wide range of climate models. Projected greenhouse gas concentrations are less sensitive to emission scenario on these time scales; recent observed climate changes provide a useful constraint on forecast warming rates despite uncertainty in climate sensitivity; and the probability of a strongly nonlinear response, although still not zero, appears to be sufficiently small that it may be neglected without making conclusions actively misleading. The TAR can and does provide a probabilistic forecast over these time scales, stating that anthropogenic warming is likely (meaning a greater than 2 in 3 chance) to lie in the range 0.1° to 0.2°C per decade over the next few decades under one "business-as-usual"-type emissions scenario, denoted IS92a (*8*).

The relation between this shorter-term probabilistic forecast and longer-term projections based on individual models is shown in the figure. On the 50-year time scales over which we can quantify the range of outcomes consistent with current observations (blue plume), the main climate models used in the TAR (represented by solid lines) appear to

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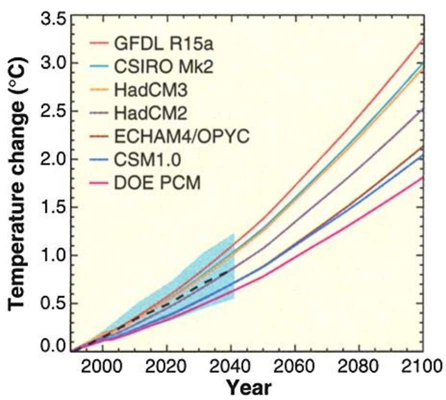

Two approaches to the analysis of uncertainty in climate change projections used by the IPCC. The heavy dashed line and blue plume show the median and 5 to 95% range of anthropogenic warming 1991–2041 under the IS92a scenario, based on reconciling complex climate model simulations with the recent observed climate change signal (*5*). To first order, this estimated uncertainty range does not depend on any particular model's climate sensitivity, ocean response time or amplitude of response to sulfate aerosols. The solid lines show the response to the IS92a emissions scenario as simulated by seven versions of a simple climate model tuned to replicate the sensitivity and ocean response time of the full-scale climate models named on the right, with all parameters including aerosol forcing as used in the TAR.

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transient climate simulations forced with SRES emissions scenarios published in the TAR (*1*). Most published impacts work uses older and unrealistic equilibrium climate scenarios for doubled CO_2 levels without the effect of aerosols, or simple sensitivity analyses where temperature or precipitation is varied by an arbitrary amount unrelated to any particular climate projection. The TAR shows clearly that the detailed regional projections needed to confidently assess impacts are unreliable (*1*). The experts summarizing impacts studies can, of course, form judgments about climate effects at different global temperature changes and their likelihood without the aid of impact analyses, much less quantified uncertainty studies for these impacts. In this event, however, it would seem especially important to explain the procedure followed and to make clear that judgments were made absent quantitative studies using transient scenarios from state-of-the-art coupled ocean-atmosphere general circulation models. A broader knowledge of the weak analytical base for assessment of impacts, as compared with climate science, might encourage badly needed research on climate-change impacts.

In the TAR assessment of mitigation measures, statements are made [Table SPM-1 in (*3*)] about the amount of emissions reductions that may be achieved by 2010 and 2020 with direct benefits exceeding direct costs. These results condition expectations about the possible cost of emissions control measures and the economic risks associated with firm reduction targets. Far from a consensus, these findings remain the subject of active and sometimes rancorous disagreement. Although the TAR presents data from a range of studies, the text does not convey the uncertainty that attends them, an unfortunate omission given the substantial background of work on which to draw (*10, 16–18*).

The IPCC provides a useful service to nations that are trying to understand and respond to climate change, and its leaders and authors deserve credit for their attempt in the TAR to be more explicit about uncertainties. However, given their importance to policy, climate-change assessments must strive to establish standards of scientific evidence no less rigorous in their uncertainty analysis than in their presentation of the underlying natural and social science. If statements of likelihood are to be taken seriously, they need to be grounded in a documented procedure that can be repeated and calibrated. Careful analysis of uncertainty is difficult, so any future assessment must choose outcomes of interest judiciously, focusing on those that are most important. Finally, uncertainty analysis should not be pasted on to the end of an assessment, but needs to be implemented from the beginning, with guidance from experts in the field.

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span something like the 10 to 90% range in global mean warming under the IS92a scenario. Crucially, there is no obvious bias toward the models' over- or underestimating the response. There is no guarantee that this agreement will extend further into the future, because it is not yet known to what extent current observations constrain the response on longer time scales. Hence, for the 2100 forecast imposed by its overall brief, the TAR is still confined to quoting the range of results from the models currently available and referring the reader to the relevant chapters for more detail on these models' validity.

It is important not to confuse reluctance to distill uncertainty down into a single summary statistic ("there is an x% chance that 2100 temperatures will be greater than y") with reluctance to acknowledge the existence of uncertainty per se. This kind of distillation can provide insight into the effect of combining different assumptions, but results are only of practical value when the factors responsible for the uncertainty are reasonably well documented and understood, which is certainly not the case for climate change in the late 21st century. When a surgeon is proposing a tried-and-tested operation, it may well be sufficient simply to inform the patient that there is a 4% chance of complications. When the procedure is highly experimental, there is no alternative but to explain to the patient as far as possible the origins and nature of the uncertainties in the outcome. The TAR would no doubt be a more convenient document for some purposes if more of the uncertainties therein were summarized numerically, but it would no longer provide an accurate representation of current research.

We should recall that the IPCC was under considerable pressure in 1990 to make a statement attributing observed climate changes to human influence "because if they don't, someone else will" (and, indeed, did). The IPCC is a cautious body, and if the evidence is not available in the peer-reviewed literature to support a statement, it will not make it, no matter how great the interest in that statement might be. In the end, this caution resulted in the attribution statement made in the Second Assessment Report having much more impact than if it had been made prematurely. We hope the research community will develop a capacity for fully probabilistic 100-year climate forecasting over the coming years and commend the efforts of many groups working toward this goal. When it happens, the IPCC will report that development. But not before.

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