important to both subseafloor mineralization and biological communities.

At both locations, metal accumulation occurred entirely by subseafloor replacement, with few readily identifiable surface expressions of an underlying hydrothermal system. The observed metal enrichment underscores the importance of shallow submarine geothermal activity as a potential source of toxic metals in areas extensively exploited by fishing. However, it is noteworthy that the degassing and shallow submarine hydrothermal venting in the Aeolian arc also appear to have provided a stepping-stone for colonization of the Mediterranean by vent organisms normally found on deep mid-ocean ridges.

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FORUM

Do We Need Better Predictions to Adapt to a Changing Climate?

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Many scientists have called for a substantial new investment in climate modeling to increase the accuracy, precision, and reliability of climate predictions. Such investments are often justified by asserting that failure to improve predictions will prevent society from adapting successfully to changing climate. This Forum questions these claims, suggests limits to predictability, and argues that society can (and indeed must) make effective adaptation decisions in the absence of accurate and precise climate predictions.

Climate Prediction for Decision Making

There is no doubt that climate science has proved vital in detecting and attributing past and current changes in the climate system and in projecting potential long-term future changes based on scenarios of greenhouse gas emissions and other forcings. The ability of climate models to reproduce the time evolution of observed global mean temperature has given the models much credibility. Advances in scientific understanding and in computational resources have increased the trustworthiness of model projections of future climates.

Many climate scientists, science funding agencies, and decision makers now argue that further quantification of prediction uncertainties and more accuracy and precision in assessments of future climate change are necessary to develop effective adaptation strategies. For instance, the statement for the May 2008 World Modelling Summit for Climate Prediction (http://wcrp.ipsl.jussieu.fr/Workshops/ModellingSummit/Documents/FinalSummitStat_6_6.pdf) argues that "climate models will, as in the past, play an important, and perhaps central, role in guiding the trillion dollar decisions that the peoples, governments and industries of the world will be making to cope with the consequences of changing climate." The statement calls for a revolution in climate prediction because society needs it and because it is possible. The summit statement argues that such a revolution "is necessary because adaptation strategies require more accurate and reliable predictions of regional weather and climate extreme events than are possible with the current generation of climate models." It states that such a revolution is possible because of advances in scientific understanding and computational power.

If true, such claims place a high premium on accurate and precise climate predictions at a range of geographical and temporal scales as a key element of decision making related to climate adaptation. Under this line of reasoning, such predictions become indispensable to, and indeed are a prerequisite for, effective adaptation decision making. Until such investments come to fruition, according to this line of reasoning, effective adaptation will be hampered by the uncertainties and imprecision that characterize current climate predictions.

Limits of Climate Prediction

Yet the accuracy of climate predictions is limited by fundamental, irreducible uncertainties. For climate prediction, uncertainties can arise from limitations in knowledge (e.g., cloud physics), from randomness (e.g., due to the chaotic nature of the climate system), and from human actions (e.g., future greenhouse gas emissions). Some of these uncertainties can be quantified, but many simply cannot, leaving some level of irreducible ignorance in our understanding of future climate.

An explosion of uncertainty arises when a climate change impact assessment aims to inform national and local adaptation decisions, because uncertainties accumulate from the various levels of the assessment. Climate impact assessments undertaken for the purposes of adaptation decisions (sometimes called end-to-end analyses) propagate these uncertainties and generate large uncertainty ranges in climate impacts. These studies also find that the impacts are highly conditional on assumptions made in the assessment, for example, with respect to weightings of global climate models (GCMs)—according to some criteria, such as performance against past observations—or to the combination of GCMs used.

Future prospects for reducing these large uncertainties remain limited for several reasons. Computational restrictions have thus far restricted the uncertainty space explored in model simulations, so uncertainty in climate predictions may well increase even as computational power increases. The search for objective constraints with which to reduce the uncertainty in regional predictions has proven elusive. The problem of equifinality (sometimes also called the problem of "model identifiability")—that different model structures and different parameter sets of a model can produce similar observed behavior of the system under study—has rarely been addressed. Furthermore, current projections suggest that the Earth's climate may soon enter a regime dissimilar to any seen for millions of years and one for which paleoclimate evidence is sparse. Model projections of future climate therefore represent extrapolations into states of the Earth system that have never before been experienced by humanity, making it impossible to either calibrate the model for the forecast regime of interest or confirm the usefulness of the forecasting process.

In addition, climate is only one of many important processes that will influence the success of any future adaptation efforts, and often it is not the most important factor. Our current ability to predict many of these other processes—such as the future course of globalization, economic priorities, regulation, technology, demographics, cultural preferences, and so forth—remains much more limited than our ability to predict future climate. This raises the question of why improved climate predictions ought to be given such a high priority in designing adaptation policies.

Alternatives to Prediction

Individuals and organizations commonly take actions without having accurate predictions of the future to support those actions. In the absence of accurate predictions, they manage the uncertainty by making decisions or establishing robust decision processes that produce satisfactory results. In recent years, a number of researchers have begun to use climate models to provide information that can help evaluate alternative responses to climate change, without necessarily relying on accurate predictions as a key step in the assessment process. The basic concept rests on an exploratory modeling approach whereby analysts use multiple runs of one or more simulation models to systematically explore the implications of a wide range of assumptions and to make policy arguments whose likelihood of achieving desired ends is only weakly affected by the irreducible uncertainties.

As one key step in the assessment process, such analyses use climate models to identify potential vulnerabilities of proposed adaptation strategies. These analyses do not require accurate predictions of future climate change from cutting-edge models. Rather, they require only a range of plausible representations of future climate that can be used to help organizations, such as water resources agencies, better understand where their climate change–related vulnerabilities may lie and how those vulnerabilities can be addressed. Even without accurate probability distributions over the range of future climate impacts, such information can prove very useful to decision makers.

Such analyses generally fall under the heading of "robust decision making." Robust strategies perform well compared with alternative strategies over a wide range of assumptions about the future. In this sense, robust strategies are insensitive to the resolution of the uncertainties. A variety of analytic approaches, such as exploratory modeling, have been proposed to identify and assess robust strategies.

Climate and Science Policy Implications

Given the deep uncertainties involved in the prediction of future climate, and even more so of future climate impacts, and given that climate is usually only one factor driving the success of adaptation decisions, we believe that the "predict-then-act" approach to science in support of climate change adaptation is significantly flawed. This does not imply that continued climate model development cannot provide useful information for adaptation. For instance, such development could further inform the plausible range of impacts considered when crafting a robust adaptation strategy. However, further scientific effort will never eliminate uncertainty; it may in fact increase uncertainty. For example, 3 decades of research on climate sensitivity (the global mean temperature change following an instantaneous doubling of carbon dioxide in the atmosphere) have not reduced, but rather have increased, the uncertainty surrounding the numerical range of this concept. The lack of climate predictability should not be interpreted as a limit to preparing strategies for adaptation.

By avoiding an analysis approach that places climate prediction at its heart, successful adaptation strategies can be developed in the face of deep uncertainty. Decision makers should systematically examine the performance of their adaptation strategies over a wide range of plausible futures driven by uncertainty about the future state of climate and many other economic, political, and cultural factors. They should choose a strategy they find sufficiently robust across these alternative futures. Such an approach can identify successful adaptation strategies without accurate and precise predictions of future climate.

Our arguments have significant implications for science policy. At a time when government expects decisions to be based on the best possible science (e.g., evidence-based policy making), we suggest that climate science is unlikely to support prediction-based decisions. Overprecise climate predictions can also lead to maladaptation if the predictions are misinterpreted or used incorrectly. From a science policy perspective, it is worth reflecting on where investments by science funding agencies can best increase the societal benefit of science. Efforts to justify renewed investments in climate models based on promises of guiding decisions are misplaced.

The World Modelling Summit for Climate Prediction called for a substantial increase in computing power (an increase by a factor of 1000, at the cost of more than a billion dollars) to provide better information at the local level. We believe, however, that society will benefit more from having a greater understanding of the vulnerability of climate-influenced decisions in the face of large irreducible uncertainties, and the various means of reducing such vulnerabilities, than from any plausible and foreseeable increase in the accuracy and precision of climate predictions.

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