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Prediction in the Earth Sciences and Environmental Policy Making

The Earth sciences, backed by formidable arrays of data gathering and processing technologies, today offer the apparently credible promise of predicting the future of nature. Policy makers, under pressure as always to deliver public benefit at low cost, have strong incentives to accept this promise as a central response to environmental issues.

As environmental problems become more pressing and budgets for research become tighter, the importance of effective prioritization and allocation of research funds and activities will increase, as will the need for timely and effective political decision making. Thus, there is increasing need to enhance the linkages between research in the predictive Earth sciences and the needs of environmental policy makers.

The authors have been investigating the role of prediction in the making of environmental policies. Their work suggests that, for virtually every environmental problem, the key to effective decision making lies in improving the decision environment itself. Such improvement may come from cost-effective, politically realistic alternatives to prediction. The goal of the decision environment must be good decisions, not simply good predictions.

The authors' investigation includes policy decisions in planning for and responding to natural hazards (weather, floods, earthquakes, asteroids) and anthropogenic hazards (global climate change, acid rain, nuclear waste), managing natural resources (oil reserves, beaches), and regulating environmental impacts (mining). The project seeks to apply the collective wisdom of a range of stakeholders (including natural scientists who make predictions and social scientists who are concerned with their use) to the issue of how scientific predictions ought to be used (or not used or not misused) in the development of effective policies relating to natural hazards, natural resources, and the environment.

A collaboration between Columbia University's Center for Science, Policy, and Outcomes, the Environmental and Societal Impacts Group at the National Center for Atmospheric Research, and the Geological Society of America, with support from the National Science Foundation, the project has convened several workshops to bring together a diverse group of people involved in various ways with the process of prediction. Among the participants were a scientist who develops climate models, the former emergency manager of a major California city, a banker from a coastal city that is subject to hurricanes, earthquakes, and beach erosion, a seismologist, a rancher, a former official at the federal Office of Management and Budget, an engineer who works on nuclear waste isolation, and a coastal geologist who studies beach erosion.

Prediction as a Process

Decision making is forward looking, so the allure of prediction is strong. As a society, we look to predictions to help us make decisions that can mitigate the impact of nature on society and of society on nature. In doing so, we need to recognize that prediction is necessarily part of a complex decision-making process, a network of interrelationships that must function well across all of its connections if predictions are to serve society effectively. This integrated process involves policy makers (who solicit and pay for predictions), scientists (who make predictions), and decision makers (who use them—for everything from deciding whether to carry an umbrella to evacuating a city in the path of a hurricane; from establishing levels of insurance risk to negotiating an international environmental agreement).

The less frequent, less observable, less spatially discrete, more gradual, more distant in the future, and more severe a predicted phenomenon, the more difficult it is to accumulate direct experience. Where direct societal experience is sparse or lacking, other sources of societal understanding must be developed or the prediction process will not function effectively. Science alone and prediction in particular do not create this understanding.

What is necessary above all is an institutional structure that brings together those who solicit and use predictions with scientists throughout the entire prediction process, so that each knows the needs and capabilities of the others. It is crucial that this process be open, participatory, and conducive to mutual respect. Efforts to shield expert research and decision making from public scrutiny and accountability invariably backfire, fueling distrust and counterproductive decisions.

Fostering Sound Decision Making

The six points that follow distill some of the most important issues associated with a healthy prediction process. The overriding theme is that for society to systematically benefit from the provision of predictive information from the Earth sciences, scientists and decision makers should together pay attention to the broad process in which predictions are made.

1. Predictions must be generated primarily with the needs of the user in mind. Television weather predictions focus primarily on temperature, precipitation, and wind, rather than thermal gradients, behavior of aerosols, and barometric pressure. For scientists to participate usefully in the prediction process, they must address the broader goals of the process, not the limited goals of science; they must listen to stakeholders. For stakeholders to participate usefully in this process, they must work closely and persistently with the scientists to communicate their needs and problems.

2. Uncertainties must be clearly articulated (and understood) by the scientists, so that users understand their implications. Failure to understand uncertainties has contributed to poor decisions that then undermine relations among scientists and decision makers; we saw this during the flooding of the Red River of the North in Grand Forks, North Dakota [*Pielke*, 1999] (see http://www.dir.esig.

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ucar.edu/esig/redriver). But merely understanding the uncertainties does not mean that the predictions will be useful. If policy makers truly understood the uncertainties associated with predictions of, for example, global climate change, they might decide that strategies for action should not depend on predictions [*Rayner and Malone*, 1998].

3. Experience is an important factor in how decision makers understand and use predictions. For instance, people hear a weather report and then make a decision about clothing, accessories (umbrella?), and mode of transport. This decision is backed by personal experience of weather and its local fluctuations, as well as the broader societal experience in the United States with a scientific and technical support infrastructure that issues on the order of 10 million weather predictions per year. In many cases, users have accumulated enough experience in comparing a weather prediction to the actual weather to personally calibrate the prediction process. Conversely, in other situations such personal experience is not possible. For example, because radioactive waste remains dangerous for hundreds of thousands of years, members of Congress have only testimony from scientists and not experience about nuclear waste disposal. The relevant science uses analogy, mathematical models, and extrapolation to predict events far in the future. Unlike weather, there is no basis in human experience for evaluating the actual performance of the disposal systems or the science. Decisions must be based on abstractions. Yet action must be taken, and the consequences of a poor prediction, or a poor decision based on a good prediction, are potentially disastrous.

4. Although experience is important and cannot be replaced, the prediction process can be facilitated in other ways, for example by being totally open about predictions, warts, and all; and by fully considering alternative approaches to prediction, such as no-regrets public policies, adaptation, and better planning and engineering. Indeed, al-

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ternatives to prediction must be evaluated as a part of the prediction process. Rather than trying to predict the impacts of hard-rock pit mines on water quality as a basis for environmental regulation, it might be more feasible to spread risk through bonding or other types of insurance. Predicting the consequences of global climate change has led to policy gridlock; other approaches to mitigation and adaptation should be sought more vigorously.

5. To ensure an open prediction process, stakeholders must question predictions. For this questioning to be effective, predictions should be as transparent as possible to the user. In particular, assumptions, model limitations, and weaknesses in input data should be forthrightly discussed. Especially in cases where personal experience may be limited (acid rain, asteroid impacts, global warming), public confidence in the validity of the prediction will derive in part from an understanding of how the prediction is generated. Black boxes generate distrust, especially when a prediction can stimulate decisions that create winners and losers. Even so, many types of predictions will never be understood by decision makers in the way that weather predictions are understood. Table 1 lists questions of the prediction process developed by project participants.

6. Last, predictions themselves are events that cause impacts on society—as best illustrated by earthquake prediction. The prediction process must include mechanisms for the various stakeholders to fully consider and plan what to do after a prediction is made.

Attention to these six issues will not guarantee that predictions will lead to benefits to society, but it will enhance the opportunities for effective use of predictions by decision makers. The result will be a healthier prediction process.

Project Background

In responding to a variety of environmental problems, policy makers have called upon Earth scientists to predict the occurrence of phenomena such as earthquakes, hurricanes, and global climate change. Many fields of Earth science have in turn become increasingly engaged in efforts to develop goals can be seen in many federal programs. Consider the following examples:

- In 1987, the U.S. government established a Global Change Research Program "to gain an adequate predictive understanding of the interactive physical, geological, chemical, biological, and social processes that regulate the total Earth system and hence establish the scientific basis for national and international policy formulation and decisions" [*Committee on Earth and Environmental Sciences*, 1992]. To date, the U.S. Congress has appropriated more than $11 billion to the program, and one of the largest international assessment processes has the mission to produce and evaluate such predictions.
- In recent years, the U.S. government has spent more than $4 billion to modernize and restructure the National Weather Service (NWS) in order "to collect and process huge amounts of atmospheric data over greater areas and at higher rates for more accurate, timely, and site-specific forecasts and warnings." NWS modernization is justified on the basis that "accurate and timely information about [hazardous] phenomena is key to mitigating their effects on the lives of our citizens" [*Friday*, 1994]. In 1992, Congress established a U.S. Weather Research Program to further enhance such weather prediction capabilities (Public Law 102-567).
- The National Earthquake Hazards Reduction Act (Public Law 95-124), enacted in 1977, states, "A well-funded seismological research program in earthquake prediction could provide data adequate for the design of an operational system that could predict accurately the time, place, magnitude, and physical effects of earthquakes." Although more recent amendments have softened this language, the U.S. Geological Survey (USGS) still retains a "primary responsibility" within the federal earthquake program to "develop methods to predict future earthquakes, including the issuance of earthquake predictions" (http://www.usgs.gov). Indeed, the USGS carried out a major earthquake prediction experiment from 1985 to 1993 along the Parkfield segment of the San Andreas Fault. In Japan, over $100 million per year is spent on earthquake prediction research. China also has a major earthquake prediction program.
- Federal regulations that govern mining on federal lands require that the future environmental impacts of a new mine be assessed

the accessible environment" owing to "all significant processes and events that may affect the disposal system" shall remain below threshold levels defined by law "for 10,000 years after disposal." That is, approval of the Yucca Mountain site seems to require a scientific prediction of maximum future radiation releases over the next 10,000 years.

These examples show that predictive Earth science is viewed by national policy makers as a valuable tool for meeting a range of societal goals, including guiding the negotiation of international environmental agreements (such as those involving global climate change); protecting the populace from natural and manmade hazards (such as earthquakes and nuclear waste); anticipating and responding to natural changes in the environment (such as from El Niño); and preserving environmental quality (such as from the impacts of resource extraction).

Prediction and Policy Making

While efforts to predict natural phenomena have become an important aspect of the Earth sciences, the value of such efforts, as judged especially by their capacity to improve decision making and achieve policy goals, has been questioned by a number of constructive critics. The relationship between prediction and policy making is not straightforward for many reasons. Among the reasons is that accurate prediction of phenomena may not be necessary to respond effectively to political or socioeconomic problems created by the phenomena (for example, better mitigation of natural hazards such as floods might depend more on reducing vulnerabilities than on better predictive information; see *Pielke* [1999]).

Also, phenomena or processes of direct concern to policy makers may not be easily predictable on useful timescales (such as with earthquakes; see *Ashida* [1996]). Likewise, predictive research may reflect discipline-specific scientific perspectives that do not provide "answers" to policy problems, which are complex mixtures of facts and values, and which are perceived differently by different policy makers (for example, regarding acid rain; see *Herrick and Jamieson* [1996]).

In addition, necessary political action may be deferred in anticipation of predictive information that is not forthcoming in a time frame compatible with such action. Similarly,

cial and intellectual resources away from other types of research that might better help to guide decision making (for example, incremental or adaptive approaches to environmental management that require monitoring and assessment instead of prediction; see *Lee* [1993]).

These considerations suggest that the usefulness of scientific prediction for policy making and the resolution of societal problems depends on relationships among several variables, such as the timescales under consideration, the scientific complexity of the phenomena being predicted, the political and economic context of the problem, and the availability of alternative scientific and political approaches to the problem.

In light of the likelihood of complex interplay among these variables, decision makers and scientists would benefit from criteria that would allow them to better judge the potential value of scientific prediction and predictive modeling for different types of political and social problems related to Earth processes and the environment.

Healthy Decisions

When the prediction process is fostered by effective, participatory institutions, and when a healthy decision environment emerges from these institutions, the products of predictive science may even become less important. Earthquake prediction was once a policy priority; now it is considered technically infeasible, at least in the near future. But in California the close, institutionalized communication among scientists, engineers, state and local officials, and the private sector has led to considerable advances in earthquake preparedness and a much decreased dependence on prediction. On the other hand, in the absence of an integrated and open decision environment, the scientific merit of predictions can be rendered politically irrelevant, as has been seen with nuclear waste disposal and acid rain. In short, if no adequate decision environment exists for dealing with an event or situation, a scientifically successful prediction may be no more useful than an unsuccessful one.

These observations fly in the face of much current practice where, typically, policy makers recognize a problem, scientists then go away and do research to predict natural behavior associated with the problem, and preaccurate predictive capabilities.

Timely, policy-relevant predictions may help policy makers respond to some environmental problems, but the misapplication or misuse of prediction research can undermine policy goals, waste scarce financial and intellectual resources, and erode the overall credibility of the scientific enterprise. Because little systematic analytical attention has been directed to this issue, our understanding of the appropriate use of scientific prediction in policy making is limited. Policy makers and scientists require new approaches to evaluating how and when scientific prediction can be productively applied to the resolution of environmental policy problems.

The interest in and demand for predictive information in support of national policy prior to the start-up of mine operations. Under regulations pursuant to the National Environmental Policy Act, this assessment must address both "direct effects" of the mine on water quality, and "indirect effects" that are "later in time . . . but still reasonably foreseeable." This requirement is commonly met by using geochemical and hydrological models to predict future environmental effects. The results of these models are often used to help design oversight and mitigation strategies for new mines.

• Design criteria for the high-level nuclear waste facility at Yucca Mountain, Nevada, include the requirement that the disposal system "provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to policy action may be delayed when scientific uncertainties associated with predictions become politically charged (in the issue of global climate change, for example; see *Rayner and Malone* [1998]).

Predictive information also may be subject to manipulation and misuse either because the limitations and uncertainties associated with predictive models are not readily apparent, or because the models are applied in a climate of political controversy and high economic stakes. This may be particularly problematic when predictions are used to justify government regulatory decisions, such as in granting permits for mines (see *Moran and Mernitz* [1995]) or in developing shorelines (see *Pilkey and Dixon* [1996]). Also, emphasis on predictive sciences moves both finan- dictions are finally delivered to decision makers with the expectation that they will be both useful and well used. This sequence, which isolates prediction research but makes policy dependent on it, rarely functions well in practice.

More information on this project can be found on the Web site (http://www.dir.ucar.edu/esig/prediction/). We welcome comments and suggestions. *Predictions: Decision Making and the Future of Nature* is being put together by the authors of this article, and plans are for it to be published next year by Island Press. It will present project case studies, background, synthesis, and analytical chapters.

Table 1. Questioning Predictions.

What is the policy goal(s) (i.e., outcome) that prediction is intended to achieve?	Specify the purpose(s) [policy goal(s)] of the prediction.
How does the process of developing predictions influence the policy process (and vice versa)?	Consider alternatives to prediction for achieving the purpose. Maintain flexibility of the system as work on predictions proceeds. Recognize that a choice to focus on prediction (as well as the choice of specific predictive technique) will constrain future policy alternatives.
What are the direct societal impacts of the prediction?	Consider alternative societal impacts that might result from the prediction (including the different roles played by prediction). Evaluate past predictions in terms of impacts on society. Recognize that the prediction itself can be a significant event. If possible, [subtract the costs/assess the impacts] of inadequate predictions [from the benefits/relative to the impacts] of successful ones.
What are the scientific limitations and uncertainties of the prediction?	Evaluate past predictions in terms of scientific validity. Recognize that different approaches can yield equally valid predictions. Recognize that prediction is not a substitute for data collection, analysis, experience, or reality. Recognize that predictions are always uncertain; assess the level of uncertainty acceptable in the particular context. Beware of precision without accuracy. Recognize that quantification and prediction are not a) accuracy; b) certainty; c) relevance; d) reality. Computers hide assumptions. Computers don't kill predictions, assumptions do. Recognize that the science base may be inadequate for a given type of prediction.
What factors can influence how a prediction is used by society?	Recognize that prediction may be more effective at bringing problems to attention than forcing them to effective solutions. Recognize that perceptions of predictions may differ from what predictors intend and may lead to unexpected responses. Recognize that the societal benefits of a prediction are not necessarily a function of its accuracy. Recognize that there are many types of prediction, and their potential uses in society are diverse.
What political and ethical considerations are raised by the generation and dissemination of a prediction?	Pay attention to conflicts of interest [among those making predictions]. Understand who becomes empowered when the prediction is made. Who are the winners and losers? Pay attention to the ethical issues raised by the release of predictions.
How should predictions be communicated in society?	Make the prediction methodology as transparent as possible. Predictions should be communicated a) in terms of their implications for societal response and b) in terms of their uncertainties.

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