Molecular biologists have not, as far as we know, identified a "prediction gene," but the quest to predict seems as deeply instinctive to the human condition as language, self-consciousness, and artistic expression. Unlike these other characterizing traits, however, the instinct to predict has not always been expressed in effective performance. Oracles, prophets, and stock market forecasters have been accorded a status in society that is commensurate with the promise—not the delivery—of tomorrow revealed.

Scientists today seek to turn prediction into a reputable profession. They bring impressive tools to the quest: powerful theoretical understanding of fundamental processes; advanced monitoring technologies that digitize nature in all its rich profusion; supercomputers that crunch gigabyte-sized databases and spit out a vision of the future. Indeed, these days, science without prediction hardly seems like science at all.

Still, even the most sophisticated scientific predictions are plagued with uncertainties. But unlike predictions based on entrails or the stars, these uncertainties can be quantified (although quantifications of uncertainty are often themselves highly uncertain). We may therefore ask: What characteristics of a scientific prediction will allow us to make a decision that is better than the one we would have made without the prediction? (Of course, the answer to this question, too, may be highly uncertain.)

1

Prediction in Science and Policy

Daniel Sarewitz and Roger A. Pielke, Jr.

Policy makers have called upon scientists to predict the occurrence, magnitude, and impacts of natural and human-induced environmental phenomena ranging from hurricanes and earthquakes to global climate change and the behavior of hazardous waste. In the United States, billions of federal dollars are spent each year on such activities. These expenditures are justified in large part by the belief that scientific predictions are a valuable tool for crafting environmental and related policies. But the increased demand for policy-relevant scientific prediction has not been accompanied by adequate understanding of the appropriate use of prediction in policy making.

In modern society, prediction serves two important goals. First, prediction is a test of scientific understanding, and as such has come to occupy a position of authority and legitimacy. Scientific hypotheses are tested by comparing what is expected to occur with what actually occurs. When expectations coincide with events, it lends support to the power of scientific understanding to explain how things work. "[Being] predictive of unknown facts is essential to the process of empirical testing of hypotheses, the most distinctive feature of the scientific enterprise," observes biologist Francisco Ayala (1996).

Second, prediction is also a potential guide for decision making. We may seek to know the future in the belief that such knowledge will stimulate and enable beneficial action in the present. Such beliefs are supported by a long—if often mythic—history, predating modern science. For instance, armed with knowledge of the coming flood, Noah was able to build the ark and avoid the catastrophic end that befell those without such foresight. Today, as decision makers debate alternative courses of action, such as the need for a new law or the design of a new program, they are actually making predictions about the expected outcome of this law or program and its future impact on society: "Decision making is forward looking, formulating alternative courses of action extending into the future, and selecting among the alternatives by expectations of how things will turn out" (Lasswell and Kaplan 1950).

Persistent and pervasive calls for scientific prediction as a basis for environmental policy making—documented throughout this book—suggest confusion about these two motives for why we predict. The value of predictions for validating scientific hypotheses does not imply a commensurate value for dictating public policy. Moreover, as we will explore in greater detail, all scientific predictions are not the same: those used to support environmental decision making are different in essence from those traditionally used to validate hypotheses. Confusion about why and how we predict can prevent appropriate allocation of intellectual and financial resources for science and environmental policy. It also sets the stage for a policy problem: Policy makers lack knowledge that can help them to anticipate—to predict, that is—the circumstances in which predictive research can contribute to effective decision making. As a consequence, some environmental policies may rely inappropriately on predictions and thus run the risk of failing to achieve their intended effects. No process exists for assessing whether particular environmental issues might or might not be amenable to solution aided by predictions, and no systematic analysis exists to support such a process. In this chapter, we try to dissect and define the problem of prediction in policy in a way that is useful for decision makers and researchers, and we begin to develop a framework for understanding the case histories, policy analysis, and recommendations that follow.

Types of Prediction

The essential context for prediction in traditional science is reductionism: the effort to break down reality into describable component parts or processes with an ultimate objective of specifying the "laws of nature." Such laws are fundamentally predictive, because they describe behavior of phenomena that is *independent of time and place* (e.g., Popper 1959). That is, the behavior is always consistent, and thus predictable. In this sense, the word *prediction* as used in the reductionist natural sciences is simply a synonym for *explanation* or *inference* (Toulmin 1961). In reductionist science, moreover, prediction pertains to the invariant behavior of individual parts, not to the processes of interaction among natural systems that contain those parts (e.g., Wilson 1998). Thus, for example, progress in physics is often measured by success in identifying and describing increasingly fundamental components of matter; in biology, by finding increasingly fundamental building blocks of life.

Natural Systems

As Oreskes discusses in the next chapter, those disciplines of the natural sciences that seek to understand complex systems—integrative earth sciences (including solid-earth, ocean, and atmospheric sciences)[1]—have not traditionally been involved with prediction (although weather prediction has been a notable exception). Rather, such disciplines have been the source of verbal, graphical, and mathematical portrayals of nature that yield insight into earth processes. This insight can allow humans to better understand, anticipate, and respond to the opportunities and constraints of the natural world. For example, historical interpretation of earthquake occurrence, combined with present-day monitoring, has led to successful strategies for mitigating earthquake losses through appropriate engineering, land-use planning, and emergency management. Such strategies do not require the prediction of specific earthquakes to deliver social benefit.

Integrative earth science disciplines have sought to understand nature "as it is," rather than as reduced to its component parts. That is, while traditional physical science isolates phenomena from their context in nature in order to understand the invariant characteristics of the phenomena, the integrative earth sciences study the context itself. In the case of geology, for example, Baker (1996) writes: "Geology does not predict the future. Its intellectual tradition focuses on the contingent phenomena of the past. . . . Contingency holds that individual events matter in the sequence of phenomena. Change one event in the past, and the sequence of subsequent historical events will change as well." This focus on interpretation, contingency, and sequence is distinct *in its essence* from the reductionist goal of identifying and describing invariant phenomena.

Over the past several decades, however, prediction has increasingly become a goal of integrative earth science disciplines. A proliferation of new technologies for the study of the oceans, atmosphere, and solid earth have led, as well, to the proliferation of massive volumes and new types of data about the environment. At the same time, rapidly increasing computer-processing capabilities permit the analysis of larger and more sophisticated data sets. These changes have allowed earth scientists to develop more intricate conceptual and numerical models about earth-system processes ranging from the flow of toxic plumes in groundwater to the global circulation patterns of the atmosphere and oceans.

While such models can be used to test the validity of hypotheses about earth processes, they are also being used to predict the behavior of complex natural phenomena as input to policy decisions.

This type of prediction is fundamentally different from the predictive aspect of traditional, reductionist scientific inquiry. Rather than identifying the invariant behavior of isolated natural phenomena, prediction of complex systems seeks to characterize the contingent relations among a large but finite number of such phenomena. In contrast to prediction in reductionist science, *these types of predictions are highly dependent on time and place.*

Most generally, efforts to predict the behavior of complex systems use two approaches:

1. mathematical characterization of the significant components of a system and the interactions of those components according to governing laws (often called first principles), to yield a quantitative predictive model; and
2. identification of specific environmental conditions that are statistically significant precursors of a particular type of event.

Prediction of ongoing, evolving processes, such as groundwater flow or atmospheric circulation, is predominantly approached through mathematical modeling. Prediction of episodic, temporally discrete events, such as earthquakes and seasonal hurricane activity, often focuses on the identification of precursors that have shown a statistical linkage but are not necessarily causal. Most predictive efforts actually involve both approaches: the development of quantitative models and the search for correlations between past and future events.

In reductionist science, predictive validity is constantly being tested through the application of theory to scientific and engineering problems. In the integrative earth sciences, testing the usefulness or precision of a predictive model usually requires a comparison with observational data. Models can be tested through "retrodiction," that is, determining the ability of the model to reproduce the behavior of past phenomena (e.g., changes in global atmospheric temperature), or through in situ measurements of ongoing behavior (e.g., sampling to determine if the behavior of a toxic groundwater plume is consistent with the model). Oreskes, Shrader-Frechette, and Belitz (1994), among others, have argued that such tests do not amount to a "verification" of the predictive capability of the model, because natural systems are not "closed." That is:

> Even if a model result is consistent with the present and past observational data, there is no guarantee that the model will perform at an equal level when used to predict the future. First, there may be small errors in input data that do not impact the fit of the model under the time frame for which historical data is available, but which, when extrapolated over much larger time frames, do generate significant deviations. Second, a match between model results and present observations is no guarantee that future conditions will be similar, because natural systems are dynamic and may change in unanticipated ways.

Still, earth scientists commonly argue that advances in theory, data collection, and computer power will deliver increasingly accurate and useful predictions of complex environmental phenomena in the future (Mahlman 1992; Wyss 1997). That such arguments occupy an important role in policy making is well illustrated by the examples of global warming (see chapter 13) and natural disaster preparedness (see chapter 7), as well as by the billions of dollars spent each year to support predictive research in these and related areas.

Social Systems

As predictions have become central to the notion of what is scientific, so have they become fundamental to the social sciences. Social scientists have long sought to emulate their physical scientist counterparts in developing invariant laws of human behavior and interaction (Ross 1991), an emulation that has often been called "physics envy." (Even in the humanities, some have sought to develop "scientific" methodologies, characterized by predictive skill [Fogel and Elton 1983].) Within the social sciences, scholars have for years debated the usefulness of aspiring to replicate the "scientific" success achieved by the physical sciences. For instance, Nobel Prize–winning economist Milton Friedman has suggested that a theory should be judged on its power to predict (Friedman 1953), whereas another Nobel Prize winner, Herbert Simon, suggests that such power is elusive even for some of our most well-accepted social science theories (Simon 1982). Indeed, although much social science research is supported to develop predictions, such predictions may prove unsuccessful for all but the most simple (and therefore obvious) social situations (Ascher 1979).

Economics has been viewed by many as the "imperial" social science, one that "will always remain valid for analyzing and *predicting* the course of human behavior and social organization" (emphasis in original) (Hirshleifer 1985). Part of its stature derives from the resemblance between the quantitative emphasis and methodologies of economics and those of physics. Sociology, on the other hand, was modeled on the biological sciences. I.B. Cohen (1994) has observed that:

> Curiously enough, the biological science of the nineteenth century has weathered the years somewhat better than the physics, requiring revisions and expansions but not the same degree of radical restructuring, while the sociology built on the biology has not done as well as the economics which was (in part, at least) linked with the physics. Apparently, the correctness of the emulated science is not intrinsically connected with the permanent value of the social science.

Within the social sciences, most disciplines have in either small or large part sought to model themselves after economics, with other methodological approaches viewed as "alternatives" (Simon 1985; Dahl 1961). In political science, a large literature exists on developing various theories of political activity based on the "rational actor" theory of economic behavior (Petracca 1991). For instance, a classic text in political science is Anthony Downs's *An Economic Theory of Democracy* (1957). More recently, scholars have used economic methods in pursuit of a predictive model of presidential elections (Lewis-Beck and Rice 1992). For some in political science, the development of predictive theories is what makes the discipline "scientific." According to David Brady, a leading political scientist, "Unless we, as a profession, can offer clear theories of how elections, institutions, and policy are connected and deduce predictions from these stories, we shall simply be telling *ad hoc* stories" (Brady 1993). Cohen (1994) argues that it is "not a fruitful question" whether or not the social sciences are "scientific" in the sense of the physical sciences. Nevertheless, he notes:

> A social science like economics—which looks somewhat like physics in being quantitative, in finding expression of its principles in mathematical form, and in using the tools of mathematics—tends to rank higher on a scale of both scientists and non-scientists than a social science like sociology or political science which seems less like an "exact science."

Thus, in social sciences, as in the case of the natural sciences, predictive capabilities are widely viewed as authoritative and legitimating. Here as well the subtext of such research is that predictive science will add to the development of fundamental knowledge of human behavior, which—aside from its intrinsic value—will enhance society's capability to organize and govern itself.

As the scientific community seeks to predict the behavior of complex systems, the boundaries between physical and social sciences are blurring, or at least overlapping. For instance, in the case of global warming, predictions of future climate impacts are, in part, based on predictions

of future population growth and energy consumption, both of which fall squarely in the realm of the social sciences. Similarly, understanding the impacts of natural hazards such as floods and earthquakes depends on future trends in economic development and demography, which are functions of broader social and policy processes.

To summarize, prediction has long been central to the process and validation of modern science. Prediction is also necessarily implicit in the process of decision making. In recent years, coincident with the rapid development of data acquisition and storage and processing capabilities, researchers and policy makers alike have looked to science as a source of predictions about the evolution of complex natural and social systems. We have argued that such activities are distinct from traditional, reductionist scientific prediction. We now look more closely at the relationship between decision making and the prediction of complex systems.

Two Birds with One Stone: How Prediction Simultaneously Fills a Policy Role and a Science Role

The predictive capacity of science holds great inherent appeal for policy makers who are grappling with complex and controversial environmental issues, by promising to enhance their ability to determine the need for and outcomes of particular policy actions. However, this appeal is partly rooted in the conflation—and perhaps confusion—of two conceptually and methodologically distinct activities: predictions as a means to advance science, and predictions as a means to advance policy. We emphasize that the traditional rationale for prediction in science was to validate reductionist theory. Only in recent years, with the rise of high-technology integrated earth science, have policy makers and scientists alike been tempted to extend this rationale to include the support of policy decisions. Today, the value of scientific predictions is increasingly viewed not just in terms of scientific understanding, but in terms of policy making, as well.

This newer, political role for prediction is seductive. If predictive science can improve policy outcomes by guiding policy choices, then it can as well reduce the need for divisive debate and contentious decision making based on subjective values and interests. Prediction, that is, can become a substitute for political and moral discourse. By offering to improve policy outcomes, scientific predictions also offer to reduce political risk, and for policy makers worried about public support and reelection, avoiding political risk is very appealing indeed. This appeal has an additional attribute: The very process of scientific research aimed at prediction can be portrayed as a positive step toward solving a policy problem. Politicians may therefore see the support of research programs that promise to deliver a predictive capability in the future as an alternative to taking politically risky action in the present.

Supply and demand for federally funded research on prediction of environmental phenomena are tightly coupled. As environmental problems become more politically complex—and response options become more controversial and costly—decision makers look toward scientists to help reduce uncertainties and dictate "rational" policy paths. Simultaneously, the growing analytical and computational sophistication of the earth sciences leads to an increased confidence in the capacity of these disciplines to predict the behavior of the environment. Furthermore, finite federal research funding dictates that decision makers and scientists naturally converge on areas of research that are expected to be mutually beneficial.

The short-term benefits for both scientists and politicians are clear: scientists receive federal funding to develop predictions; politicians can point to predictive research as "action" with respect to societal problems, while deferring difficult decisions as they await the results of research. Such an arrangement is seen in a number of nationally important policy issues, such as global climate change, nuclear waste disposal, and natural hazard mitigation.

Over the long term, will this arrangement lead to improved policy making, disappointed expectations, or some combination of both? Prospects for success will almost certainly vary depending on the phenomenon being predicted and the policy problem being addressed. An analytical framework that allows policy makers and scientists to evaluate how and when scientific prediction can benefit the policy process would help ensure an effective allocation of financial and intellectual resources. In particular, a useful framework must evaluate the capacity of predictive research to contribute to positive policy outcomes in light of the following six concerns:

1. Phenomena or processes of direct interest to policy makers may not be easily predictable on useful geographic or time scales. For example, early optimism about the predictability of earthquakes (Press 1975) has been eroded by several decades of scientific failure (see chapter 7).
2. 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 hurricanes and floods may be achieved through effective planning that does not depend on better predictive information (Pielke 1997; chapter 5, this volume; chapter 4, this volume). In the case of acid rain, the political solution of using tradable permits to reduce sulfur oxide emissions did not depend on the predictive results emerging from a ten-year, half-billion-dollar federal research program (see chapter 12).
3. Necessary or feasible political action may be deferred in anticipation of predictive information that may not be forthcoming in a useful time frame. For example, societal adaptation to inevitable future climate impacts has been held in abeyance by the expectation that predictions of global climate change will guide policy choices (chapter 13). Similarly, action may be delayed when scientific uncertainties associated with predictions become politically charged, as seen in the case of both global climate change and high-level nuclear waste disposal (chapter 10).
4. Predictive information may be subject to manipulation and misuse, because the limitations and uncertainties associated with predictive models are often not readily apparent to nonexperts, and because the models are often applied in a climate of political controversy and/or high economic stakes (Rushefsky 1984). For example, in such cases as mining on federally owned land and replenishment of sand on public beaches, mathematical models are used to predict costs and environmental impacts. The scientific assumptions that guide the use and interpretation of such models may be influenced by powerful economic and political interests (chapters 8 and 9).
5. Criteria for scientific success in prediction may be different from criteria for policy success. For example, efforts to model global climate change have led to considerable increases in scientific insight over the past decade. During this time, however, global political controversy over appropriate responses to climate change has not eased and has probably increased. Progress in the science has therefore not translated into commensurate progress in the public realm (chapter 13). As well, scientifically reputable predictions that are not developed with the needs of policy makers in mind can in fact backfire and inflame political debate, as seen in the case of oil and gas resource appraisals (chapter 11).
6. Emphasis on predictive sciences moves both financial and intellectual resources away from other types of scientific activity that might

better help to guide decision making, such as monitoring, assessment, and small-scale policy experiments. Resource allocation for science can therefore influence policy options. If decision makers lack data about present environmental trends, or lack insight into the implications of different policy scenarios, they are less likely to use adaptive approaches to environmental problems, and more likely to wait for a predictive "prescription" (Lee 1993; Brunner and Ascher 1992; chapter 14, this volume).

These concerns 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 time frame within which predictions are sought (e.g., tomorrow's weather vs. the next century's climate conditions), the intrinsic scientific complexity of the phenomena being predicted, the political and economic context of the problem, the compatibility of scientific and political goals, and the availability of alternative scientific and political approaches to the problem. If policy makers wish to design environmental research policies that are fiscally responsible, scientifically efficient, and socially beneficial, they will need to evaluate environmental phenomena and problems in the context of these and related variables. Such an evaluation process must begin with a clear picture of the prediction process itself. The ten case histories that constitute the heart of this volume are intended to paint this picture in all its richness, diversity, and complexity.

Conclusion

Scientific prediction is commonly portrayed as a necessary precursor to—and a desirable determinant of—action on environmental policy. In such portrayals, scientific prediction is a source of objective information that can cut through political controversy and help define a path for "rational" action. Because policy making is itself a forward-looking process, this view of prediction may seem plausible. In practice, however, there have been few systematic evaluations of the performance of prediction in the policy realm.

Short-term predictions, especially those associated with discrete, extreme weather events such as floods and hurricanes, have often proven useful in supporting emergency management strategies. Attempts to provide longer predictive lead-times for discrete events such as earthquakes have generally been unsuccessful, although they have heightened public awareness. Efforts to predict events or phenomena with complex, diffuse, and regional impacts, such as acid rain, energy supply and consumption, the behavior of radioactive waste in a geological repository, and global climate change, have rarely contributed to the resolution of policy debates and have often contributed to political gridlock. This experience in part reflects the intrinsic scientific challenge of prediction, but it also derives from the complex scientific and policy context within which the predictive research takes place.

The idea that research programs focused on prediction will catalyze political action requires an extrapolation of the concept of scientific prediction itself, from its traditional significance as a test of fundamental and reductionist laws of nature, to a newer role as a technique that seeks to extract policy-relevant predictive certainty from research on complex processes. Given the difficulties of achieving such relevant certainty, the role of scientific prediction in policy making is itself highly uncertain. A better understanding of prediction in science and policy can help define a more realistic and positive role for science in society and a clearer path toward resolution of the many environmental challenges that face humanity.

Notes

1. We include solid-earth, ocean, and atmospheric sciences under the term *integrative earth sciences*.

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2

Why Predict? Historical Perspectives on Prediction in Earth Science

Naomi Oreskes

Underlying the ten case studies presented in this book is an implicit assumption that scientists have to make predictions. Do they? Before we rush headlong into the scientific, social, and political agenda of scientifically based prediction in aid of public policy, we might ask the question, why predict?

Many people think that it is inherent in the nature of science to make predictions, because prediction is integral to an ideal of scientific method based on testing theories by their consequences. But this kind of prediction—logical prediction—is distinct from the temporal prediction that forms the primary subject of the case studies presented here. Predicting the future—earthquakes, floods, asteroid impacts, climate change—has not traditionally been a major part of the work of earth scientists. On the contrary, for the better part of at least two centuries, most earth scientists eschewed temporal prediction, viewing it as beyond the scope of their science. Times have changed, and earth scientists now routinely attempt to predict the future. But, as the case studies in this volume poignantly demonstrate, these attempts rarely achieve their scientific or societal goals. Why are we making temporal predictions if they are not generally successful? Why have earth scientists now embraced temporal prediction as a goal, when previously they avoided it? Knowing the answers to these questions may affect the way we present our science in the public policy area, and perhaps even the way we do it in the laboratory.

Even logical prediction has come to preeminence in our understanding of science only relatively recently. In the twentieth century, it became conventional wisdom that science works by testing theories through their logical predictions, and therefore that the goal of science *is* to test theories by comparing their predictions to observations. This