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Prediction in science and policy

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Abstract

Prediction in traditional, reductionist natural science serves the role of validating hypotheses about invariant natural phenomena. In recent years, a new type of prediction has arisen in science, motivated in part by the needs of policy makers and the availability of new technologies. This new predictive science seeks to foretell the behavior of complex environmental phenomena such as climate change, earthquakes, and extreme weather events. Significant intellectual and financial resources are now devoted to such efforts, in the expectation that predictions will guide policy making. These expectations, however, derive in part from confusion about the different roles of prediction in science and society. Policy makers lack a framework for assessing when and if prediction can help achieve policy goals. This article is a first step towards developing such a framework. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction to a policy problem

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 a large part by the expectation that

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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, perhaps because the relation between prediction and policy has not been viewed as problematical by scientists or decision makers. A need for greater understanding, however, derives from both the scientific challenge of developing useful predictions of complex natural phenomena, and the policy challenge of translating progress in science into effective societal action. New insight into the relationship between prediction and policy may be necessary to ensure effective allocation of finite intellectual and financial resources, and to enhance the achievement of policy goals.

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 authoritativeness and legitimacy. Scientific hypotheses are tested by comparing what is expected to occur and what actually occurs. When expectations coincide with events, it lends support to the power of scientific understanding to explain how things work.

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.[1] Dewey observed that the “very essence of civilized culture is that we… deliberately institute, in advance of the happening of various contingencies and emergencies of life, devices for detecting their approach…” [1]. Indeed, 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” [2].

Confusion about these two motives for why we predict—validation of the success of scientific research, and guidance of our decisions—obscures the role and value of scientific prediction in society, and may prevent the appropriate allocation of intellectual and financial resources for the development of predictions. This confusion sets the stage for a policy problem: Policy makers lack knowledge that can help them to anticipate—to predict, if you will—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 [3,4].

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[1] Carl Mitcham (personal communication, 1998) points out that such predictions have fulfilled a larger, spiritual purpose as well—to demonstrate, and validate, our connection to a higher, transcendent power.

Here, 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 further policy analysis and action.

2. A taxonomy of scientific prediction

Prediction is central to the process of science—it is fundamental to the scientific method. Scientists test their ideas by comparing predictions based on theory to actual events in nature or the laboratory. This methodology permits the elucidation of invariant—and therefore predictive—principles of nature, such as Newton's laws or Maxwell's equations [5,6]. Prediction is thus a crucial means of testing and confirming hypotheses. This sort of prediction has countless societal applications. Most conspicuously, the predictability afforded by revealing invariant natural laws allows for ever more potent manipulation of the natural world through technological innovation.

In recent years, however, scientists have begun to pursue a different type of prediction. Instead of seeking to deduce fundamental laws of nature, they use suites of observational data and sophisticated numerical models in an effort to foretell the behavior or evolution of complex phenomena. These activities are made possible by rapid advances in computer and data acquisition technologies. Scientists and policy makers alike have come to view this second type of prediction as a powerful tool for helping to guide political decisions and resolve societal problems. These predictions of complex phenomena seek to ascribe time, place and characteristics to events. Such efforts are distinct from the development of more general scientific insights about the future (often referred to as analogies, scenarios, foresight activities, projections, or sensitivity analyses). Scientific insight tells us that floods are more likely to occur on flood plains than on hillsides; scientific predictions seek to tell us which flood plain, on what day, and to what extent.

The role of prediction in testing and advancing our scientific understanding of nature has been vindicated throughout the history of science, and is a foundation for the authoritative status of scientific knowledge in modern society [7]. The more recent role of prediction in science—to directly contribute to societal goals through the foretelling of the behavior of complex systems—has not been subjected to rigorous evaluation based on societal contributions, but is instead implicitly legitimated by the success of traditional predictive science.

2.1. *Reductionist natural science*

In the traditional physical sciences, the invariant, inherent characteristics of a physical phenomenon are sought by conducting experiments that study a phenomenon in isolation from its natural context. This approach allows the phenomenon to be precisely described in mathematical terms. Further experiment and observation can reinforce the validity of this mathematical description, and lead to its general acceptance by scientists and engineers who have not themselves conducted the actual experiments. Mathematical descriptions of the invariant behavior of a physical phenomenon—the period of a pendulum; the arc of a projectile; the deflection of an electron in a magnetic field or light in a gravitational field—are essentially predictive, because such behavior is *independent of time and place*. That is, given knowledge (or experimental control) of the mathematical parameters, the behavior will always be consistent—and thus predictable. The ability to predict the future date of a solar eclipse, for example, is a confirmation of the invariance of the gravitational "laws" that dictate the orbital path of the earth and the moon.

Prediction is therefore a tool for testing the validity of a theory. For example, currently accepted theories of how the universe was formed require the existence of "dark matter"—mass in the universe that has not yet been observed, but which must exist if the theories are correct. Cosmological theory "predicts" the existence of dark matter. But confirmation or refutation of the theory awaits experimental or observational evidence that either supports or conflicts with the theory's predictions. (Indeed, highly publicized recent experiments indicating that neutrinos have mass may partly bear out the prediction of dark matter [8].)

But prediction is also implicit in the practical applications of science: electronic engineers take for granted that electrons will behave in consistent ways that are describable by equations. This consistency allows them to manipulate the behavior of electrons in order to achieve practical goals, from designing light bulbs to building supercomputers. Aerospace engineers are similarly able to predict the orbits of satellites that they launch. Bunge points out that such activities, which he calls technological forecasts, are in fact used to control, rather than predict, the future [9].

Prediction is increasingly important in the life sciences, as well. The rise of molecular biology has been enabled by technologies that allow a reductionist approach to studying life and life forms. "Designer animals" can be genetically engineered to test the function of specific genes. The Human Genome Project identifies connections between specific genes and the propensity for contracting various diseases, which may allow doctors to predict their onset.

The essential characteristic of prediction in traditional science is reductionism: the effort to break nature down into describable component parts or processes with an ultimate objective of specifying the "laws of nature." In this effort, prediction pertains to the invariant behavior of individual parts, not to the processes of interaction among natural systems that contain those parts [10]. Thus, for example, progress in physics is often measured by increasing success in identifying and describing increasingly fundamental components of matter [11]. In this sense, the word "prediction" as used in the reductionist natural sciences is simply a synonym for "explanation" or "inference" [12].

2.2. *Integrative earth sciences*

Those disciplines of the natural sciences that seek to understand complex systems—integrative earth sciences[2]—have not traditionally been involved with predic-

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[2] We include solid earth, ocean, and atmospheric sciences under the term "integrative earth sciences."

tion (although weather prediction is 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 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 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 [13]." 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 increasingly 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 increasingly 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 these components, to yield a quantitative predictive model;
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, are predominantly approached through mathematical modeling.

Prediction of episodic, temporally discrete events, such as earthquakes and seasonal hurricane activity, often focus on the identification of precursors. 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. For 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 et al., 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 [14].

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 [15,16]. That such arguments occupy an important role in policy making is well illustrated by the examples of global warming and natural disaster preparedness.

2.2.1. Global warming

In the summer of 1988, amid heat waves and drought, a prominent scientist testified before Congress that "global warming is here" [17]. The spectacle of a hellish future climate captured the attention of the media and policy makers. One result was the initiation by Congress of the US Global Change Research Program, with an overarching objective to predict future climate change to "establish the scientific basis for national and international policymaking related to natural and human-induced changes in the global earth system" [18]. Through 1998, more than $13 billion (current dollars) has been appropriated by Congress to the Program, making it among the largest science initiatives ever undertaken. The Program's research contributes to an ambitious international assessment process, which seeks to predict future global climate as input to international negotiations on climate change. The predictions themselves have become embroiled in political controversy [19,20].

2.2.2. Natural disasters

For many years, a primary response to the prospect of extreme weather events has been to try to predict their onset. Scientists have forecast floods, hurricanes, and even seasonal precipitation patterns with improving success, and these predictions have been frequently used to save lives and reduce damages [21]. While there remain considerable difficulties associated with the effective use of such forecasts [22], recent years have seen the development of more ambitious predictive goals. The Federal Emergency Management Agency (FEMA) is leading an effort to develop a suite of computer models and data sets aimed at allowing communities to predict the magnitude and consequences of future disasters, model their level of preparation, and enhance response and recovery. The project, called HAZUS (HAZards United States), is planned to cover earthquakes, floods, and wind hazards. A private sector catastrophe modeling industry has developed since Hurricanes Hugo (1989) and Andrew (1992) that seeks to predict future and real-time losses for clients, primarily in the insurance industries. To date, little public information is available on the performance of the FEMA or private-sector modeling efforts.

2.3. Social sciences

As predictions have become central to the notion of what is scientific, so have predictions 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 [23], an emulation that has often been called “physics envy.” (Even some in the humanities have sought to develop “scientific” methodologies characterized by predictive skill [24].) 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 [25], whereas another Nobel Prize winner, Herbert Simon, suggests that this power is elusive even for some of our most well-accepted social science theories [26]. 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 [27].

Economics has been viewed by many as the “imperial” social science which “will always remain valid for analyzing and *predicting* the course of human behavior and social organization” [28]. Part of its stature is due to the “resemblance” between the quantitative emphasis and methodologies of economics and physics [29]. Sociology, on the other hand, was modeled on the biological sciences. I.B. Cohen 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 [30].

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” [31,32]. In political science, a large literature exists on developing various theories of political activity based on the “rational actor” theory of economic behavior [33]. For instance, a classic text in political science is Anthony Downs’ *An Economic Theory of Democracy* [34]. More recently, scholars have used economic methods in pursuit of a predictive model of presidential elections [35]. 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” [36]. Cohen 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 that:

> 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” [37].

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 on human behavior which—aside from its intrinsic value—will in turn 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, consider the examples of global warming and natural hazards discussed in the previous section. 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. In the case of catastrophe models, prediction of future damage depends in part on how and where people build, which are functions of broader social and policy processes.

To summarize, prediction has always 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 computer storage and processing capabilities, researchers and policy makers alike have looked to science as a source of predictions about the evolution of complex 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.

3. 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 as a means to advance policy. The demonstrated success of prediction in traditional reductionist science creates enhanced legitimacy and demand for the much newer and less proven predictive activities of the integrated earth sciences. Thus, the value of scientific predictions becomes increasingly viewed not just in terms of scientific understanding, but 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, because the very process of scientific research aimed at prediction can be portrayed as a positive step in the policy making process. 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, in a period of constrained federal research funding, 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 such prospects 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 [38] has been eroded by several decades of scientific failure [39].
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 may be achieved through effective planning that does not depend on better predictive information [40].
3. Necessary and/or feasible political action may be deferred in anticipation of predictive information that may not be forthcoming in a useful timeframe; similarly, such action may be delayed when scientific uncertainties associated with predictions become politically charged. In the case of global climate change, significant reductions in greenhouse gas emissions are technologically and perhaps politically feasible in the present, but necessary action has been held hostage to a scientific debate about the predicted impacts of such emissions [41].
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 non-experts, and because the models are often applied in a climate of political controversy and/or high economic stakes [42]. For example, in such cases as mining on federally owned land, and replenishment of sand on public beaches, mathematical models are used to predict environmental impacts. The scientific assumptions that guide the use and interpretation of such models may be influenced by powerful economic and political interests [43,44].
5. 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 scenario-building. 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” [45,46].
6. 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 progress in the public realm.

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 decade’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 role played by prediction itself. Here, we have tried to take a first step towards creating such clarity.

4. Conclusion

Scientific prediction is commonly portrayed as a necessary precursor to—and a desirable determinant of—action on environmental policy. In this portrayal, 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 obvious. 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 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. 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 an ongoing test of fundamental and reductionist laws of nature, to a newer role as a technique that extracts 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. We believe that a better understanding of prediction in science and policy can help define a more realistic and positive role for science in the policy realm. Ultimately, such understanding can actually broaden the options open to policy makers for applying new scientific knowledge to the resolution of environmental problems.

References

[1] Dewey J. How we think. Buffalo, NY: Prometheus Books, 1910:16.
[2] Lasswell HD, Kaplan A. Power and society: a framework for political inquiry. New Haven: Yale University Press, 1950:xv–xvi.

[3] Rayner S, Malone EL, editors. Human choice and climate change. Columbus, Ohio: Battelle Press, 1998.
[4] Sherden WA. The fortune sellers: the big business of buying and selling predictions. New York: John Wiley and Sons, 1998.
[5] Hempel CG. Philosophy of natural science. Englewood Cliffs, NJ: Prentice-Hall, 1966.
[6] Popper KR. The logic of scientific discovery. New York: Basic Books, 1959.
[7] Rorty R. Objectivity, relativism, and truth: philosophical papers, vol. I. Cambridge, UK: Cambridge University Press, 1991.
[8] Browne M. Mass found in elusive particle; universe may never be the same. New York Times 5 June 1991:A1.
[9] Bunge M. Toward a philosophy of technology. In: Mitcham C, Mackey R, editors. Philosophy and technology; readings in the philosophical problems of technology. New York: Free Press, 1972:62–76.
[10] Waldrop MM. Complexity: The emerging science at the edge of order and chaos. New York, NY: Simon and Schuster, 1992.
[11] Weinberg S. The answer to almost everything. New York Times 8 March 1993:A17.
[12] Toulmin S. Foresight and understanding. New York: Harper and Row, 1961:35.
[13] Baker V. The geological approach to understanding the environment. GSA Today 1996;6(3):41.
[14] Oreskes N, Shrader-Frechette K, Belitz K. Verification, validation, and confirmation of numerical models in the earth sciences. Science 1994;263:641–6.
[15] Mahlman JD. Testimony before the committee on science, space, and technology, US House of Representatives, on priorities in global climate change research. Washington, DC: U.S. Government Printing Office, 1992:26–36.
[16] Wyss M. Cannot earthquake be predicted? Science 1997;278:487.
[17] Shabecoff P. Global warming has begun, expert tells Senate. New York Times 24 June 1988:A1.
[18] US Global Change Research Program (USGCRP) Committee on Earth and Environmental Sciences (CEES). Our changing planet: a US strategy for global change research. Washington, DC: OSTP, 1989:9.
[19] Brunner RD. Policy and global change research: a modest proposal. Climatic Change 1996;32:121–47.
[20] Edwards P. Global comprehensive models in politics and policymaking. Climatic Change 1996;32:149–61.
[21] Katz R, Murphy AH, editors. Economic value of weather and climate forecasts. Cambridge, UK: Cambridge University Press, 1997.
[22] Pielke RA Jr. Who decides? forecast and responsibilities in the 1997 Red River flood. Applied Behavioral Science Review, in press.
[23] Ross D. The origins of American social science. Cambridge, UK: Cambridge University Press, 1991.
[24] Fogel RW, Elton GR. Which road to the past?: two views of history. New Haven, CT: Yale University Press, 1983.
[25] Friedman M. Essays in positive economics. Chicago, IL: University of Chicago Press, 1953.
[26] Simon HA. Reason in human affairs. Stanford, CA: Stanford University Press, 1982.
[27] Ascher W. Forecasting: an appraisal for policy-makers and planners. Baltimore: The Johns Hopkins University Press, 1979.
[28] Hirshleifer J. The expanding domain of economics. American Economic Review 1985;75:54. Emphasis in original.
[29] Heilbroner R. Economics as universal science. Social Research 1991;58(2):457–74.
[30] Cohen IB. Interactions: some contacts between the natural sciences and the social sciences. Cambridge, MA: The MIT Press, 1994:6.
[31] Simon HA. Human nature in politics: the dialogue of psychology with political science. American Political Science Review 1985;79:293–304.
[32] Dahl RA. The behavioral approach in political science: epitaph for a monument to a successful protest. American Political Science Review 1961;55:763–72.
[33] Petracca MP. The rational choice approach to politics: a challenge to democratic theory. The Review of Politics 1991;53:289–320.

[34] Downs A. An economic theory of democracy. New York, NY: Harper 1957.

[35] Lewis-Beck MS, Rice TW. Forecasting elections. Washington, DC: Congressional Quarterly Press, 1992.

[36] Brady D. Review Essay: The causes and consequences of divided government: Toward a new theory of American politics? American Political Science Review 1993;87(1):194.

[37] Cohen IB. Interactions: some contacts between the natural sciences and the social sciences. Cambridge, MA: The MIT Press, 1994:4.

[38] Press F. Earthquake prediction. Scientific American 1975;232:14–23.

[39] Geller RJ, Jackson DD, Kagan YY, Mulargia F. Earthquakes cannot be predicted. Science 1997;275:1616–7.

[40] Pielke RA. Meeting the promise of flood forecasting. Natural Hazards Observer 1997;22(1):8–9.

[41] Brunner RD. Global climate change: defining the policy problem. Policy Sciences 1991;24:291–311.

[42] Rushefsky ME. The misuse of science in governmental decision making. Science, Technology, and Human Values 1984;9(3):47–59.

[43] Moran RE, Mernitz S. Acid mine drainage and political conflicts in the third-party EIS. In: Hotchkiss WR editor. Water Resources at Risk (American Institute of Hydrology). 1995:36–39.

[44] Pilkey, OH, Dixon KL. The corps and the shore. Washington, DC: Island Press, 1996.

[45] Lee, K. Compass and gyroscope: integrating science and politics for the environment. Washington, DC: Island Press, 1993.

[46] Brunner RD, Ascher W. Science and social accountability. Policy Sciences 1992;25:295–331.

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