Exploring the concept of climate surprises. A review of the literature on the concept of surprise and how it is related to climate change

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A Review of the Literature on the Concept of Surprise and How It Is Related to Climate Change

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CONTENTS

CONTENTS (Cont.)

FIGURES

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ABSTRACT

This report examines the concept of climate surprise and its implications for environmental policymaking. Although most integrated assessment models of climate change deal with average values of change, it is usually the extreme events or surprises that cause the most damage to human health and property. Current models do not help the policymaker decide how to deal with climate surprises. This report examines the literature of surprise in many aspects of human society: psychology, military, health care, humor, agriculture, etc. It draws together various ways to consider the concept of surprise and examines different taxonomies of surprise that have been proposed. In many ways, surprise is revealed to be a subjective concept, triggered by such factors as prior experience, belief system, and level of education. How policymakers have reacted to specific instances of climate change or climate surprise in the past is considered, particularly with regard to the choices they made between proactive and reactive measures. Finally, the report discusses techniques used in the current generation of assessment models and makes suggestions as to how climate surprises might be included in future models. The report concludes that some kinds of surprises are simply unpredictable, but there are several types that could in some way be anticipated and assessed, and their negative effects forestalled.

SUMMARY

The general concept of surprise is a familiar one. We all know what it means to be confronted by something unexpected in our daily lives. We use the term in many aspects of our experience, to describe both natural and behavioral phenomena. But when it comes to defining what does or does not constitute a surprise, the concept is less clear. Who was surprised? When were they surprised? Why were they surprised? How surprised were they? These are difficult questions to answer. Knowing more about surprises, particularly those involving the natural environment, is critical, however, because the surprising events are usually the ones that cause the most grief and hardship. Of particular importance are global surprises, such as those related to climate, which have the potential to affect the health and well-being of billions of people. To be able to draw some climate surprises into the realm of the predictable and the anticipatable would mean being able to conduct more effective response planning and disaster mitigation.

A number of researchers, in a variety of disciplines, have attempted to come to grips with the concept of surprise. To provide a flavor of current thinking on the topic and a preview of the directions this study has taken, the following excerpts from the writings of these researchers are offered:

- "Surprises occur when causes turn out to be sharply different than were conceived, when behaviors are profoundly unexpected, and when action produces a result opposite to that intended — in short, when perceived reality departs qualitatively from expectation" (Holling 1986).

- "The degree of surprise is a function of the strength of expectations (i.e., how long they have been held), the signal value of the surprise event, and the salience of the hazard to the beholder" (Kasperson 1994).

- "Most of our current models and projections do not have the capability to deal with surprises and random events due, in large part, to the large number and heterogeneous nature of such surprises. It is usually assumed and hoped that, in the long-term, surprises and discontinuities will average themselves out" (Brooks 1986).

- "The heterogeneity of time and the complex physical relations between a system and its context necessarily involve the formation of surprises" (Timmerman 1986).

- "It is important to understand how long-term trends (determined through current models and projections and observations) predispose systems toward surprises and discontinuities or toward greatly amplified responses to small random events. Unfortunately, knowing that a system is becoming more predisposed to certain catastrophic events does not tell us when these events will occur" (Brooks 1986).

- "Our perceptions of what is surprising and what is to be expected are strongly conditioned by our necessary, but largely unexamined, myths about how the world is" (Timmerman 1986).

- "Surprise is an attempt to bridge (or perhaps paper over) the gap between some event or functional response of a system and the interpretation of that event or system by observers or managers" (Timmerman 1986).

- "Society's current management process is responsible for generating more surprises by systematically underestimating the potential for error and overestimating our understanding of the system. This process encourages the perpetuation of the status quo. This is management failure; we need to expand the uncertainty bounds" (Kasperson 1994).

- "A surprise is only a surprise if it is noticed by the holder of the beliefs that it contradicts" (Thompson 1986).

- "Surprises are sometimes searched for and manufactured" (Kasperson 1994).

- "The institutions of science (e.g., funding sources, peer review practices, hiring, promotion, and tenure decision-making) resist innovation, reward the conventional, resist and fail to reward interdisciplinary approaches, and resist surprises" (Saleska 1994).

- "Since surprise is inevitable, we should strive to make public policy that accounts for it" (Saleska 1994).

This report explores current thinking on the topic of surprise as it relates to climate change and provides guidance to members of the assessment modeling community on ways in which they may incorporate the notion of surprise into quantitative modeling frameworks. The report draws from a variety of types of literature on surprises, including psychological, meteorological, military, and humorous writing, as well as from decision theory.

1 INTRODUCTION

The most memorable events are frequently the most surprising ones; indeed, surprises may be the most influential events of any era (Kates and Clark 1996).

When talking about climate surprises, there are two distinct types that must be considered: the surprise associated with the occurrence of an event (type A) and the surprise associated with the impact of that event (type B). These broad categories can be further divided into knowable and unknowable aspects; and these, too, can be further subdivided. With each subdivision, we get deeper and deeper into the proverbial forest — that is, farther away from the concept of climate surprise (i.e., the forest) — while learning more and more about the specific taxonomic elements of surprise (i.e., the trees). It is our objective to look at some of the trees in the forest, as well as at the forest (the notion of surprise) itself.

If a bottom-line assessment had to be made immediately, we would be forced to conclude that most climate surprises are knowable at some level of awareness. Through scenario-playing and historical reenactments, many of the potential societal impacts of those surprises can also be identified. However, problems arise because we do not know the precise timing, location, intensity, or magnitude of the climate surprise (type A) itself. Surprises arise as well from the way people deal with information (with probabilities, with rare events, with history, with their understanding of the climate system, and so on). With regard to type B surprises, the societal impacts of surprise, perceptions of reality play a dominant role in determining what is viewed as a surprising event and/or impact, as well as who is surprised by the occurrence of the event and/or its impacts.

In discussing the issue of surprises in the context of the current debate over global warming of the atmosphere and its potential environmental and societal impacts, Robert M. White, former president of the National Academy of Engineering and the first administrator of the National Oceanic and Atmospheric Administration (NOAA), suggested that "surprise was the last resort of scoundrels." By this, he was referring to the raising of the possibility by some people that there would be horrendous surprises if the climate were to change. In other words, if all rational arguments fail to convince others that there is a real problem, invoke the specter of "nasty surprises."

There is value to discussing surprise in the context of climate change. Surprise has been discussed in many other contexts, including the military, sports, medical, environmental, and political. It is appropriate to transfer experience gained in these disciplines to the notion of surprises in climate change. The following is an attempt to review the literature on the concept of "surprise," in an attempt to shed light on its utility for developing a better understanding of the climate-change issue.

A climate surprise can be broadly defined as a gap between one's expectations about climate and what actually happens. Perhaps one of the easiest things to do when addressing climate surprises is to provide examples of (i.e., speculation about) unexpected physical changes in the climate system. In fact, climate-related, record-setting events are occurring somewhere in some part of the climate system every year. They occur everywhere and more frequently than we might think. Climate is nonstationary; the variables that make up the climate of a locality, as well as of the entire globe, are continually changing.

Each locale on the globe has its own climate-related hazards to cope with: floods, droughts, high winds, fires, tornadoes, hurricanes, tidal waves, blizzards, ice storms, hail, frosts, and so on. While those who live in a particular locale may be aware in a general way of their local hazards, they do not necessarily know when they will occur or what their intensities will be. As a result, people are often surprised to some degree when the potential hazards become a reality. The zone in which hazards occur can also shift slightly and, as a result, create new surprises for adjacent, previously unaffected, regions.

It is difficult to understand why we are so often surprised, even in situations that one would think should not be surprising. In a sense, there are expectable surprises (what Myers [1995] calls "anticipatable" surprises), as well as unexpectable ones. For example, people who live in an area that is susceptible to flooding know it. If someone were to tell them that flooding is possible, they would acknowledge that as a fact. What they do not know, however, is when that flooding will take place or how bad it is likely to be. When it happens, many people are surprised. The same is true for volcanic eruptions and tidal storm surges. These are knowable and, therefore, expectable occurrences, but their intensity and timing are likely to be surprising.

There are other kinds of surprises as well, the kind that we often think of — the kind that is unexpectable in every sense. The sudden awareness in the mid-1980s of the drastic thinning of the ozone layer in the stratosphere is a good example of an unexpectable surprise. We just didn't know that such a thing was possible. As Myers (1995, p. 358) notes,

> *[i]t might seem fruitless to speculate about seemingly unknown problems in the environmental field. But recall that at the time of the first major international conference on the environment in Stockholm in 1972, there was next to no mention of what have now become established as front-rank problems: global warming, acid rain, and tropical deforestation.*

Other potential surprises related to climate change, with varying degrees of probability, have also been suggested: the breakup of the West Antarctic ice sheet, a switch in ocean currents around the globe, counterintuitive climate anomalies like untimely freezes in Florida, rapid changes in sea level, summerless years (e.g., 1816), flash flooding, and so forth. Surprise can also come from the unexpected timing of an event or sequence of events or from a change in the location of an event, in its magnitude, or in its duration, as well as in the location and/or magnitude of its impacts. Paleoclimatologist Overpeck (1996, p. 1826) gave us something to consider when he suggested that "a major challenge will be to anticipate future climate surprises of the type recorded in the paleoclimatic record of the last 10,000 years."

There has been considerable speculation about climate surprises and climate-related surprises that could occur, if the global climate were to become warmer in the next several decades. Those surprises could be associated with actual events or speculation by people trying to conjure up just about every type of climate anomaly one could imagine. An example of the latter is the "runaway" greenhouse effect, discussed below.

The earth has a certain temperature attributed to the existence of the greenhouse effect. This warmth has been conducive to the emergence of life on earth. In discussion of the consequences of the burning of fossil fuels and the emission of greenhouse gases, there has been an occasional mention of the possibility of a "runaway" greenhouse effect; that is, once a certain (unknown) threshold level of greenhouse gases in the atmosphere has been crossed, there may be no way to stop the heating up of the atmosphere.

With the warming of the earth's atmosphere attributed to an enhanced greenhouse effect induced by human activity, images of the planet Venus have been generated as the end result of an uncontrolled warming process. Venus has extremely high surface temperatures caused by the greenhouse effect. If Venus-like conditions were to develop on earth, all life would cease. Overpeck (1996, p. 1820) reminds us that "the paleoclimatic record leaves little doubt that warm interglacial climates are, even in the absence of any human forcing, capable of generating significant decade- to century-scale climatic surprises."

There is a growing number of people interested in climate and climate-related surprises. Many in positions of authority are interested in the possibility of surprise, because no one wants to be blindsided by it. Without insights into surprise (causes, effects, responses), policymakers would remain unprepared for preventing, mitigating, or adapting to the ramifications of climate surprises. The military, the business community, the energy sector, economic development planners, insurance companies, individuals, and societies in general are all concerned in one way or another with surprise. In fact, this is one of the major reasons why governments throughout the world support weather and climate modelers and forecasters to try to predict the behavior of the atmosphere on various time scales — just as they employ economists to make projections about future states of the economy and military forecasters to foresee national security threats.

There are several reasons why it is necessary for societies to improve their understanding of surprise. For example, Canadian ecologist Holling (1986) argues that the notion of surprise can be useful for increasing individual, sector, and societal sensitivity to climate and climate-related surprise; surprise provides a focus for discussing the interaction between ecosystems and society.

Reporting on ecological surprises, Holling (1986, p. 293) notes that "to relate our understanding of the behavior of local ecosystems to the ways societies perceive and manage those systems, the concept of surprise is needed."

Overpeck (1996, p. 1820) argues that, although most research on abrupt change should not be ruled out during the current interglacial,

> *[i]t is now clear that climate variability in many regions of the world, including Greenland, was significantly greater during the last 150 years .... More importantly, many of these past Holocene events appear to have been large enough that, if they were to recur in the future, they would have major impact on humans.*

2 WHAT IS SURPRISE?

Senator Bill Bradley once asked a panel of atmospheric scientists at a hearing on issues of global climate change, "Just what kind of surprises did you have in mind?" (Schneider and Turner, 1994). Regardless of the specific definition one chooses to use, the notion of surprise has an obvious central element, as suggested in the following phrases used in the comprehensive Oxford English Dictionary to define surprise: "an act of assailing or attacking unexpectedly or without warning"; "anything unexpected or astonishing"; "the feeling or emotion excited by something unexpected or for which one is unprepared"; "unexpected occurrence." Clearly, there is an element common to just about all definitions of surprise: the unexpected. This notion is at the root of any typology of surprise.

Holling (1986) defines surprise in the following way: "Surprises occur when causes turn out to be sharply different than was conceived, when behaviors are profoundly unexpected, and when action produces a result opposite to that intended" (p. 294). As Holling also notes, surprise concerns both natural systems and the people who seek to understand the world around them. Surprises can occur in ecosystems, economics, technology, institutions, psychology, and climate.

Brooks (1986) writes about surprises "in relation to the interaction between technology, human institutions and social systems" (p. 326). He clusters types of surprise into three subgroups: (1) unexpected discrete events, (2) discontinuity in long-term trends, and (3) the sudden emergence into political consciousness of new information (p. 326). Unexpected discrete events include such occurrences as major natural catastrophes, political revolutions, and nuclear accidents. Discontinuities in long-term trends include the "stagflation" phenomenon in OECD countries in the 1970s. The sudden emergence into political consciousness of new information includes the relationship between CFCs and stratospheric ozone depletion and the impact of air pollution on central European forests (p. 326).

It may come as a surprise to scientists to learn that research on humor can provide insights into surprise. This is because humor relies on the notion of "expectation." For example, "the more dissimilar the stimuli from the class typical quality, the more surprising the effect" (Giora 1991, p. 475). In terms of surprise, the "informative messages are too distant from the messages preceding them" (i.e., they are out of the realm of expectations). With regard to a joke, there is no surprise when "the distance between the first and the last constituents is filled in by the gradually more informative messages" (Giora 1991, p. 475). The analysis of humor helps to illustrate the importance of subjective factors in surprise.

Holling (1986) also stresses the importance of expectations, stating that surprise occurs when perceived reality departs *qualitatively* from expectation (p. 294). An important implication of this is that experience shapes concepts and that incomplete concepts eventually produce surprise. In addition, "the longer [or the more firmly] one's view is held beyond its time, the greater the surprise and the resultant adjustment" (p. 294).

Definitions of surprise can be made very specific (i.e., tailored) to an event, a process, an activity, and so forth. Thus, what is surprising to corn growers may not be a surprise to cotton growers. Definitions can also differ from person to person; Thompson et al. (1990) note that "each surprise is relative to the convictions about the world that are held by the person who is surprised" (p. 74). The same can be said of the level of social organization at which there is surprise: individual, group, region, nation, or world.

In his essay, "Environmental Unknowns," Myers (1995) focuses on two potentially major sources of future surprise: discontinuities and synergisms. He states that "discontinuities occur when ecosystems absorb stresses over long periods without much outward sign of injury, then reach a disruption threshold at which the cumulative consequences finally reveal themselves in critical proportions" (p. 358). He observes that such discontinuities can also occur in the socioeconomic sphere. Synergisms are cases where "when one problem combines with another problem, the outcome may not be a double problem but a super-problem" (p. 360). These two potential sources of surprise could become increasingly important, Myers argues, because "as human communities continue to expand in numbers and demands, they will exert increasing pressure on ecosystems and natural resource stocks, whereupon environmental surprises will surely become more frequent" (p. 360).

According to Holling (1986), a surprise is the result of a conflict between the real world (i.e., objective reality) and the conceptions (e.g., expectations and images) that people have formed about that world. While conceptions do not necessarily reflect reality in an adequate way, actions taken based on those conceptions of reality will have real consequences. Thus, expectations must be taken seriously.

The view that surprise can result from the interaction between people's expectations about how reality should work and how reality does work was explored by Thompson et al. (1990) in their book, *Cultural Theory*. The authors present three axioms in their development of a theory of surprise (p. 70):

1. *An event is never surprising in itself.*

2. *An event is potentially surprising only in relation to a particular set of convictions about how the world is.*

3. *An event is actually surprising only if it is noticed by the holder of that particular set of convictions.*

Their assessment of surprise focuses on its subjective aspects. Expectations about future happenings are formed by one's experiences, gained indirectly as well as directly. Thus, the possibility of surprise can exist in just about any situation, because individuals do not often form similar perceptions about the same concrete event. What surprises one person or group may not surprise another person or group. Events, however, can be viewed as surprising from an objective standpoint. The importance of the subjective aspects of surprise is reflected in a question raised by Myers (1995). He argues that some of the unanticipated environmental problems that have occurred since 1972 could have been detected if we had thought to look for them. He then asks, "So does the difficulty lie with 'ignorance' or 'ignore-ance'?" (p. 358).

There have been several attempts in the past decade to create a typology of surprise: a typology for climate surprise, global change surprise, ecological surprise, technological surprise, military surprise, and so on. Even a quick review of the surprise-related literature shows that there are a lot of ways to identify and categorize surprise — by modeling, expert judgment, educated guesses, backcasting, and by raw, unbounded speculation. One could argue that speculation has dominated the literature with regard to identifying climate-change surprises.

One of the most recent attempts to bring some order to (i.e., create a typology for) environmental surprises, including those attributed to climate change, was undertaken by Kates and Clark (1996). Before that, there was the workshop of the Aspen Global Change Institute (henceforth referred to as Aspen) that focused directly on anticipating global change surprise (Schneider and Turner 1995). Thompson et al. (1990) set out to develop a culturally derived typology of surprise. In the mid-1980s, Clark and Munn (1986) edited and contributed to a volume in which several contributors addressed surprise issues. Holling, for example, wrote about ecological surprises; Brooks wrote about technological surprises. These are just some of the attempts by researchers to gain a glimpse of possible surprises that might eventually affect societies around the globe.

Yet another approach to identifying potential causes, effects, and responses to surprise is to rely on analogical reasoning. Holling notes that, "such analogies at the least suggest that a formal comparative study of different cases could help provide an empirical basis to classify the timing of key phases of societal responses to the unexpected; in detecting surprise, in understanding the source and cause of surprise, in communicating that understanding and in responding to surprise" (p. 313). A novel idea was raised by Thompson et al. (1990), who suggested that "we will have to collect our surprises (as if they were botanical specimens) and scrutinize them for their similarities and differences. This is what our typology does .... It not only tells us how many kinds of surprises there are and how they differ, it tells us how nice or nasty these various surprises might be" (pp. 72-73).

3 WHO IS SURPRISED?

Not everyone is surprised by unusual climate-related events or climate-related impacts. Kates and Clark (1996) point out that "few surprises ... are surprises to everyone" (p. 10). For example, policymakers and the public are frequently surprised by events that may not be surprising to the scientific community. The explosion of the space shuttle Challenger provides such an example. Although a group of NASA engineers had calculated that the probability of a failure in the solid rocket boosters (in part, due to cold ambient temperatures) was around 1 in 35, NASA administrators believed the likelihood was only 1 in 100,000 (NASA 1985). What is surprising for one person with the power to act on information (e.g., the O-ring failure) may not be surprising to the person who produced that information (i.e., the engineer). Thus, effective communication among different groups may provide one way to reduce the possibility of surprise.

Droughts in the American Great Plains provide another example. They have recurred in this region during the 1930s, 1950s, 1970s, and 1990s. While historians and atmospheric scientists are well aware of the likelihood of drought occurring somewhere in the region, many farmers whose experience extends back only a decade or two have not yet witnessed a drought on the order of magnitude of the 1930s. As a result of their lack of direct experience, many farmers in the region are surprised, to varying degrees, whenever their agricultural activities are adversely affected by drought (Saarinen 1966).

Thompson et al.'s (1990) second axiom of surprise states that an event is potentially surprising only in relation to a particular set of convictions about how the world is. Thus, who is likely to be surprised centers on a person's expectations about an event. Because people have different experiences and knowledge and, therefore, expectations, they can (and often do) respond differently to the same stimulus.

In his search for the essence of surprise, Casti (1994) offers a similar observation (p. 263):

> *We have seen two simple choice situations — societal preferences and sports drafts — in which the logical structure of the decision process can lead to unexpected collective outcomes when each individual tries to stay true to his or her own preferences. Thus, we conclude that a major source of surprise is simply our human inability to trace through the logical consequences of our assumptions.*

The Aspen Global Change Institute (AGCI) workshop in the mid-1990s produced a relatively comprehensive typology of global change surprise (Figure 1). The Aspen typology categorizes surprises according to "level of ignorance" and distinguishes them based on the characteristics of the ignorance responsible for each particular type of surprise.

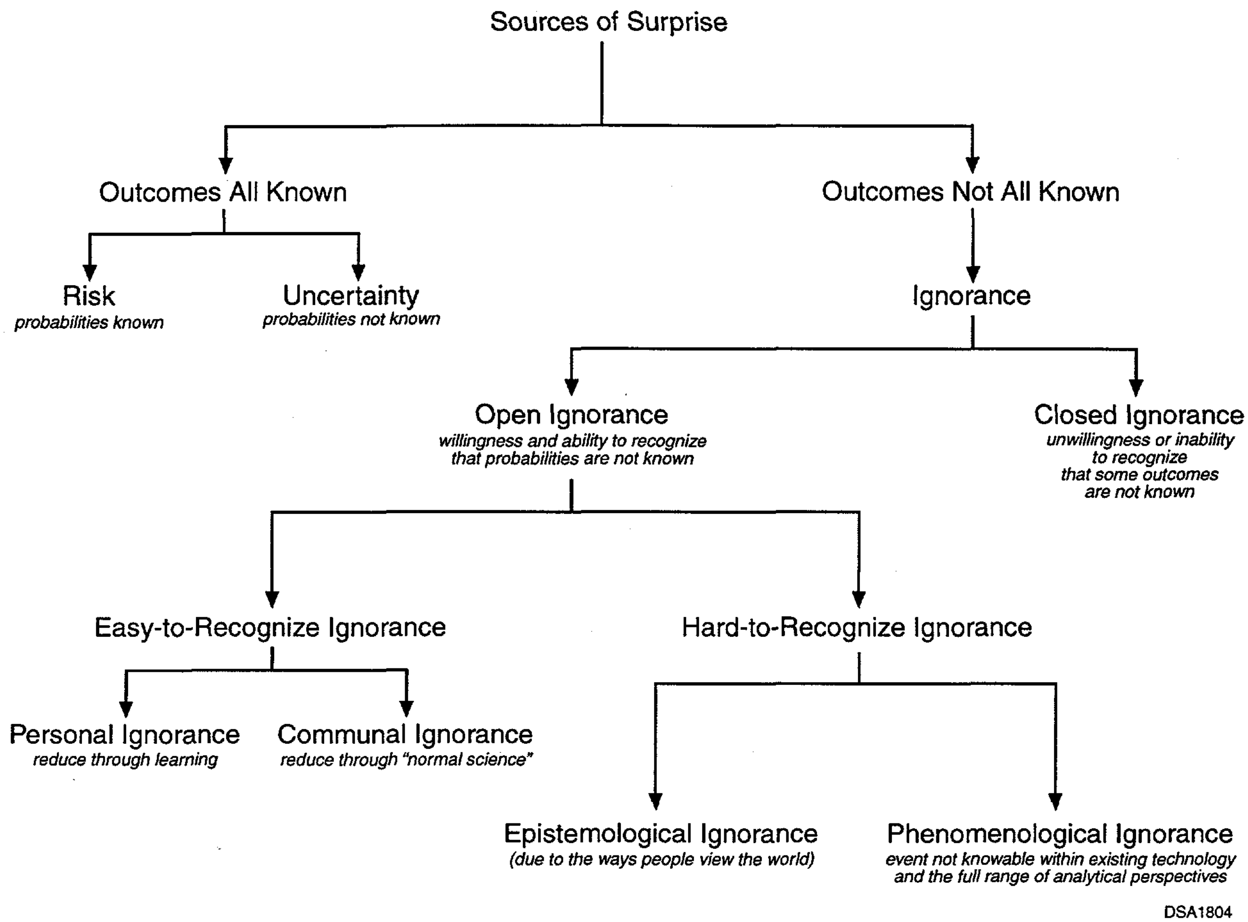

FIGURE 1 A Typological Map of Surprise (adapted from *Elements of Change 1994, Part 2*, S.J. Hassol and J. Katzenberger, Eds., Aspen Global Change Institute, 1995, with permission; after M. Faber, R. Manstetten, and J.L.R. Proops, "Humankind and the environment: an anatomy of surprise and ignorance," *Environmental Values*, 1(3):217-241 [1992])

The Aspen typology seeks to distinguish among (a) risk, (b) uncertainty, and (c) surprise. Risk and uncertainty arise when a type of event can be expected to occur somewhere and at some time, but the event is nevertheless surprising because it occurs at an unexpected time or place. This category consists of "knowable" (expectable) surprises, described by Aspen as "outcomes all known," and encompasses "risk" (i.e., probabilities are known) and "uncertainty" (i.e., probabilities are not known).

When not all outcomes are known, a more complex hierarchy exists, which includes human frailties regarding the recognition of remarkable outcomes. Some surprises arise from epistemological ignorance, in which human perspectives of the way the world operates are at odds with the actual system. The hierarchy culminates in phenomenological ignorance — the ultimate unforeseeable surprise — which is beyond the capability of human perspective and analytical technology to recognize.

Lee (1993) addresses these differences in his book, *Compass and Gyroscope.* He provides a story to make his point in a section appropriately entitled, "Avoidable Error and Genuine Surprise" (p. 65):

> *What does it mean to be prudent when there is uncertainty? First, recognize the possibility of surprise. Second, plan to act to detect and to correct avoidable error .... External events and consequences of action can be grouped into three broad classes. Consider a horse race. Some events are expected: some horses will finish ahead of others. Other events are the result of random or unpredictable processes: it is often unknown which horse will finish first. Still other events are surprises, unpredicted and unexpected: an earthquake could bring down the grandstand during the race .... Risk analysis examines ... the first two classes of events. But by definition, it is difficult to describe or to estimate the probability of the third class, surprises.*

In the early 1970s, there was considerable speculation and ensuing scientific and public concern that the earth might be moving into an Ice Age. Many people no longer remember, but for a few years then, speculation abounded. Much of the evidence cited by scientists and others was logical; for example, it had been 10,000-11,000 years since the end of the last Ice Age. This general knowledge was reinforced by specific physical changes and by circumstantial evidence as well: fish that had been caught for the last several decades off the northern coast of Iceland were found along the southern coast in the early 1970s; the growing season in England had been shortened by a couple of weeks; Arctic sea ice was found to the south of its normal limit in the midst of North Atlantic shipping lanes; and the 1940-70 period was cooler than the long-term average at that time. Science-based books, novels, and popular magazine articles appeared on bookshelves: *Fire and Ice*, *Weather Conspiracy*, *The Cooling*, etc. Even the U.S. Central Intelligence Agency produced reports on the potential impacts of a global cooling of the atmosphere on the agriculture and energy sectors of America's rival superpower, the Soviet Union.

It is difficult to determine what the level of surprise about the possible return to an Ice Age was among various groups in society (policymakers, scientists, the public). In retrospect, it appears that people seemed to have accepted at the time the global cooling hypothesis as a real possibility. It was plausible and perhaps not very surprising. Ice Ages were known to have occurred in the past, and we all learned about them in school. An Ice Age was a natural occurrence, one in which human activities were not implicated as a causal factor in the global cooling process (notwithstanding the view of some people that nuclear testing was affecting the global climate).

In the mid-1970s, the arguments (and evidence) shifted toward the possibility of global warming and away from global cooling. The belief that human activities could alter the global climate came as a surprise to many: The earth's atmosphere was robust — or so we thought — and it could handle anthropogenic insults through natural mechanisms (e.g., cloud feedback).

These days, people seem to be continually surprised by changes seen in the earth's system, although a growing number of people are coming to believe in the possibility of a human-induced global warming. In time, the general public will be less likely to be surprised when it hears suggestions that warming is already occurring or that it has already caused major environmental changes somewhere on the globe. Many people, nevertheless, would still be surprised if solid evidence were to be produced supporting those who believe that global warming is already under way. They would likely have trouble accepting the possibility that humans can alter the earth's life-support system.

But why should we (scientists and government agencies responsible for climate concerns) be surprised if fossil-fuel burning and tropical deforestation were to lead to global warming? Swedish chemist Arrhenius suggested such a possibility in the 1890s, as did Callendar in the mid-1930s and in the 1950s. At that time, however, and until the early 1970s, global warming was viewed as a positive occurrence that would avert the return of an Ice Age or as a neutral societal experiment, the outcome of which was unknown (Revelle and Suess 1957). And, as Kates and Clark (1996) suggest, "it is important to note that people tend to pay more attention to unanticipated events when the consequences are harmful" (p. 10).

Depending on one's world view of the interactions between human activities and natural processes, surprises may or may not appear. A pessimist is likely to hear about, if not be attracted to, worst-case scenarios of climate change. A pessimist would not only tend to believe that such scenarios were possible, but would also expect them to come about. Such thinking has produced books with such cataclysmic titles as *The Climate Bomb*, *Hothouse Earth*, and *Dead Heat*. An optimist, on the other hand, would likely expect that societies will be willing to halt their adverse environmental activities, if they learn that such activities are threatening the earth's life-support mechanisms. Optimists might also believe that yet-to-be-developed technologies would be able to arrest, if not reverse, such catastrophic environmental change. Unfortunately, a blind faith in technology tends to encourage a "business-as-usual" attitude, which makes people vulnerable to surprises when technologies are unable to cope effectively with the worst-case scenario.

This is related to the idea of Thompson et al. (1990) that the nature of an individual's beliefs affects the kinds of things that will be surprising to that individual. They developed a typology of surprise built around the notion of archetypal belief systems (Figure 2). Thompson et al. argue that, for example, if an individual stipulates that the world is capricious, he will not be surprised if the actual world appears to operate in a capricious way. If, however, the actual world is benign, then the individual who expects capriciousness will be surprised by "unexpected runs of good luck" (p. 71). In practice, however, "the world is never just one way; it is constantly changing." Thus, the holders of any kind of belief system will be periodically vulnerable to some sorts of surprise.

Stipulated World \ Actual World	Capricious	Ephemeral	Benign	Perverse/ Tolerant
Capricious (Fatalist's myth)		Expected windfalls don't happen	Unexpected runs of good luck	Unexpected runs of good and bad luck
Ephemeral (Egalitarian's myth)	Caution does not work		Others prosper	Others prosper
Benign (Individualist's myth)	Skill is not rewarded	Total collapse		Partial collapse
Perverse/ Tolerant (Hierarchist's myth)	Unpredict-ability	Total collapse	Competition	

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FIGURE 2 A Typology of Surprises (Source: M. Thompson, R. Ellis, and A. Wildavsky © 1990; reprinted by permission of WestviewPress)

Surprise should not be represented in black-and-white terms — all or nothing, zero or one — as it would be treated in a binary system. It is best described in terms of "fuzziness." The notion of fuzzy thinking can also be used to identify *who* is surprised and to what extent. As noted earlier, a person can be mildly surprised or greatly surprised. The degree of surprise depends on many factors (experience, core beliefs, expectations, knowledge about a region, etc.).

For example, the occurrence of the 1982-83 El Niño Southern Oscillation (ENSO) event in the equatorial Pacific Ocean is considered to have been a total surprise to the scientific community. In a binary system, that translates into a "zero" with regard to who knew in advance about the onset of the event, which became the biggest in a hundred years. That it was a surprise to an overwhelming number of ENSO researchers is a fact that no one can deny. Most researchers were surprised by the timing of its onset and its intensity, as well as by the widespread nature of its impacts, both ecological and societal. However, a close scrutiny of the research community uncovered the fact that a few Australian scientists suspected that an event was beginning before it was recognized to have begun in late 1982. Whom did they tell? Who listened to them? Who believed them? This situation is likely to be repeated for other climate-related changes that "someone" — often a "voice in the wilderness" — has observed. We must, however, keep in mind the possibility that someone somewhere may have expected such a change and was, therefore, not surprised by it when it happened.

4 DEGREES OF SURPRISE

At first, we might tend to think of surprise in black-and-white, all-or-nothing terms. One is either surprised or one is not surprised. However, a closer look at what people say about surprise reinforces the view that surprise is best represented by shades of gray. In an analysis of a surprise military attack, Kam (1984) suggests that one of the most important characteristics of a surprise is its degree. Degree can range from a slight surprise to a total surprise. The notion of surprise is an interesting one in that there are many different adjectives used to qualify it: highly surprising, true surprise, complete surprise, genuine surprise, total surprise, element of surprise, strategic or tactical surprise, and so on. And then there are such qualifiers as sufficiently surprised, somewhat surprised, very surprised. And what should one make of the notion of a "semi-surprise" (Myers 1995, p. 358)?

Just as surprise results from a conflict (more correctly, a step-like or abrupt disconnection) between the awareness of an actual event and one's expectations about it, the degree of surprise is a product of several factors. Kasperson (1994, p. 162) notes that "one hypothesis is that the degree of surprise is a function of the strength of expectations, the signal value of the event, and the salience of the hazard to the beholder; each of these variables is important to the strength of the response."

Kam goes on to provide a review of literature on military surprise attack. He explains Lanir's (1983) distinction between situational and fundamental surprise. "Situational surprise exposes errors in assumptions and predictions but does not undermine basic conceptual foundations." Fundamental surprise, on the other hand, exposes very basic conceptual flaws.

An analogous distinction exists in the climate-dependent energy sector. Tussing and Harris (1992) suggest (p. 69) that,

> *[i]n understanding why [energy] forecasters' performance records have been so bad, it is important to distinguish between the inability of analysts to foresee specific political surprises that disrupted existing market arrangements, and their lack of insight into the basic technical and economic processes that govern supply and demand for energy goods.*

Kasperson et al. (1988) expand on the notion of the signal value of risk in their book, *The Social Amplification of Risk.* The authors argue that the "signals" produced by an event include several different types of information. Each type of information has different implications: (1) the first type of information contained in a signal includes observable factual information, as in, "The global mean temperatures will rise 2.5 degrees Celsius by 2050"; (2) the second type of information is inferential, as in, "Climate change will cause the extinction of many species and the flooding of coastal areas"; (3) the third type of information is value-laden, as in "This climate shift will be catastrophic for the environment"; and (4) the final type of information contained in a signal is *symbolic*, as discussed below.

Victor and Salt (1995) assert that "among the [climate] symbols that drive politics are the fear of surprise and catastrophe." Symbols "evoke specific images (e.g., 'big business,' 'the military/industrial complex,' 'high technology,' etc.) that carry strong value implications" (Kasperson et al. 1988, p. 180). One could add other symbols to the list, such as "climate modification," "the climate crisis," and "the greenhouse conspiracy." Symbols for climate change are plentiful. They include political cartoons on global warming, photographs of smokestacks belching gases into the atmosphere, and such analogies as a "runaway" greenhouse effect. Tidal waves, floods, deserts, crops withering in the field, and famine victims are all images used to reinforce what the scientific community generally believes could be expected from a global warming of the atmosphere. Kasperson et al. (1988) write that "adding or deleting symbols may well be the most powerful single means to amplify or attenuate the original message" (p. 180).

Symbols resonate with other ideas in popular culture; they are likely to be perceived as valid, because of the scientific uncertainties that surround such technical issues as global warming. Much of the information conveyed to the public by the media is found in the visual images that appear in the electronic and printed media (e.g., recall the adage that "a picture is worth a thousand words"). For example, as a newscaster presents climate-change news, value judgments are inevitably formed (or reinforced) on the part of the audience when at the same time the public is shown pictures of floods ravaging a town or some other spectacular image of disaster. Victor and Salt (1995) suggest that "because symbols play such a prominent role [in the climate issue], it may turn out that agendas will be set by those countries — primarily the rich democracies — that can use symbols effectively."

Kasperson et al. (1988) observe that social amplification (or attenuation) of a particular event is affected by the amount of information, the disputing of information, dramatization, and symbolic connotations (p. 184). For example, a large volume of information will tend to amplify the perception of risk (or no risk) among the public, even if the large volume of information is from only one source and is repeated again and again. They argue that "it is much harder to unscare people than to scare them" (p. 184), meaning that it is easier to generate a perception among the public of the dangers of global warming than it would be to eliminate that perception later, if new information were to indicate that the threat had been overstated in the first place. It turns out that what surprises people is heavily dependent on their perceptions of reality, which are heavily influenced by the media.

Value judgments can also be conveyed through the tone of a commentator's voice, the placement of a story in relation to other stories, or by other tactical means. For an excellent example of the subtle, sometimes subliminal, influence of tone or word choice, see Martin (1979) in *The Bias of Science*. Martin compared the use of adjectives and tone in scientific articles by British and American scientists who held opposing views in the early 1970s on the potential impacts of a large fleet of high-flying supersonic transports (SSTs) on the chemistry of the stratosphere. The interesting fact is that, using the same basic scientific information, these two sets of scientists drew totally opposing pictures of and conclusions about the environmental impacts of a high-flying SST fleet. The American scientists concluded that severe damage to the stratospheric ozone shield would ensue, whereas the British researchers concluded that there would be no negative impact on the ozone layer. (Note that at that time the British and French had developed an SST [the Concorde], while the U.S. scientific community opposed the development of such a fleet for the United States.)

In fact, the attraction of the media to dramatic stories can also distort reality. For example, while writing about the media's coverage of oil spills, Mielke (1991) observed that "it takes time to investigate the long-term effects; results often are not available for a year or more. Press coverage of these later results generally is minimal and largely confined to the more scientific literature" (p. 7). Mielke also argued that "once the press portrays the possibility, or existence, of substantial damages, a subsequent withdrawal of such claims does not alter the perceptions of extensive damage held by a large portion of the population" (p. 8).

Dramatization plays an important role in the social amplification of a particular risk. Issues that provide for dramatic, attention-grabbing stories draw media attention, whereas issues considered to be less dramatic tend to be downplayed by the press. This amplification and attenuation of signals can be important in setting up the public to experience possible surprises that could be generated by global warming or other forms of environmental change. Disputes over the validity of scientific information tend to reinforce the pre-existing beliefs of individuals. If certain risks are feared by a population, then debates among experts tend to increase public anxiety about the likelihood of those risks (Kasperson et al. 1988). The innate reaction to anxiety in many individuals is to retreat to the safety of familiar beliefs. Disagreements among experts reinforce disagreements among interest groups. Such scientific disagreements make some people more susceptible to being surprised.

Another factor to consider in the amplification of risk is the "symbolic connotations" of a signal. These events can be especially important, insofar as they interact with the heuristics (e.g., simplifying mechanisms, including analogies) used by individuals to make sense of a complex world and of conflicting information. As with dramatization, this can distort the "objectivity" of assessments of uncertainty and risk, thereby setting up individuals and governments to be surprised.

An important factor that can affect the degree of surprise is the impact of preceding similar events on one's expectations about the occurrence of such events. Distress produced by contradictions between perceptions of reality and reality itself (i.e., cognitive dissonance) can be reduced by altering one's expectations so that an event "makes more sense" (i.e., the event meshes with what the individual expects) or by devaluing (i.e., "discounting") the importance of the event in order to hold on to one's original perceptions and expectations. In actuality, there is a strong tendency for individuals to hold on to their beliefs and expectations. If events have gone a certain way for some period of time, people are likely to expect them to continue to do so (i.e., things will persist). When events do not occur as expected (or occur when unexpected), reaction will depend on how much concern an individual has about the event or its impacts and how much contradiction (i.e., difference) there is between the event and one's expectations.

Kuhn (1990) explores how paradigm shifts occur in science only after repeated anomalies force individuals to question their core beliefs. Lakatos (1981) has explored how scientific communities are willing to "sacrifice" lightly held hypotheses in order to "protect" their core beliefs and methodologies. As Thompson et al. (1990) later note, "a persistent pattern of surprises forces individuals to cast around for alternative ways of life (or theories) that can provide a more satisfying fit with the world as it is" (p. 69).

An example of such a paradigm shift is the discovery of the human-induced thinning of the stratospheric ozone layer, especially over the Antarctic in 1984 (Farman 1985, p. 207). According to British researcher Joseph Farman, outlier measurements of stratospheric ozone, which indicated dramatic ozone depletion in the early spring in the Southern Hemisphere, had been rejected by computer analogues, which interpreted those measurements (i.e., observations) as the result of instrument error. The repeated appearance of these "outlying" data, however, raised the concern of Farman, who called for a reevaluation of all the data. This reevaluation of the outlying data and discovery of the ozone hole led to a broadening of research in atmospheric chemistry and the potential environmental impact of chlorofluorocarbons (CFCs) on stratospheric ozone concentrations during the Antarctic spring time (and later on Arctic ozone levels, as well). This is an example of an unexpectable surprise.

As another example, farmers often regard the occurrence of a specific drought episode as an aberration when measured against their perception of what constitutes normal rainfall in their locale. Such perceptions (or, more correctly, misperceptions) can result for a variety of reasons. A leading reason may be that they never experienced (personally) a major drought. Another reason could be a belief that new technologies would enable them to cope better with drought. Yet another reason for misperception results from discounting past droughts (e.g., "We've already had our one-in-a-hundred-year drought"). In fact, this was one of the factors that prompted farmers in the American Great Plains, following several years of good rains and high grain prices, to remove large sections of the tree belts that had been put in place during the Dust Bowl years of the 1930s. This left cultivated fields vulnerable to hot dry winds and the resulting loss of topsoil due to wind erosion, when runs of dry years returned in the 1950s and again in the 1970s. Despite the apparent surprise of farmers in the Midwest, the region's rainfall record clearly shows that drought is an expectable feature of the region's climate.

There is a tendency to discount the significance of information that tends to contradict strongly held convictions. There are at least two ways in which individuals can reduce cognitive dissonance between their beliefs and reality: (1) they can alter their expectations to encompass the new event; or (2) they can either interpret or ignore the event in such a way as to protect entrenched beliefs. One could argue that the latter occurs more often than the former, and is in itself a frequent source of surprise. For example, White, in *Nobody Wanted War* (1970), wrote about "selective inattention." This is a situation in which people discard incoming information that does not conform to their pre-existing opinions. In essence, the value of such conflicting information is discounted to zero.

5 GOOD OR BAD SURPRISES?

Predominant interest in climate surprises has centered on surprises that would have adverse societal and environmental impacts. Little consideration has been given to the possibility of surprises with favorable outcomes. Yet, surprises can have beneficial consequences ("pleasant surprises") as well as adverse ones ("nasty surprises"). It is also possible to have a climate surprise with mixed consequences. One can conceive of surprises that would be initially and predominantly destructive, but yield positive consequences in the long term or positive secondary effects in the near term. For example, Hurricane Andrew devastated southern Florida in 1992; however, the need for the reconstruction of local communities sparked a regional economic boom. The same could be said of the 1994 earthquake in Northridge, California. It is necessary to consider the impacts of climate-related surprises on all stakeholders. This suggests the general need to consider the level at which society is surprised: the individual, group, subnational region, nation, international region, and the globe.

Nevertheless, there remains a strong bias among researchers and government agencies toward considering the destructive effects of surprises. A focus on adverse surprises should not in itself be surprising. For example, one could argue that surprises with adverse consequences tend to be more important in their policy implications. Victor (1994) observed that "fears and evidence of surprises are key elements of climate politics because they can provide both a window for political actions by focusing on the costs of unchecked global warming and thus help marshal support in favor of costly anti-greenhouse actions."

While it is easier for political decisionmakers to lay claim directly or indirectly to successes, they are often more concerned about minimizing damage in times of adversity. Attributed to President Kennedy is the view that "success has many fathers but failure is an orphan." Thus, there is growing interest in developing early-warning systems to reduce the occurrence of expectable adverse surprises (i.e., failures) and, when possible, to mitigate or adapt to the potential negative impacts of such surprises. Favorable consequences do not apparently attract the same level of concern, advanced warning, or response by society to take advantage of the positive environmental changes that might accompany a "pleasant" surprise. Perhaps this is because of what Lee (1993) has suggested: "Most of the time those exercising power are aware that they could learn to do better but do not feel a strong urge to grasp that opportunity because they are already too busy" (p. 177). Nevertheless, the pursuit of positive opportunities to improve societal well-being makes as much objective sense as the avoidance of negative consequences.

Since natural and human-built systems tend to adapt to recent conditions, climate-change surprises, whether of an adverse or beneficial nature, might produce considerable dislocations in the short term, requiring individual and societal adjustments. Some societies will be able to make those adjustments on short notice, while others will not. For example, anchoveta and sardines seem to replace each other in parts of Peruvian and Chilean coastal waters. However, fishermen do not know when such a species replacement will occur. Whereas the Peruvians focus on catching anchoveta and are generally unprepared to catch sardines (different nets are required, for example), the Chilean fishing industry has prepared itself for such expectable shifts in their coastal biological resources. The Chileans can go after either species, because they have made the necessary modifications to their fish-catching equipment.

As noted earlier, adverse surprises can provide windows for positive change. Kates and Clark (1996) note that a common characteristic of surprises is that "they open windows of opportunity for increasing our capacity to manage environmental problems." The discovery of the ozone hole, for example, provided a major boost in political support for strengthening the Montreal Protocol by speeding up the timetable for the global phasing out of CFC production. Victor and Salt (1995) note that "when attempting to develop such a [climate] framework, it helps to have a smoking gun, such as a dead forest or an ozone hole to spur action" (p. 280).

The Aspen Global Change Institute workshop in 1994 was one exception (see also Glantz 1990), in that it did examine several possible technological surprises that could reduce the risk of the occurrence of a carbon-dioxide-induced global warming (e.g., a breakthrough in energy-production efficiency or the development of environmentally benign energy alternatives). Positive surprises were also mentioned by Schneider (1996) when he referred to the "potential photosynthetic enhancement of crops, forests and other biota." Kates and Clark (1996, pp. 10–11) also suggest that positive surprises could emanate from adverse environmental change:

> *As it happens, there have also been a number of positive environmental surprises that would temper our gloomy expectations of environmental degradation and human suffering if we would only recognize them. For example, the biomass of temperate forests has been increasing in recent years despite — and possibly because of — the effects of acid rain and other pollutants. Yet, while the negative effects of acid rain on particular places or species of trees have been widely disseminated and are common knowledge, this positive development is little known outside of professional circles.*

Schneider (1996), however, warns against letting the possibility of positive climate-change surprises dull our consideration of the potentially negative ones (p. 96):

> *Thus, surprises need not be negative, but not to anticipate the negative ones simply because some could be beneficial would be equivalent to not anticipating negative threats to security or health and thus foregoing personal insurance or defence investments.*

Timmerman (1986) considers both the favorable and unfavorable consequences of surprise in his article, "Mythology and Surprise in the Sustainable Development of the Biosphere" (in Clark and Munn 1986). He explores the potential responses of individuals and communities to surprise and argues that surprises can be (a) merely anomalies, or they can produce (b) shocks, (c) epiphanies, or (d) catastrophes.

Anomalies are "surprises that are marginal, puzzling, but not enough to alter perceptions" (Timmerman 1986, p. 494). Shocks are serious surprises that "freeze the system or cause it to behave inappropriately." Epiphanies allow constructive reshaping of expectations by revealing the "essential characteristics of the system dynamics in a useful way." Catastrophes are "surprises that destroy a system before it can make any use of the event." Timmerman believes that it might be possible to foster epiphanies and avoid catastrophes by making social systems more resilient.

6 OPEN SURPRISES

Considerable effort has been directed toward understanding and anticipating "open surprise." Open surprises arise out of one's recognized lack of knowledge (i.e., *recognized* ignorance). The Aspen typology distinguishes between *open* ignorance (that is, where there is a willingness to admit that there are some outcomes that are not known) and *closed* ignorance (that is, where people are unwilling or unable to recognize that some outcomes are not known). Open ignorance is then subdivided into (a) "easy-to-recognize ignorance" and (b) "hard-to-recognize ignorance." The latter includes epistemological and phenomenological ignorance. Frequently, limitations on the use of existing theories and methodologies will foster an inability to accept the fact that not all possible outcomes are known.

Open surprises also include those characterized by the Aspen group as "easy-to-recognize ignorance" and could be described as cases where we "know what we don't know." Open surprises arise from a lack of understanding, which can be remedied by scientific progress using existing theories, measuring devices, and methods. In most cases, these surprises include known types of problems that receive the attention of researchers as a result of normal scientific inquiry. These sorts of surprises include common events that elude detection/prevention, according to Kates and Clark (1996). Open surprises do not necessarily involve deeply held expectations, although they can involve a dramatic contrast between an event and expectations about its possible occurrence. One of the key issues raised by an analysis of open climate surprises is the need for effective communication among scientists, policymakers, and the public. Real-world candidates for open surprises include shifts in oceanic thermohaline circulation (ocean current flip-flops that affect salinity and the temperature distribution of the atmosphere) and the evolution of a new "Garden of Eden" through enhanced CO_2 fertilization, as well as the capacity of the oceans to absorb CO_2, generate super hurricanes (i.e., supercanes), and stabilize cloud feedback.

Overpeck (1996) examined the potential sources of "warm climate surprises." He argues that there is an incorrect but "widespread belief that the full range of natural interannual- to centennial-scale climate variability is well represented in the instrumental record of the last century." He notes that "the paleoclimatic record leaves little doubt that warm interglacial climates are, even in the absence of any human force, capable of generating significant decade- to century-scale climate surprises." Thus, a major source of climate-related surprise may result from the relative brevity of human life spans and the common misperception that we have records far enough back to have directly or indirectly witnessed many of the earth's incremental and drastic changes.

Research on ENSO has uncovered an interesting aspect of surprise. ENSO researchers often set up conditions that unwittingly ensure they will eventually be surprised by an ENSO event. The fact is that the climate research community began to focus on the coupling of the atmosphere and the ocean to better understand El Niño events only a couple of decades ago (in the late 1960s). The research community has made considerable progress since Bjerknes (1966, 1969) identified the linkage between equatorial oceanic processes and atmospheric circulation in the Pacific. However, the time span encompassed by direct observation and reliable proxy information is quite short. In other words, the time series for ENSO becomes less reliable as we go back in time to the turn of this century and beyond.

As new discoveries were made, scientists led themselves to believe that they had finally come to understand the ENSO warm-event phenomenon well enough to know how to forecast its onset, growth, and decay phases. That was the case in early 1982 when Rasmusson and Carpenter published their article describing the "canonical" (typical) El Niño event, only to have an anomalous El Niño event occur later in that year. The 1982-83 event immediately shattered the notion of a canonical ENSO and led researchers to conclude that no two El Niño events were alike. Such a reactive statement may yet prove to have set ENSO researchers up for another climate surprise.

The fact that there was no cold event between 1973 and 1987 was also surprising to researchers, as was the apparent (and controversial) "protracted" event that occurred in the 1991-95 period. Thus, by not accepting the possibility that they may not yet have solved the ENSO mystery, researchers are constantly setting themselves and the public up to be surprised when future events take different courses than have yet been witnessed first- or second-hand.

7 CLOSED SURPRISES

Of the various types of climate surprise, perhaps the most difficult to address are those that arise from ignorance. Closed surprises include both "closed ignorance" and "hard-to-recognize ignorance." Closed surprises are produced by surprising consequences or causes, according to Kates and Clark (1996). They occur when "our expectations about causation itself have failed" and when they have "expected but mistakenly attributed consequences." These are essentially unexpectable surprises. They involve an event, the occurrence of which is in stark contrast to deeply held expectations.

Such problems are not addressed in advance of their onset for a variety of reasons. The rare event may not as yet have been identified as such by scientists. They may not be addressed because they have not as yet been measured (no instrumentation has detected the rare event). They may also lack attention because the dominant research paradigms at a given point in history did not recognize the possible occurrence of certain surprising events. A good example of this is the delayed identification of the linkages between the production of CFCs, their impact on stratospheric ozone, and the development of the Antarctic ozone hole.

Such surprises are seldom detected in a timely way — that is, in a way that provides enough lead time for societies to develop an effective response. Even when adequate instrumentation does exist, they may lack timely identification because individuals and institutions tend to discount information that goes against their deeply held convictions. Closed surprises are, in a sense, inevitable.

There are, however, changes that could be made in the way research is undertaken, as suggested by Schneider (1996): There is a need for "generating new processes for imagining imaginative outcomes (best accomplished by improving the process of interdisciplinary exchanges)." Rethinking the structure and function of research organizations, which are usually based along disciplinary lines, might help to anticipate climate-change surprises that are at present unimaginable.

The Aspen typology of surprises identifies two types of hard-to-recognize ignorance. The first is described as "epistemological ignorance," which arises from the way people view the world; the second is "phenomenological ignorance," which is "not knowable within existing technology and the full range of analytical perspectives" (Schneider and Turner 1994, p. 135). Several authors have addressed the issue of how scientific thinking, institutions, and methods may render our society more vulnerable to certain types of surprise.

Holling, in "The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change" (1986), treats surprise as a source of information for understanding the interaction between "the natural system and the people who seek to understand causes, to expect behaviors, and to achieve some defined purpose by action" (p. 294). Specifically, Holling postulates that our reliance upon a view of nature as "equilibrium centered" has led not only to bad theory but also to bad policy. He argues that nature could be better understood as resilient, rather than stable. Such a notion has implications for climate surprises.

Slow increases in greenhouse-gas concentrations might be "so successfully absorbed and ignored [by the global community] that a sharp, discontinuous change becomes inevitable" (Holling 1986, p. 295). Feedback mechanisms can become overloaded, and as a result, effects can suddenly cascade out of control. Holling suggests that "small-scale events cascade upward." To rely on the output of climate models for policymaking is dangerous, because they are based on equilibrium assumptions and there is a possibility that small changes in forcing factors can produce dramatic, nonlinear changes in effects.

Considering *nature* as resilient rather than stable raises the question of whether *societies* are resilient, an issue examined briefly by Brooks (1986) in his essay, "The Typology of Surprises in Technology, Institutions, and Development" (in Clark and Munn 1986). Given the prospect of climate change, it is extremely important that society's institutions be structured for resilience in the face of yet-to-be-identified climate change, climate fluctuations, and extreme events. (See Gunderson et al. [1995] for suggestions about how to do this.)

Another notion raised by Holling (1986) with implications for climate surprises is that of "fast" and "slow" variables. Changes in the environment caused by slow variables can eventually lead to different stability domains. Yet, observers are often unaware of, or unconcerned about, the potential importance of slow variables. This lack of interest or awareness results in part from the difficulty, as noted earlier, of observing slow causal factors on time scales of interest to researchers (for most, the length of their careers as researchers). In addition, funding agencies are not so eager to support the monitoring of incremental changes in the environment for periods of time that, to them, seem endless (more than several years). One exception to this rule is the Long-Term Ecological Research (LTER) network in North America, which has been supported for at least two decades and seeks to continue the protection of selected ecological sites from one generation of researchers to the next.

One problem with slow variables is that they cause incremental, almost imperceptible, changes in the short term. However, in the long term, those increments can add up to produce a major discontinuous environmental change. Researchers focused on the importance of the fast variables tend to view the slow variables as constants.

Myers addresses surprises that result from "discontinuous change" in his article, "Environmental Unknowns" (1995). He argues that "the most advanced climate models are largely unable, because of their very structure, to encompass the possibility of nonlinear interactions" (p. 359). He notes that paleoclimatological research seems to indicate that climate change (with concurrent changes in biota) has often occurred abruptly in the past. He asks, "What if such jump effects were to be triggered, perhaps in multiple forms, by global warming?" (p. 359). He later points out that "whereas the increase in fossil fuel consumption can be linear, the atmospheric pollution's response often is not" (p. 359). Thus, discontinuous change is always a possibility when underlying causal mechanisms are insufficiently understood.

Myers (1995) considers "synergisms" as another potential source of surprise. Interactive effects are often multiplicative rather than additive, especially in biotic systems. He presents the following example: "A plant that experiences reduced sunlight, and hence less photosynthesis, is unduly prone to the adverse effects of cold weather, water shortage, insect pests, or diseases" (p. 359).

An example of destructive synergisms was witnessed in the recent plight of the North American honey bee population. A climate anomaly interacted synergistically with a 12-year-old plague of mites to devastate a biological system. This devastation, in turn, produced adverse social and economic effects (Crenson 1996). Honey bees depend on the body heat generated by rapid motion within the hive to keep them alive during the winter. A varroa mite infestation (and, to a lesser degree, tracheal mite infestation) lowered hive populations. With fewer bees to generate heat, hives were much less capable of surviving the winter. A cold winter and wet spring had a devastating effect on the weakened bee population. Similarly, the cold weather left bees in an inferior position to overcome mite infestation. The net result was the destruction of 90% of wild bees and similar dramatic declines in kept-bee populations (80% in Maine, 67% in Wisconsin, etc.).

In other parts of the world, the collapse of the bee population could have had dramatic adverse impacts on agriculture, because of the essential role played by bees in pollinating crops of all kinds. In North America, fortunately, most farmers are able to rent bees for pollination. Crenson (1996) points out, however, that "those who depend on wild bees for pollination are in for a rough summer. Gardeners and small farmers who can't afford to rent colonies from beekeepers won't see very much in the way of cucumbers, melons, apples, blueberries, and the dozens of other crops that won't produce without bees." It is also important to note that a continued absence of bees for pollination could reduce the genetic diversity of some food crops through the loss of wild stocks.

8 CATEGORIES OF SURPRISE

Authors have categorized surprise in a number of different ways. These include, but are not limited to, the following: a contrast between an event and expectations, the kind of effect the event has on the system affected by the surprise, and the nature of the expectations that have been contradicted by the surprising change.

Simon (1985) wrote about bounded rationality as a guiding principle for understanding human actions. He suggests that the ideal of the rational economic actor is not always sufficient to explain human behavior and proposes that it would be more useful to understand people as "boundedly" rational. Simon (p. 294) states that, in order to understand and predict human behavior, the following is necessary:

> *To deduce the procedurally or boundedly rational choice in a situation, we must know the choosing organism's goals, the information and conceptualization it has of the situation, and its abilities to draw inferences from the information it possesses.*

Applying the notion of bounded rationality enables us to understand why it is that human behavior often does not match up to the ideal predicted by rational-choice models. Simon did not write about surprise. However, if surprise is defined as a consequence of expectations failing to encompass all possible events, it would be useful to identify and evaluate the kinds of factors that delimit one's capacity for "rational action." This implies that the factors Simon explored as necessary components for the understanding of human behavior could be useful for distinguishing among different types of surprises, as well as for understanding why such surprises occur.

Simon argues that rational decision making is limited by (1) the unavailability of information and (2) variations in processing information. These are two likely sources of surprise. Although the former may be beyond one's control, it may be possible to improve the ability of an individual to draw more rational inferences from information received and, hence, reduce the possibility of surprise.

Kates and Clark (1996) draw upon their insights from risk assessment research to develop a typology of surprise that includes social response (Figure 3). They focus on the distinction between events, their consequences, and the causal connections between them, pointing out that "such distinctions are important because the chance that something will go wrong may be more or less independent of the harm it will cause." The first distinction they draw in their typology is between "surprising events" and "surprising consequences or causes." Some surprises may be expectable, when it is known that such events could occur. However, such events can still be surprising, because they can occur at an unexpected time or place, or with an unexpected intensity. Surprising

	Surprising Events		Surprising Consequences/Causation	
Description	Rare events with serious consequences	Common events that elude detection/prevention	Unexpected consequences	Expected but mistakenly attributed consequences
Examples	Bhopal Seveso, Italy Three Mile Island Chernobyl Mount St. Helens	Legionnaire's disease Hanta virus Lyme disease Radon gas in homes Zebra mussels in the Great Lakes	CFCs Lead in paint and gasoline Asbestos fibers Secondary cigarette smoke	Stratospheric ozone depletion Ground-level ozone damage Forest damage
General social responses	Hazard identification, event prevention, consequence reduction			
Specific social responses	Emergency response to reduce consequences	Screening and monitoring for earlier detection	Modes of analysis to consider the unthinkable	Modes of analysis that emphasize multiple and unknown causation

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FIGURE 3 Types of Surprise and Societal Response (reproduced, with permission, from R.W. Kates and W.C. Clark, "Expecting the Unexpected," in *Environment* 38:(2):29, 1996)

consequences or causes occur when an event is unexpectable, or when an expectable surprise occurs at an unexpected time or place.

Kates and Clark divide surprising events into "rare events with serious consequences" (such as Bhopal, Seveso, Mount St. Helens, and Chernobyl) and "common events that elude detection/prevention" (e.g., the Hanta virus, Lyme disease, and radon gas in homes). They divide "surprising consequences/causation" into "unexpected consequences" (e.g., the effects of asbestos fibers, the health impacts of lead in paint, and the harmful effects of secondary cigarette smoke) and "expected but mistakenly attributed consequences" (e.g., stratospheric ozone depletion, ground-level ozone damage, and forest damage). Each of these types of surprise is associated with different kinds of social response that range from traditional emergency-response planning, through the establishment of screening and monitoring programs, to rethinking traditional modes of analysis.

Brooks (1986) explores the interactions that can develop between social and technological systems. He identifies three general types of surprise: (1) unexpected discrete events, (2) discontinuities in long-term trends, and (3) the sudden emergence into political consciousness of new information. Unexpected discrete events include such recent industrial accidents as Chernobyl and Bhopal, as well as major natural disasters. These are examples of singular, rare events with very large, but predictable, consequences.

Discontinuities in long-term trends include "the acceleration of U.S. oil imports between 1966 and 1973, the onset of the stagflation phenomenon in OECD countries in the 1970s, [and] the decline in the ratio of energy consumption growth to GNP growth in OECD countries after 1973." The sudden emergence into political consciousness of new information includes "the relation between chlorofluorocarbon production and stratospheric ozone, the deterioration of central European forests apparently due to air pollution, the discovery of the recombinant DNA technique, and the discovery of asbestos-related cancer of industrial workers."

Thus, Brooks distinguishes between surprises based on the varying nature of the surprising events. Unexpected discrete events are relatively sudden and isolated. Changes in long-term trends involve the accumulation of incremental changes over time or the various combinations of different events to affect the expected trend. In the case of the sudden emergence into political consciousness of new information, such information about an event may actually have been available for some time to some people, but was surprising nonetheless, when policymakers or the public became aware of it.

9 EXAMPLES OF SURPRISES

Events that are surprising because of where or how frequently they occur may become more common, if human-induced climate change takes place. In such cases, an event (such as a drought, flood, freeze, etc.) is not necessarily an unknown regional phenomenon, but it can be dramatically surprising to the inhabitants of the specific location in which it occurs, because it seldom or never has occurred there. The examination of historical instances of climate surprises and their effects can be instructive for imagining the consequences of future surprises. It can also help to identify those subtle indicators that might prove to be harbingers of future climate changes, much as lichens are considered the first indicators of damage from acid rain.

9.1 FLORIDA FREEZES

A set of five freezes that struck Florida during wintertime in the 1980s provides an example of a climate-related surprise arising from a change in frequency of occurrence. Two of those freezes, in the winters of 1983 and 1985, killed approximately one-third of Florida's commercial citrus trees (Miller 1988). Miller reported that "overall, it appears that lost output, tree losses, and expenses incurred in an effort to protect or salvage trees imposed costs on the order of two to two-and-a-half billion dollars on Florida grove owners." These losses had considerable secondary effects as well, such as (1) reducing employment in the Florida citrus industry and (2) serving as the catalyst for the entrance of Brazil into the U.S. frozen orange juice concentrate market.

The Florida citrus case study also shows how events that occur in unexpected places or with unexpected frequency can be damaging because the region has become adapted to conditions that had existed in earlier decades. Growers in freeze-prone areas are prepared to take a number of preventative measures to reduce their vulnerability to freezes, even though it may reduce their profits in the event that freezes do not occur — a risk-averse strategy. One such measure was to plant a greater proportion of early-bearing Hamlins rather than Valencias, which at that time yielded a higher price but would be more vulnerable to cold (Miller 1988). If freezes are considered to be a significant hazard in an area, orange growers tend to adjust their crop portfolio accordingly.

9.2 DENGUE FEVER IN COSTA RICA

An example of a climate surprise related to location is the spread of disease into an area where it had not existed previously. In Costa Rica, dengue fever, for example, had traditionally been confined to a narrow area in the mountains. Higher temperatures during 1995, however, enabled the disease-bearing mosquitoes to spread to coastal areas. Dengue subsequently spread northward to the Texas border. Over 140,000 people in Latin America had been infected by September 1995, and more than 4,000 died (Linden 1996). Linden also noted the concerns of medical specialists that malaria could spread poleward, covering 60% of the planet (it currently covers 42%), if global warming were to occur. Thus, one can surmise that areas that have not suffered from malaria (or other vector-borne diseases) in past decades could be surprised by its resurgence.

9.3 NONUNIFORM FORCING

Different geographical regions can be affected very differently by global climate change. Schneider (1996) addresses the spatial dimension of surprise from a different perspective: the effects of nonuniform forcing. Paleoclimatological studies of ice cores have shown that different, sometimes opposing, regional climate shifts have occurred in the past. He notes the following:

> *Also, there was a celebrated and dramatic fluctuation at the end of the most recent Ice Age in which warm-weather flora and fauna had just become established in Europe when about 10,800 years ago there was a quick return to Ice Age-like conditions, at least in Europe and to some extent downstream into Eurasia with weaker signals over the rest of the world .... This Younger Dryas period lasted about several hundred years, and may have seen regional temperature changes at the rate of degrees per century, although it is doubtful that global temperature change rates were more than a few times higher than the sustained global average rate of about one degree per millennium.*

Schneider also comments on the role that shifts in ocean currents can play in such events. The North Atlantic currently evaporates more water than it accumulates from rivers or from precipitation. This leads to an accumulation of salt, which, because of its higher density, causes water to sink during the winter, drawing farther north the warm waters of the Gulf Stream. This, in turn, keeps Europe much warmer during the winter than would otherwise be the case. If smaller climate changes were to affect the salinity of the North Atlantic (increased precipitation over the ocean, more freshwater input from rivers, etc.), this could create a much more dramatic regional shift (Schneider 1996). Changes in the type and amount of cloud cover could have a surprising effect on the rate and degree of global warming.

Another example of a regional-forcing surprise is the role that sulfate aerosols may play in the climate-change issue. These aerosols have partially compensated at the regional level for global warming over the industrial nations that produce most of these aerosols. Such regional differences could spark secondary surprises as well, such as widening the gap between the "haves" and the "have nots." This in turn could spark widespread migration, or a refugee crisis of global proportions, or could otherwise endanger global stability (Schneider 1996).

9.4 THE 1994 SUMMER IN JAPAN

Nishioka and Harasawa (1996) suggest that Japanese experiences during the summer of 1994 may provide useful examples of possible future climate-change impacts:

> *The Summer of 1994 was the hottest summer we have ever had in Japan. The mean temperatures during July, August, and September were about 2.1 degrees Celsius above the ordinary mean temperatures for this period. This trend corresponds with conditions of global warming in the middle of the 21st century that the Intergovernmental Panel on Climate Change (IPCC) predicted.*

Many second-order surprises occurred in Japan that summer. The authors grouped the consequences of the hot summer into five categories of effects: agricultural and marine products, wildlife, health, natural disasters, and industry/economy. Among other things, they found considerable increases in rice yields, beer consumption, wasp infestation, forest fires, food poisoning, and demand for electricity. While some of these second-order effects could have been easily predicted, others were surprising. Figure 4 illustrates the amazing complexity and interrelatedness that can result from a local change in climate.

Another concern raised by the hot summer of 1994 in Japan relates to human health impacts. In addition to an increase in the occurrence of sunstroke, heatstroke, and dehydration, air pollution effects (from photochemical smog and hydrogen sulfide) became more dramatic, highlighting the possible synergistic effects between human health and environmental problems. The increased rate of food poisoning, if it were to continue long term, could force cultural shifts in food preparation. Food poisoning affected 10,442 people during July and August of 1994, compared with a previous nine-year average of 9,085 cases for the same months.

The increase in wasp infestations raises yet another issue: unwanted (and unexpected) changes in pest populations. Climate change can affect the size and location of animal and plant populations. The latter could also have human health effects, if changes in pest populations produced increases in the occurrence of disease or changes in the movement of climate-sensitive disease carriers from one area to another (e.g., malaria outbreaks shifting poleward).

9.5 THE 1991-92 ENSO EVENT

Today, there is considerable hope resting on the forecasting of ENSO events several months in advance. The science, and therefore the understanding, of ENSO has improved considerably since the early 1980s. Following the big ENSO of 1982-83, researchers Cane and Zebiak successfully forecast the 1986-87 ENSO event. This prompted researchers who had been reluctant to "go public" with their forecasts of ENSO to issue public pronouncements.

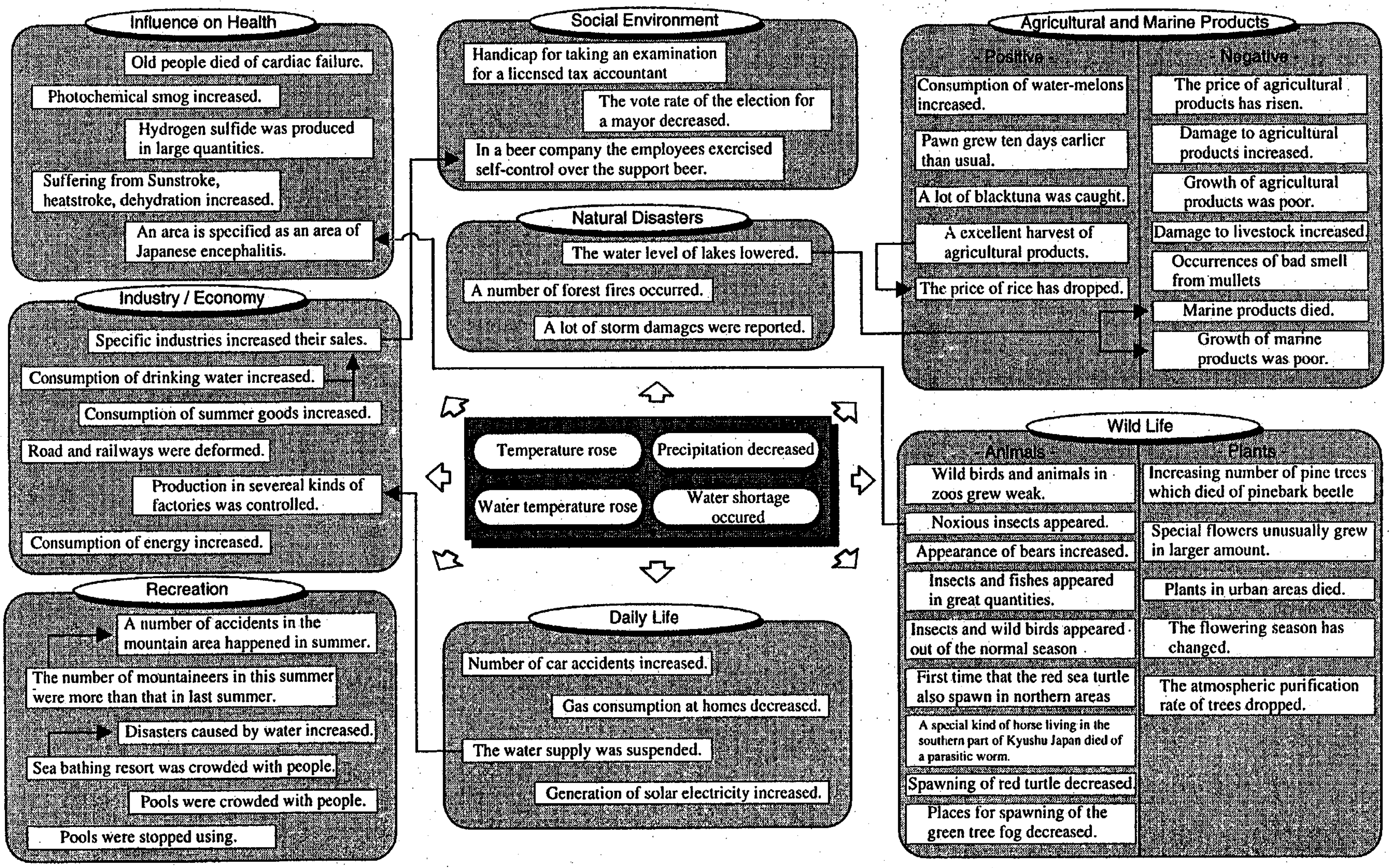

FIGURE 4 Impacts of the 1994 Hot Summer in Japan (Source: S. Nishioka and H. Harasawa 1996; with permission)

Some researchers forecast an ENSO event for 1990, but Cane and Zebiak said that their model did not show that such an event would develop. They did, however, forecast an event to begin in 1991 and to decay at the end of 1992. It began as they predicted, but the event did not really end in November, and in 1993 the surface waters in the eastern equatorial Pacific unexpectedly began to heat up again. The 1993 event decayed, only to have another ENSO event emerge in 1994. This sequencing of changes (heating and cooling) in sea-surface temperatures across the equatorial Pacific caught ENSO researchers by surprise. They were surprised that the event did not terminate in late 1992 and that other events began in 1993 and 1994.

The element of surprise related to ENSO events appears to be the result of perceptions held by the scientific community that, following each ENSO event, it had come to understand the phenomenon. However, the succeeding event evolved in a different way: it began earlier, the sea-surface temperature rose faster, it developed in an unexpected way, its impacts around the globe (called teleconnections) were different than previously observed, and so on. The phenomenon has been studied as a coupled system for only a few decades, and scientists have not yet witnessed all the various ways that ENSO can evolve. A realization by scientists that they still have much to learn about the phenomenon would be a major step toward reducing the possibility of future surprises.

10 COGNITIVE BIAS AND LOGICAL REASONING

An individual's comprehension of "circumstances" is conditioned by many factors, such as his/her societal context, prior knowledge of a subject, and *a priori* beliefs. Girotto and Politzer (1990), psychologists whose research has explored cognitive bias, assert that each of these factors affects "primary logical skills" (p. 88). Although it has long been accepted that belief affects the logical process, the degree to which this occurs is still debated. Girotto and Politzer suggest that, under conditions of uncertainty, subjects are likely to draw conclusions that are consistent with their beliefs. Kates (1976), in a discussion of perceptions of environmental hazards, notes that "74% of our respondents chose the random explanation for the recurrence of events" (p. 146). That events recurred implies to some degree that they could have been anticipated. Yet, "nonrational" factors persistently influence logical thinking.

Evans and Pollard (1990), in their essay "Belief Bias and Problem Complexity in Deductive Reasoning," identified deductive reasoning as a process susceptible to distortions caused by *a priori* beliefs. In a deductive sequence, an argument is valid when "the truth of the premises entails the truth of the conclusion. An argument is invalid so long as its conclusion need not necessarily be true, given the truth of its premises" (p. 131). They cite studies that claimed that a subject would tend to overlook the important connection between premise and conclusion and, instead, would determine a conclusion to be true if, intuitively, it *felt* correct. Belief replaces the logical steps that mediate both the premise and the conclusion. They assert that logically invalid statements are more susceptible to the influence of belief bias than are valid claims (pp. 131–132).

Evans and Pollard (1990) discuss two specific models that explain bias: the Selective Scrutiny Model and the Misinterpreted Necessity Model. The Selective Scrutiny Model assumes that a subject, when confronted with a logical sequence, will assess the conclusion. If the conclusion appears correct — that is, if the conclusion mirrors the subject's assumptions — the subject will tend to accept the logical sequence as correct. Only when a conclusion contradicts a subject's assumptions will he/she scrutinize the logic. These authors maintain that the "uncritical acceptance of believable conclusions causes error" (p. 132). Where such errors exist, surprises result.

The Misinterpreted Necessity Model distinguishes between logical necessity and possibility. In discussing deductive logical sequences, a conclusion is correct only if it is necessitated (i.e., logically required) by the premises. Evans and Pollard explain that mere consistency between premise and conclusion, though logically invalid, is compelling enough for an uncritical person as evidence of validity. This model assumes that a conclusion is "evaluated with respect to its logical relation to the premises," unlike the case with the Selective Scrutiny Model (Evans and Pollard 1990, p. 132). If the conclusion is necessarily true or false, it is understood as such, but if necessity is absent, a person will assert validity or falsity based on his/her prior assumptions. Here, in the absence of necessity, possibility is invoked and error is introduced into the logical process. It can be effectively argued that the uncritical acceptance of flawed deductions creates a niche for surprise. A system's behavior will be more surprising when the basic assumptions about its parameters have not been critically assessed.

In his essay "Are There Biases in Analogical Reasoning?" Keane (1990) explores analogy as a heuristic device that contributes to cognitive bias. Uncertainty is negotiated (i.e., subjectively determined) with reference to that which is less uncertain. This is done by making reference to that which is familiar in an effort to understand the unfamiliar. Keane argues that analogical reasoning is a powerful and useful tool when one is confronted with uncertainty. He believes that there is little evidence for systematic bias in analogical reasoning, although analogies can be misapplied (see also Jamieson 1987 and Glantz 1991).

Orzeck (1994) explores the interface between scientific thinking and psychology in "Psychology in a Physical World." His project identifies parallels between "everyday" life and "scientific thinking" (p. xi). Through the course of a series of fictitious dialogues, Orzeck shows that the mishandling of uncertainty or the tendency to adhere arbitrarily to a particular point of view has psychological precedent. The distortion of empirical reality by subjective presuppositions (cognitive bias) occurs because of anxiety, which is inherent in situations of uncertainty. Rather than accept intellectual confusion, individuals and institutions are inclined to "accept ... delusions which go for what they see as fact or truth .... We are anxious to settle for fictions because we feel we must predict" (pp. 13-14). The psychological burden of prediction weighs heavily, as scientific prediction and ego often become intertwined.

10.1 COGNITIVE BIAS AND THE INTERPRETATION OF PROBABILITIES

Another variety of cognitive bias is related to the interpretation of probabilities. In "Experts in Uncertainty: Opinion and Subjective Probability in Science," Cooke (1991) credits probabilistic reasoning with a subtlety and formalism not associated with inferential reasoning. He explains that, unlike inferential reasoning, probabilities cannot be regarded apart from their mathematical expression (pp. 48–49). Inferential sequences depend on consistency between premise and conclusion; a valid conclusion can only be achieved in concert with valid premises. Probabilistic sequences, however, can disaggregate a logical sequence into degrees of uncertainty, and, in the case of inferential premises, degrees of validity. In inferential sequences, "almost-valid" premises do not yield "almost-valid" conclusions. Such approximations generate discontinuities (i.e., possible surprises) that complicate one's ability to deduce correctly B from A. Probability, on the other hand, can account for varying levels of certainty, and it can provide a quantitative basis for speculation about the validity of a conclusion with reference to the potential occurrence of any given course of events (pp. 50, 61).

According to Cooke, the subjective distortion of probabilities is caused by different types of bias: (a) motivational bias, which is the deliberate distortion of judgment; (b) ideological distortions; and, most importantly, (c) misperceptions of probabilities (p. 63). Rational preference falls under both motivational bias and ideological distortions. Cooke explains that rational preference (a bias first discussed by L. J. Savage (1972) in "Foundations of Statistics") is a heuristic device that involves the subjective use of probabilities and the notion of utility. A decisionmaker's preference figures strongly in the assessment of probabilities, inasmuch as he/she prefers one response over another. This preference is governed by the perceived utility of the preferred response over the alternatives. Rational preference is important, because it recognizes that the opinions of various credible individuals will vary and will affect the respective perception of probabilities (Cooke 1991, p. 87).

Preference implies choosing a particular behavior and relates one's perceptions directly to one's actions. Preference "is regarded as a relation between acts" (Cooke 1991, p. 89). A course of action is selected based on expected outcomes, and outcome "is surely determined by the true state of the world, but it is not part of that state" (p. 89). Cooke also notes a problematic rupture between the present and future. Regardless of how well one understands the present, the future still remains ambiguous.

Kates (1976) explains that, while an individual or group may be aware of a hazard — and aware of various actions that could be taken to mitigate the hazard — they commonly underestimate the importance of acting. He observes that "many take some positive action to reduce losses, but few take preventive action much in advance of the hazard event" (p. 147).

Numerous ways exist in which probabilities can be misperceived. One significant way in which probability judgments are manipulated is through representativeness. In their essay "Probability Judgement," Birnbaum et al. (1990) describe the manner in which likelihoods are assessed with reference to cultural models. The way in which a scenario is presented influences the way in which it is assessed. Assumptions about reality — about combinations of factors external to the given problem — figure into the judgment of possibility. The objective nature of a mathematically generated probability is subjectivized with reference to the cultural context.

Equiprobability bias is another significant way in which objective probabilities can be misunderstood. This form of bias explores the relationship between two possible scenarios. Is scenario A or scenario B more likely, or are both scenarios equally probable? The classic example, cited by Lecoutre et al. (1990), involves the roll of two sets of dice: "[t]he following results are considered. R[oll]1: 'a 5 and a 6 are obtained;' and R[oll]2: 'a 6 is obtained twice'" (p. 570). The authors assert that most respondents understand both rolls to be equally probable. In fact, roll 1 is more probable; two sixes can be obtained in only one way, whereas the 5–6 combination can occur in two ways. The importance of such errors to environmental and climate-related research is direct.

Misreading a scenario and acting upon information that has been misread will tend to increase the likelihood of generating future surprising events.

Wright and Ayton (1990), in "Biases in Probabilistic Judgment: A Historical Perspective," describe a person's revision of probability assessments based on changes in the presentation of data. Research by Petersen et al. (as described by Wright and Ayton) concludes that a person's revision of opinion tends to be conservative, with certain exceptions. They observed that revisions were more conservative when, after being given a body of data, a person was asked for assessments. He/she was less conservative when asked to revise his/her assessments numerous times during the process of assimilating the information. The researchers concluded that the sequence in which data are presented strongly influences a person's resulting subjective assessments (Wright and Ayton 1990, pp. 425–427).

Ayton and Wright (1990), in a different article entitled "Uncertain Memories: Evaluating the Competence of Probabilistic Cognition," explore measures of confidence in subjective assessments. They investigate the concept of "calibration," defined as the consistency between projections and actual events. The authors describe research that reveals that subjects are typically overconfident when formulating subjective probabilities. Numerous explanations for this error have been proposed. People may overestimate their ability to anticipate events because they fail to see flaws in the simplifying mechanisms that they use to assess probabilities.

The authors underscore the difficulty of translating uncertainty into quantitative terms, recognizing that, despite calibration errors, subjective probability measures are infrequently entirely wrong. Assertions tend to be miscalibrated in a consistent manner, indicating some degree of predictive validity. However, they emphasize that explanations for consistent miscalibration are limited by the lack of a viable theoretical framework. Overconfidence can be tempered just by recognizing its existence. According to Ayton and Wright, subjects who recognize their own uncertainty, or who account for alternative explanations for a scenario, are less inclined toward overconfidence and predictive error.

According to Orzeck (1994), probability is "a problem of the likelihood of knowing something." It expresses one's imperfect attempts at achieving prediction that can ultimately prevent surprise. Probability is a measure by which, with various degrees of confidence and success, a subject's knowledge of the world is correlated with the world itself. Casti (1994), in "Complexification: Explaining a Paradoxical World Through the Science of Surprise," characterizes probability with a reference to surprise: "One of the principal uses of probability theory is to provide a numerical measure of our sense of how surprising the occurrence of a particular event would be. By the foregoing arguments, we find that the concept of surprise is intimately tied up with the connective structure linking events in the space of possible outcomes" (p. 209).

Probability statements are used in an effort to anticipate events or circumstances. These probabilities are qualified by measures of confidence. When an individual acts upon a probabilistic statement (that is, when probability becomes subjective), he/she does so with the understanding that events in the specified confidence interval, regardless of probability of occurrence of those events, either will or will not occur. When a statement about the future asserts a 90% certainty, a subject can either regard the overwhelming likelihood that this event will occur or focus on the slim chance that the event will not occur. If the subject abides by the probability, trusting the 90% likelihood that a projected event will occur, he/she will be surprised if it does not (e.g., Dr. James Hansen's controversial comments to the media about the high probability that the severe drought in North America in 1988 was the result of global warming, while other scientists argued that it was the result of a La Niña [or cold event] in the tropical Pacific Ocean).

Surprising events, or at least those that are viewed as genuine surprises, are frequently those for which the probabilities of occurrence are perceived to be extremely low or are not perceived at all. Although such events elude conventional probabilistic thinking, their prediction is not entirely futile. Cooke (1991) explains that such events result from a combination of factors, each of which can be measured by an independent probability. Anticipation of extreme and rare events can be achieved through the successful calibration of predictions of their "ingredient events" (p. 36). Cooke believes that consistently poor calibration is the result of flawed methodology, suggesting that "most measures used to score calibration are mathematically dubious, at best. Failure to appreciate this fact has led to inappropriate experimental designs whose results must remain ambiguous" (p. 64).

10.2 COMPLEXITY

> *There are no surprises in simple systems; simple systems give rise to behaviors that are easy to deduce if we know the inputs (decisions) acting upon the system and the environment .... Complex processes, on the other hand, generate counterintuitive, seemingly acausal behavior that's full of surprises.*

Casti (1994, p. 271) suggests that the uncertainty confronting scientists is more commonly attributable to "an inherent vagueness, or lack of information, either in the linguistic description or in other circumstances surrounding the situations we find ourselves confronting," than it is to systematic randomness. Probabilities are based on assumptions, the parameters of which may (or may not) correlate with real-world conditions.

Attempts to transcend probability theory, such as fuzzy set theory (see, e.g., Kosko 1993), assume that uncertainty is not synonymous with randomness; theories of complexity allow for the penetration of surprise by looking beyond probabilistic assumptions and into the higher-order deterministic processes that regulate systems. Such an approach may be better adapted to anticipating high-impact events that occur only rarely.

Basic to an understanding of complexity is the distinction between determinism and predictability. For a system to be deterministic, "its future states are completely fixed by its current state and its rule of dynamical motion" (Casti 1994, p. 87). That a system is deterministic, however, does not imply that it is predictable. Chaotic systems, which are deterministic in a complex and seemingly random way, are difficult to predict. Casti suggests that surprising behavior results from the "interaction among simple parts of a complex system" (p. 230). He also argues for the formalization of the concept of complexity, one which recognizes the inherent irreducibility of basic systems due to "cascading" effects.

These effects have been best captured by Edward Lorenz and his "butterfly effect." This phenomenon is based on the assumption that a minor change in input at a given spatial and temporal location can trigger effects that subsequently cascade through other spatial and temporal locations. Climate systems demonstrate this kind of behavior. They are unstable even at the local level (Casti 1994, pp. 89–90). A Lorenz attractor, which is related specifically to climate dynamics, is derived from the butterfly effect. It is used to account for the possible outputs of a system that has assimilated a given set of initial conditions. The Lorenz attractor is an effort to deduce possible outcomes, on the basis of the cascading complexity of a climate system.

Projections of future events are often based on the Lorenz attractor. Various scenarios can be generated to reflect possible outputs of a system. Trends extrapolated into the future can be made into scenarios that are, in theory, free of surprise. Such scenarios are described as salient, even if they are not probable. They are considered salient because they are based on either empirically documented or possible behavior. Cooke (1991) notes that, because of the negligible probability associated with a surprise-free scenario, saliency must not be confused with prediction (see also Jamieson 1988).

Complexity has also been used in the development of catastrophe theory, the proponents of which aspire to account for discontinuities in the behavior of a system. "[C]atastrophe theory deals with the fixed points of families of functions. Catastrophes occur when, as we move in a continuous way through the family — usually by smoothly changing parameters describing the system — a stable fixed point of the family loses its stability. This change of stability forces the system to move abruptly to the region of a new stable fixed point" (Casti 1994, p. 55; for critiques of catastrophe theory, see Casti 1994, pp. 47–48).

In summary, the subjective nature of cognition can lead to distortions of understanding that predispose an individual or organization to surprise. Bias in logical inference and bias in the interpretation of probabilities are examples. Theories of probability and complexity are tools that can be utilized in the management of uncertainty. Each has its distinct approach to uncertainty. Each has certain advantages and disadvantages, strengths and weaknesses. Surprise can be better anticipated and managed if the mechanisms that create it are understood.

11 SURPRISES THAT PROBABLY SHOULD NOT BE SURPRISING, BUT ARE

There are certain types of change that surprise us, when they probably should not. These generally fall into the category of slowly developing changes that we fail to recognize — out of habituation, apathy, or inexperience — until they suddenly cross a threshold of significance and jolt us into awareness of their importance.

11.1 HABITUATION

This is one of the types of surprise that seemingly should not be a surprise at all. It frequently results from changes in perceptions or from not paying attention to correctly understanding normal conditions (i.e., surprises caused by habituation). A surprise resulting from habit refers to the possibility that the frequent occurrence of a certain type of event can lull individuals into believing that they fully understand the phenomenon. This generates a false sense of security, which is reinforced by the human tendency to discount (i.e., put a lower value on) similar events of the past, even the recent past. The possibility of becoming habituated to potential warnings so that someone is surprised by an event can be seen in a military context with the attack on Panamanian defense forces by the United States in 1989. One author stated:

> *Despite intensified training and other visible signs of a buildup, U.S. forces still had a strong element of surprise in their favor when the operation began. Part of this, Army commanders in Panama believe, was due to a slow but steady growth in these activities that "desensitized" the Panamanians* (Ropelewski 1990).

11.2 CREEPING (SLOW ONSET) SURPRISES

> *Even if a particular environmental trend seems manageable today, we should not rule out sudden and dramatic changes that occur as population-related pressures exceed critical natural thresholds* (Population Action International 1996, p. 47).

Surprises are not always caused by sudden, discontinuous change. They can be produced by creeping change as well, if expectations are not altered, or are not altered fast enough, to take new information into account. This can also result when there is an absence of clearly identifiable thresholds of environmental change. The lack of clear thresholds of change delays the issuance of warnings until a dire situation has developed, such as the appearance of visible changes to the landscape.

For example, the proposed incremental progression of a human-induced global warming of the earth's atmosphere would occur over several decades. During this period, many incremental, imperceptible environmental changes would likely occur. Such small changes would likely escape notice until a crisis situation becomes recognized (Glantz 1994, 1998). By the time a crisis emerges, however, it may be very expensive or even impossible to correct the problem. Once the crisis is recognized, many individuals will be surprised by this "sudden emergence into political consciousness of new information" (Brooks 1986).

Brooks (1986) addresses a similar topic in his typology of surprise, in which one major type of surprise is that of "ideas suddenly coming into public awareness." This kind of surprise frequently occurs when no clearly identifiable or previously defined thresholds exist to indicate the progression of change. The deterioration of the Aral Sea can serve as an example of this.

Members of the Soviet scientific community had been warning Soviet leaders for decades that irrigation projects in Soviet Central Asia were diverting so much water from the Amudarya and Syrdarya (feeder rivers to the Aral Sea) that the sea would be deprived of needed annual river water and would eventually dry up. One of the earliest warnings came in a scenario produced by Tsinzerling in the late 1920s, in which projections about the demise of the Aral Sea and associated ecosystems were spelled out (Tsinzerling 1927). Such pleas or projections, however, had little impact on those Politburo members in the Kremlin who had the decision-making power to actually address the problem. Agriculture officials in the Soviet Union were graded by their superiors on the basis of their ability to produce increasingly large amounts of cotton. Warnings about the decline of the sea level were largely ignored by them. Only after a number of different thresholds of environmental change had been passed did higher officials take notice. By then, a few decades later, the seriousness of the decline of the Aral Sea was a surprise to many Soviet leaders. This was a surprise that had crept up on decision makers over a period of at least 40 years (Glantz et al. 1993, 1998).

"Creeping surprises" can also be generated as a result of the time scales of political processes, especially the time in office for public officials. Because there is a strong tendency for political leaders to focus on short-term problems that determine the future of their careers (e.g., in two-, four-, or six-year increments), rather than the consequences of adverse long-term environmental change, longer-term changes are often (and easily) viewed as "someone else's problem." This situation exists in bureaucratic settings as well. Holling (1986) notes that major policy changes in natural resource management agencies tend to accompany power transfers between generations. Frequently, the generation in power will have considerable intellectual and career investment in perpetuating a given way of doing things. A later generation would likely have different training and experience, coupled with a desire to "make its own mark." Only when the new generation comes to power can real (i.e., fundamental) change occur.

11.3 DISCOUNTING

A common source of surprise is the relatively limited experience of human generations compared with the millions of years of biogeochemical processes of the earth. For example, there is a tendency for people to assume that climate patterns that last for a decade or two are representative of longer-term patterns. As a result, the experiences of previous generations are frequently given less value than those of the present generation (i.e., those experiences are discounted). There are many examples of discounting.

One such example would be the situation in the West African Sahel in the late 1960s (Glantz 1994). A two-decade period of above-average rainfall in the 1950s and 1960s, which resulted in above-the-long-term-average rainfall in normally dry areas, led the inhabitants of the region and their governments to adopt new land-use practices (e.g., putting rangelands into cultivation or keeping too many livestock on the rangelands). These practices, however, proved to be inappropriate for the longer-term climate regime of the Sahel, as well as for its soils. After 1968, rainfall in the Sahel declined (Glantz and Katz 1977, p. 192) and the regional climate regime shifted back toward aridity. This shift made it difficult, if not impossible, for farmers and herders to continue their activities. Many were forced to abandon the land and migrate to wetter regions in the south. This left the abandoned land open to desertification processes (e.g., soil erosion and dust storms).

One key lesson from this Sahelian example is that a 20-year period is an insufficient length of time for individuals to correctly perceive long-term fluctuations in regional climate, especially in arid areas where rainfall is skewed to dryness. Unfortunately, a 20-year (or decadal-scale) climate fluctuation is long enough to lull inhabitants (and their governments) into a false sense of security about what to expect from their interactions with regional climate conditions. In fact, the West African Sahel had witnessed two previous extended drought periods earlier in the twentieth century.

Discounting is not just a problem for developing countries. As suggested earlier, similar examples can be found in the United States. Young farmers in the Midwest have come to discount the lessons and events of the Dust Bowl days in the 1930s (and even the lessons of the 1950s). As a result, they are often surprised when severe drought returns to the region. Frequently, people view past events that they may never have experienced personally (and, in some cases, even ones they *have* experienced) as aberrations, discounting the past and assuming that the world is different today.

At the other end of the time scale, when climate change exerts its influence in a matter of years or decades, it is essential that national authorities and international agencies discern the short-term variance from the long-term trends and react quickly. Failure to anticipate environmental changes and failure to respond in a timely and effective way is tantamount to courting disaster. For example, recent evidence suggests that ENSO warm events in the Pacific Ocean are linked (teleconnected) to below-average rainfall in southern Africa (e.g., Glantz 1994; Cane et al. 1994).

The 1991–92 ENSO event coincided with one of the worst droughts in southern Africa this century, which affected tens of millions of people.

Cane et al. (1994) show a strong correlation between sea-surface temperatures in the Pacific Ocean and maize yields in Zimbabwe. They suggest that such correlations be further tested and developed to provide early warning (up to one year) of impending drought and famine conditions. Such a lead time would enable international food security agencies to respond effectively. By discounting past droughts in the region, humanitarian agencies have developed a tendency to react to drought conditions, rather than to pursue a proactive course.

Just as there is a tendency for people to discount the past, rendering themselves vulnerable to recurrent events that should not be surprising at all, there is also a tendency to discount the future and, hence, increase their vulnerability. This, perhaps, can be best illustrated by the exploitation and depletion of parts of the Ogalalla aquifer in the U.S. southern Great Plains. This could be characterized by the following hypothetical reasoning: "Water is needed now. Don't worry today about what will happen ten years from now. By then, new technologies will save us." These sorts of surprises are related to creeping environmental change. In some instances, discounting the future may be justified on the grounds of the preferences of the people who have a stake in the future of a finite resource. One reason for a preference to discount the future is a blind faith that tomorrow's technology will solve the problems we create today (Brook 1997).

A related form of discounting occurs when we try to compare historical surprises with present-day surprises. There are many reasons why the damage from present-day climate surprises appears to be larger than from historical events. Take, for example, the case of hurricane damage. Observers tend to forget that inflation and the general increase in property ownership inflates the value of damage caused in modern times. In addition, there are far more people living in coastal areas now than there were at the turn of the century, as well as more commercial buildings, businesses, and supporting infrastructure. Pielke and Landsea (1997) examined the 30 most damaging hurricanes that have occurred in the United States since 1925 and converted them to a common scale of 1995 economics and demographies.

By escalating the effects of historical episodes, they determined that, in fact, recent hurricanes were no longer "the worst." Four of the top five occurred prior to 1950. Pielke and Landsea conclude that the United States has actually been quite fortunate in recent decades with regard to storm losses; they caution that the historical record suggests it may only be a matter of time before a single, devastating storm exacts $50 billion or more in damage. In support of this notion, hurricane-forecaster William Gray has suggested that the 1960–1990 period was a relatively inactive one compared to previous decades. He believes there is a high probability of a return to decades of more active hurricane seasons.

12 RESPONSES TO SURPRISE

Effective societal responses to climate fluctuations and change will require effective political action within the context of scientific uncertainty. Given the many ways that surprise can be manifested, as well as the inherently subjective nature of perceiving and anticipating events, societal responses to climate carry with them a heavy burden. The welfare of societies, economies, and the natural environment are all affected by actions of policymakers — and inaction is also a form of action.

Political decision makers often rely on the advice of experts whose inputs can be judged on the basis of either knowledge or opinion. Opinion necessitates an interpretation of uncertainty. Opinion is involved in the forecasting of future events, as well as the subjective determination of probabilities. The value of such opinion (more correctly, expert judgment) is based on an expert's familiarity with a body of knowledge underlying the opinion-forming process. This has been increasingly recognized since World War II, when think-tanks such as the Rand Corporation were developed (Cooke 1991). The ways in which experts form opinions and policymakers react to opinions can influence the degree to which future surprise is likely.

Cooke asserts that the opinions of experts are often assimilated by policymakers in a manner devoid of method. Because projections offered by experts in this context are based on uncertainty, and are therefore inclined toward bias, various experts in a particular field can offer dissimilar visions of the future. In order to evaluate the divergence of expert opinions, policymakers, according to Cooke, would do better to act on information that is subject to methodological scrutiny. It is Cooke's objective, in *Experts in Uncertainty*, to move toward the development of a methodology that can resolve heuristic bias, which cascades, through uncertainty, from science into the policy process. (See also Kellogg and Schware 1981.) Streets (1989) has suggested that integrated assessment can be used to mediate the flow of information from scientific research to policy analysis and can serve as a framework for quantifying uncertainty.

Risk assessment, which navigates uncertainty at a collective level, faces challenges that are not necessarily relevant to assessment at the individual level. Cooke asserts that the notion of utility — the perceived benefit from any course of action — that fuels the interpretation of probabilities operates only at the individual level. The subjective nature of probabilities is the point around which much of risk assessment revolves. The effective use of subjective probabilities at the collective level requires a consensus regarding what an optimal course of action may be. Expecting this consensus is, according to Cooke, naive (1991, p. 10; see also National Defense University 1978; Stewart and Glantz 1985).

Achieving consensus is often made difficult by the divergent interests of political actors. An expert's opinion may be embraced or rejected at the policy level, based on its compatibility with the needs of influential political figures at that moment. Uncertainty, as evidenced by the varying knowledge-based opinions of numerous experts (i.e., expert judgment), may be prematurely dismissed because of political bias (i.e., preference). (See Parisi and Glantz 1992 for a discussion of this problem with respect to tropical deforestation estimates.) Consensus, in this case, gives way to compromise, which is intrinsic to a rational political process. This subjectivity is dangerous; at the level of policy, experts have to "reckon with very powerful interests that can impose a significant 'drift' on experts' opinions" (Cooke 1991, pp. 44-45). The discarding of projections because of bias can enhance the likelihood of surprise.

Cooke explores efforts to overcome distortion caused by political preferences. He discusses the Rand Corporation's Delphi Method, which assesses the views of many experts whose opinions differ widely. This method strives for consensus by incorporating divergent views into one large-scale projection. Ideally, it reduces the weight of bias in the forecasting process.

The conclusions of experts can be correlated by eliminating error in the projection process; key elements of the scientific method — reproducibility, accountability, empirical control, and neutrality — can all contribute to the increased accuracy of expert opinion (pp. 81–83). Error can be further reduced by clarifying and questioning basic assumptions. Uncertainty in modeling, which is often accounted for by adding a series of qualifiers (caveats) to a statement, can be handled responsibly by accounting for its extent, as opposed to just its presence.

The mitigation of surprise will not necessarily lead to the complete absence of its impacts. In "Perspective 2000," Clark (1986) explains that uncertainty could be better managed, despite problems with prediction. Effective management, he argues, is based less on assessing the likelihood of surprise than on accepting the inevitability of surprise. Anticipating the possibility of surprise — but not of any specific surprise — is a valuable mechanism by which researchers and policymakers can better understand the dynamics of systems that often change in unexpected, sometimes destructive ways (Clark, in Newton et al. 1990). Given the inevitability of surprise, it is also important to address the uncertainty of societal responses to the consequences (Holling 1986). Kates and Clark (1996) suggest that surprise affords a "window of opportunity" (p. 10). Surprise indicates that previously unidentified or ignored or misunderstood factors may prove to be important. Shifting attention to these factors can reduce future individual and societal vulnerability to surprise.

There are at least two important approaches to addressing the uniqueness of a climate surprise. The first is to enhance the ability of scientific institutions to anticipate potential surprises. The second is to improve societal coping mechanisms, either in preparation for surprise or for a societal response to the surprise once it occurs. Myers (1995) suggests that societies need to "shift away from developing more knowledge about what we already know in essence, and toward attempting to learn something about what is virtually a black hole of knowledge and understanding." To do this, he suggests that "we need incentive systems that promote rather than discourage research into environmental unknowns," such as discontinuities and synergisms.

Brooks (1986) also underscores the importance of studying nonlinearities. He argues that there should be "a systematic search for examples of nonlinearities in the past" in order to gain more understanding of how nonlinearities in general might manifest themselves in the future. Brooks argues that research should also be launched to look at surprises based on the data that were available before the surprise occurred, to determine how it could have been anticipated, mitigated, or avoided. He suggests that researchers consider "what might have happened or what alternative choices might have been made, if the participants had been more sensitive to underlying, longer term trends." He further suggests considering what the secondary effects and consequences of those alternative actions might have been. This is somewhat similar to the "what is" versus "what ought to be" approach that has been used to identify better ways societies could have responded to recent extreme climate-related events (see, for example, Glantz 1977, 1988).

Slovic has argued that an understanding of the indirect consequences of an unfortunate event is essential to understanding its significance. He notes that "an unfortunate event can be thought of as analogous to a stone dropped in a pond" (Slovic 1987, p. 283). "Ripples" expand outward to affect related areas. As an example, he explores the impact on the future of the nuclear industry of the accident at Three Mile Island. The psychological "ripple effect" is especially important in understanding the public's perception of such atmospheric phenomena as climate change or stratospheric ozone depletion.

Kates and Clark (1996) propose possible policy actions to deal with surprise. In order to improve warnings of unexpected events, they suggest that we "monitor hazards not only where they are supposed to be, but also where they are not." They also believe in the value of "backcasting" (found in "Perspectives 2000" and a number of other sources cited in their paper; see also Glantz 1988), in order to be more sensitive to the impacts on society of potentially surprising climatic events. Backcasting encourages creative thinking and can be useful in attempts to anticipate surprises. Kates and Clark also suggest the use of historical retrodiction, "which examines empirical cases of surprise to determine whether the seeds of future surprises are apparent to hindsight and, if so, how they can be recognized ahead of time" (p. 31).

To improve the ability of the scientific community to anticipate potentially surprising events and to reduce the likelihood of surprise (e.g., by strengthening early warning systems), the Aspen workshop suggested encouraging synthesis work ("putting the puzzle together"), focusing more research effort on outlying events, supporting work on the edge of problem areas, promoting "process- as well as product-oriented research," pursuing backcasting activities, devoting more effort to "multiplicity and constructive duplication," instituting a "skeptical welcoming of advocacy science," airing the professional evaluation of unconventional views, and encouraging strategic paradigms to develop resilience in social and natural systems.

Most of these suggestions can be viewed as attempts to make individuals and institutions more aware of events that do not fit current expectations. It is hoped that this will make people more willing to alter expectations in constructive ways. These ideas could help to further Timmerman's goal of utilizing surprise by encouraging epiphanies and avoiding catastrophes.

Ultimately, we can reduce but not eradicate the likelihood of being surprised. Climate-related surprise in some form is inevitable. Thus, it is important to improve our ability to respond to surprises once they occur. Kates and Clark (1996) point out that in cases "where it is expectations regarding the timing or location, but not the causation, of hazards that are violated" (p. 30), there is a need for "quick and effective action to reduce the consequences" of those events. *Elements of Change 1994* offers a number of suggestions about how to deal better with surprise once it occurs, including the diversification of economic systems, avoiding an overdependence on one major technology (technological monocultures), providing robust social safety nets, developing region-specific adaptive management systems, developing effective disaster-coping mechanisms, encouraging organizational memory, and fostering social learning (Hasol and Katzenberger 1995).

Brooks (1986) draws on Breznitz's (1985) concept of "response pools" to suggest how societies might better cope with surprise. A response pool is an individual's "repertory of behavioral responses on which they draw to meet challenges presented by their environment." An individual or organization with a wide variety of behaviors and technologies to draw upon has greater flexibility to respond to change. These response pools affect the evolution of organizations and communities, much as genetic variability within populations affects biological evolution. Brooks stresses the need to avoid technological monocultures, in order to maintain a wide range of possible technological responses to surprising change.

Military scholars raise a number of issues concerning surprise attack that may be relevant for dealing more effectively with the possibility of climate surprises. Hybel (1986, p. 159) states that "it is imperative to recognize the critical role played by the concept *sense of vulnerability*. The chance of achieving surprise is higher when the victim's sense of vulnerability is low." Extrapolating this concept to climate surprise, it could be argued that the awareness of the possibility of surprise could itself increase our sense of vulnerability and, thus, decrease the chance of surprise.

Betts (1982) argues that military surprise often occurs not due to an intelligence failure, but due to an unwillingness of leaders to believe intelligence information they receive or an inability to respond to it appropriately. Some of the factors Betts feels are responsible for such leadership failures are clearly not relevant for climate surprises (e.g., leaders may be afraid to take steps to reduce military vulnerability because they do not wish to precipitate a war accidentally). Nonetheless, this issue could have relevance for climate-change surprise. It is important for political leaders to understand and be aware of the level of scientific understanding of the climate system and to be willing to act in an informed way on the scientific "intelligence" they receive.

Betts also emphasizes the importance of planning to deal with surprise if it occurs, rather than depending only on reducing the probability of surprise. Finally, he argues that *political and* *psychological factors responsible for military surprise may be more important than warning systems, but that warning systems are much easier to improve.* It may be worth considering these ideas in the context of climate-related surprises.

The "forecasting by analogy" approach to climate-related impact assessment was developed as a way to identify a society's ability to cope with environmental changes of both the quick-onset and the slow-onset (e.g., creeping) types. By looking back at recent societal coping tactics and strategies in dealing with extreme climate-related events, one can identify strengths and weaknesses in societal coping mechanisms. Doing so enables decisionmakers to identify in advance at least some of the potential first- and second-order impacts and surprises that could follow in the wake of future, similar climatic anomalies. Forecasting by analogy could help to uncover and prepare for potential climate and climate-related surprises (Glantz 1988, 1992).

The consideration of surprise can be useful (if not essential) for identifying creative ways to respond to climate-related impacts of surprise. For example, Pierre Dansereau states that:

> *The openness, the very naivete that permits the entry of surprise is at the source of invention and discovery. The effect of surprise is to break continuity, a necessity inherent even to the best-organized and coherent minds. Without an urge to surprise yourself, you have blocked all access to innovation and even to the understanding of reversals and revolutions. Should we proceed on the premise that change is inevitable and essential, then the ability to surprise becomes mandatory* (in Newton et al. 1990, p. 33).

Among the most important changes that one can make to improve responses to surprise are those that involve the incorporation of adaptive management techniques. It should also be understood, as Thompson et al. (1990) put it, that "Surprises — the mistakes we go on and on making — are profound truths" (p. 72). Adaptive management techniques seek to embrace surprise, and to experiment with policies in order to learn from surprise. Adaptive management structures are founded on resilience. As Timmerman notes, "Uncertainty is harnessed in the service of understanding."

In grappling with the possibility of a future rare-event, high-damage occurrence, the informed manager is confronted with the proaction/reaction dilemma. Should he/she take anticipatory action to prevent damage should the event occur, or is he/she better off saving the costs of anticipatory action and only reacting to the event should it occur? In fact, there is an array of possible actions and outcomes, as shown in Figure 5. Many of these outcomes result in money being wasted, which perhaps is the reason managers often decline to take anticipatory action, "betting" that the event will not occur.

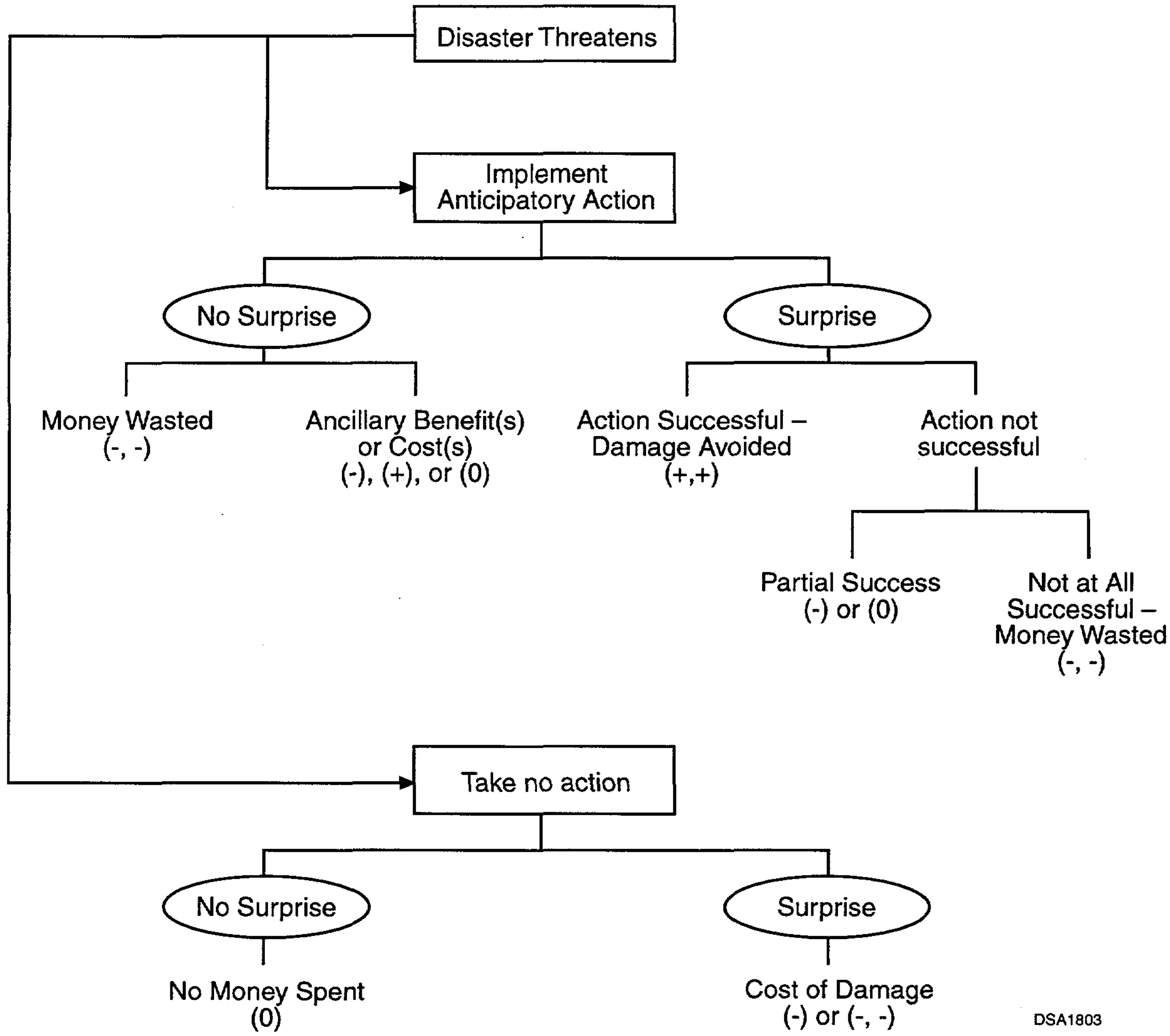

FIGURE 5 Possible Outcomes and Costs Associated with Anticipatory Action

Two examples can be cited to support the assertion that there are no easy answers to the proaction/reaction dilemma. The first example concerns the reaction of decision makers and technical analysts to a climate surprise. In 1983 and 1984 the Great Salt Lake rose five feet. This was completely unexpected, despite a ten-year history of planning by the State of Utah. Damage to recreation areas, waterfowl habitats, roads, drainage canals, and industrial facilities amounted to nearly \$200 million. Throughout the period 1983–1985, decision makers adopted cheap, "bandaid" measures to cope with the situation. In 1986 it became apparent that the lake level was due for a substantial additional rise, because of heavy precipitation earlier in the year in surrounding areas. During a four-year period (1982–1986), the lake level had risen a total of 12 feet, each year's increase being a surprise to local planners as well as to meteorologists. A more drastic solution to the problem was therefore initiated ("the west desert pumping project") at a construction cost of \$60 million. However, almost as soon as this project was completed, drier conditions began to prevail over northern Utah, and the lake level began to fall. Acrimony and resentment developed among the decision makers, their technical advisors, and their constituents and lasted for many years (see Morrisette 1988).

The second example concerns an attempt to anticipate an extreme climate-related event and plan for it. This example relates to drought forecasting in Washington's Yakima Valley in the mid-1970s. As a result of drought fears in the western United States in 1976, the Bureau of Reclamation performed a technical analysis in the first few months of 1977 of likely water supplies and demands in the Yakima Valley, a major agricultural production region. The Bureau forecast severe water shortages and devised a rationing scheme based on the principle of "prior appropriation" that prevails in the western states. The Bureau's forecast of reduced streamflow and the resulting rationing program effectively forced many farmers with junior water rights to devise expensive ways to protect their fruit orchards, to forego production entirely during the next growing season, or to take other drastic and costly actions they would not otherwise have contemplated. As it turned out, for a variety of identifiable reasons, more water was available in the rivers than had been predicted. The consequences included legal action against the U.S. Government by many affected farmers, community unrest, and loss of credibility of the governing bodies and their technical advisors (see Glantz 1982).

Numerous other climate-related examples from the United States and elsewhere on the globe could be cited: hurricane damage in the southeastern states; drought in the Mississippi River Basin in 1987 and 1988, followed in 1993 by flooding of midwestern communities established in the Mississippi floodplain; and the unprecedented flooding in the Netherlands that occurred in early 1995. Each is an example of a climate-related surprise, and each illuminates different aspects of the extraordinarily complex relationships among scientific knowledge and its use, the demands made of decisionmakers, and the impacts of climate and climate-related forecasts on the lives and livelihoods of members of the public. Integrated assessment models that limit their spheres of influence to average or typical values — or even to expected extreme values — may be doing a disservice to decisionmakers and the constituents they serve. Organized and directed thinking is urgently needed in this area.

The property insurance industry is understandably concerned about variability in the frequency and severity of extreme weather events. The annual insured cost of windstorms worldwide has risen from $0.5 billion in the 1960s to over $11 billion in the early 1990s (Dlugolecki 1995). The industry is finding it hard to cope with such losses and has begun to limit coverage and raise premiums. The industry is taking action to improve its risk assessment methods, develop techniques for event prediction, and become involved proactively in such issues as land use in flood plains and new construction design.

Although the industry is still somewhat vulnerable to large-scale disasters, Cochrane (1993) has concluded that the effect of a $100 billion natural catastrophe could be absorbed (see Pielke and

Landsea, cited above, regarding the possibility of a "$50 billion hurricane"). While this may be true at the national level, there would undoubtedly be major disruption of local economic institutions, with failures at the micro level (Dlugolecki 1995). Low and Shen (1996) estimate that a hurricane that struck both Miami and Fort Lauderdale would incur as much as $100 billion damage and bring down many local financial institutions.

13 JUDGMENT AND DECISION RESEARCH

Judgment and decision research concerns itself with the methods people use to cope with uncertainty and complexity in their environment. Since climate surprises are a direct reflection of uncertainty and complexity, this research provides insight into the relationship between climate surprises and decisionmaking.

In the following sections, we briefly review the two major approaches to judgment and decision research: *coherence* and *correspondence*. Although these approaches are complementary, they have developed in relative isolation from one another. Adherents of one approach rarely practice the other, and the results may seem contradictory to an observer who is not familiar with the fundamental meta-theoretical differences between the approaches.

Finally, we discuss the implications of both approaches for understanding climate surprises. One approach suggests that surprises are due in part to faulty understanding of environmental uncertainty. The other approach suggests that surprises are a necessary, unavoidable consequence of adapting to an uncertain environment. These conclusions are not contradictory. *Surprise is a product of both the environment and of human cognition.*

13.1 OVERVIEW OF RESEARCH APPROACHES AND RESULTS

Hammond (1996a,b) identified two major traditions of judgment and decision research: coherence and correspondence. Each is briefly described below.

13.1.1 Coherence Research

Taking uncertainty as their point of departure, one group of researchers, led by Ward Edwards (1954), recognized in the 1950s that there are elegant formal models for dealing with uncertainty: probability theory, Bayes theorem, decision theory, inferential statistics, and others. They asked, "How do people match up against these models?" This was the beginning of what is now known as coherence research. In 1955, it was reasonable to ask the question, "Are people intuitive statisticians?" In other words, can normative theories of decisionmaking under uncertainty serve as descriptive models of human behavior? Four decades later, we know the answer to that question: "Definitely not! Well, maybe — that is, sometimes, under some conditions, but not always." Actually, the answer is, "It depends."

It is true that the inability of people to apply logical or mathematical or probabilistic or statistical reasoning to problems that require it has been repeatedly demonstrated in laboratory studies. Many books and hundreds of papers have been written on people's inability to apply statistics or to reason in accordance with probability theory when it is appropriate. A course on the psychology of judgment and decisionmaking might consist entirely of examples of the limited reasoning ability of college students in psychology laboratories and the shortcomings of professionals who should know better. In fact, there are texts that do just that (e.g., Plous 1993).

Here is just one example of research in the coherence tradition (Kahneman and Tversky 1972). Suppose that there are two programs in a high school. Boys are a majority (65%) in program A, and a minority (45%) in Program B. There is an equal number of classes in each of the two programs. You enter a class at random, and observe that 55% of the students are boys. What is your best guess? Does the class belong to program A or to program B?

Most subjects (67 out of 89) picked program A because the class had more boys, and so did program A. This is an example of an important heuristic: "representativeness" (Kahneman and Tversky 1972). We judge an event to be a member of a set of events if its characteristics are similar to our belief about members of that set. This is a good rule of thumb in a lot of situations, but not this one. Some people might feel that the answer could be "either program," because 55% is midway between 45% and 65%. They would have noticed a quantitative relationship, and made a reasonable guess, but they also would be wrong. The correct answer is Program B, because the variance of a binomial will be larger for $p = 0.45$ than for $p = 0.65$. Therefore, there will be more variability in the number of boys in Program B's classes, and it is more likely that a class in Program B will have as many as 55% boys.

Although any statistician can calculate the answer to this problem, it is surprising to most people. This is an example of surprise that results because human intuition does not always follow the rules of probability theory. Why does it matter that students (in this case Israeli high school students) fail such a difficult question? It matters, because, unfortunately, they also fail much easier questions. Furthermore, it is not only students who make these kinds of mistakes. They have been found in studies of the decisions of scientists, statisticians, physicians, and other professionals.

Eddy (1982) asks us to imagine that a physician has a patient with a breast mass that he thinks is probably benign. He interprets "probably" as a probability of 0.99. The physician is 99% sure, but not completely sure, that the mass is benign. This is his "prior probability." The physician orders a mammogram and receives a report that the radiologist thinks the mass is malignant. What should the physician do? If he read the literature available in 1982, he would find statements like: "The accuracy of mammography is approximately 90 percent"; "A positive report of carcinoma is highly accurate"; and "The accuracy of mammography in correctly diagnosing malignant lesions averages 80 to 85 percent."

If he wanted more specific information, he could find these data, indicating a sensitivity of 0.79 and specificity of 0.92 (see below).

Results of X-Ray	If Malignant Lesion (cancer)	If Benign Lesion (no cancer)
P (Positive test) =	0.792	0.096
P (Negative test) =	0.208	0.904

The physician's subsequent action for this patient might be influenced by his judgment about the likelihood that the woman has a malignant lesion. Eddy sampled 100 physicians and found that most of them thought the probability would be around 75%. We can calculate that likelihood using the data given and Bayes theorem:

$$P(ca|\,pos) = P(pos|\,ca)P(ca) \,/\, [(P(pos|\,ca)P(ca) + P(pos|\,be)P(be)], \text{ or}$$
$$P(ca|\,pos) = (0.792)(0.01) \,/\, [(0.792)(0.01) + (0.096)(0.99)] = 0.077$$

So, the actual probability is about 0.08. The physicians' judgments were off by almost a factor of 10! Does this matter? It only matters if the statement above is true, that is, "the physician's subsequent action might be influenced by his judgment about the likelihood that the woman has a malignant lesion." In fact, this is a basic tenet of coherence research:

> *Probabilistic thinking is important if people are to understand and cope successfully with real-world uncertainty.* (Lopes 1991, p. 66).

Lola Lopes, a former president of the Judgment and Decision Making Society, wrote that this statement is generally accepted uncritically by most people in the field, but not by everyone (e.g., Gigerenzer and Murray 1987).

The first paragraph of a recent paper by Timmermans et al. (1996, p. 107) is typical:

> *Accurate estimations of probability in diagnosis and prognosis are important for physicians, because these probabilities influence their diagnostic and therapeutic decisions. Objective probabilities, based on epidemiological research, are often not available. In these instances, physicians must rely on their own judgment and apply their probability estimates to* individual *patients. Research has shown that the accuracy of probability estimates of both experts, such as physicians and of lay people in general is often inadequate ....*

Notice the two elements: (1) probability judgments are important because they influence decisions made under uncertainty; and (2) people are not very good at making probability judgments.

The statement made by Timmermans et al. (1996) could easily be adapted for climate surprises as follows:

> *Accurate estimations of probability of climatic events are important for climatologists, policymakers, and the public because these probabilities influence their decisions (e.g., their decision to prepare for climate change or for unprecedented events such as the rise in the level of the Great Salt Lake). Since climate is changing and the climate record is short (except for some tree-ring and ice-core studies), objective probabilities are rarely available. As a result, the public and policymakers must rely on their own judgment and apply their probability estimates to guide their climate-related decisions. Research has shown that the accuracy of probability estimates of both experts and lay people in general is often inadequate.*

Many judgment and decision-making papers contain statements like this. Support comes from a line of research called the "heuristics and biases" approach, after the title of a classic paper by Tversky and Kahneman (1974) called "Judgment under uncertainty: heuristics and biases." The heuristics and biases paradigm has inspired a large body of creative work by Tversky and Kahneman, their students, their colleagues, and many other researchers. An overview of this research is provided by Cooke (1991), which is discussed elsewhere in this report.

Perhaps inevitably, this successful work has also become controversial. Studies have shown that differences in instructions to subjects or other experimental arrangements can produce more positive results (Gigerenzer 1991, 1996; Kruglanski et al. 1984). Some have argued strongly that the results of these laboratory studies have little to do with how we function in the real world (Ebbesen and Konecni 1980). After all, despite being poor intuitive statisticians, humans have accomplished a lot in an uncertain world. It has also been argued that the results have been misinterpreted and oversold (Lopes 1991).

The implications of coherence (heuristics and biases) research for climate surprises is clear. If people are not good intuitive statisticians, then they are likely to make erroneous probability judgments, and they will be surprised by the occurrence of events they did not expect (because they believed them to have low probability, or because they hadn't thought about them at all), or they will be surprised by the nonoccurrence of events they did expect (because they had judged them to have high probability). If people act on erroneous beliefs, they are likely to be unprepared for surprise.

As Hammond has pointed out, heuristics and biases research exemplifies one theory about what constitutes good judgment. This is called "coherence theory." Coherence research measures the quality of judgment against the standards of logic, mathematics, and probability theory. Coherence theory argues that decisions made under uncertainty should be coherent with respect to the principles of probability theory.

Heuristics and biases research has produced many insights, but there is another approach to judgment and decision research that is equally important and leads to somewhat different conclusions. This approach is based on a different standard for measuring the quality of judgment, called "correspondence theory."

13.1.2 Correspondence Research

Correspondence research measures the quality of judgment against the standards of empirical accuracy. Correspondence theory argues that decisions under uncertainty should result in the least number of errors possible, within the limits imposed by irreducible uncertainty. For example, a correspondence theorist would want his/her doctor to be accurate. In choosing a doctor, he/she would want to know the doctor's past record of accurate diagnoses and errors. If the doctor has a history of excessive errors, he/she would seek treatment elsewhere. It may well be that doctors who know probability theory are more accurate, but the correspondence theorist would want proof.

Remarkably, there has been very little research on the relation between coherence and correspondence. That is to say, the relation between statistical rationality, which is the focus of coherence research, and accuracy, which is the focus of correspondence research, has rarely been studied.

For example, skill in making daily high-temperature forecasts is measured by comparing the forecasts with actual temperatures for a number of days. We can summarize skill over the period by using various statistical measures, such as mean squared error and correlation coefficients. Weather forecasting is clearly judgment under uncertainty, but it does not require explicitly making judgments about probability (although another type of forecast — probability of precipitation — does involve judging probabilities). How accurate are the forecasts? Why are some forecasters more accurate than others? How could the forecasts be made more accurate? These are questions the coherence researcher asks. It is obvious that similar questions could be asked about climate forecasts and expectations, and they could be asked about the climate expectations of lay people, policymakers, and climatologists.

It could be that forecasters who are able to understand and apply probability theory make better weather forecasts, even of temperature, but no one has checked. The separation between coherence and correspondence research has been so complete that the two approaches have almost never been used in the same study. This situation was described by Hammond (1996a) in a recent paper; he calls for a convergence of approaches.

Correspondence researchers are interested in how people achieve empirical accuracy. They rarely study probability judgments. They study judgments under uncertainty, but not judgments about uncertainty. They do many laboratory studies, but they are particularly interested in situations where people are making familiar judgments that are important to them. Examples include teachers, clinical psychologists, weather forecasters, climatologists, stockbrokers, bank-loan officers, accountants, physicians, nurses, and patients. They analyze the sources of empirical accuracy and error, and they focus on such things as the reliability of judgment and the use and misuse of multiple, interrelated, fallible, items of information.

The results of hundreds of correspondence studies can be summarized briefly: Human competence in making judgments and decisions under uncertainty is impressive. However, sometimes performance is not. Why? Because sometimes task conditions degrade the accuracy of judgment (Hammond 1996a, p. 282).

If humans are generally competent when making judgments and decisions under uncertainty, why do they seem to perform poorly in anticipating and preparing for climate surprises? Correspondence research suggests that our inability to make probability judgments that are in accordance with statistics and probability theory is only part of the problem. An important aspect of the problem is the nature of the task. There are two task conditions that inevitably lead to poor predictions and decision-making errors. One is a high degree of uncertainty and another is a low rate of occurrence. Climate surprises have both these qualities.

Within the correspondence approach, many researchers have been influenced by the work of the psychologists Egon Brunswik and Kenneth Hammond. Although many would not call themselves "Brunswikians," Brunswik's (1952, 1956) lens model and theory of probabilistic functionalism and Hammond's social judgment theory and cognitive continuum theory provide a theoretical framework for correspondence research. Although Brunswik died in 1955, his argument that psychology should study both the organism and the environment has not.

Hammond (1996b) has recently argued that coherence and correspondence represent two distinct kinds of judgmental competence that have been studied by different groups of researchers. He points out that humans share with other animals a "remarkable degree of competence in our judgments about the physical world around us." This kind of "correspondence competence" has evolutionary roots and is innate. The other kind of competence, "coherence competence," is not something we are born with, but we are born with the "potential for achieving it." Our ability to learn mathematics, logic, and probability, and to apply that learning to judgment and decisionmaking, is unique among all species.

13.2 IMPLICATIONS FOR CLIMATE SURPRISES

Surprise is clearly subjective, because what is surprising to one person is not always surprising to another. The expectations that are necessary for surprise are also subjective. To say that they are subjective, however, does not mean that they are totally independent of reality. Expectations are formed in different ways, depending on whether we face a familiar situation or a new one. In familiar situations that we encounter repeatedly, we acquire expectations through learning. For example, we expect daylight to begin at a certain time each morning (depending on season). If it did not, we would be both surprised and concerned — and probably afraid. If we commute by car to work, we learn to expect certain events along the way, like having to stop for most of the traffic lights. If we make the trip without having to stop, we are surprised and probably delighted. We know that this was a chance occurrence, however, and the next day we expect more red lights. *Expectations that are learned from experience are based on* ***correspondence*** *— that is, they are derived from empirical observation.*

We also have expectations in unfamiliar situations. If we go to visit an unfamiliar country, we have expectations about what we will find, based on reports from people who have been there, guide books, and travelogues. If we do not find what we expect, we are surprised. We may feel misled, or we may decide that things have changed and that the information we were given was dated. *Expectations that are derived from theories or stories, rather than from actual experience, are based on* ***coherence*** *— that is, they are deduced from what we know or think we know.*

These examples illustrate two points. First, expectations are usually grounded in experience — either personal experience or the experience of others. Second, when we are surprised, we seek a coherent explanation. If none can be found, the surprise may lead to concern or fear — or, in the best of circumstances, learning. Since some surprises are unavoidable in an uncertain world, the best we can do is make use of them as opportunities for learning. The psychological research reviewed elsewhere in this report has shown that surprises provide important learning opportunities. This may be the "silver lining" for some climate surprises.

13.2.1 Coherence Research (heuristics and biases)

We argued above that lack of coherence in judgment can lead to surprises. Judgments about the likelihood of events have been shown to be flawed under certain conditions. According to the representativeness heuristic, expectations about which events are more likely will be influenced by recent and memorable events, rather than by the long-term climate record or model-based predictions of climate change. That can lead to erroneous or biased expectations, which increase the likelihood of surprise. Various attempts to "de-bias" judgments have met with only limited success (e.g., Arkes 1991; B¸y¸kkurt and B¸y¸kkurt 1991; Lopes 1987; and Sjoberg 1982).

An example of how even the judgments of experts can be subject to biases is provided by Stewart and Glantz (1985). They reviewed a survey of climatologists conducted by the National Defense University (1978) that concluded that climate change should not be a major concern in future agricultural planning. Stewart and Glantz showed that the method used did not account for known biases in probability judgments, and that the conclusion was based on averaging divergent viewpoints. Therefore, the conclusions of the study were only partly indicative of the state of expert knowledge at the time. They were strongly influenced by the method used to elicit judgments.

Although some climate surprises may be caused by biased probabilistic expectations, that remains to be empirically demonstrated. There are several untested links in the chain stretching from "heuristics and biases research" to climate expectations and decisionmaking. This would be a fruitful area for future study of the nature and causes of climate surprises.

13.2.2 Correspondence Research

Correspondence research, particularly that conducted within the "lens model" framework, shows that people, like other animals, are able to adapt to an uncertain environment. That adaptation involves learning about relations in the environment and learning to use "multiple fallible indicators" to make judgments under uncertainty. In most cases, successful adaptation involves identifying the most relevant cues in the environment and making use of regularities that are often masked by the noise resulting from complexity and uncertainty. Thus, before modern weather forecasting, farmers learned to rely on the cues that were available to them to predict the weather by observing regularities.

This method of adapting to the environment works well for common events, but not for rare or unusual or unprecedented events. Thus, surprises are an inevitable by-product of a generally successful strategy for coping with an uncertain environment. It can also be argued that a strategy that focuses on surprises can significantly reduce the efficiency of coping with ordinary events. Thus, one lesson of correspondence research is that some climate surprises are a necessary result of the process of adapting to an uncertain environment; strategies aimed at eliminating all climate surprises are not only doomed to fail, but they may result in costs that exceed their benefits. The following section further elaborates on this point.

13.2.3 Duality of Error

Surprises are a natural consequence of environmental uncertainty, and there are usually costs involved in anticipating surprises. In making decisions under uncertainty, one must be concerned about two kinds of error. Consider the 2×2 decision table, representing 1,000 hypothetical climate events, below:

Outcome	Decision or Action: Do Not Prepare for Climate Surprise	Decision or Action: Prepare for Climate Surprise
Climate surprise occurs	2	8
Climate surprise does not occur	600	390

The events might be things like "a 15-foot rise in the level of the Great Salt Lake" or "a 500-year flood in Grand Forks." The frequencies in the table indicate that, over a 1,000-year period, the event is rare, occurring only 10 times, for a base rate of 0.01. In the real world, many climate surprises are much rarer. The table also indicates that there is uncertainty about when to prepare for surprise. The uncertainty results in errors of two kinds. There are 390 "false positives," that is, 390 times preparation was made for an event that did not occur (see Glantz 1982). There are also two "false negatives;" that is, on two occasions no preparation was made for an event that did occur.

The climate surprises of most concern are the false negatives. These are the events that, for whatever reason, we do not prepare for, and the consequences are serious. It is an inevitable consequence of uncertain events with low base rates, however, that we can avoid false negatives only at the expense of a great number of false positives. Each false positive has a variety of costs, depending on the event. Although the costs of a false positive are less than the costs of a false negative, they occur in greater numbers. It is also likely that false positives eventually lead to a greater chance of false negatives, because of the "crying wolf" phenomenon.

One consequence of uncertainty about future climate and the duality of error is disagreement among experts and policymakers. As Hammond (1996b) argues, each kind of error will develop its own constituency. One group will argue that policy should focus on preventing false negatives, while another will argue the same for false positives. If one side prevails, there will necessarily be more of the other kind of error, and eventually policy will focus on preventing that error. An oscillation of policy will be the result. Moreover, disagreement is more likely to lead to inaction than to action. This contributes to inertia in preparing for surprises, which may magnify their effects.

Climate surprises, preparation, and response to unusual or unprecedented climate events result from a complex interaction between an uncertain environment and human behavior within that environment. Research on judgment and decision-making suggests that humans are unprepared to make certain kinds of decisions under uncertainty, and, at the same time, that we have adapted extremely well to living in an uncertain environment. The implications are that some climate surprises may be avoidable, but others are the inevitable result of environmental uncertainty. Efforts to reduce the negative impacts of climate surprises by reducing uncertainty about climate are important. Without such a reduction in uncertainty, efforts to eliminate climate surprises may bear a high cost due to a large increase in false positives.

14 HUMOR STUDIES

To researchers preoccupied with climate change, it may be a "genuine surprise" to them to learn that the study of humor can provide insights into climate surprise. But there are academic scholars whose research focuses on improving our understanding of humor. Humor studies provide insights into several aspects of surprise, because jokes rely on an element of surprise to be effective. Humor studies introduce the concept of "expectation" — the gap between what one expects to occur and what actually occurs. The width of this gap can have a direct bearing on whether a joke is funny or not, as does the nature of any "explanatory" material filling the gap.

Why are jokes funny? In order to be viewed as funny, jokes are frequently dependent upon some form of surprise. The degree of humor in a joke is often dependent on the way the storyteller sets up the listeners with certain expectations and then violates those "guided" expectations by delivering a "punch line" containing unexpected and counterintuitive information. (This is analogous to setting up one's opponents in order to surprise them, as Kam noted with regard to military operations.)

Giora (1991) elaborates on "verbal jokes whose point consists in semantic ambiguity." Jokes that rely on surprise originating from intentional or unintentional ambiguity can be useful for considering some of the kinds of surprise that can arise as a result of scientific uncertainty in the climate-change issue.

An expectation with which an event can be contrasted must be generated by the storyteller, or there is no surprise and the joke will not be humorous. As Thompson et al. (1990) suggest in their third axiom of surprise, an event "is actually surprising only if it is noticed by the holder of that particular set of convictions." People evaluate new events that confront them through the matrix of expectations that they hold at a given time. With regard to joke-telling, an expanded matrix of expectations needs to be created by the storyteller. Giora explains that in order to be funny, jokes must obey what she calls the "relevance requirement for text completeness."

The relevance requirement of humor was illustrated in an experiment performed by Ertel (cited in Nerhardt 1977). In this experiment, subjects were asked to read portions of text with varying degrees of grammatical error. Ertel's study discovered that the texts that the subjects found most funny were the ones that had a moderate level of variation from proper language. Texts that differed by a wide margin were not considered as funny; no expectation had been generated, so none could be violated. Similarly, texts that were too similar to normal language were also viewed as not being funny, because there was no element of surprise.

Again, according to Giora (1991), humorous jokes must also obey the "graded informativeness requirement" and must, therefore, cause "the reader to perform a linear shift." Giora says that "for a text to be a joke, it is necessary that it proceeds directly from the unmarked to the marked constituent so that the gap is maintained and felt" (p. 475). (Giora's "constituents," or "sections of words" in a joke, are different sets of information.) As she later states, "explaining a joke kills it by filling in the gap." By analogy, for an event to be surprising there must be some sort of contrast between the event and expectations. A surprise requires both a punch line and a perceived gap between the punch line and established expectation. As the "gap" is filled with information, the degree of surprise is reduced.

Examples illustrate this condition. The first example is a joke that successfully maintains the relevance requirement but violates the listener's expectations:

> *"Did you take a bath?" a man asked his friend who had just returned from a resort. "No," his friend replied, "only towels. Is there one missing?"* (Giora 1991, p. 472)

In this example, the expected meaning of the phrase "take a bath" has been modified by the storyteller to mean "steal," thereby setting up an expectation about how this story might end. The next example, as a variation of this joke, illustrates what happens when the last piece of information falls within the realm of an expected possibility.

> *"Did you take a bath?" a man asked his friend who had just returned from a resort. "No," his friend replied, "just a shower."* (Giora 1991, p. 473)

In the first example, the punch line is only somewhat informative because "given the set of things that can be done in a resort place, it is cognitively distant from the prototypical members" (Giora 1991, p. 473). But the second example does not create a major shift in expectations — it is not surprising, and therefore not particularly funny.

Adding more information in the form of "gradually informative messages" allows expectations to be adapted gradually, but it also reduces the element of surprise associated with the punch line and thus kills the joke. Giora (an Israeli) gives another variation of the joke:

> *"Did you take a bath?" a man asked his friend who had just returned from a resort. "No," his friend replied, "just a shower. But, to tell you the truth, I also did what all Israelis do in hotels, I took ash-trays and towels."* (p. 475)

Giora's study of humorous texts and drawings found that people have a tendency to look for what they expect. This tendency is produced by the need to process information efficiently in a complex world (as they perceive it). She found that "jokes manipulate our tendency to minimize the number of readings .... Possibly, what enables such a manipulation of ambiguity is our tendency to save mental effort" (Giora 1991, p. 481). Thus, people tend to interpret things according to their expectations.

The discussion of jokes and what makes them humorous has relevance to several issues related to climate surprise. One in particular is the need for a disjunction between expectations and the real world (analogous to the punch line). Today, there is considerable speculation about the kinds of surprises governments and individuals might expect from a gradual warming of the global atmosphere over the next several decades. However, what seems to be surprising to us today may actually prove not to be a surprise as we get closer to the expected event, such as a 2°C warming or a 50-cm sea-level rise by 2050 or 2070. These are both creeping environmental changes and, as such, one could argue that societies will tend to adjust their activities and their perceptions in such a way that the gap between perception and the expected surprise will decrease as time goes on. This is especially true in the event of sea-level rise, as witnessed in two examples: the rise of the Great Salt Lake in the early 1980s (Morrisette 1987) and the rise in the level of the Caspian Sea since 1978 (Glantz and Zonn 1997). As we approach the years designated for change to appear, the surprise associated with the change could be totally eliminated.

15 METHODS FOR INCORPORATING THE CONCEPT OF SURPRISE INTO CLIMATE ASSESSMENT MODELS

The difficulty of dealing with climate change in a quantitative manner is accentuated by several facts. First, the changes are occurring on a global scale in ways that require a global response, yet impacts are manifested at the local level. Second, the changes are occurring slowly over time, yet they are punctuated by extreme events that may have catastrophic consequences. The variations of temporal and spatial scale are compounded by the natural variability of the climate system. Third, scientists do not yet have a complete understanding of the workings of the planet's ocean-atmosphere-biosphere system, and so all predictions of the pace and scope of climate change are subject to uncertainty. Fourth, to develop truly effective strategies for dealing with climate change, integrated assessment models are essential, and these require the linkage of socioeconomic models to physical models that describe the evolution of the planetary system.

The socioeconomic models, like the physical models, are based on an imperfect understanding of human social systems, and so are themselves subject to a great deal of uncertainty. The issue that is most prominent in the third and fourth points is the issue of uncertainty. Given that our models cannot predict with complete accuracy the evolution of the earth's climate and mankind's economic systems, we will no doubt face surprises in the future.

The challenge is to incorporate uncertainty into our models of climate change and its interaction with human civilizations, so that surprises can be better anticipated. This section examines more closely the question of uncertainty and how it might be modeled in a variety of ways within the current generation of climate-change models.

The question of incorporating uncertainty within models of natural and human systems in order to better anticipate surprises is not a new or unique one. In other disciplines, similar problems are encountered that require similar modeling techniques. There is much to be learned by a cross-disciplinary examination of problem-solving. Examples range from models based on stochastic control theory that are used to maneuver rockets and airplanes while their trajectories are being randomly perturbed by atmospheric disturbances, to models from the stochastic optimization literature that are used to determine investment portfolio configurations that promise the highest expected return at a given level of risk.

Many integrated assessment models have been built around an optimization framework (Manne and Richels 1991). In these models, the components that describe the physical response of the earth's ocean-atmosphere system to greenhouse-gas inputs of anthropogenic origin are usually highly simplified (sometimes linear), dynamic models of the output of general circulation models. In particular, the models link the input of greenhouse gases to carbon-stock dynamics and temperature changes over time.

These models are usually represented as a series of nonlinear or linear equations that link variables from one (time) stage to the next. The components of the models that describe human systems also include a series of equations that model the dynamics of population, capital, production, and consumption over time. The element that drives the whole system of equations, though, is often an objective function to be maximized that models the preference for consumables by human populations over time. That is, the entire system of equations can describe many trajectories of social and physical evolution. The objective function, and the goal of finding its maximum, determines which of the many possible trajectories will actually occur. It is hoped that this properly simulates the way in which the dynamics will occur in reality.

These types of models can handle the concept of uncertainty in a number of ways. The most straightforward and least realistic way is to simply explore the nature of future states through *scenario analysis*. What this means is that different data sets that represent different hypothesized trajectories of the random components of the model (e.g., interest rates, damage rates that connect temperature increase to economic cost, and ocean uptake of carbon over time) are inserted into the deterministic model. The model is then run with each data set separately to see how the modeled trajectory of development changes. An analysis of how the trajectory changes as the scenario changes can give the modeler some idea of the importance of the different elements of uncertainty.

The biggest problem with this modeling strategy is that it does not attempt to model uncertainty explicitly. That is, no attempt is made to change the model so that uncertainty becomes an integral part of its structure. Thus, the presence of uncertainty in our current decisionmaking cannot be properly modeled.

A clear example of the limitations of scenario analysis comes to us from the field of finance. In finance, one seeks to develop models that determine how portfolios are constructed. If one models this with a deterministic model and then explores how decisions change as the scenarios change, one finds that when a scenario in which stocks have high returns and bonds are low is looked at, the model suggests that all money be put in stocks. Likewise, if one looks at the opposite situation, the model suggests that all money be placed in bonds. At no point does the model suggest that a portfolio be built in order to properly hedge against surprise returns on investment.

The same result occurs, albeit in a potentially more complicated way, if integrated climate-change issues that are fundamentally uncertain are modeled by using deterministic models and scenario analysis. As a result of this, alternative techniques are required. Note that with most of these techniques, the underlying randomness is required to be described by probability distributions (e.g., distributions are estimated to describe the likelihood of carbon accumulation by the oceans being high, medium, or low).

Chance-constrained programming is one potential method of dealing with uncertainty. In this framework, the optimization model of integrated assessment has probabilistic constraints added that require certain conditions be met with prescribed probabilities. Thus, for example, one might require that any trajectory of human economic development ensure that the probability of significant sea-level rise in the southern hemisphere be no more than 0.1%. This kind of constraint would make sense if the goal of the integrated assessment model were to find a feasible path of economic growth that kept the likelihood of catastrophic events to a minimum. It would also make sense if one could show that decision makers consistently make decisions that avoid excessively large risks of significant sea-level rise over time.

Decision-making under recourse is another potential means of modeling uncertainty. In this modeling framework, decisions are divided into those decisions made prior to the realization of uncertain or surprise events, and those decisions made after and in response to initial decisions and the realization of uncertain events. Examples include the finance model already discussed, in which initial decisions regarding the structure of a portfolio occur prior to knowledge about the eventual returns of various financial instruments, and recourse decisions (e.g., updating the portfolio) occur after the realization of returns. The objective function of the model must be altered to account for the presence of uncertainty.

The way in which the restructuring occurs is to have a deterministic component of the objective function that describes the payoff or cost associated with the first-stage decisions, and then a second component of the objective function that is some combination of the moments of the payoff or cost from the second-stage decisions. A common moment to use is the first moment or expected value. Including some sort of second-moment information ensures that the objective function will drive the model toward a solution that considers the importance of risk.

In practice, some combination is often used, like that in the Markowitz modeling of efficient portfolio construction. Decision-making with recourse can be extended to any number of decision stages. That is, one can have random variables that become known to the decision maker at different points during the time horizon being modeled. Those decisions made prior to particular realization points are considered first-stage decisions with respect to that realization point. They might very well be recourse decisions, however, for the realization point of a random variable, the value of which becomes known to the decision maker at an earlier date.

In this multistage case, the expectations and moments are nested. Efficient computational techniques exist for models of decision-making with recourse. The model of decision-making under uncertainty with recourse can also be extended to robust optimization. In this approach, strategies of even greater robustness than those provided by the standard approach are sought by restricting the amount of recourse that can be undertaken once the realization of the random variable is observed. This is important when it does not make sense for the system to undergo dramatic and fast changes in response to observations of random events.

For example, the world's economy will very likely not change overnight into one where fossil fuels are not burned — even if it is discovered with 100% certainty that life as we know it depends on this happening in a very short time. This kind of change is too great for the world to undergo in a short period of time. By restricting the "spread" of the recourse decisions, one finds hedging decisions that are very robust against a variety of outcomes and more meaningful in a policy context.

Both the chance-constrained programs and the various types of decision-making problems under uncertainty with recourse require some knowledge of the probability distributions governing the random elements of the model. These distributions may be very hard to determine. There are several methods for tackling this problem. One technique requires that these distributions simply be estimated, and then the sensitivity of the results to perturbations of the distributions can be determined. In this way, the analyst can determine how robust the hedging solutions are to uncertainty regarding the uncertainty in the model.

Another technique involves *forming a min-max or max-min problem*, depending on the direction of optimization of the underlying optimization model. In this technique, one tries to determine the trajectory of development that is optimal for the worst possible distribution from a family of distributions that, perhaps, possess the same expected value or standard deviation. What is meant by worst is the distribution that is most unfavorable in terms of the optimization problem under uncertainty. Thus, the trajectory of development that is determined will be extremely robust, because it is found to be the best solution given the fewest assumptions on the distributions governing the uncertain elements of the model. Both of these techniques make the problem significantly more difficult to solve, however, because it is no longer an optimization problem, but, rather, a saddle-point problem.

These general ideas can be extended in many directions in order to richly model a variety of situations within an integrated assessment model. One example might be the incorporation of functions within the constraints of such a model that are themselves the solutions to other optimization problems (e.g., in Stackleberg games, the decision space of one agent might be influenced by the decisions of another agent). Many other combinations are possible.

Another kind of integrated assessment model is one based on *discrete event simulation*. These models are very good for describing human systems like those found in production or manufacturing environments. They might work very well to create integrated assessment models that incorporate uncertainty, if combined with continuous time models (or their time-discretized brethren) that describe the evolution of the physical system.

Many kinds of problems can be looked at by using this formalism. In particular, maximization of expected utility given a fixed horizon, maximization of utility given a random stopping time that corresponds to the nth event (e.g., an event might be the occurrence of a particular weather pattern, or economic phenomenon), and maximization of utility given a random stopping time that corresponds to the nth event of a particular type (e.g., the horizon is considered to be reached when the nth world recession is observed). These models are particularly difficult to solve, because they are usually highly discontinuous. Progress has been made, though, in tackling these difficult problems (Glasserman 1991; Ho and Cao 1991; Rubinstein 1986; and Glynn 1987).

Another class of integrated assessment model is based solely on systems of equations (that are themselves often derived from systems of differential equations), with no guiding explicit objective function needing maximization or minimization. The systems of equations simply describe the physical and economic dynamics of global change. Uncertainty can also be incorporated into these models by drawing on work from the *stochastic control theory* literature (Astrom 1970).

In these models, the co-evolution of the ocean-atmosphere and socioeconomic systems can be likened to the trajectory of an aircraft. The controls within the aircraft correspond to various controls within the economy that directly affect how much of what types of emissions are produced, how populations spread over time, and what types of new technologies are developed. These controls are the "levers" that can potentially be adjusted to control the development of both the manmade and natural systems. In the case of an aircraft, its path is constantly being perturbed away from the desired direction by random atmospheric events. To counteract this, the pilot must constantly update the configuration of the controls in order to counteract the effects of the atmospheric disturbances. In some cases, the pilot will actually fly around particularly unpleasant atmospheric conditions, because he knows from experience that the flight will proceed with a greater probability of smoothness, if he flies in more stable skies.

This reactionary and anticipatory behavior also makes sense, if the trajectory being followed is one that models the interactions between the natural and socioeconomic systems. Stochastic control theory helps in determining the probability of observing different trajectories, given particular control strategies. It can help one determine control strategies that minimize the probability of seeing particularly nasty trajectories (e.g., runaway economic collapse). Being able to anticipate the effects of decisions is important, because, as Gottinger (1995) expressed it, a model can show "*when it pays to act and learn and when to learn and act.*"

Stochastic control theory also offers a technique called *Kalman filtering* (Balakrishnan 1984), which can be used to update control strategies in real time, given that the system being controlled is not fully understood. That is to say, the Kalman filtering scheme allows observations of the state to be noted, a more complete picture of the dynamics of the system to be constructed, and controls to be updated in order to steer the system along a course that seems most benevolent. Kalman filtering even allows for the case when the state of the system is observed imperfectly. This is very useful for integrated assessment models, where it is clear that the data used to summarize the states of the physical and socioeconomic systems are imprecise.

Exploring integrated assessment, using techniques from control theory, can also lead one to the *bifurcation theory of differential equations* — in particular, the way in which seemingly random behavior can actually be generated through deterministic means. This goes by the more popular name of "chaos theory." Some work has already been done in this direction (Milik et al. 1996). This could be a fruitful area of modeling for those wishing to explore the area of uncertainty without reliance on probabilistic concepts.

Many of the techniques useful for optimization models that have been mentioned above can be extended to the case where the integrated assessment model is based on game notions of competitive equilibrium. A straightforward application of the decision-making problem with recourse method of problem formulation has been used in a multiagent framework, in which multiple agents (representing utility companies and large commercial customers) each attempt to maximize their own expected utilities subject to constraints that are, in one way or another, functions of the actions of their competitors. Because each agent solves a stochastic programming problem (in order to determine optimal hedging strategies), the equilibrium solution to such a system is termed a stochastic equilibrium.

Work in this direction has been explored by Gurkan et al. (1996). In this technique, solutions to the underlying stochastic equilibrium problem are sought by using techniques from sampling theory, combined with deterministic methods for solving variational inequalities (which are a useful means for modeling a variety of equilibrium phenomena, among other things).

Attempts are being made to improve the ability of integrated climate models to produce reliable, policy-relevant information. The Model Evaluation Consortium for Climate Change Assessment (MECCA) was formed in 1991 with the goal of providing a detailed quantification of the uncertainties inherent in climate model projections (Henderson-Sellers et al. 1995). The project is concerned about the "collapse of confidence" and "explosion of uncertainty" that can occur when individual model components are linked. By comparing the results from different models under standardized conditions, the level of confidence can be increased.

16 CONCLUDING OBSERVATIONS

"Unpleasant surprises in the greenhouse?" This warning comes from one of the early prophets of climate change, Wallace S. Broecker. From his perspective, we are playing Russian Roulette with climate and no one knows what lies in the active chamber of the gun (Schotterer and Andermatt 1990).

There is a wealth of literature on surprise, if one takes into account other concepts and notions related to it, such as chaos, stability, anomaly, uncertainty, risk, discontinuity, synergism, shock, vulnerability, resilience, cognitive dissonance, probability, bias, and the unexpected. There has also been a tailoring of definitions and typologies of surprise to various needs as determined by specific activities and interests: climate surprise, global change surprise, military surprise, economic surprise, cultural surprise, environmental surprise, health surprise, technological surprise, ecological surprise, and surprises in sports, humor, and so on.

A review of typologies of various kinds of surprise suggests that we should no longer look at climate and climate-related surprise in binary or black-and-white terms. The true situation is that there are varying degrees of surprise, ranging from slightly surprising events to totally surprising events. One might even add that a total absence of surprise would be surprising.

The focus of societies has often been on surprises that produce adverse consequences for the environment and for society. This has been the case with global warming. Until the early 1990s, there was a great reluctance on the part of research funding agencies and governments (especially the industrialized ones) to raise the issue of winners and losers in the event of global warming. This situation was unlike that of the early 1970s when the possibility of the onset of an Ice Age was suggested. At that time, there was little reluctance to suggest which countries might win if the global climate regime were to cool, and which ones might lose (Glantz 1990). It became politically incorrect to discuss the possibility of winners and losers. Now it is acceptable to discuss winners and losers in a global warming context, even though no reliable measures of what is meant by a "win" or a "loss" have been developed.

Surprises, for the most part, are subjectively determined. There are events for which the probability of occurrence can be calculated; although they may be rare, such events can indeed be expected. Thus, there are knowable surprises. There are also unknowable surprises, such as the development of severe seasonal Antarctic ozone depletion or the Tunguska meteor fall in the early 1900s — totally unexpected occurrences, never before experienced by living generations at the time of discovery. Societies, however, have not witnessed the full range of climate conditions, and so they are not in a position to know all the possible changes that the global climate system can go through.

Modeling is one of several ways that researchers can try to identify "anticipatable" surprises. But models cannot be expected to identify the full range of potentially knowable climate surprises, let alone their first- and second-order effects on ecosystems and societies. Therefore, any approach that might identify ways to uncover potential climate or climate-related surprises should be considered. Kates and Clark (1996) note that there are "a number of techniques one can use to anticipate them." These include:

> *... surprise theory, which focuses on the principles underlying unexpected events and developments ... historical retrodiction, which examines empirical cases of surprise to determine whether the seeds of future surprises are apparent to hindsight .... Other techniques proposed include contrary assumptions, asking experts, models of systems dynamics and, finally, imaging in which an unlikely event is postulated and attempts are made to construct a plausible scenario to explain it.*

Victor (1995) cautioned "surprise hunters," when he observed the problems that could be generated by overfocusing on surprise with regard to the climate-change issue. He suggests that "surprises can be positive or negative, actual, theoretical, or artificial, i.e., generated by models, journalists or pundits." Victor predicts a vast oversupply of surprises that will find scientists spending their time in attribution — e.g., is an event (surprise) caused by global warming? There are many potential causes for observed changes in natural systems.

The challenge for the climate-change research community, whose attention is focused on the physical changes in the global and regional climate regimes that might accompany global warming, is to provide insight to policymakers so that they will build flexibility into their decisions, allowing for the chance occurrence of knowable surprises. The same is true for those concerned with identifying surprises in the areas of climate-related impacts (e.g., agriculture, energy, food, water, and public safety).

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