The Contextual Importance of Uncertainty in Climate-Sensitive Decision-Making: Toward an Integrative Decision-Centered Screening Tool

Susanne Moser, Ph.D.

Susanne Moser Research & Consulting
and
University of California—Santa Cruz

May 5, 2009

1. Introduction

As human-induced climate change is increasingly accepted as fact, and decision-makers begin to grapple seriously with the policy and management implications, climatic changes have the potential to become relevant to decision-making, but the challenges of effectively linking science to policy-making and management practice are real and difficult to overcome. While uncertainties in climate change projections matter in important ways to those who must design and decide on mitigation policies, this paper focuses on the relevance of uncertainty to resource and land management at various levels of governance that addresses adaptation questions. Clearly, decision-makers in the Great Lakes region at local, state and regional levels will face precisely such questions. This then raises several important questions, including:

- In what ways can climate change science support adaptation decision-making?
- When and to what extent does uncertainty in climate change projections matter to decision-makers concerned with adaptation challenges?
- How do we frame – and contain – the amount and type of uncertainty analysis that matters for the decisions at hand?
- What do decision-makers need to know about scientific uncertainties in order to account for them appropriately in their decisions?

These types of questions force us to link and integrate scientific advances forged on uncertainty assessments within weather forecasts, climate variability and change projections, and impact analyses with those made in the understanding of the role of science in practical decision- and policy-making. Echoing a vast body of literature[1] and experience, the ultimate goal of such an integrative effort is to ensure that scientific information effectively connects with the needs of decision-makers as they begin to address adaptation questions.[2]

---

[1] For example, Baeckstrand 2002; Cash et al. 2003; Dresler and Schaefer 1998; Glasser 1995; Jones, Fischhoff, and Lach 1999; Malone and Yohe 2002; National Council for Science and the Environment 2000; Pielke Jr. 1997; Pielke Jr. and Conant 2003; Pulwarty and Melis 2001; Steel et al. 2004; Wynne 1992; Jacobs, Garfin, and Lenart 2005; van Kerkhoff 2005; Lemos and Morehouse 2005; van Kerkhoff and Lebel 2006; Karl, Susskind and Wallace 2007, and a relevant synthesis of the literature relevant to climate-related decision support by National Research Council 2009).

[2] The term "decision-maker" is used here as shorthand to mean a wide range of individuals at different levels of governance deciding whether or not to take which courses of action in any given climate-sensitive sector: public officials setting policies at federal, regional, state or local levels; private-sector business managers helping to determine the business strategy of their company; private-sector or public agency officials deciding over resource

Importantly, this integrative work must *shift the focus to the decision-maker*, the decision-making process, and the relevance of weather and climate information, and specifically the relevance of obtaining information about uncertainty in climate research. The objective then is to develop a systematic approach to determining where and when uncertainty matters: Where is the decision-making environment particularly sensitive to uncertainty in the information provided? Is it useful and necessary, and if so, when, to produce an "end-to-end" characterization of uncertainty (e.g., from emission scenarios to model uncertainties to climate sensitivity to climate impacts to vulnerability and adaptation or mitigation policy options)? And if not, what do decision-makers need to constructively and appropriately take climate change into account in their decisions?

This paper proposes such a systematic approach and illustrates it with examples relevant to the Great Lakes region. The approach has been tested already in a case study of adaptation decisions in coastal management in California, but additional testing in "real-world" contexts would help strengthen it and prove its broad utility. The following sections begin with a conceptual discussion of the usefulness and fit of scientific information in the decision-making process, present the basic premises and objectives of the proposed approach, and then lay it out in a way that is cognizant of the decision process and of the constraints that decision-makers face. Along the way, the chapter offers examples to illustrate the meaning and application of the approach. Suggestions for testing the approach further are also made, before concluding with an appraisal of its potential usefulness and limits. The ultimate hope is that the proposed tool will give scientists and decision-makers a procedure to identify those instances where (even uncertain) science can most effectively support decision-making.

2. The Usefulness of Scientific Information in the Decision-Making Process

Science that aims to support decision-making must pass—at the very least—the usefulness test. Additional important criteria that need to be met in order for the science–decision-making interaction to work effectively have been identified. These criteria include salience or relevance, credibility (which Jones, Fischhoff, and Lach (1999) include indirectly in their usefulness criteria), legitimacy of process (Moser 1997; Gieryn 1999; Cash 1998; GEA Project 1997; Mitchell et al. 2006; Cash and Moser 2000), and efficacy (again, included under the rubric of "usefulness" by Jones et al. 1999). As many recent studies and reviews have found, there is no clear, natural or easy fit between the world of research and that of decision-making (Figure 1a) (e.g., NRC 2009).[3] Instead, in most instances that fit has to be actively created, or—as (Sarewitz

allocations; individuals determining their personal/private business operations (such as choosing crops, planting and harvesting dates) or choosing residential locations; and so on.

[3] For example, Healey and Hennessey 1994; Healey and Ascher 1995; Jones, Fischhoff, and Lach 1999; Pulwarty 2003; Pulwarty and Melis 2001; Alcamo, Kreileman, and Leemans 1996; Baeckstrand 2002; Boesch 1999; Bradshaw and Borchers 2000; Cash et al. 2003; Cashmore 2004; Catizzone 2000; Cortner 2000; Dresler and Schaefer 1998; Fabbri 1998; Glasser 1995; Gieryn 1999, 1995; James 1999; Korfmacher 1997; Malone and Yohe 2002; NRC Commission on Geosciences 1994; Pielke Jr. 1997; Pielke Jr. and Conant 2003; Swets, Dawes, and Monahan 2000; Moser 1998; Moser, Cash, and Clark 1998; NRC 1981; Hall and Lobina 2004).

and Pielke 2007) put it, the supply and demand of science in decision-making has to be carefully reconciled.

A number of studies have examined and illustrated the criteria that need to be met, in order to have a science—decision-making fit. Particularly useful for the purposes here is that by Jones, Fischhoff, and Lach (1999) (Figure 1b).

Insert Figure 1 about here

The arrows go in both directions in the above depiction, suggesting that the initiative for seeking a better link between science and decision-making can come from either end of the spectrum. In the case where decision-makers actively seek scientific information, they have already passed the receptivity and maybe even the accessibility hurdles. In the case where scientists seek to offer their information to decision-makers, there may already be at least a willingness to make that information relevant and compatible—even if the details have still to be worked out (further detail on this below). From a pragmatic point of view, it would be naïve, however, to assume this kind of mutual openness. Indeed, the fact that one or the other side is minimally open to input from the other is frequently the biggest initial stumbling block between science and decision-making (e.g., (Lindblom 1980; Nutley, Walter, and Davies 2007).

A second critical issue to identify is where or when in the decision process science can insert itself, and what functions science can play at these different stages of the decision process.[4] Typically decision theorists identify a number of decision functions or stages in the decision process. Below, one of the more comprehensive ones is illustrated (based on a rational approach to decision-making; see (Clark 2002)) (Figure 2).

Insert Figure 2 about here

The information needs differ significantly during different stages of this process (e.g., during the analytical intelligence-gathering and the promotion stages). Similarly, the degree and nature of influence that scientific input has at different stages varies with the degree of usefulness (discussed above) and with the stage in the decision process at hand. In fact, science can influence the direction of that process, move it forward, or initiate another iteration of the decision-making process through its influence (Mitchell et al. 2006). To understand when and how that happens, it is often necessary to also understand the wider policy context and history of the decision-making process itself (Herrick and Pendleton 2000; French and Geldermann 2005).

[4] For the purposes here, I will forgo an explicit treatment of the ways in which decision-making can inform science at each of these stages. Fuller discussions of the processes in which "stakeholders" contribute to the development of scientific research agendas and assessment processes can be found elsewhere (e.g., http://www.harvard.edu/gea/). However, ideally, a back-and-forth iterative process between scientists and decision-makers should evolve as a result of using the approach proposed here.

Thus, this cycle of decision steps or decision functions should not be viewed as one in which steps follow each other linearly. Rather, "real-world" decision processes are iterative, messy, and science entering into that process will be drawn into that dynamic (IAI) 2005). The decision process and the points of entry for science into it are delineated here for three reasons:

1. The issue of ***timing of scientific input is critical***, and scientists need to understand where in the process they enter the decision-making arena. The (unspoken) rules of their participation in the process may be quite different at different stages. Here, the meaning of "timing" refers to the stage in the decision-making process. Another aspect of timing relative to the decision calendar will be discussed below.
2. By highlighting the different nature of scientific input at various stages in the process, it becomes clear that the ***nature and detail of scientific information required or acceptable will also vary***. As Herrick and Pendleton (2000, p.358) suggested, "To suggest that predictive modeling may not be especially useful in some situation […] is not to argue that scientific information will not be useful. Not all "good science" is predictive."
3. ***Scientific uncertainty*** (and hence the need to characterize it with varying degrees of sophistication) ***varies in its impact and importance across the different stages of the decision process***. In other words, scientific uncertainty is not uniformly important, but sensitive in its relevance to the specific decision context. For example, it may influence the way a problem is defined; the degree to which it is taken seriously; it may also help mobilize different sets of decision supporters or antagonists (actors, stakeholders) than if the problem was less uncertain; it may affect the set of choices open to or perceived as rational by a decision-maker; or it may affect the weighing of options by the decision-maker, and so on.

Finally, to put a finer point on the issue of usefulness, i.e., on finding the "right" science for the "right" entry point in the decision process, it is important to understand the management challenge from the perspective of the decision-maker (e.g., Moser 2006; NRC 2009). Essentially, the issue at hand here is an institutional one with historical roots in the evolution of management institutions, political boundaries and other structural constraints on the decision-making process. Understanding this perspective is crucial to avoid some of the common types of frustration and misunderstandings between scientists and decision-makers. For example, what may be a crucial logical or causal link between the climate and a given impact to the scientist, may be completely irrelevant and uninteresting (beyond the sheer curiosity value) to the decision-maker, if that particular impact falls outside his or her purview of authority.

To illustrate this point in more detail, it may be helpful to use a concrete example in which a scientist's and a decision-maker's issue perception (and problem definition) significantly differ. A hypothetical climate impacts assessor may, for example, study the impact of climate variability and change on the amount of thermally suitable habitat of commercially harvested whitefish. The scientific assessment suggests that suitable habitat may decline significantly, especially in shallow lakes, over the next fifty years (Kling et al. 2003). This potentially highly relevant scientific information is offered to a busy decision-maker at the state level in Michigan, who—after merely a glance—places the report on to the growing "read-(maybe)-later" pile.

Meanwhile, that same decision-maker sits in his office and has to determine how to balance the competing needs and objectives for the particular streams and lakes in his jurisdiction over the coming year: the productivity of whitefish and other commercial and recreational fisheries, hydropower generation, endangered species protection, and maintenance of recreational opportunities. The issue of flood protection is also a consideration, but only tangential to his particular area of influence. It falls under someone else's decision authority. The varying competing objectives are discussed and decided upon in a watershed-wide working group, but some goals are also set in the state capitol or by Congress. The decision-maker—in his given sphere of control—has to find a compromise between all these goals with a particular set of management options at his disposal, and not for the next 50 years, but for the coming season or year. Besides the objectives that have to be met, there are political, social, institutional and economic considerations that also constrain or favor particular outcomes and management options—issues that would be fatal professionally to neglect.[5]

For the climate impacts study to enter effectively into the decision challenge that this manager faces, the *scientific information has to link to the specific decision objectives* (outcomes, goals) *and/or the feasible management options* (choice set, levers) at hand for a given *decision timeframe*, i.e., the time scale over which today's decisions have implications, *at the right time*. Typically, decision-makers and scientists—in collaboration—have to build the conceptual and data "bridge" between their different issue definitions and match the delivery of information with the decision calendar. In the example above, the link would have to be made between climate, lake water levels, water temperature and other habitat quality criteria, whitefish ecology, and fisheries economics. Several of these variables relate to the competing objectives the decision-maker has to balance (e.g., lake levels <> hydropower generation; water temperature, habitat quality and fish ecology <> endangered species protection; whitefish survival rate <> fisheries productivity and economic impacts). Further scientific analysis could lay out under what climatic conditions the management objectives can no longer be met. Alternatively, further research could identify whether novel or altered management strategies could help meet the given objectives. In addition, these altered management strategies would have to fit into the decision calendar (timely information relative to the seasonal needs of the decision-maker) (e.g., Pulwarty and Melis 2001; Sarewitz and Pielke 2007; McNie 2007; Tribbia and Moser 2008) and be acceptable to all stakeholders involved.

It is only then that theoretically relevant scientific information has truly met decision-making needs. It would have met the four conditions of usefulness mentioned above (see Figure 1) (adapted from Jones, Fischhoff, and Lach (1999)):

Usefulness = f(Rv, C, A, Rc)

Rv: Relevance

- Does the research time scale match the decision-making time scale?
- Can climate variables affect the parameters under control of the decision-maker?
- Can climate variables affect the decision outcomes?

[5] For an empirically documented case of just such differences between scientific input and decision-maker needs, see Moser (1997). Other match and mismatch cases are collected in Sarewitz, Pielke Jr, and Byerly Jr. (2000) and further discussed in Sarewitz and Pielke (2007).

C: Compatibility

- Is climate science output compatible with form needed for decision-making?
- Does climate science output feed into existing decision models or procedures?
- Can existing decision models accept probabilistic information as input?

A: Accessibility

- Where in the decision process can this climate science output enter?
- Is the climate science perceived as a credible and legitimate input to the decision process?

Rc: Receptivity

- Is the decision-maker (and other relevant stakeholders) willing to use climate science output?
- Do decision-makers consider climate information worth knowing?

Based on the above discussion of the science–decision-making linkage, it is now possible to lay out the premises and objectives of a screening tool that identifies the usefulness of climate information and the need for information about uncertainty. The basic argument running through this paper is that where and whether climate and uncertainty information matter is an empirical question rather than one that can be answered ex ante (see also Moss 2007).

3. Premises and Objectives

The approach proposed here springs from a number of premises—each flowing from the understanding of the science-policy interface described above. Ideally, it will satisfy these requirements and simultaneously meet a series of objectives. In cases where it does not, the hope is that it can—with relatively little effort on a case by case basis—be adapted to meet them. The overarching goal, as stated above, is to develop a widely applicable tool that links the scientific analysis with information use and helps to identify those instances where uncertainty needs to be assessed, characterized, and communicated to the decision-maker.

Premises:

1. The approach must ***place the decision-maker and the real-world process of making a decision at the center***. Differently put, scientific products and information must fit into the actual decision-making process rather than into a theoretical model of decision-making or simply serve to advance scientific knowledge (NRC 2005, 2009; NRC Roundtable on Science and Technology for Sustainability 2005)(see also Scheraga, this volume).
2. The approach ***does not—a priori—lend primacy to science and scientific information in the decision-making process over other decision inputs, but it does assume that credible, relevant and accessible scientific information can be an important input*** into many decisions. This importance is elevated to the extent that decisions affect complex systems, span longer time horizons, need to address significant risks and uncertainties, and pursue multiple objectives.

3. The approach ***does not assume a particular normative approach to decision-making under uncertainty*** (e.g., a “wait-and-see” approach that favors delaying action in the face of uncertainty, or a precautionary approach that favors preventive action in the face of uncertainty). Instead, it assumes that value judgments of this sort are made throughout the decision-making process, and that a well-informed decision process would benefit from a better understanding of the risks, uncertainties, complete unknowns, and the degree of confidence scientists place in particular climate information.
4. The approach ***does not—a priori—favor a “top-down”*** (global climate model to local impacts) ***assessment approach nor does it alternatively favor a “bottom-up”*** (vulnerability-focused) ***assessment approach*** (Dessai and Hulme 2003). Instead, these two approaches are considered complementary, produce different scientific information, and imply a different decision focus or purpose, with implications and usefulness to the decision-maker varying accordingly.

Objectives:

1. The approach ***should work for all kinds of weather and climate-sensitive decisions***, rather than be narrowly defined to work only for questions of climate variability, or only for questions of long-term climate-change.
2. The approach ***should be applicable in a variety of decision-making contexts***. This may include decision contexts in various natural resource or hazard management situations (e.g., water, agriculture, forest, or coastal management), i.e., contexts where ongoing resource management and potential adaptation decisions will have to be made. In principle, however, the approach should also work in contexts where decisions may be focused on mitigation efforts (e.g., in the energy or transportation sectors).
3. The approach ***should also work for a range of decision-makers***, be they in the private sector, public sector, or in mixed settings. Typically, multiple decision-makers are involved, but there may be a lead or coordinating authority.
4. The approach ***should be applicable at a variety of scales***. Many climate-sensitive resource-related (adaptation) decisions are made at state, regional, and local levels, but may also involve higher levels of governance. Mitigation decisions (or planning/development decisions that affect greenhouse gas emissions) tend to be made at international, national or state levels, but frequently do involve regional and local levels, especially in contemporary America.

The following section then introduces an approach that aims to meet the premises and objectives discussed above while being cognizant of the realities of decision-making. Subsequent sections illustrate a case example of how this tool can be applied. Further research will be necessary to empirically test and refine it, and to determine the larger significance of this approach.

4. DUST – Decision Uncertainty Screening Tool

To systematize the identification of climate and uncertainty information needs in the course of decision-making, it is useful to classify decision situations. Different types of decisions pose different scientific challenges, and hence require different approaches to characterizing scientific uncertainty. Many attempts at classifying decisions exist, using, for example, the substantive decision context (e.g., food production, energy distribution, water resource management), the scope or magnitude of the decision (e.g., measured in affected $ value), the time horizon of the decision (e.g., short- versus long-term), or the type of decision in the management context (e.g., operational, investment, design, or planning decisions) as the underlying principle of distinction (e.g., NRC 1981; Clark 2002; Sarewitz, Pielke Jr., and Byerly Jr. 2000).

For the purposes here, decisions are primarily categorized using the fundamental elements that are common to all decisions. The basic "building blocks" of decisions are:

- The **present conditions** (P) (state variables) defining the base line or the perceived problem;
- The **objective(s)** (O) or goals of a decision (sometimes with specified **criteria** (c) what would satisfy these objectives);
- The **choice set** (C) or management options (levers or control variables) available to achieve the objective(s) (sometimes with explicit, but often only implicit **attributes or preferences** (a) attached to each choice);
- Decision **constraints** (X) (such as social, technical, economic or political factors that arise in the context in which the decision is being made); and
- **Externalities** (E) (known or unexpected impacts that arise from the decision that were not explicitly included in the weighing of the decision).

Underlying all of these basic building blocks is a specific problem definition (for further discussion, see the section on Usefulness of Scientific information in the Decision-Making Process above), which as a frame for the decision problem mobilizes certain perceptions and conceptualizations of the problem, potential solutions, and feasible means to resolve it.

Using these decision elements, two fundamentally different types of decisions are derived – optimization and evaluation decisions. Each is described in turn below.

(1) Optimization decisions

The basic question the decision-maker asks in this type of decision is: *What decision (i.e., what strategies or choices) will produce the desired outcome?"* Or more colloquially, what path shall I pick (choices) to get to Rome (outcome)? This decision problem has also been described as "learn now, then act" (Kann and Weyant 2000). More formally, this type of decision can be depicted as:

$$\boxed{\mathbf{O_c\ (+\ E) \Rightarrow C_a\ f(P,\ X)?}}$$

Given the present situation (P) and certain constraints (X), which choices (C) with specified attributes (a) will optimally combine to produce the desired (c) outcome (O) (and minimize the creation of unacceptable externalities (E))?

Optimization decisions have a specified outcome in mind and involve choosing among a set of choices or strategies to achieve it. Outcomes are very specific typically, but in general can be described as achievement of a positive outcome, avoidance of a negative outcome, or compliance with a required outcome (which essentially is nothing but a singled-out case of either of the two other objectives).

Note that the term "optimization" does not imply an unrealistic assumption about utility maximizing or other forms of finding an "objectively ideal" solution to a problem. Rather, most decision-makers will "satisfice," i.e., choose from a limited set of options with bounded rationality. The term optimization simply refers to the fundamental type of decision problem. (See also Footnote 7 below, and Marx and Weber, this volume).

Insert Textbox 1 here
----

(2) Evaluation decisions
The basic question the decision-maker asks in this type of decision is: *What outcome does a given (set of) decision(s) have?* More colloquially put, a decision-maker may ask, I wonder where all these different paths lead? (Also described as an "act now, then learn" problem in the words of Kann and Weyant (2000). More formally expressed, this type of decision can be depicted as:

$$\boxed{\mathbf{C_a \Rightarrow O_c\ (+E)\ f(P, X)?}}$$

Given the present situation (P) and certain constraints (X), what outcome (O) with certain desired criteria (c) will result from selecting particular choices (C) with specified attributes (a), and what externalities (E) may they produce?

Evaluation decisions start out from a set of policy options or strategies and assess the potential outcomes and tradeoffs among these choices.[6] Evaluation decisions may ask:

- What are the advantages and disadvantages of each of the choices in my set?
- Which single choice from my set is the best (or worst) with regard to a specified attribute or outcome criterion?
- What combination of choices maximizes the benefits and opportunities (or minimizes the risks, costs or other negative consequences) in the aggregate?
- What combination of choices distributes the risks, costs and benefits most equitably (or politically most defensibly)?
- Which (combination of) choice(s) retains the greatest amount of future flexibility, which involves irreversibility?

Insert Textbox 2 here
----

[6] A new type of methodology has been developed in recent years that may be seen as a hybrid of the optimization and evaluation decision types, depending on how the decision is formulated. This new method—called Robust Adaptive Planning—uses computer-assisted reasoning to examine management strategies that avoid major system failures, breakdowns, or surprises (Lempert, Popper, and Bankes 2002; Lempert, Popper, and Bankes 2003).

Both types of decisions must take into account the criteria by which outcomes are measured, the attributes that characterize the available choices, and any other constraints, and externalities together determining the acceptability of the final decision.

The simple distinction between the two different types of decision challenges neglects the fact that knowledge about any one aspect in these decisions varies from relatively certain to uncertain, to deeply uncertain, to completely unknown. This fact, while not novel to decision-making (albeit pressing in the case of long-term climate change), suggests very different analytical approaches from a scientific perspective (Morgan and Henrion 1990; Lempert, Popper, and Bankes 2003) (see also the discussion in Easterling et al., this volume). Where deep uncertainty and ignorance persist, subjective expert judgment becomes a critical and necessary input. In communicating uncertainty to decision-makers (see below), this needs to be made transparent.

Further necessary distinctions among different types of decisions

Considering the ultimate interest in what kind of climate information is needed, to what extent uncertainty matters, and if so, how it should best be assessed and characterized, further distinctions needs to be made among the already identified basic types of decisions. The first of these relates to the *decision time horizon*. Does the decision pertain to the near future (e.g., an extreme weather event, a growing season, or a few years) or does it reach into the far future (as perceived by the decision-maker), such as in siting decisions (e.g., 5, 10, 25, 50, or 70 years)? Another dimension relates to the *number of opportunities to revisit a decision*, or—differently put—the number of iterations in the decision-making process. Is the decision a one-time decision or are there opportunities for sequential decisions (incl. updates of the data informing the decision, and learning) over time? The implications of these distinctions for the demands on scientific information are made clear in the following examples:

1. ***Near-term/single decision moment***: A farmer in Illinois has to choose the set of crops to plant for the coming year. Long-range seasonal forecasts suggest it is likely to be a wetter-than-normal year. Spring weather has already been very wet and caused some delays in planting dates. But if moisture levels are maintained without being excessive during key times of the growth cycle, crop yields could be very good. Once the seed is in the ground, that farmer will have to deal with the consequences of his choice, no matter how the rest of the year turns out in terms of weather. If it continues to be wetter than usual, he may encounter harvest losses; if it becomes drier than usual, he may have to absorb the cost of irrigation or the loss in yield. Or he may just turn out lucky…(see the chapter by Easterling et al., this volume, for a detailed discussion of uncertainty in agricultural decision-making) [evaluation problem]

2. ***Near-term/multiple decision moments***: Over the course of the year, a water resource manager in Michigan (e.g., an operator of one of the 13 remaining hydropower facilities along the Manistee, Muskegon, Au Sable, Grand and Kalamazoo Rivers) has to make numerous decisions adjusting the water volume/level in the reservoir. Each time updated weather and climatic forecasts are available, some limited adjustments can be made based on the newer information as to how much water should be stored or released. Given the seasonality of precipitation, runoff, air and stream temperature, and changes in electricity

demand by consumers and the water needs of aquatic life, however, some of these decision points involve irreversible decisions (for that storm event or season). The water released to protect against possible major runoff and flooding episodes or to provide cooler and more water to fish cannot be returned for storage and later release or electricity production during times when the water and power demands peak. [optimization problem]

3. ***Long-term/single decision moment***: For years, a small community on the shores of Lake Superior may have dealt with lake level fluctuations and shoreline erosion by demanding that homes be setback a reasonable distance from the shoreline, moved back if and when erosion threatens to undermine a building, but may have also allowed decks and piers to be built further out into the lake when lake levels were lower to permit water access for recreational boating. Current climate change projections suggest lake levels will fall as climate warms, potentially encouraging greater shoreline development and closer to the water's edge. Despite the projected long-term trend of lake-level fall, historical experience suggests lake levels vary and scientists emphasize that they will continue to do so in the future. Exposed lake sediments may be toxic, and water quality concerns suggest limiting development may continue to be a good idea (see the detailed discussion of shoreline management challenges with climate change discussed by Mackey, this volume. What should the community do? What is a reasonable course of action? How should long-term trends, the range of risks, and the societal benefits of development be weighed against each other? [evaluation problem]

4. ***Long-term/multiple decision moments***: In light of credible new projections of climate change, a public health official in Chicago is charged with designing a heat-emergency management system for the metropolitan area. She is considering a program involving multiple stakeholders (from all levels of government) and with multiple elements or management options that will be triggered by different levels of criticality. Criticality is defined by a combination of meteorological and social conditions. Over the years, the new system is being put in place and tested as heat waves hit the city. In numerous places, the system works smoothly, in others it fails. While the process is time-consuming, requires considerable staff resources, and regrettable shortfalls affecting individuals' health are repeatedly being experienced, lessons are being learned and incorporated in subsequent management of heat emergency situations. As heat waves get worse with climate change, the city is nonetheless adequately prepared. [optimization problem]

Essentially then, decisions can be categorized into a three-dimensional space that spans between decision types, decision time horizons, and decision opportunities (see Figure 3 below).

Insert Figure 3 here

Based on this three-dimensional decision typology (loosely derived from (Kann and Weyant 2000), we can now identify different types of policy and uncertainty analyses that could be conducted.

Uncertainty analyses for different decision problems

In general, sequential decision-making under uncertainty can make use of uncertainty assessment approaches that determine optimal policies at different points in time. This allows update of all critical aspects of the decision: input/state variables, data informing the decision, or the decision set (control variables) and any of the criteria used to evaluate outcomes. In short, sequential decision-making allows learning, and in some instances can be less risky, at least for those decisions that can be made incrementally (see also NRC 2009).

Where a decision is made only once over a given decision timeframe, uncertainty grows with the length of the timeframe for all aspects of the decision. The only exception is information about current conditions and the currently available set of decision options. Such decision situations do not allow learning and adjustment over time. It only allows finding out whether a decision was – based on the best judgment at the time – a good or a bad one, thus permitting decisions some learning for similarly challenging, future decisions. In these types of one-time decisions then, whatever uncertainty is present at the time of decision-making will propagate through the optimization or evaluation process, hence the use of so-called uncertainty propagation models in policy analysis. The following tabular overview of approaches to policy analysis hinges on the type of problem a decision-maker faces (Table 1; for mathematical formulations of these different types of policy analyses, see e.g., Kann and Weyant 2000; Morgan and Henrion 1990).

Insert Table 1 here

Once the basic necessary type of analysis has been identified, the next step is to formulate—formally or informally—the decision problem using the basic decision elements. This problem formulation helps identify what is understood with high confidence, and what is more uncertain, entirely unknown, or can only be subjectively evaluated. These distinctions will then enable formal uncertainty analyses of the involved data, model parameters and underlying model structures (the three basic types of uncertainty commonly discussed in the literature). Such quantitative approaches have been described in great detail in classic treatises such as (Morgan and Henrion 1990; Cullen and Frey 1998; Edwards, Miles Jr., and von Winterfeldt 2007). Table 2 below provides a suggestive overview of the types of analyses that could be done and what type of information they would yield.

Insert Table 2 here

Communicating Uncertain Results

The science–decision-making interaction does not end with the formal decision and uncertainty analysis. The obtained results must be presented in understandable form back to the decision-maker (e.g., Webster 2003; Patt and Dessai 2005; Dabelko 2005; Moser 2006; Moss 2007; Patt 2007; Morgan et al. 2009). Critical considerations here include:

- Some decision-makers are increasingly familiar with or even trained in uncertainty analysis, but this should not be assumed as the norm.
- Results from an uncertainty analysis can—in principle—be presented numerically, graphically, or simply in words. Which of these forms works best with the specific decision-maker at hand must be explored in the specific situation. Descriptive terms used to distinguish levels of uncertainty should be consistently defined and used (NRC 2006; Moss and Schneider 2000; Morgan et al. 2009).
- Whatever form of communication is chosen, the link must be made back to the decision problem (objectives and decision choice sets) the manager faces in light of the stage of the decision process (Moser 2006).
- Experience reported by scientists and decision-makers reiterates over and again that it may not be enough to quantify the degree of uncertainty; frequently, decision-makers need or want transparency (Herrick and Pendleton 2000), especially when subjective expert judgment is involved. They want to understand the reason for the uncertainty (e.g., is it due to natural variability, lack of understanding of the processes producing certain impacts, unpredictable changes in technology or society more generally, or underlying assumptions—such as discount rates—of the model?). This deeper understanding helps to increase the likelihood that communicated uncertainty is actually understood adequately (Pielke 2001; NRC 1989, 1996; Morgan et al. 2009). It also will help decision-makers in their assessment of the climate information, and, in turn, to explain certain decision choices to other stakeholders. In any multi-stakeholder/multi-decision-maker situation, such explicit communication is particularly critical (e.g., Demeritt and Langdon 2004).

Putting it all together

The Decision Uncertainty Screening Tool (DUST) proposed here is essentially a step-by-step process of identifying where and how climate science could inform the decision process, getting successively more specific, until the needed uncertainty analyses are identified, carried out, and the results are communicated back to the decision-maker. As a systematic, step-by-step procedure, it is likely to be much more linear and clear than the actual process may turn out to be. But for clarity's sake, the seven steps are summarized together with a reminder about the purpose of each step. This summary then links together the range of aspects discussed above: usefulness of science in the decision process, decision typologies, policy analyses, and uncertainty assessments and communication.

Step 1: Identify the stage in the decision process where science would enter

The usefulness of science varies by stage in the decision-making process. The first step in DUST is to identify the stage of the decision-making process (Figure 1), so that the most useful input at that particular time and in the specific context of the decision-making process can be determined. The goal is the identification of places where science would enter the decision-making process, and what the nature of such input would be.

Step 2: Explore whether scientific input would be truly useful

Through direct interaction between scientist and practitioner it can be determined in more detail what type of scientific input would be most useful. The goal is to obtain a clearer understanding of the decision-maker's receptivity, the venues, formats, and specific data needs as well as any relevant timing issues that would make information useful.

Step 3: Identify the specific decision challenge
Step 3 in DUST is to identify the particular decision that practitioners face, i.e., whether it is an optimization or evaluation-type of decision. As a first approximation, scientists ascertain the specific decision challenge at hand: what are the decision objectives and choices to which scientific information has to be linked?

Step 4: Identify the type of decision problem the decision-maker faces
In Step 4 of DUST, additional information is obtained from the decision-maker to more clearly specify the type of decision that is being faced: what is the decision time horizon and how many opportunities are there to revisit the decision? The answers to these questions help identify the appropriate type of policy/decision analysis to be conducted.

Step 5: Identify necessary uncertainty analyses
The type of uncertain decision that practitioners face (identified in Steps 3 and 4) help identify the relevant uncertainty analysis. In Step 5 then, the appropriate uncertainty assessment is matched with decision-relevant variables and objectives. Much time and energy can be saved by focusing only on those analyses that can truly make a difference for the decision at hand.

Step 6: Conduct identified uncertainty analyses
Finally, Step 6 is to actually conduct the relevant and necessary uncertainty analysis to answer the remaining decision-relevant question: how does uncertainty in specified aspects of the problem affect the decision?

Step 7: Communicate uncertainties back to the decision-maker
Once the uncertainty analysis has been completed, the results have to be communicated back to the decision-maker in effective ways. "Effectiveness" does not just mean quantitatively accurate, but in verbal and graphic formats that are understandable and meaningful to the decision-maker, and pertinent to the decision at hand. The goal is to provide effective feedback to the decision-maker, linking analysis to his or her specific decision problem.

5. Toward Greater Refinement of DUST

DUST has been applied in a case study of adaptation to climate change by California coastal managers (Moser 2005). The extent of such local adaptation at the time (2005-06) was so limited that detailed uncertainty analysis was not yet necessary. Following the step-by-step approach revealed, however, what types of information California coastal managers would need, including what they would like to know about the types, nature, and degree of uncertainty (Tribbia and Moser 2008). These insights can better inform what type of science is being conducted, and has led to several changes in information and training services provided by such agencies as NOAA and the San Francisco Bay Conservation and Development Commission.

Further testing of cases that progress through the entire suit of steps involved in DUST would be highly desirable. Ideally, the testing of DUST would involve both scientists and decision-makers. Pragmatically, this may be the most important and challenging thing to achieve. As mentioned above, to get scientists and decision-makers to collaborate can be the most difficult step of all.

The testing of various empirical test cases would not involve a full uncertainty assessment (Steps 6 + 7, above) for all identified instances where it might be useful and scientifically feasible. But instead, the testing would be conducted in a joint working session in which

- Decision-makers assess whether their decision-process is captured adequately in concept;
- Decision-makers offer empirical descriptive detail of their specific decision, involved players, relevant criteria and objectives, and the decision-process;
- Decision-makers identify their climate information needs or at least identify climate-sensitive decision points (if necessary with the help of scientists);
- Scientists explain in general terms what type of climate information they could offer (e.g., global model outputs, regionally downscaled projections, for certain climate variables etc.) (note, any one scientist, of course, can't provide all of this information, but within the project, the relevant expertise may be available);
- Scientists explain in general terms the current level of understanding and confidence in the information they could provide (e.g., what factors principally determine the output; how well processes are understood, how well processes or outcomes can be predicted, what cannot be known and why, etc.);
- Decision-makers and scientists together determine in iterative fashion what information about climate and about uncertainty is needed specifically, in what form, when and how frequently, as well as how uncertainties would need to be described (in words, numbers, or graphically) to be understandable and useful to decision-makers.

This process should be recorded by the participants or a recorder. The results of working through the DUST model are likely to confirm some aspects of it and suggest modifications of others. Integrating test results into a revised DUST model is also likely to be iterative as multiple test cases may suggest alternative or confirm consistent modifications. The testing may also result in the development of different versions of the screening tool for different decision situations. In short, the question of evaluating the test results of the DUST model should not simply result in a conclusion such as "it is useful or it is not," but instead result in one or more revised versions of the screening tool to help scientists and decision-makers identify useful entry points for scientific information in specific decision situations (see also NRC 2009).

An additional benefit of the testing may be the identification of ways to simplify or streamline the DUST model. The final model, however, should be—in Einstein's words—"as simple as possible, but not simpler."

6. What DUST is not

Before concluding with a reiteration of the potential value of the DUST model, it may be useful to reiterate what DUST is not. Clearly, DUST is…

… *not an integrated assessment tool.*
Integrated assessments are models that quantitatively link inputs (drivers) and outputs (impacts) from a range of complex sub-models (e.g., climate, natural resources, economic sectors etc.). Frequently they are used to assess the consequences of certain policies or drivers of change on sectors of interest. Many integrated assessors have urged that uncertainty analysis be an integral part of such complex modeling. DUST can be viewed as a support tool to integrated assessments.

… *not a policy analysis tool*.
Policy analysis employs tools such as cost-benefit analysis, which in turn rests on a range of theoretical underpinnings, such as utility theory, contingent valuation or statistical decision theory, to identify defined optimal strategies or outcomes. While DUST starts out from a distinction of fundamentally different decision types that link outcomes with means, it only uses this categorization to aid the identification of appropriate uncertainty analysis approaches.

… *not a decision-making tool.*
As a tool that can help identify information needs, in particular about uncertainty of climate science, it can be viewed as a decision *support* tool. By itself, however, it will not help identify preferred solutions, only identify information that may help decide between potential solutions. An effort was made to avoid theory-prescribed, unrealistic assumptions about decision situations, decision-makers or their objectives.

… *not an uncertainty assessment methodology.*
DUST simply aims to identify when and where what types of existing uncertainty analyses should be conducted in particular decision situations. As such it parallels the approach described in (Kann and Weyant 2000).

While DUST is theoretically informed (e.g., by decision theoretical ideas such as bounded rationality and economic concepts such as satisficing, etc.), it aims to reflect the "messiness" of empirical reality more so than any one particular theoretical understanding of the decision-making process (see also Marx and Weber, this volume). As such it also tries to avoid many of the pitfalls of conventional policy analysis and decision-support tools (Morgan et al. 1999). For example, the DUST model places the decision-maker and his/her challenges in the center. This should not be read as a conceptualization of the decision-making situation *as consisting of only one* decision-maker – clearly an unrealistic situation in most contexts. Instead, there will almost always be several decision-makers with different (even competing) information needs, objectives, and constraints. But, to match scientific information effectively with the decision-makers' information need, the fit must be individualized (or at least match the needs of groups of similar decision-makers).

DUST is also designed to be flexible enough to transfer from context to context. It does *not assume a static set of values, objectives, or an unrealistic set of managerial choices*. It simply creates a systematic framework in which the actual set constituting the decision situation must be considered.

Maybe most importantly, the approach does *not assume that climate information must be used in a particular situation,* even if theoretically there exists a logical link between climate and what is being managed. It simply offers a systematic method to find out whether climate and uncertainty information could be useful to the decision-maker (see the valuable discussion in Dessai et al. 2009). The uncertainty analysis tools identified through DUST may reveal, for example, that (better) climate information would not substantially affect or improve a given decision. This by itself would be a valuable finding that could initiate additional research or changes in the decision-making process (for a case study of this situation see Jones, Fischhoff, and Lach 1999).

A final limit of the approach offered here is that DUST does not address the many decision-external reasons, such as institutional barriers, personal competition or limitations, lack of social acceptability, or lack of resources that frequently constrain the use of scientific information in decision-making (Moser 1998; Moser 2009). Scientists, however, should be cognizant of such barriers and uncertainties in the human dimensions of the decision-making process. Appropriate framing of the decision problem may help overcome some of them.

7. Potential Benefits and Impacts of this Approach

Testing and refining the DUST model to enhance its usefulness is a crucial step toward integrating geophysical climate modeling work, the impacts analyses, decision science and science policy, as well as the world of practical decision-making. If the model proves useful, it would help the research community come closer to fulfilling its promise of producing assessment science that closes the science–society gap, thus becoming truly useful to decision-makers.

From the outset the screening tool is designed to be “transferable” to a range of decision-making contexts (see Premises and Objectives above). Further vetting among experts and testing in a range of empirical settings will make DUST a useful approach that is available for wider use by the scientific and practitioner community. It offers itself particularly for use in existing or future scientist–decision-maker collaborations (e.g., applied science problems, stakeholder-informed assessment processes, ongoing integrated climate assessment efforts). It may also be of educational value to beginning scholars, or students entering into applied science fields where a better understanding of the science—decision-making interaction would be particularly valuable.

If adopted for wider use the impact of the DUST model could go even further. Ideally, the proposed approach can serve multiple purposes:

1. From a science perspective, the approach may serve a ***streamlining and prioritization function for uncertainty assessment***. Ideally, it will help to systematically identify where, when, und with what scientific methods uncertainty should be assessed, to whom this uncertainty needs to be communicated, and what forms of characterization and explanation would be most useful to the decision-maker.
2. From a decision-making perspective, the approach may lead to ***greater transparency and awareness***.[7]
3. The approach may also serve an ***educational function for scientists*** about the real-world decision-making process and the use and usefulness of scientific information in that process.

[7] This may or may not always be a desirable outcome in the eyes of decision-makers.

4. In a complementary fashion, the approach may also serve an ***educational function for decision-makers*** about the relevance of climate information to their decisions, about the state-of-knowledge of climate change science, and about the degree of certainty and confidence scientists have in different aspects of the problem.
5. In accomplishing (3) and (4), the approach could also serve the function of a "***boundary object***" – i.e., a tangible "product" or "tool" around which scientists and decision-makers can interact, learn from each other, fine-tune products, build mutual trust and understanding, but also maintain the necessary boundary between science and decision-making. As such, interaction around boundary objects can help ensure credibility and legitimacy while enhancing the relevance of scientific information to decision-makers. It is easy to envision, e.g., that only the early steps of the DUST model are implemented, which would serve the boundary object and educational functions, and thus enhance the science—decision-making interface.

Thus, even a partial fulfillment of these envisioned and intended outcomes would be a major step forward in not only improving the usefulness of climate science for decision-making, but, in fact, to elevate the public discussion about decision-making in the face of uncertainty.

8. References

Alcamo, J., E. Kreileman, and R. Leemans. 1996. Global models meet global policy: How can global and regional modellers connect with environmental policy makers? What has hindered them? What has helped? *Global En`* 6 (4):255-259.

Baeckstrand, K. 2002. Civic science for sustainability: Reframing the role of scientific experts, policy-makers and citizens in environmental governance. Paper read at 2000 Berlin Conference on the Human Dimensions of Global Environmental Change: Knowledge for Sustainability Transition: The Challenge for Social Science, December 6-7, 2002, at Berlin, Germany.

Boesch, D. F. 1999. The role of science in ocean governance. *Ecological Economics* 31 (2):189-198.

Bradshaw, G. A., and J. G. Borchers. 2000. Uncertainty as information: Narrowing the science-policy gap. *Conservation Ecology* 4 (1):Art No.1.

Cash, D. 1998. *Assessing and addressing cross-scale environmental risks: Information and decision systems for the management of the High Plains aquifer*. Cambridge, MA: JFK School of Government, Harvard University.

Cash, D. W., W. C. Clark, F. Alcock, N. M. Dickson, N. Eckley, D. H. Guston, J. Jäger, and R. B. Mitchell. 2003. Knowledge systems for sustainable development. *PNAS* 100:8086-8091.

Cash, D. W., and S. C. Moser. 2000. Linking local and global scales: Designing dynamic assessment and management processes. *Global Environmental Change - Human and Policy Dimensions* 10:109-120.

Cashmore, M. 2004. The role of science in environmental impact assessment: process and procedure versus purpose in the development of theory. *Environmental Impact Assessment Review* 24 (4):403-426.

Catizzone, M. 2000. Building dialogue between scientists and policy makers! *IGBP Newsletter* 42:12-13.

Clark, T. W. 2002. *The Policy Process: A Practical Guide for Natural Resource Professionals*. New Haven, CT: Yale University Press.

Cortner, H. J. 2000. Making science relevant to environmental policy. *Environmental Science & Policy* 3 (1):21-30.

Cullen, A. C., and H. C. Frey. 1998. *Probablistic Techniques in Exposure Assessment: A Handbook for Dealing with Variability and Uncertainty in Models and Inputs*. New York: Plenum Press.

Dabelko, G. D. 2005. Speaking their language: How to communicate better wit policymakers and opinion shapers - and why academics should bother in the first place. *International Environmental Agreements* 5:381-386.

Demeritt, D., and D. Langdon. 2004. The UK Climate Change Programme and communication with local authorities. *Global Environmental Change Part A* 14 (4):325-336.

Dessai, S., and M. Hulme. 2003. Does climate policy need probabilities? In *Tyndall Centre for Climate Change Research Working paper,* 42pp. Norwich, UK: University of East Anglia, Tyndall Centre for Climate Change Research.

Dessai, S., M. Hulme, R. Lempert, and R. Pielke Jr. 2009. Do we need better predictions to adapt to a changing climate? *EOS Transactions of the AGU* 90 (13):111-112.

Dresler, P., and M. Schaefer. 1998. Regional forums linking science and management. *Geotimes* 43 (4):24-27.

Edwards, W., R. F. Miles Jr., and D. von Winterfeldt eds. 2007. *Advances in Decision Analysis: From Foundations to Applications*. Cambridge, UK: Cambridge University Press.

Fabbri, K. P. 1998. A methodology for supporting decision making in integrated coastal zone management. *Ocean & Coastal Management* 39 (1-2):51-62.

French, S., and J. Geldermann. 2005. The varied contexts of environmental decision problems and their implications for decision support. *Environmental Science & Policy* 8 (4):378-391.

Gieryn, T. F. 1995. Boundaries of science. In *Handbook of science and technology studies,* eds. S. Jasanoff, T. Pinch, J. C. Petersen and G. E. Markle, 393-443. Thousand Oaks, CA: Sage Publications.

———. 1999. *Cultural boundaries of science: Credibility on the line*. Chicago, IL: Chicago University Press.

Glasser, R. D. 1995. Linking science more closely to policy-making: Global climate change and the national reorganization of science and technology policy. *Climatic Change* 29 (2):131-143.

Global Environmental Assessment Project. 1997. A Critical Evaluation of Global Environmental Assessment: The Climate Experience: A Report of the First Workshop on Global Environmental Assessment and Public Policy. Paper read at A Workshop convened jointly by the Committee on the Environment of Harvard University, the Center for the Application of Research on the Environment (CARE) of the Institute of Global Environment and Society, Inc., and the International Institute for Applied Systems Analysis,, June 1997, at Calverton, MD.

Hall, D., and E. Lobina. 2004. Private and public interests in water and energy. *Natural Resources Forum* 28 (4):268-277.

Healey, M. C., and W. Ascher. 1995. Knowledge in the policy process: Incorporating new environmental information in natural resources policy making. *Policy Sciences* 28:1-19.

Healey, M. C., and T. M. Hennessey. 1994. The utilization of scientific information in the management of estuarine ecosystems. *Ocean & Coastal Management* 23 (2):167-191.

Herrick, C. N., and J. M. Pendleton. 2000. A decision framework for prediction in environmental policy. In *Prediction: Science, Decision making and the Future of Nature*, eds. D. Sarewitz, R. Pielke Jr and R. Byerly Jr., 341-358. Washington, DC: Island Press.

Inter-American Institute for Global Change Research (IAI). 2005. Linking the Science of Environmental Change to Society and Policy: Lessons from Ten Years of Research in the Americas. (Group D on Communicating Science). Workshop report from a meeting in Ubatuba, Brazil, 27 November - 2 December 2005. São José dos Campos: IAI.

Jacobs, K., G. Garfin, and M. Lenart. 2005. More than just talk: Connecting science and decisionmaking. *Environment* 47 (9):6-21.

James, F. C. 1999. Lessons learned from a study of habitat conservation planning. *BioScience* 49 (11):871-874.

Jones, S. A., B. Fischhoff, and D. Lach. 1999. Evaluating the science-policy interface for climate change research. *Climatic Change* 43:581-599.

Kann, A., and J. P. Weyant. 2000. Approaches for performing uncertainty analysis in large-scale energy/Economic Policy Models. *Environmental Modeling and Assessment* 5 (1):29-46.

Kling, G. W., K. Hayhoe, L. B. Johnson, J. J. Magnuson, S. Polasky, S. K. Robinson, B. J. Shuter, M. M. Wander, D. J. Wuebbles, D. R. Zak, R. L. Lindroth, S. C. Moser, and M. L. Wilson. 2003. *Confronting Climate Change in the Great Lakes Region: Impacts on Our Communities and Ecosystems*. Cambridge, MA and Washington, DC: Union of Concerned Scientists and the Ecological Society of America.

Korfmacher, K. S. 1997. Invisible successes, visible failures: Paradoxes of ecosystem management in the Albemarle-Pamlico Estuarine Study. Granville, OH.

Lempert, R. J., S. W. Popper, and S. C. Bankes. 2002. Confronting surprise. *Social Science Computer Review* 20 (4):420-440.

———. 2003. *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*. Santa Monica, CA: RAND.

Lindblom, C. E. 1980. *The policy-making process*. 2nd ed. Englewood Cliffs, NJ: Prentice Hall.

Malone, T. F., and G. W. Yohe. 2002. Knowledge partnerships for a sustainable, equitable, and stable society. *Journal of Knowledge Management* 6 (4):368-378.

McNie, E. C. 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environmental Science & Policy* 10:17-38.

Mitchell, R. B., W. C. Clark, D. W. Cash, and N. Dickson eds. 2006. *Global Environmental Assessments: Information, Institutions, and Influence*. Cambridge, MA: The MIT Press.

Morgan, G., H. Dowlatabadi, M. Henrion, D. Keith, R. Lempert, S. McBrid, M. Small, and T. Wilbanks. 2009. Best practice approaches for characterizing, communicating, and incorporating scientific uncertainty in decisionmaking. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. *SAP 5.2*, Washington, DC: NOAA.

Morgan, M. G., and M. Henrion. 1990. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. New York, NY: Cambridge University Press.

Morgan, M. G., M. Kandlikar, J. Risbey, and H. Dowlatabadi. 1999. Why conventional tools for policy analysis are often inadequate for problems of global change. An editorial essay. *Climatic Change* 41:271-281.

Moser, S. C. 1997. Mapping the territory of uncertainty and ignorance: Broadening current assessment and policy approaches to sea-level rise. Dissertation, Graduate School of Geography, Clark University, Worcester, MA.

———. 1998. Talk globally, walk locally: The cross-scale influence of global change information on coastal zone management in Maine and Hawai'i, 114 pp. Cambridge, MA: John F. Kennedy School of Government, Harvard University.

———. 2005. Which Uncertainties Matter for Decision-Making? Development of an Integrative Decision-Centered Screening Tool with an Application to Coastal Management in California (Poster). U.S. Climate Change Science Program Workshop on *"Climate Science in Support of Decision Making"*. Arlington, VA, November 14-16.

———. 2006. *Climate Scenarios and Projections: The Known, the Unknown, and the Unknowable As Applied to California*. Synthesis Report of a workshop held at the Aspen Global Change Institute, 11-14 March 2004 in Aspen, Colorado. Elements of Change. Aspen, CO: AGCI.

———. 2009. Whether Our Levers Are Long Enough and the Fulcrum Strong? -- Exploring the Soft Underbelly of Adaptation Decisions and Actions. In *Living with climate change: Are there limits to adaptation?*, eds. W. N. Adger et al., 313-343. Cambridge, UK: Cambridge University Press.

Moser, S. C., D. W. Cash, and W. C. Clark. 1998. Local Response to Global Change: Strategies for Information Transfer and Decision Making for Cross-Scale Environmental Risks, Workshop Summary. Paper read at Local Response to Global Change: Strategies for Information Transfer and Decision Making for Cross-Scale Environmental Risks, 1998, at BCSIA, Harvard, University, Cambridge, MA.

Moss, R. H. 2007. Improving information for managing an uncertain future climate. *Global Environmental Change* 17 (1):4-7.

Moss, R. H., and S. H. Schneider. 2000. Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting. In *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC*, eds. R. Pachauri, T. Taniguchi and K. Tanaka, 33-51. Geneva: World Meteorological Organization.

National Council for Science and the Environment. 2000. *Recommendations for improving the Scientific Basis for Environmental Decisionmaking: A report from the First National Conference on Science, Policy, and the Environment*. Washington, DC: National Academy of Sciences.

National Research Council - Commission on Geosciences, E. a. R. 1994. *Environmental Science in the Coastal Zone: Issue for Further Research*. Washington, DC: National Academy Press.

National Research Council (NRC). 1981. *Managing Climatic Resources and Risks. Report from the Panel on the Effective Use of Climate Information in Decision Making*. Washington, DC: National Academy Press.

———. 1989. *Improving Risk Communication*. Washington, DC: National Academy Press.

———. 1996. *Understanding Risk: Informing Decisions in a Democratic Society.* Washington, DC: National Academy Press.

———. 2006. *Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts*. Washington, DC: National Academy Press.

———. 2005. *Decisionmaking for the Environment: Social and Behavioral Science Research Priorities*. Washington, DC: National Academy Press.

———. 2009. *Informing Decisions in a Changing Climate*. Washington, DC: National Academies Press.

National Research Council Roundtable on Science and Technology for Sustainability. 2005. *Knowledge-Action Systems for Seasonal to Interannual Climate Forecasting: Summary of a Workshop*. Washington, DC: National Academies Press.

Nutley, S. M., I. Walter, and H. T. O. Davies. 2007. *Using Evidence: How Research Can Inform Public Services*. Bristol, UK: The Policy Press.

Patt, A. 2007. Assessing model-based and conflict-based uncertainty. *Global Environmental Change* 17 (1):37-46.

Patt, A., and S. Dessai. 2005. Communicating uncertainty: Lessons learned and suggestions for climate change assessment *Comptes Rendus Geosciences* 337 (4):425-441

Pielke Jr., R. A. 1997. Policy for science for policy: A commentary on Lambright on ozone depletion and acid rain. *Research Policy* 26:157-168.

Pielke Jr., R. A., and R. T. Conant. 2003. Best practices in prediction for decision-making: Lessons from the atmospheric and earth sciences. *Ecology* 84 (6):1351-1358.

Pulwarty, R. S. 2003. Climate and water in the West: Science, information and decision-making. *Water Resources Update* 124:4-12.

Pulwarty, R. S., and T. S. Melis. 2001. Climate extremes and adaptive management on the Colorado River: Lessons from the 1997-1998 ENSO event. *Journal of Environmental Management* 63:307-324.

Sarewitz, D., R. Pielke Jr, and R. Byerly Jr. 2000. *Prediction: Science, Decision making and the Future of Nature*. Washington, DC: Island Press.

Sarewitz, D., and R. A. Pielke. 2007. The neglected heart of science policy: reconciling supply of and demand for science. *Environmental Science & Policy* 10:5-16.

Steel, B., P. List, D. Lach, and B. Shindler. 2004. The role of scientists in the environmental policy process: A case study from the American west. *Environmental Science & Policy* 7 (1):1-13.

Swets, J. A., R. M. Dawes, and J. Monahan. 2000. Better decisions through science. *Scientific American* (October):82-87.

Tribbia, J., and S. C. Moser. 2008. More than information: What coastal managers need to plan for climate change. *Environmental Science & Policy* 11 (4):315-328.

Vogel, C., S. C. Moser, R. E. Kasperson, and G. D. Dabelko. 2007. Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Global Environmental Change* 17 (3-4):349-364.

Webster, M. 2003. Communicating Climate Change Uncertainty to Policy-makers and the Public. *Climatic Change* 61 (1-2):1-8.

Wynne, B. 1992. Uncertainty and environmental learning: Reconceiving science and policy in the preventive paradigm. *Global Environmental Change* 6 (2):87-101.

Moser - Textboxes

Textbox 1: Examples of Climate-Sensitive Optimization Decision Problems

What is the best way (C) to protect a home from devastating flood loss (O)? Choices for the homeowner may include elevating or structurally reinforcing the home, removing heaters from the flood-prone ground floor, buying (more) flood insurance, doing nothing and hoping that there will be no major flood etc. Choices at the local or state government level may include changes in dam operations, building of flood retention basins, strict implementation of building codes, removal of houses out of a flood plain, better flood insurance coverage, etc.

To cost-effectively minimize (O) the number and severity of occasions when the sewer system in the southern Great Lakes region is overwhelmed by storm runoff and regular discharge of affluent, where and how quickly do existing sewage pipes have to be replaced with bigger ones (C)? In this instance, the choice set is already reduced to an engineering solution (land-use and management changes are not considered here), but the question is where to focus first and what the replacement pipe size should be to minimize both costs and spillage events. (For a detailed description of sewage and stormwater runoff challenges with climate change, see Scheraga, this volume)

By 2100, CO_2 concentration in the atmosphere must be 450ppm or less (O). How can the global community get there (C)? Choices at any level of government may include various combinations of carbon taxes, regulations, trading and incentive programs, technology investments, and so on. In order to minimize the cost of achieving the ambitious goal, approaches may be combined in a particular way, while additional considerations – such as equity, feasibility, political acceptability etc. may lead to a different 'optimal' combination of approaches.

Textbox 2: Examples of Climate-Sensitive Evaluation Decision Problems

To ensure the survival of endangered species, such as Michigan's Kirtland's warbler (O) should conservation planners protect habitat (C1), protect the jack pine on which the bird depends (C2), or try to physically relocate the warbler to habitats with similar soil, vegetation and temperature conditions further north (C3)? This decision is between different management options to achieve one desirable goal. (For more discussion of challenges faced by plant and wildlife species with a rapidly changing climate, see Root and Hall, this volume.)

What is the cost and benefit (O) of increasing irrigation of a farmer's crops (C) if temperature and precipitation changes manifest as currently projected? This decision does not start out from a desired agricultural yield, but wants to know the impact of a particular management approach and the net income of the farmer.(For more detailed discussion of agriculture and climate change, see Easterling et al., this volume.)

Given projected changes in streamflows and lake levels, how would a certain change in the controlled release of water (C) at the Robert Moses Niagara Power Plant, downstream of the Niagara Fallsaffect in-stream water flows over the course of the year (important for aquatic life) (O1) and overall energy production (O2)? This is a typical trade-off question that requires management strategies for multiple objectives to be balanced in new ways.

Moser - Tables

Table 1: Types of decisions and relevant policy analyses

Types of Decision	Policy Analyses	Remarks
One-time, near-term optimization	Optimization with resolved (known) uncertainty	Essentially a special case of stochastic dynamic optimization
One-time, long-term optimization	Finite-horizon stochastic optimization	
Sequential, near-term optimization	Infinite-horizon (dynamic) stochastic optimization	May be too computationally demanding
Sequential, long-term optimization	Infinite-horizon (dynamic) stochastic optimization	Quite computationally demanding
One-time, near-term evaluation	Single-period (but multiple policies) decision analysis; Single-policy uncertainty analysis	
One-time, long-term evaluation	Single-period (but multiple policies) decision analysis; Single-policy uncertainty analysis	
Sequential, near-term evaluation	Multi-period decision analysis	
Sequential, long-term evaluation	Multi-period decision analysis	

Table 2: Information gleaned from various types of uncertainty analyses

Types of analysis	What can be learned
Exploratory modeling/Computer-assisted reasoning	Reveals model-based uncertainties and unknowns; used to explore plausible futures where little is known about them
Multi-model comparison	Reveals model-based uncertainties; important when model structures are less well known
Sensitivity analysis	Reveals the impact of varying model inputs (through single or joint variation); important when model structure is well known
Multi-scenario comparison	Reveals the impacts of different assumptions about the world (can be understood as a subset of the sensitivity analysis)
Propagation of uncertainty in input variables through a deterministic (or stochastic) model (e.g., use of decision trees, numerical simulation techniques or expert solicitation to develop plausible distributions for input variables)	Reveals the spread (frequency and/or probability) of outcomes due to this uncertainty in the input variable
Value of Information, Value of Uncertainty techniques	Reveal the impact of having perfect knowledge or having knowledge about uncertainty on a specified outcome
Model validation/comparison against empirical data or analogues in time or space	Suggests a level of confidence one can have in model results

(Sources: Based on Kann and Weyant 2000, Morgan and Henrion 1990, Lempert 2002, Lempert, Popper, and Bankes 2002, and Lempert, Popper, and Bankes 2003)

Moser – Figures & Captions

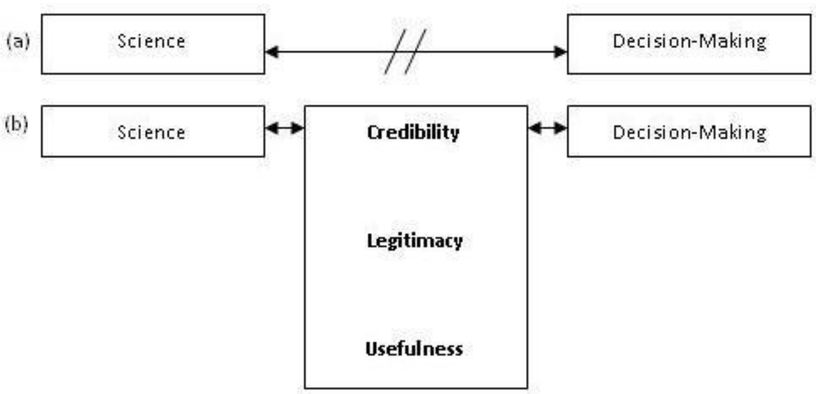

Figure 1: Linking Science and Policy-Making (expanding on Jones, Fischhoff, and Lach 1999)

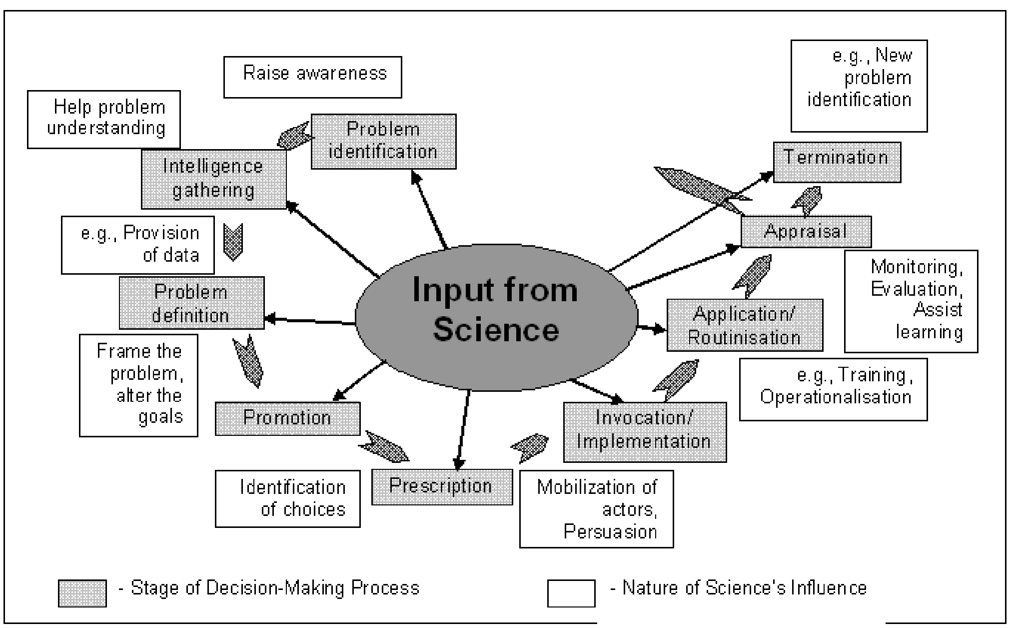

Figure 2: Scientific Input at Various Stages of the Decision Process and the Nature of Influence (from Vogel et al. 2007). Figure reprinted with permission from Elsevier.

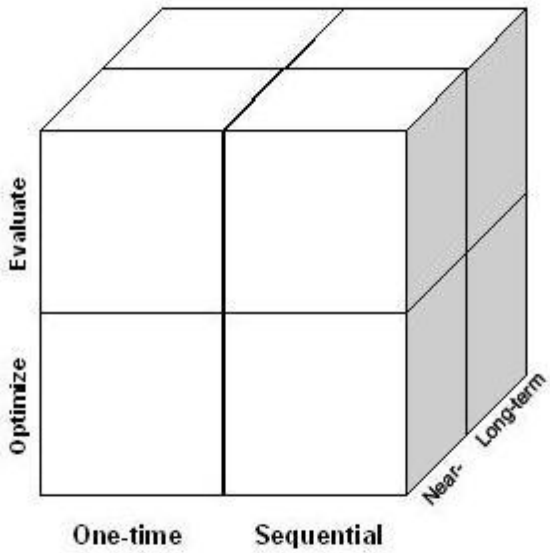

Figure 3: Three-dimensional Typology for Climate-Sensitive Decisions