demonstrate that the future climatic conditions will remain below dangerous levels.

The consequence of adverse conditions is often framed in economic terms, such as the monetary value of a loss or the number of jobs lost. And because human behavior is so complex, there is even greater uncertainty in the prediction of future economic conditions than there is in the prediction of climate change alone. Yet, despite uncertainty about the future, cost-benefit analyses are conducted on a daily basis as aids for policy makers on issues of critical importance to the nation such as health care, social security, and defense. Similarly, individuals weigh the costs and benefits of taking certain actions, like purchasing insurance, to minimize risk for themselves and their families.

The dominant purpose of science in climate change decision-support is prediction, or as typically stated in the policy arena, ***forecasting***. The accuracy of the provided forecasting, and the confidence that can be conveyed about that information, are critical factors. But another factor that may actually dominate the issue is ***the usability of the information***. Forecasting in policy arenas has formal constraints in terms of decision support that go well beyond the scientific quality domains. Science-based forecasting can be useless to policy decision support if it is not ***formulated properly***, ***communicated properly***, and ***used properly***. Within the scope of climate change projects that are incorporating UQ themes and are aimed at decision-support, an important task is to understand the formal requirements of forecasting for policy support and embedding these requirements in the overall prediction context.

The prediction problems of climate change that are relevant to policy are called ***integrated assessment***. Because policy will be driven regionally, integrated assessment must be performed at the regional level. Embedding UQ themes in integrated assessment at the regional level is an enormously complex technical problem. The complexity of the challenge of climate forecasting in a form that is relevant for policy-making support is understood. This understanding implies an understanding that in their current form, the IPCC assessments summarize the state of the science rather than provide policy-relevant information that can be usefully leveraged. The IPCC seems to increasingly understand this and is implying increased policy relevance in future assessments. Obviously they operate in a void to the extent that at this time there is not even a direction from policy makers as to how often scientific assessments of the kind IPCC delivers should be executed.

As stated above, UQ starts with the need to manage risk. The climate change problem is easily understood as existing within a regulatory environment in which the risk that is being managed is the margin of the Earth from climate tipping points. The modeling and simulation community's fundamental view that UQ is an organizing principle for generating, communicating, and using scientific information within a risk-informed decision environment is fully compatible with climate change projects.

In a recent analysis, Sandia researchers used computer models to predict the near-term impacts of climate change on state-level economies from 2010 through 2050 because, in the absence of quantifying the near-term cost, the need to address climate change seems more remote and has a diluted sense of urgency. The forecasts from the economic models we applied will almost certainly be highly inaccurate, but this approach is the only coherent option available to inform current decision making. An imprecise prediction can be useful for comparing options to address a significant problem if we assume that such a prediction adequately defines the future relative to the choices to be made and, more importantly, represents a mutually agreed upon basis from which stakeholders can debate alternatives on common ground. This same reasoning applies to climate change. While better science could reduce some of the uncertainty, this reduction will occur after the time frame for effective contemporary policy action. The IPCC climate projections (IPCC 2007b), along with any limitations and nuanced caveats associated with their usage, represent the best and the most visible climate-science reference for timely framing of the national and international assessment of climate-change risk.

NASA imagery of an ice-free Northwest Passage (vertically to the right of center). Researchers use this information to plan expeditions to the ice and to study the interactions between the ocean and sea ice from season to season. This data visualization shows Arctic sea ice from 1-Jan-07 to 16-Sep-07.

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SAND2010-7066P (October 2010)

Sandia National Laboratories is a multiprogram laboratory managed & operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Assessing Climate Uncertainty

The uncertainty in climate change and in its impacts is of great concern to the international community. While the ever-growing body of scientific evidence substantiates present climate change, the driving concern about this issue lies in the consequences it poses to humanity. Policy makers will most likely need to make decisions about climate policy before climate scientists have quantified all relevant uncertainties about the impacts of climate change. Sandia scientists seek to develop a risk-assessment methodology to evaluate uncertain future climatic conditions.

Understanding Uncertainty

All people deal with uncertainty every day. We may have a general expectation of how the coming hours will be spent and what will be the result, but that expected outcome is never certain. Something could come up at work that steers us away from our goal, or we could slip and fall down the stairs and end up in the emergency room. However, if we spent all of our time worrying about the worst outcomes, we might never leave our homes and that, too, would change the expected outcome. So, we assess risks and try to manage them as the day unfolds to bring us as close to our goals as we can make possible. By looking back on previous days like the one we feel we are about to experience and visualizing how this one may go, we undertake our own version of modeling and simulation to make a prediction about the next few hours.

We may only spend a few moments visualizing this, but during that time, we are calculating a great number of variables. As evidence of this, there are whole industries that focus on only small aspects of that coming day. Take, for example, the automobile insurance industry: most of us commute between 20 and 40 minutes from our homes to work each morning. This industry invests a vast amount of resources to answer the question, "Will I arrive at work safely this morning?" A nationwide insurance company just released a study that indicates that the average U.S. driver will be involved in a vehicular accident once every 10.2 years (the average for Albuquerque was slightly lower at every 9.9 years). The insurance industry uses these data along with similar statistical analyses about the behavior of different driver age groups, the car you drive, and your gender to determine a premium that you will pay—they are trying to predict people's behavior for 20–40 minutes twice a day in order to provide you with the contractual policy protections while collecting enough money to stay in business. (This example leaves aside shareholder profits/stock dividends.)

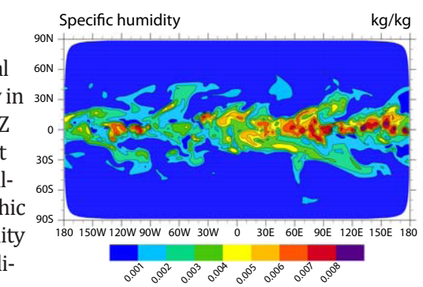
The economic enterprises of the U.S. have learned to employ tools to manage risks and reduce uncertainties in all sorts of activities. The government has empowered regulatory agencies and bodies to try to do the same where the economic motive may not provide enough incentive. These tools include case studies of past accidents and incidents, statistical analyses of the safety of an entire industry over decades, and/or psychological evaluations of human behavior when presented with specific situations or stimuli.

Using Modeling and Simulation to Reduce Uncertainty

As the analysis and predictive attempts become more complex, human understanding of the myriad factors and the relative weight assigned to any single one can significantly change the analytical result. To reduce this human-introduced uncertainty, scientists began using computers to perform the necessary calculations according to specific rules of interaction (algorithms) that establish agreed-upon emphasis and weight (in the collective judgment of the relevant professional community). Sandia National Laboratories has decades of experience in this modeling and simulation business in the field of nuclear weapons design and reliability.

Briefly, a device can have hundreds of essential components —each must survive the initiation of the nuclear explosion long enough to fulfill its purpose. If it is consumed before that point, then the device as a whole could fail. The simple answer would seem to be to over engineer the device—build it so strongly that nothing could possibly fail. However, if the designers follow that course, they could end up with a weapon so massive that no airplane or missile could carry it.

The U.S. national laboratories' approach a solution to this dilemma with science. We study materials to learn their properties in exquisite detail. We study high-energy interactions in weapons tests, laboratory experiments, and after testing ceased in 1992 with machines like the National Ignition Facility in Livermore, the Z Machine here at Sandia, the Dual-Axis Radiographic Hydro Test facility and Proton Radiography at Los Alamos, and the Atlas pulsed-power machine at the Nevada Test Site.



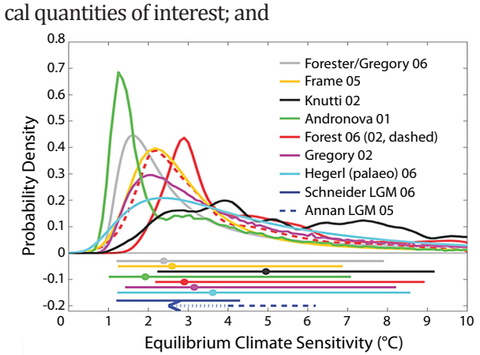
Advanced numerical methods will be required such as those related to adaptive mesh refinement, multi-scale physics, and scalability on massively parallel computers. An example of this is the new highly scalable Spectral Element Atmospheric Model developed by Sandia for the Community Climate Simulation model Dycore (Mark Taylor, SNL, 2007).

The data from these experiments have helped to significantly refine our computer models and increased the precision and accuracy of their predictions.

Unfortunately, while these experiments have vastly increased the national security science community's knowledge in many areas, with an accompanying increase in the predictive power of the computer modeling, we can never know all that there is to know about the materials/physics involved. The data our researchers collect are limited by factors like the sensitivity of the diagnostic instruments that capture the data, the number of experiments we can complete, the personnel available and their experience and expertise, the funding available, and, ultimately, by the sheer number of factors involved—when researchers make a leap in scientific understanding, they can unveil a whole new area of physics that they didn't know existed and that they know nothing about.

This is where uncertainty quantification (UQ) comes in. Uncertainties are always present and play an important role in using simulation tools to predict behavior of a physical system. Dealing with uncertainty in prediction is ***inevitable***. UQ methodology seeks to identify "important" areas of uncertainty—where an uncertainty will cause the widest variability in the computational model's outcomes. If UQ researchers can identify a factor that will lead to the greatest variability in outcome, they can guide the researchers to where their efforts can be best applied to understanding the materials science or high-energy physics to reduce the system's overall uncertainty and variability. UQ as a methodology focuses on

1. identifying and characterizing all plausible sources of uncertainty;
2. accurately propagating uncertainties through a computational model and interpreting uncertainties in the physical quantities of interest; and



Uncertainty in climate change due to a doubling of atmospheric CO_2. Shown here is the comparison between different estimates of the probability density (or relative likelihood) for climate sensitivity (i.e., temperature increase °C). All the probability curves have been scaled to integrate to unity between 0°C and 10°C sensitivity. The bars show the respective 5% to 95% ranges and the dots the median estimate.

3. performing sensitivity analyses to determine the most important contributors to uncertainty in system responses.

A key aspect of characterizing uncertainty is dividing/categorizing uncertainties into uncertainty due to the inherent randomness of the system or environment (i.e., uncertainty due to chance) and uncertainty due to lack of knowledge about the system or environment.

Propagating uncertainty addresses two questions

1. How are input uncertainties propagated through the model?
2. How are uncertainties in the model itself estimated?

Input uncertainty refers to any uncertainty in any input quantity for the model, including parameters, boundary conditions, forcing functions, environments, and scenarios. Uncertainties in the model itself can be due to lack of knowledge of the physical processes or due to approximations made that eliminate certain aspects of the physical processes of interest.

A sensitivity analysis (SA) is typically directed at two closely related goals. First, to determine which computational simulation inputs have the ***largest effect***, either locally or globally, on one or more computational outputs. Second, to determine which uncertain simulation inputs produce the ***largest change in uncertainty*** of one or more simulation outputs.

UQ and SA for computational science are active areas of research in general, focusing on development of robust and efficient methods. Developing more sophisticated, accurate, and computationally resource-appropriate methods of UQ and SA are critical, especially when our goals center on forecasting extreme events with complex computational models. The most appropriate strategy further depends on the type of uncertainties present.

Uncertainty in Climate Forecasting

While the national security science community has decades of experience working to minimize uncertainty in weapons, the study of climate and the factors that lead it to change over time is much more rudimentary. Recent Greenland ice core evidence shows that when the climate system is left to itself and given the variability of natural forces, it tends to be wildly erratic. Looking from the perspective of the past several million years, climate change is the norm, and long-term stability is the exception. Moreover, major shifts in climate over large areas can be remarkably fast. Our sense of climate stability is comforting but it is illusory because the entire history of human civilization is so short.

The Earth's climate is a vast and complex system. Studying climate change reveals that there are a variety of margins. All

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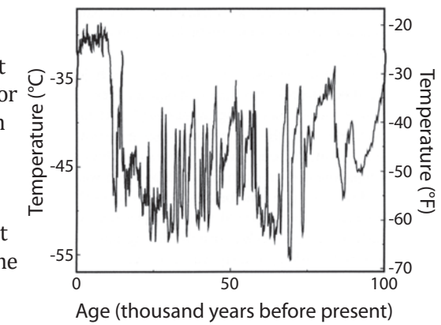
margins imply the existence of a threshold, and the margin is some measure of the distance from that threshold. The most obvious thresholds are ***tipping points***. The margin is defined as the distance from a tipping point in any climate-related dimension that seems appropriate (temperature, greenhouse gas concentrations, time, integrated planetary albedo, etc).



*Temperature record and ice-sheet elevation in central Greenland for the past 100,000 years. K.M. Cuffy & G.D.Clow. **J. Geophys. Res.**, 102:26,383-26,396, 1997.*

Within the context of decision-support it is wise to recognize other margins, for example the ***margin of risk***—the notion of how much climate change risk can society/humanity tolerate. Worrying about this in the context of integrated assessment leads us to worrying about extreme events lying far in the tail of the (subjective) probability distributions that arise in analyzing climate change. Another margin is ***margin of error***, for example in modeling and simulation. A third margin is ***margin of confidence***, for example policy makers' confidence in acting upon the aggregate information regarding climate change available at any given time.

Margins are uncertain. Consider tipping points. The current knowledge implies that the threshold associated with a climate change tipping point (no matter how it is defined) is uncertain. That means that the margin, the current distance from that tipping point, is uncertain. Even if the tipping point threshold were completely certain, the margin itself would still be uncertain because of the incompleteness of the science community's knowledge of the current climate system and what it is doing. Finally, there is structural uncertainty in the definition of tipping points (not just quantifying of their thresholds) because of subject-matter debates. Thus, in climate research, scientists have the same coupling of margins with uncertainty that the national security science community has in the nuclear weapons program, and in other regulatory policy environments.

Quantifying Uncertainty to Empower Policy Making

The human history of agriculture, cities, and civilization itself arose during an extended time of relative climate quiescence. Because the entire human experience is associated with ***anomalous*** climate stability, humanity is inclined to continue to expect more of the same. National security is tied to trade systems, utility infrastructures, transportation networks, political alliances, energy policies, agricultural practices, supply chains, business investments, and military actions. All of these sectors make plans based on implicit assumptions that the climate will not be significantly different in a decade from what it is now.

Humanity's success in using the Earth system to our advantage has depended, to a large extent, on its relative stability. Our approach is to think of the Earth's climate along with the factors that affect it as a system, which allows us to adopt language and concepts of systems engineering. We can think of a stable climate as being analogous to a properly-functioning engineered system while an abrupt climate change is analogous to the failure of an engineered system.

The impacts from climate change are largely negative. From a policy perspective, the incentive to act comes by comparing the risk (cost) of inaction with the cost of action to successfully mitigate climate change. Risk is often characterized in terms of probability and consequence. A spectrum of conditions (or events) is involved with climate change for assessing risk. At one end of the spectrum are those conditions that may occur frequently (high probability) and result in minimal damage (low consequence). An example of a high-probability, low-consequence type of event would be excessive rainfall that results in damage to the roof of your house. At the other end of the spectrum are conditions that do not occur frequently (low probability) but may be life changing or catastrophic (high consequence) if they do occur. Examples of low-probability, high-consequence types of risks would be a prolonged severe drought in an area and, at the very extreme, an asteroid collision with Earth.

The less society understands about climate change, the larger the tail on the uncertainty distribution for climate change becomes. Greater extremes in climatic conditions imply greater societal consequences should those extremes occur. Accordingly, the greater the uncertainty is, the greater is the risk. Risk derives and increases from "not knowing." The efforts of those skeptical of climate-change projections to demonstrate limitations in the accuracy of climate-change analyses may cause climate scientists to change the priorities of their research, but the real effect of emphasizing limitations is to accentuate the level of uncertainty in future climatic conditions. Rather than justifying a lack of response to climate change, the emphasis on the uncertainty enlarges the assessed risk and reinforces the responsibility for pursuing successful long-term mitigation policy. If those skeptical of climate change want to halt government initiatives in climate policy, the burden is on them to reduce the uncertainty and