Non-Technical Summary

Vaclav Smil (2007), one of the most wide ranging intellects of our day, observes that "the necessity to live with profound uncertainties is a quintessential condition of our species." Two centuries ago, Benjamin Franklin (1789), an equally wide ranging intellect of his day, made the identical observation in more colorful and colloquial language when he wrote that "in this world nothing is certain but death and taxes" and of course, even in that case, the date of ones death, and the amount of next year's taxes are both uncertain.

Those views about uncertainty certainly apply to many aspects of climate change and its possible impacts, including:

- How the many complex interactions within and among the atmosphere, the oceans, ice in the Arctic and Antarctic, and the living "biosphere," shape local, regional and global climate;
- How, and in what ways, climate has changed over recent centuries and is likely to change over coming decades;
- How future human activities and choices may result in emissions of gases and fine particles and may change land use and vegetation that together can influence future climate;
- How those changes will affect the climate;
- What impacts a changed climate will have on the natural and human world; and
- How the resulting changes in the natural and human world will feed back on and influence climate in the future.

Clearly the climate system, and its interaction with the human and natural world, is a prime example of what scientists call a "complex dynamic interactive system."

This report is not about the details of what we know, do not know, could know with more research, or may not be able to know until years after climate has changed, but about these complex processes. These issues are discussed in detail in a number of other reports of the U.S. Climate Science Research Program (CCSP), as well as reports of the Intergovernmental Panel on Climate Change (IPCC), the United States National Research Council, and special studies such as the United States National Assessment, and the Arctic Climate Impact Assessment[8].

However, for non-technical readers who may not be familiar with the basics of the problem of climate change, we offer a very simple introduction in Box NT-1

BOX NT-1 Summary of Climate Change Basics

Carbon dioxide is released to the atmosphere when coal, oil or natural gas is burned. Carbon dioxide is not like conventional air pollutants such as sulfur dioxide, oxides of nitrogen or fine particles. When the emissions of such conventional pollutants are stabilized, their atmospheric concentration is also quickly stabilized since these pollutants remain in the atmosphere for only a matter of hours or days. The relationship between emissions and concentrations for these conventional pollutants is illustrated in this simple diagram:

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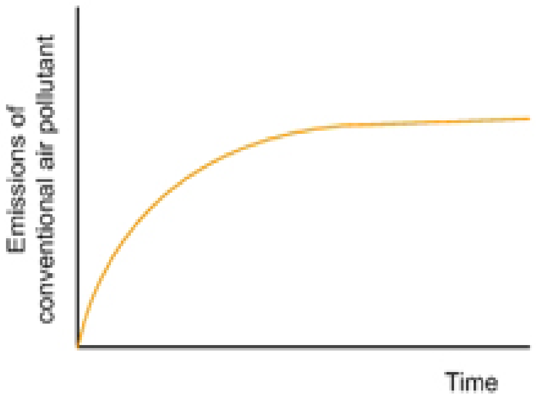
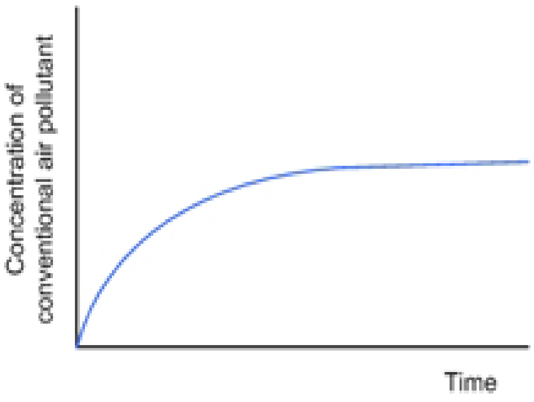
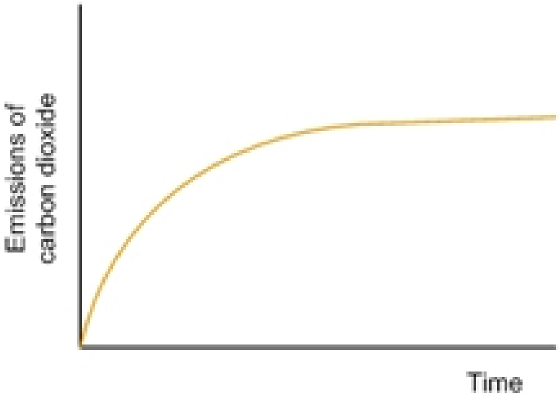
[8] For access to the various reports mentioned in this sentence see respectively: <www.climatescience.gov/>; <www.ipcc.ch>; <www.nationalacademies.org/publications/>; <www.usgcrp.gov/usgcrp/nacc/default.htm>; and <www.acia.uaf.edu/>.

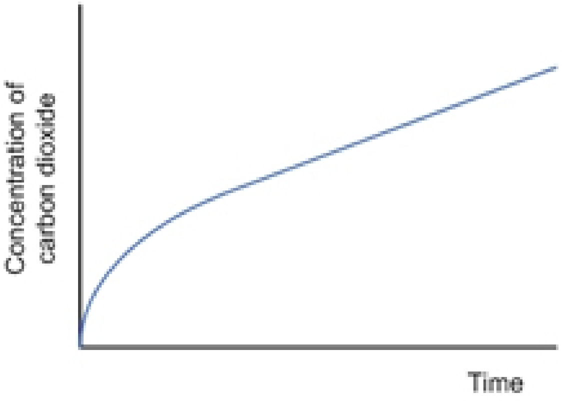




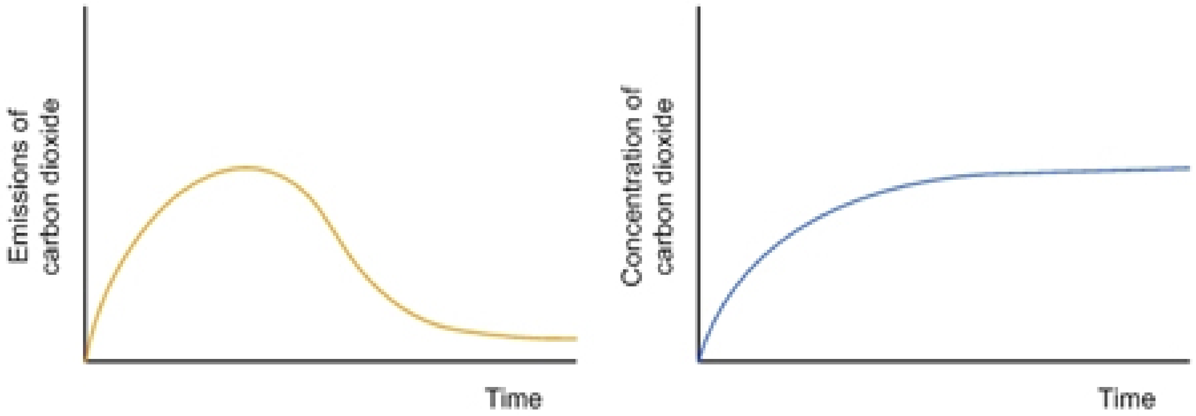
This is not true of carbon dioxide or most other greenhouse gases.

Much of the carbon dioxide that is emitted stays in the atmosphere for over 100 years. Thus, if emissions are stabilized, concentrations will continue to build up, in much the same way that the water level will rise in a bathtub being filled from a faucet that can add water to the tub much faster than a small drain can let its drain out. Again the situation is summarized in this simple diagram:





In order to stabilize atmospheric concentrations of carbon dioxide, worldwide emissions must be dramatically reduced (most experts would say by something like 70 to 90% depending on the assumptions made about the processes involved and the concentration level that is being sought). Again, here is a simple diagram:



Summarizing, there are three key facts that it is important to understand to be an informed participant in policy discussions about climate change:

- When coal, oil and natural gas (*i.e.* fossil fuels) are burned, carbon dioxide (CO_2) is created and released into the atmosphere. There is *no* uncertainty about this.
- Because CO_2 (and other greenhouse gases) trap heat, if more is added to the atmosphere, warming will result that can lead to climate change. Many of the details about how much warming, how fast, and similar issues *are* uncertain.
- CO_2 (and other greenhouse gases) are not like conventional air pollution such as SO_2 , NO_x or fine particles. Much of the CO_2 that enters the atmosphere remains there for more than 100 years. In order to reduce concentration (which is what causes climate change), emissions must be dramatically reduced. There is no uncertainty about this basic fact, although there is uncertainty about how fast and by how much emissions must be reduced to achieve a specific stable concentration. Most experts would suggest that a reduction of between 70 and 90% is needed. This implies the need for dramatic changes in energy and other industrial systems all around the globe.

END BOX NT-1

This report provides a summary of tools and strategies that are available to characterize, analyze and otherwise deal with uncertainty in characterizing, and doing analysis of climate change and its impacts. The report is written to serve the needs of climate scientists, experts assessing the likely impacts and consequences of climate change, as well as technical staff supporting private and public decision makers. As such, it is rather technical in nature, although in most cases we have avoided mathematical detail and the more esoteric aspect of the methods and tools discussed – leaving those to references cited throughout the text.

The report explores eight aspects of this topic. Then, in Section 9, the report concludes with some guidance for researchers and policy analysts that is based both on relevant scientific literature and on the diverse experience and collective judgment of the writing team.

Part 1: Sources and types of uncertainty

Uncertainty arises in a number of ways and for a variety of reasons. First, and perhaps simplest, is uncertainty in measuring specific quantities, such as temperature, with an instrument, such as a thermometer. In this case, there can be two sources of uncertainty.

The first is random errors in measurement. For example, if you and a friend both look at typical back-yard thermometer, and record the temperature, you may write down slightly different numbers because the two of you may read the location of red line just a bit differently. Similar issues arise with more advanced scientific instruments.

The second source of uncertainty that may occur involves a "systematic" error in the measurement. Again, in the case of the typical back-yard thermometer, perhaps the company that printed the scale next to the glass, didn't get it on in just the right place, or perhaps the glass slid a bit with respect to the scale. That could result in all the measurements that you and your friend write down being just a bit high or low, and, unless you checked your thermometer against a very accurate one (*i.e.*, "calibrated" it), you'd never know this problem existed. Again, similar issues can arise with more advanced scientific instruments.

Beyond random and systematic measurement errors lies a much more complicated kind of potential uncertainties. Suppose, for example, you want to know how much rain your garden will receive next summer. You may have many years of data on how much rain has fallen in your area during the growing season, but, of course, there will be some variation from year-to-year. You can compute the average, but if you want to have an estimate for *next* summer, the average does not tell you the whole story. In that case, you will want to look at the distribution of the amounts that fell over the years, and figure out the odds that you will get varying amounts by examining how often that amount occurred in the past.

Continuing with this example, if sum rainfall in your region is gradually changing over the years (either because of natural long-term variability or because of systematic climate change) using the distribution of past rainfall will not be a perfect predictor of future rainfall. In this case, you will also need to look at (or try to predict) the trend over time.

Finally, suppose that you want to know the odds that there will be more rain than the 45 inches, and suppose that over the past century, there has been only one growing season in which there has been more than that much rain. In this case, since you don't have enough data for reliable statistics, you will have talk to experts (and perhaps have them use a combination of models, trend data, and expert judgment) to get you an estimate of odds.

Finally, suppose (like most Americans, the authors included) you know nothing about sumo wrestling, but you need to know the odds that a particular sumo wrestler will win the next international championship. In that case, your best option is probably to carefully interview a number of the world's leading sumo coaches and sports commentators and "elicit" odds from each of them. Analysts often do very similar things when they need to obtain odds on the future value of specific climate quantities. This process is known as "expert elicitation." Doing it well takes careful preparation and execution. Results are typically in the form of distributions of odds called "probability distributions."

All of these examples involve uncertainty about the value of some quantity such as temperature or rainfall. There can also be uncertainty about how a physical process works. For example, before Isaac Newton figured out the law of gravity, that says the attraction between two masses (like the sun and the earth; or an apple and the earth) is inversely proportional to the product of the two masses and inversely proportion to the square of the distance between them, people were uncertain about how gravity worked. However, they certainly knew from experience that something like gravity existed. We call this kind of uncertainty "model uncertainty." In the context of the climate system, and the possible impacts of climate change, there are many cases were we do not understand all the physical, chemical and biological processes that are involved – that is there are many cases in which we are uncertain about the underlying "causal model." This type of uncertainty is often more difficult to describe and deal with than uncertainty about the value of specific quantities, but progress is being made on developing methods to address it.

Finally there is ignorance. For example, when Galileo Galilei first began to look at the heavens through his telescope, he may have had an inkling that the earth revolved around the sun, but he had no idea that the sun was part of an enormous galaxy, and that our galaxy was just one of billions in an expanding universe. Similarly, when astronomers built the giant 200-inch telescope on Mount Palomar they had no idea that at the center of our galaxy lay a massive "black hole." These are examples of scientific ignorance. Only as we accumulate more and more evidence that the world does not seem to work exactly like we think it does, do scientists begin to get a sense that perhaps there is something fundamental going on that they have not previously recognized or appreciated. Modern scientists are trained to keep looking for indications of such situations (indeed that's what wins Nobel prizes) but even when a scientist is looking for such evidence, it may be very hard to see, since all of us, scientists and non-scientists alike, view the world through existing knowledge and "mental models" of how things around us work. There may well still be a few things about the climate system, or climate impacts, about which we are still completely ignorant – and don't even know to ask the right questions.

While Donald Rumsfeld (2002) was widely lampooned in the popular press, he was absolutely correct when he noted that "…there are known unknowns. That is to say, we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know we don't know." But perhaps the ever folksy but profound Mark Twain put it best when he noted "It ain't what you don't know that gets you in trouble. It's what you know for sure that just ain't so."

Part 2: The importance of quantifying uncertainty

In our day-to-day discussion, we use words to describe uncertainty. We say:

"I think it is very likely she will be late for dinner."

"I think it is unlikely that the Pittsburgh Pirates will win next year's World Series."

"I'll give you even odds that he will or will not pass his drivers test."

"They say nuclear war between India and Pakistan is unlikely next year."

"The doctor says that it is likely that the chemical TZX causes cancer in people."

People often ask, “Why not just use similar words to describe uncertainty about climate change and its impacts?”

Experimental studies have found that such words can mean very different things to different people. They can also mean very different things to the same person in different situations.

Think about betting odds. Suppose that to one person "unlikely" means that they think there is only 1 chance in 10 that something will happen, while to another person the same word means they think there is only one chance in a thousand that that same thing will happen. In some cases, that difference could be very important. For example, in the second case, you might be willing to make a big investment in a company if your financial advisor tells you they are "unlikely" to go bankrupt – that is the odds are only 1 in 1000 that will happen. One the other hand, if by unlikely the advisor actually means a chance of 1 in 10, you might not want to put your money at risk.

The same problem can arise in scientific communication. For example, some years ago members of the EPA Science Advisory Board were asked to attach odds to the statement that a chemical was "likely" to cause cancer in humans or "not likely" to cause cancer in humans. Fourteen experts answered these questions. The odds for the word likely ranged from less than 1 in 10 down to about 1 in 1000! The range was even wider for the odds given on the word "not likely." There was even an overlap…where a few experts used the word "likely" to describe the same odds that other experts described as "not likely."

Because of results like this it is important to insist that when scientists and analysts talk about uncertainty in climate science and its impacts, they tell us in quantitative terms what they mean by the uncertainty words they use. Otherwise nobody can be sure of what they are saying.

The climate community has been better than a number of other communities (such as environmental health) in doing this. However, there is still room for improvement. In the final section of the report, the authors offer advice on how they think this should best be done.

Part 3: Cognitive challenges in estimating uncertainty

Humans are very good at thinking about and doing lots of things. However, experimental psychologists have found that the way our brains make some judgments, such as those involved in estimating and making decisions about uncertainty, involves unconsciously using some simple rules. These simple rules (psychologists call them "cognitive heuristics') work pretty well most of the time. However, in some circumstances they can lead us astray.

For example, suppose I want to estimate the odds that when I drive to the airport tomorrow morning, I'll see a state police patrol car. I have made that trip at that time of day many times in the past. So, unless there is something unusual going on tomorrow morning, the ease with which

I can imagine encountering a state police car on previous trips, will probably give me a pretty good estimate of the odds that I'll see one tomorrow.

However, suppose that instead I had to drive to the airport tomorrow at 3:30 a.m. I've never done that before (and hope I'll never have to do it). However, if I try to estimate the odds of encountering a state police car on that trip, experience from previous trips, or my imagination about how many state police may be driving around at that time of night, may not give me a very accurate estimate.

This strategy, that our minds use subconsciously to estimate probabilities in terms of how easily we can recall past events or circumstances, or imagine them in the future, is a "cognitive heuristic" called "availability”. We make judgments in terms of how available experience or imagination is when our minds consider an issue of uncertainty.

Section 3 of the report describes several such cognitive heuristics. The description is largely non-technical so readers who find these issues interesting should find they could read this part of the report without much difficulty.

The other issue discussed in Section 3 of the report is overconfidence. There is an overwhelming amount of evidence from dozens of experimental studies done by psychologists and by decision analysts, that when people judge how well they know an uncertain quantity, they set the range of their uncertainty much to narrowly.

For example, suppose you ask a whole bunch of your adult friends how high Mt. McKinley in Alaska is, or how far it is between Philadelphia and Pittsburgh. But, you don't ask them just for their best guess. You ask them for a range. That is, you say, "give me a high estimate and a low estimate of the distance in miles between Philadelphia and Pittsburgh such that there are only 2 chances in 100 that the real distance falls outside of that range." Sounds simple, but when thousands of people have been asked thousands of questions like this, and their uncertainty range is compared with the actual values of the answers, the real answers fall outside of the range they estimated much more than 2% of the time (indeed, sometimes as much as almost half the time!).

What does this mean? It means that we all tend to be overconfident about how well we know things that we know are uncertain. And, it is not just ordinary people making judgments about ordinary things such as the weight of bowling balls or the distance from Philadelphia to Pittsburgh. Experts have the same problem.

What does all this have to do with climate change? It tells us that when scientists make estimates of the value of uncertain quantities, or when they, or decision makers, make judgments about uncertain science involving climate change and its impacts, these same processes will be operating. We can't completely get rid of the biases created by cognitive heuristics, nor can we completely eliminate over confidence. But, if we are aware of these tendencies, and the problems they can lead to, we may all be able to do a better job of trying to minimize their impacts.

Part 4: Statistical methods and models

Statistical methods and models play a key role in the interpretation and synthesis of observed climate data and the predictions of numerical climate models. The section provides a summary of some of the statistical methods being used for climate assessment, including procedures for detecting longer-term trends in noisy records of past climate that include year-to-year variations as well as various more periodic fluctuations. Such methods are especially important in addressing the question, "what long-term changes in climate are occurring?"

The section also discusses a number of other issues such as methods to assess how well alternative mathematical models fit existing. Methods for hypothesis testing and model selection are presented, and emerging issues in the development of statistical methods are discussed.

Rather than give a detailed technical tutorial, the focus of this section is more on identifying key strategies and analytical tools, and then referring expert readers to relevant review articles and more detailed technical papers.

Many non-technical readers will likely find much of the discussion in this section too detailed to be of great interest. However, many may find it useful to take a look at the boxed section "Predicting Rainfall: An illustration of frequentist and Bayesian approaches" that appears at the end of the section in which the problems of developing probabilistic descriptions (or odds) on the amount of future rainfall in some location of interest are discussed, first in the presence of various random and periodic changes (wet spells and dry spells) and then in the more complicated situation in which climate change (a long-term trend) is added.

Part 5: Methods for estimating uncertainty

Many of the facts and relationships that are important to understanding the climate system and how climate may change over the coming decades and centuries will likely remain uncertain for years to come. Some will probably not be resolved until substantial changes have actually occurred.

While a variety of evidence can be brought to bear to gain insight about these uncertainties, in most cases no single piece of evidence or experimental result can provide definitive answers. Yet research planners, groups attempting to do impact assessment, policy makers addressing emissions reductions, public and private parties making long-lived capital investment decisions, and many others, all need some informed judgment about the nature and extent of the associated uncertainties.

Two rather different strategies have been used to explore the nature of key uncertainties about climate science, such as the amount of warming that would result if the concentration of carbon dioxide in the atmosphere is doubled and then held constant (this particular quantity is called the "climate sensitivity").

The first section of Section 5 discusses a number of different ways in which climate models have been used in order to gain insight about, and place limits on the amount of uncertainty about key aspects of the climate system. Some of these methods combine the use of models with the use of expert judgments.

The second section of Section 5 discusses issues related to obtaining and using expert judgments in the form of probability distributions (or betting odds) from experts on what a key value might be based on their careful consideration and synthesis of all the data, model results and theoretical arguments in the literature. Several figures in the latter part of this discussion show illustrations of the types of results that can be obtained in such studies. One of the interesting findings is that when these methods are used with individual experts, the resulting impression of the overall level of uncertainty appears to be somewhat greater (that is the spread of the distributions is somewhat wider) than the results that emerge from consensus panels such as those of the IPCC.

Part 6: Propagation and analysis of uncertainty

Probabilistic descriptions of what is known about key quantities, such as how much warmer it will get as the atmospheric concentration of carbon dioxide rises or how much the sea level will increase as the average temperature of the earth increases, can have value in their own right as an input to research planning and in a variety of assessment activities. Often, however, annalists want to incorporate such probabilistic descriptions in subsequent modeling and other analysis. Today, this is usually done by running the analysis over and over again on a fast computer, using different input values, from which it is possible to compile the results into probability distributions. This approach is termed "stochastic simulation." Today a number of standard software tools are available to support such analysis.

Some climate analysis uses a single model to estimate what decision or policy is "optimal" in the sense that it has the highest "expected value" (*i.e.*, offers the best bet). However, others argue that because the models used in such analysis are themselves uncertain, it is not wise to search for a single "optimal" answer but rather one should search for answers or polices that are likely to be pretty good across a wide range of models and future outcomes. Section 6 presents several examples of results from such analysis.

Part 7: Making decisions in the face of uncertainty

There are a number of things about climate change, and its likely consequences, that are unique. However, uncertainty, even irreducible uncertainty, is not one of them. In our private lives, we decide where to go to college, what job to take, whom to marry, what home to buy, when and whether to have children, and countless other important choices, all in the face of large, and often, irreducible uncertainty. The same is true of decisions made by companies and by governments.

A set of ideas and analytical methods called "decision analysis" have been developed to assist in making decisions in the face of uncertainty. If one can identify the alternatives that are available, identify and estimate the probability of key uncertain events, and specify preferences (utilities) among the range of possible outcomes, these tools can provide help in framing and analyzing complex decisions in a consistent and rational way. Decision analysis has seen wide adoption by private sector decision makers – such as major corporations facing difficult and important decisions. While more controversial, they have also seen more limited application to public sector decision making, especially in dealing with more technocratic issues.

Of course, even if they want to, most people do not make decisions in precise accordance with the norms of decision analysis. A large literature, based on extensive empirical study, now exists on "behavioral decision theory." This literature describes how and why people make decisions in the way that they do, as well as some of the pitfalls and contradictions that can result. Section 8 provides a few brief pointers into that literature, but does not attempt a comprehensive review. That would require a paper at least as long as this one.

For both theoretical and practical reasons there are limits to the applicability and usefulness of classic decision analysis to climate-related problems. Two strategies may be especially appealing in the face of high uncertainty:

- Resilient Strategies**:** In this case, the idea is to try to identify the range of future circumstances that one might face, and then seek to identify approaches that will work reasonable well across that range.

- Adaptive Strategies**:** In this case, the idea is to choose strategies that can be modified to achieve better performance as one learns more about the issues at hand and how the future is unfolding.

Both of these approaches stand in sharp contrast to the idea of developing optimal strategies that has characterized some of the work in the climate change integrated assessment community, in which it is assumed that a single model reflects the nature of the world with sufficient accuracy to be the basis for decision making and that the optimal strategy for the world will be chosen by a single decision maker.

The "precautionary principle" is another decision strategy often proposed for use in the face of high uncertainty. There are many different notions of what this approach does and does not entail. In some forms, it incorporates ideas of resilient or adaptive policy. In some forms, it can also be shown to be entirely constant with a decision analytic problem framing. Precaution is often in the eye of the beholder. Thus, for example, some have argued that while the European Union has been more precautionary with respect to CO_2 emissions in promoting the wide adoption of fuel efficient diesel automobiles, the United States has been more precautionary with respect to health effects of fine particulate air pollution, stalling the adoption of diesel automobiles until it was possible to substantially reduce their particulate emissions.

Part 8: Communicating uncertainty

Many weather forecasters and other technical professionals have argued that one should not try to communicate about uncertainty to non-technical audiences. They suggest laypeople won't understand and that decision makers want definitive answers – that is, advice from what are often referred to as "one armed scientists"[9].

We do not agree. Non-technical people deal with uncertainty, and statements of probability, all the time. They don't always reason correctly about probability, but they can generally get the gist (Dawes, 1988). While they may make errors about the details, for the most part people manage to deal with probabilistic precipitation forecasts from the weather bureau, point spreads at the track, and similar probabilistic information. The real issue is to frame things in familiar and understandable terms.

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[9] The reference, of course, being to experts who always answered his questions "on the one hand…but on the other hand…," the phrase is usually first attributed to Senator Edmund Muskie.

When should probability be communicated in terms of odds (the chance that the Pittsburgh Pirates will win the World Series this year is about 1 in 100) or in terms of probabilities (the probability that the Pittsburgh Pirates will win the World Series this year is 0.01)? Psychologist Baruch Fischhoff and colleagues (2002) suggest that:

- Either will work, if they're used consistently across many presentations.
- If you want people to understand one fact, in isolation, present the result both in terms of odds and probabilities.
- In many cases, there's probably more confusion about what is meant by the specific events being discussed than about the numbers attached to them.

Section 7 briefly discuses some empirical methods that can be used to develop and evaluate understandable and useful communications about uncertain technical issues for non-technical and semi-technical audiences. This approach uses "mental model" methods to learn in some detail what people know and need to know about the topic. Then having developed a pilot communication, working with members of the target audience, the message is extensively tested and refined until it is appropriately understood. One key finding in this literature is that there is no such thing as an expert in communication – in the sense of someone who can tell you ahead of time how a message should be framed, or what it should say. Empirical study is absolutely essential to the development of effective communication.

The presence of high levels of uncertainty offers people who have an agenda with an opportunity to "spin the facts." Combine this with the fact that many reporters are not in a position to make their own independent assessment of the likely accuracy of scientific statements, the tendency of the press to seek conflict and to find and report the views of those holding widely divergent views, and do so in just a few words and with very short deadlines, and it is small wonder that the issue of climate change and its associated uncertainties has presented particularly challenging issues for members of the press who are trying to cover the issue in a balanced and responsible way.

In an environment in which there is high probability that many statements a scientist makes about uncertainties will immediately be seized upon by advocates in an ongoing public debate, it is small wonder that many scientists choose to just keep their heads down, do their research, and limit their communication to publication in scientific journals and presentations at professional scientific meetings.

While we do not reproduce it here, the latter portion of Section 8 contains some thoughtful reflection on these issues from several leading scientists and members of the press.

Part 9: Some simple guidance for researchers

The final section of the report provides some advice and guidance to practicing researchers and policy analysts who must address and deal with uncertainty in their work on climate change, impacts, and policy.

However, before turning to specific recommendations, the section begins by reminding readers that doing a good job of characterizing and dealing with uncertainty can never be reduced to a simple cookbook. Researchers and policy analysts must always think critically and continually ask themselves questions such as:

- Does what we are doing make sense?
- Are there other important factors which are, as or more important, than the factors we are considering?
- Are there key correlation structures in the problems that are being ignored?
- Are there normative assumptions and judgments about which we are not being explicit?

The balance of the final section provides specific guidance to help researchers and analysts to do a better job of reporting, characterizing and analyzing uncertainty. Some of this guidance is based on available literature. However, because doing these things well is often as much an art as it is a science, the recommendations also draw on the very considerable[10] and diverse experience and collective judgment of the writing team.

Rather than reproduce those recommendations here, readers are referred to the discussion at the end of Section 9.

NON-TECHNICAL SUMMARY REFERENCES

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[10] Collectively the author team has roughly 200 person-years of experience in addressing these issues both theoretically and in practical analysis in the context of climate and other similar areas.

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