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The Scientific Consensus on Climate Change: How Do We Know We're Not Wrong?

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2.1 Introduction

In December 2004, *Discover* magazine ran an article on the top science stories of the year. One of these was climate change, and the story was the emergence of a scientific consensus over the reality of global warming. *National Geographic* similarly declared 2004 as the year that global warming "got respect" (Roach 2004).

Many scientists felt that respect was overdue. As early as 1995, the Intergovernmental Panel on Climate Change (IPCC) had concluded that "the balance of evidence" supported the conclusion that humans were having an impact on the global climate (Houghton et al. 1995). By 2007, the IPCC's Fourth Assessment Report found a stronger voice, declaring that warming was "unequivocal," and noting that it is "extremely unlikely that the global climate changes of the past fifty years can be explained without invoking

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human activities" (Alley et al. 2007). Prominent scientists and major scientific organizations have all ratified the IPCC conclusion (Oreskes 2004). Today, all but a tiny handful of climate scientists are convinced that earth's climate is heating up and that human activities are a primary driving cause (Doran and Zimmerman 2009; Anderegg et al. 2010; Cook et al., 2016).

Yet many Americans continued to wonder. A 2006 poll reported in *Time* magazine found that only just over half (56 percent) of Americans thought that average global temperatures had risen—despite the fact that virtually all climate scientists think that they have.[1] Since 2006, public opinion has wavered—influenced by short-term fluctuations in weather, as well as by political and cultural considerations whose relationship to climate change is indirect at best (Leiserowitz et al. 2011, and refs cit.). But one thing that has remained consistent is a gap between the virtually unanimous opinion of scientists that man-made climate change is underway and the continued doubts of a significant proportion of the American people (Leiserowitz et al. 2011; see also Borick et al. 2010). Moreover, as Jon Krosnick and his colleagues have stressed, while the scientific community has for some time believed that the evidence of climate change "justifies substantial public concern," the public has not broadly shared that view (Krosnick et al. 2006, see also Lorenzoni and Pidgeon 2006).

This book addresses the scientific study of climate change and its impacts. By definition, predictions are uncertain, and people may wonder why we should spend time, effort, and money addressing a problem that may not affect us for years or decades to come. Some people have gone further, suggesting that it would be foolish to spend time and money addressing a problem that might not actually even be a problem. After all, how do we really know?

This chapter addresses the question: how *do* we know? Put another way, even if there is a scientific consensus, how do we know it's not wrong? If the history of science teaches anything, it is humility. There are numerous historical examples where expert opinion turned out to be wrong. At the start of the twentieth century, Max Planck was advised not to go into physics because all the important questions had been answered, medical doctors prescribed arsenic for stomach ailments, and geophysicists were confident that continents did not drift. In any scientific community there are individuals who depart from generally accepted views, and occasionally they turn out to be right. At present, there is a scientific consensus on global warming, and that consensus has been stable for at least a decade. But how do we know it's not wrong?

2.2 The Scientific Consensus on Climate Change

Let's start with a simple question: What is the scientific consensus on climate change, and how do we know it exists? Scientists do not vote on contested issues, and most scientific questions are far too complex to be answered by a simple yes or no response. So how does anyone know what scientists think about global warming?

Scientists glean their colleagues' conclusions by reading their results in published scientific literature, listening to presentations at scientific conferences, and discussing data and ideas in the hallways of conference centers, university departments, research institutes, and government agencies. For outsiders, this information is difficult to access: scientific papers and conferences are by experts for experts and are difficult for outsiders to understand.

Climate science is a little different. Because of the political importance of the topic, scientists have been motivated and asked to explain their research results in accessible ways, and explicit statements of the state of scientific knowledge are easy to find.

An obvious place to start is the Intergovernmental Panel on Climate Change (IPCC). Created in 1988 by the World Meteorological Organization and the United Nations Environment Programme, the IPCC evaluates the state of climate science as a basis for informed policy action, primarily on the basis of peer-reviewed and published scientific literature (IPCC 2005). The IPCC has issued five assessments, with a sixth due in 2014. Already in 2001, the IPCC had stated the consensus scientific opinion that Earth's climate is being affected by human activities. This view is expressed throughout the report, but perhaps the clearest statement is this: "Human activities … are modifying the concentration of atmospheric constituents …that absorb or scatter radiant energy… [M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" (McCarthy et al. 2001, 21). The 2007 IPCC reports updates this to "very likely" (Alley et al. 2007).

From a historical perspective, the IPCC is a somewhat unusual scientific organization: it was created not to discover new knowledge but to compile and assess existing knowledge on a politically sensitive and economically significant issue. Its conclusions might be skewed by these extra-scientific concerns. But the IPCC is by no means alone in its conclusions; its results have been repeatedly ratified by other scientific organizations.

All of the major scientific bodies in the United States whose membership's expertise bears directly on the matter have issued reports or statements that confirm the IPCC conclusion. One is the National Academy of Sciences report, *Climate Change Science: An Analysis of Some Key Questions* (2001), which originated from a White House request. Here is how it opens: "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise" (National Academy of Sciences 2001, 1). The report explicitly addresses whether the IPCC assessment is a fair summary of professional scientific thinking and answers yes: "The IPCC's conclusion that most of the observed warming of the last 50 years is likely to have been due to the increase in greenhouse gas concentrations accurately reflects the current thinking of the scientific community on this issue" (National Academy of Sciences 2001, 3).

Other US scientific groups have agreed. In February 2003, the American Meteorological Society adopted the following statement on climate change: "There is now clear evidence that the mean annual temperature at the Earth's surface, averaged over the entire globe, has been increasing in the past 200 years. There is also clear evidence that the abundance of greenhouse gases has increased over the same period… Because human activities are contributing to climate change, we have a collective responsibility to develop and undertake carefully considered response actions" (American Meteorological Society 2003). So too says the American Geophysical Union: "Scientific evidence strongly indicates that natural influences cannot explain the rapid increase in global near-surface temperatures observed during the second half of the 20th century" (American Geophysical Union Council 2003). Likewise the

American Association for the Advancement of Science: “The world is warming up. Average temperatures are half a degree centigrade higher than a century ago. The nine warmest years this century have all occurred since 1980, and the 1990s were probably the warmest decade of the second millennium. Pollution from ‘greenhouse gases’ such as carbon dioxide (CO_2) and methane is at least partly to blame” (Harrison and Pearce 2000). In short, these groups have all affirmed that global warming is real and substantially attributable to human activities. (And today, the observed increase in mean global temperature is nearly a full degree, centrigrade.)

If we extend our purview beyond the United States, we find this conclusion further reinforced. In 2005, the Royal Society of the UK, one of the world’s oldest and most respected scientific societies, issued a “Guide to Facts and Fictions about Climate Change,” debunking various myths asserting that climate change is not occurring, that it is not caused by human activities, that observed changes are within the range of natural variability, that CO_2 is too trivial to matter, that climate models are unreliable, and that the IPCC is biased and does not fairly represent the scientific uncertainties.

On the latter point, the report takes pains to underscore the scientific authority of the IPCC, noting that “the IPCC is the world’s leading authority on climate change and its impacts,” and that its work is backed by the worldwide scientific community.[2] This point was underscored in 2007, when the National Academies of 13 countries (G8+ 5) issued a joint statement calling attention to the problem of anthropogenic climate change, and urging a rapid transition to a low carbon society.[3]

One website dedicated to evaluating the scientific consensus on climate change counts 27 scientific societies that have formally endorsed the conclusion that “most of the global warming in recent decades can be attributed to human activities”—just in North America, Europe, and Australia—as well as 13 National Academies in Africa.[1] If we were to do a comprehensive count of scientific societies in Asia, Africa, and South America, the figure would no doubt be still higher.

Consensus reports and statements are drafted through a careful process involving many opportunities for comment, criticism, and revision, so it is unlikely that they would diverge greatly from the opinions of the societies' memberships. Nevertheless, it could be the case that they downplay dissenting opinions.[3]

One way to test that hypothesis is by analyzing the contents of published scientific papers, which contain the views that are considered sufficiently supported by evidence that they merit publication in expert journals. After all, any one can *say* anything, but not anyone can get research results published in a refereed journal.[4] Papers published in scientific journals must pass the scrutiny of critical, expert colleagues. They must be supported by sufficient evidence to convince others who know the subject well. So one must turn to the scientific literature to be certain of what scientists really think.

Before the twentieth century, this would have been a trivial task. The number of scientists directly involved in any given debate was usually small. A handful, a dozen, perhaps a hundred, at most, participated—in part because the total number of scientists in the world was small (Price 1986). Moreover, because professional science was a limited activity, many scientists used language that was accessible to scientists in other disciplines as well as to serious amateurs. It was relatively easy for an educated person in the nineteenth or early twentieth century to read a scientific book or paper and understand what the scientist was trying to say. One did not have to be a scientist to read *The Principles of Geology* or *The Origin of Species.*

Our contemporary world is different. Today, hundreds of thousands of scientists publish over a million scientific papers each year.[5] The American Geophysical Union has over 60,000 members in 135 countries, and the American Meteorological Society has nearly 14,000. The IPCC reports involved the participation of many hundreds of scientists from scores of countries (Houghton et al. 1990; Alley et al. 2007), still more if reviewers are included in the head count. No individual could possibly read all the scientific papers on a subject without making a full-time career of it.

Fortunately, the growth of science has been accompanied by the growth of tools to manage scientific information. One of the most important of these is the database of the Institute for Scientific Information (ISI). In its Web of Science, the ISI indexes all papers published in refereed scientific journals every year—over 8500 journals. Using a key word or phrase, one can sample the scientific literature on any subject and get an unbiased view of the state of knowledge.

Figure 2.1 shows the results of an analysis of 928 abstracts, published in refereed journals during the period 1993–2003, that I completed in 2004, to evaluate the state of scientific debate at that time, using the Web of Science data base.[6]

After a first reading to determine appropriate categories of analysis, the papers were divided as follows: (1) those explicitly endorsing the consensus position, (2) those explicitly refuting the consensus position, (3) those discussing methods and techniques for measuring, monitoring, or predicting climate change, (4) those discussing potential or documenting actual impacts of climate change, (5) those dealing with paleoclimate change, and (6) those proposing mitigation strategies. How many fell into category 2—that is, how many of these papers present evidence that refutes the statement: "Global climate change is occurring, and human activities are at least part of the reason why"? The answer is remarkable: none.

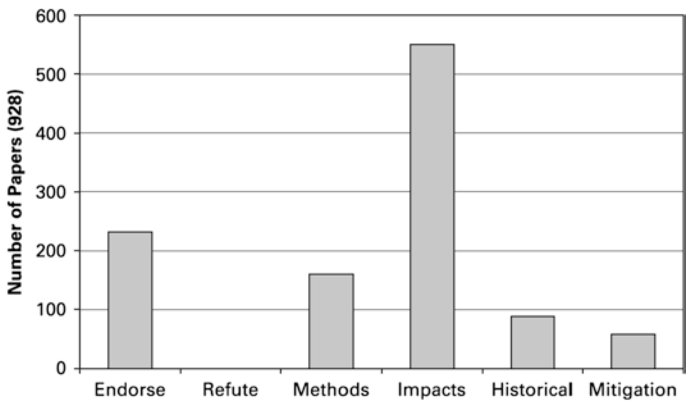

Fig. 2.1 A Web of Science analysis of 928 abstracts using the keywords "global climate change." No papers in the sample provided scientific data or theoretical arguments to refute the consensus position on the reality of global climate change (It should be acknowledged that in any area of human endeavor, leadership may diverge from the views of the led. For example, many Catholic priests endorse the idea that priests should be permitted to marry (Watkin 2004))

A few comments are in order. First, often it is challenging to determine exactly what the authors of a paper do think about global climate change. This is a consequence of experts writing for experts: many elements are implicit. If a conclusion is widely accepted, then it is not necessary to reiterate it within the context of expert discussion. Scientists generally focus their discussions on questions that are still disputed or unanswered rather than on matters about which everyone agrees.

This is clearly the case with the largest portion of the papers examined (approximately half of the total)—those dealing with impacts of climate change. The authors evidently accept the premise that climate change is real and want to track, evaluate, and understand its impacts. Nevertheless, such impacts could, at least in principle, be the results of natural variability rather than human activities. Strikingly, none of the papers used that possibility to argue against the consensus position.

Roughly 15 percent of the papers dealt with methods, and slightly less than 10 percent dealt with paleoclimate change. The most notable trend in the data is the recent increase in such papers; concerns about global climate change have given a boost to research in paleoclimatology and to the development of methods for measuring and evaluating global temperature and climate. Such papers are essentially neutral with respect to the reality of current anthropogenic change: developing better methods and understanding historic climate change are important tools for evaluating current effects, but they do not commit their authors to any particular opinion about those effects. Perhaps some of these authors are in fact skeptical of the current consensus, and this could be a motivation to work on a better understanding of the natural climate variability of the past. But again, none of the papers used that motivation to argue openly against the consensus, and it would be illogical if they did because a skeptical motivation does not constitute scientific evidence. Finally, approximately 20 percent of the papers explicitly endorsed the consensus position, and an additional five percent proposed mitigation strategies. In short, by 2003, the basic reality of anthropogenic global climate change was no longer a subject of scientific debate.[7]

Some readers were surprised by this result and questioned the reliability of a study that failed to find arguments against the consensus position when such arguments clearly existed. After all, anyone who watched Fox news or MSNBC or trolled the Internet knew that there was an enormous debate about climate change, right? Well, no.

First, let's make clear what the scientific consensus is. It is over the reality of human-induced climate change. Scientists predicted a long time ago that increasing greenhouse gas emissions could change the climate, and now there is overwhelming evidence that it *is* changing the climate. These changes are *in addition* to natural variability. Therefore, when contrarians try to shift the focus of attention to natural climate variability, they are misrepresenting the situation. No one denies the fact of natural variability, but natural variability alone does not explain what we are now experiencing. Scientists have also documented that many of the changes that are now occurring are deleterious to both human and nonhuman communities (Arctic Council 2004, IPCC AR4). Because of global warming, sea level is rising, humans are losing their homes and hunting grounds, plants and animals are losing their habitats, and extreme weather events (particularly droughts and heat waves) are becoming more common and in some cases more extreme (Kolbert 2006; Flannery 2006, IPCC AR4, IPCC 2012).

Second, to say that man-made global warming is underway is not the same as agreeing about what will happen in the future. Much of the recent and continuing debate in the scientific community involves the likely rate of future change. A good analogy is evolution. In the early twentieth century, paleontologist George Gaylord Simpson introduced the concept of "tempo and mode" to describe questions about the manner of evolution—how fast and in what manner evolution proceeded. Biologists by the mid-twentieth century agreed about the reality of evolution, but there were extensive debates about its tempo and mode. So it is now with climate change. Virtually all professional climate scientists agree that human-induced climate change is underway, but debate continues on tempo and mode.

Third, there is the question of what kind of dissent still exists. My analysis of the published literature was done by sampling published papers, using a keyword phrase that was intended to be fair, accurate, and neutral: "global climate change" (as opposed to, e.g., "global warming," which might be viewed as biased). The total number of scientific papers published over that 10-year period having anything at all to do with climate change was over 10,000; it is likely that some of the authors of the unsampled papers expressed skeptical or dissenting views. But given that the sample turned up no dissenting papers at all, professional dissention must have been very limited.

Recent work has supported this conclusion, showing that 97–98 percent of professional climate scientists affirm the reality of anthropogenic climate change as outlined by the IPCC (Anderegg et al. 2012; see also Cook et al. 2013, 2016). This also affirms the conclusions of Max and Jules Boykoff (2004, see also Freudenburg and Muselli 2010; Boykoff 2011) that the mass media have given air and print space to a handful of dissenters to a degree that is greatly disproportionate with their representation in the scientific community. Many articles on climate change, for example, will quote two mainstream scientists and one dissenter, where an accurate reflection of the state of the science would be to quote 30 or 40 mainstream scientists for every dissenter. (On television and radio the situation is even worse, where a debate is set up between one mainstream scientist and one dissenter, as if the actual distribution of views in the scientific community were fifty-fifty.) There are climate scientists who actively do research in the field but disagree with the consensus position, but their number is very, very small. This is not to say that there are not a significant number of *contrarians*, but to point out that the vast majority of them are not climate scientists.

In fact, most contrarians are not even scientists at all. Some, like the physicist Frederick Seitz (who for many years challenged the scientific evidence of the harms of tobacco along with the threat of climate change), were once scientific researchers but not in the field of climate science. (Seitz was a solid-state physicist.) Others, like Michael Crichton, who for many years was a prominent speaker on the contrarian lecture circuit, are novelists, actors, or others with access to the media, but no scientific credentials. What Seitz and Crichton have in common, along with most other contrarians, is that they do no new scientific research. They are not producing new evidence or new arguments. They are simply attacking the work of others, and doing so in the court of public opinion and in the mass media rather than in the halls of science.

This latter point is crucial and merits underscoring: the vast majority of books, articles, and websites denying the reality of global warming do not pass the most basic test for what it takes to be counted as scientific—

namely, being published in a peer-reviewed journal. Contrarian views have been published in books and pamphlets issued by politically motivated think tanks and widely spread across the Internet, but so have views promoting the reality of UFOs or the claim that Lee Harvey Oswald was an agent of the Soviet Union.

Moreover, some contrarian arguments are frankly disingenuous, giving the impression of refuting the scientific consensus when their own data do no such thing. One example will illustrate the point. In 2001, Willie Soon, a physicist at the Harvard-Smithsonian Center for Astrophysics, with several colleagues published a paper entitled "Modeling Climatic Effects of Anthropogenic Carbon Dioxide Emissions: Unknowns and Uncertainties" (Soon et al. 2001). This paper has been widely cited by contrarians as an important example of a legitimate dissenting scientific view published in a peer-reviewed journal.[8] But the issue under discussion is how well models can predict the future—in other words, tempo and mode. The paper does not refute the consensus position, and the authors acknowledge so: "The purpose of [our] review of the deficiencies of climate model physics and the use of GCMs is to illuminate areas for improvement. Our review does not disprove a significant anthropogenic influence on global climate" (Soon et al. 2001, 259; see also 2002).

The authors needed to make this disclaimer because many contrarians *do* try to create the impression that arguments about tempo and mode undermine the whole picture of global climate change. But they don't. Indeed, one could reject all climate models and still accept the consensus position because models are only one part of the argument—one line of evidence among many.

Is there disagreement over the details of climate change? Yes. Are all aspects of climate past and present well understood? No, but who has ever claimed that they were? Does climate science tell us what policy to pursue? Definitely not. But it does identify the problem, explain why it matters, and give society insights that can help to frame an efficacious policy response (e.g., Smith 2002; Oreskes et al. 2010).

So why does the public have the impression of disagreement among scientists? If the scientific community has forged a consensus, then why do so many Americans have the impression that there is serious scientific uncertainty about climate change?[9]

There are several reasons. First, it is important to distinguish between scientific and political uncertainties. There are reasonable differences of opinion about how best to respond to climate change and even about how serious global warming is relative to other environmental and social issues. Some people have confused—or deliberately conflated—these two issues. Scientists are in agreement about the reality of global climate change, but this does not tell us what to do about it.

Second, climate science involves prediction of future effects, which by definition are uncertain. It is important to distinguish among what is known to be happening now, what is likely to happen based on current scientific understanding, and what might happen in a worst-case scenario. This is not always easy to do, and scientists have not always been effective in making these distinctions. Uncertainties about the future are easily conflated with uncertainties about the current state of scientific knowledge.

Third, scientists have evidently not managed well enough to explain their arguments and evidence beyond their own expert communities. The scientific societies have tried to communicate to the public through their statements and reports on climate change, but what average citizen knows that the American Meteorological Society even exists or visits its home page to look for its climate-change statement?

There is also a deeper problem. Scientists are finely honed specialists trained to create new knowledge, but they have little training in how to communicate to broad audiences and even less in how to defend scientific work against determined and well-financed contrarians (Moser and Dilling 2004, idem 2007; Hassol 2008; Somerville and Hassol 2011). Moreover, until recently, most scientists have not been particularly anxious to take the time to communicate their message broadly. Most scientists consider their "real" work to be the production of knowledge, not its dissemination, and often view these two activities as mutually exclusive, or at least competitive. Some sneer at colleagues who communicate to broader audiences, dismissing them as "popularizers."

If scientists do jump into the fray on a politically contested issue, they may be accused of "politicizing" the science and compromising their objectivity.[10] This places scientists in a double bind: the demands of objectivity seem to suggest that they should keep aloof from contested issues, but if they don't get involved, no one will know what an objective view of the matter looks like. Scientists' reluctance to present their results to broad audiences has left scientific knowledge open to misrepresentation, and recent events show that there are plenty of people ready and willing to misrepresent it.

It's no secret that politically motivated think tanks such as the American Enterprise Institute and the George Marshall Institute have been active for some time in trying to communicate a message that is at odds with the consensus scientific view (Gelbspan 1997, 2005; Mooney 2006; Oreskes and Conway 2012). These organizations have successfully garnered a great deal of media attention for the tiny number of scientists who disagree with the mainstream view and for nonscientists, like Crichton, who pronounce loudly on scientific issues.

This message of scientific uncertainty has been reinforced by the public relations campaigns of certain corporations with a large stake in the issue.[11] The most well-known example is ExxonMobil, which in the late 1990s and throughout the 2000s, ran a highly visible advertising campaign on the op-ed page of the *New York Times.* Its carefully worded advertisements—written and formatted to look like newspaper columns and called op-ed pieces by ExxonMobil—suggested that climate science was far too uncertain to warrant action on it (Supran and Oreskes, 2017).[12] One advertisement concluded that the uncertainties and complexities of climate and weather mean that "there is an ongoing need to support scientific research to inform decisions and guide policies" (Environmental Defense 2005; see also van den Hove et al., 2002). Not many would argue with this unobjectionable claim, unless it is taken to imply that decisions and policies taken now would be premature. Our scientists have long ago concluded that existing research warrants that decisions and policies be made *today*.[13]

In any scientific debate, past or present, one can always find intellectual outliers who diverge from the consensus view. Even after plate tectonics was resoundingly accepted by earth scientists in the late 1960s, a handful of persistent resisters clung to the older views, and some idiosyncratics held to alternative theoretical positions, such as earth expansion. Some of these men were otherwise respected scientists, including Sir Harold Jeffreys, one of Britain's leading geophysicists, and Gordon J. F. MacDonald, a one-time science adviser to Presidents Lyndon Johnson and Richard Nixon. Both these men rejected plate tectonics until their dying day, which for MacDonald was in 2002. Does that mean that scientists should reject plate tectonics, that disaster-preparedness campaigns should not use plate tectonics theory to estimate regional earthquake risk, or that schoolteachers should give equal time in science classrooms to the theory of earth expansion? Of course not. That would be silly and a waste of time. In the case of earthquake preparedness, it would be dangerous as well.

No scientific conclusion can ever be proven, and new evidence may lead scientists to change their views, but it is no more a "belief" to say that earth is heating up than to say that continents move, that germs cause disease, that DNA carries hereditary information, that HIV causes AIDS, and that some synthetic organic chemicals can disrupt endocrine function. You can always find someone, somewhere, to disagree, but these conclusions represent our best current understandings and therefore our best basis for reasoned action (Oreskes 2004).

2.3 How Do We Know We're Not Wrong?

Might the consensus on climate change be wrong? Yes, it might be, and if scientific research continues, it is almost certain that some aspects of the current understanding will be modified, perhaps in significant ways. This possibility can't be denied. The relevant question for us as citizens is not whether this scientific consensus *might* be mistaken but rather whether there is any substantive reason to think that it *is* mistaken.

How can outsiders evaluate the robustness of any particular body of scientific knowledge? Many people expect a simple answer to this question. Perhaps they were taught in school that scientists follow "the scientific method" to get correct answers, and they have heard some climate-change deniers suggesting that climate scientists do not follow the scientific method (because they rely on models, rather than laboratory experiments) so their results are suspect. These views are wrong.

Contrary to popular opinion, there is no scientific method (singular). Despite heroic efforts by historians, philosophers, and sociologists to identify "the" scientific method, they have failed. There is no generally agreed-upon answer as to what the methods and standards of science are (or even what they should be). There is no methodological litmus test for scientific reliability and no single method that guarantees valid conclusions that will stand up to all future scrutiny.

A positive way of saying this is that scientists have used a variety of methods and standards to good effect and that philosophers have proposed various helpful criteria for evaluating the methods used by scientists. None is a magic bullet, but each can be useful for thinking about what makes scientific information a reliable basis for action.[14] So we can pose the question: how does current scientific knowledge about climate stand up to these diverse models of scientific reliability?

The Inductive and Deductive Models of Science

The most widely cited models for understanding scientific reasoning are induction and deduction. *Induction* is the process of generalizing from specific examples. If I see 100 swans and they are all white, I might conclude that all swans are white. If I saw 1000 white swans or 10,000, I would surely think that *all* swans were white, yet a black one might still be lurking somewhere. As David Hume famously put it, even though the sun has risen thousands of times before, we cannot *prove* that it will rise again tomorrow.

Nevertheless, common sense tells us that the sun will rise again tomorrow, even if we can't logically prove that it's so. Common sense similarly tells us that if we had seen 10,000 white swans, then our conclusion that all swans were white would be more robust than if we had seen only 10. Other things being equal, the more we know about a subject, and the longer we have studied it, the more likely our conclusions about it are to be true.

How does climate science stand up to the inductive model? Does climate science rest on a strong inductive base? Yes. Humans have been making temperature records consistently for over 150 years, and nearly all scientists who have looked carefully at these records see an overall temperature increase since the industrial revolution. (Houghton et al. 1990; Bruce et al. 1996; Watson et al. 1996; McCarthy et al. 2001; Houghton et al. 2001; Metz et al. 2001; Watson 2001; Weart 2008). According to the IPCC's AR4, the temperature rise over the 100-year period from 1906 to 2005 was 0.74 °C [0.56–0.92 °C] with a confidence interval of 90 percent (Alley et al. 2007). The empirical signal is clear, even if all the details are not.

How reliable are the early records? And how do you average data to be representative of the globe as a whole, when most of the early data comes from only a few places, generally in Europe? Scientists have spent quite a bit of time addressing these questions; most have satisfied themselves that the empirical signal is clear (Edwards 2010). Even if scientists doubted the older records, the more recent data show a strong increase in temperatures over the past 30 to 40 years, just when the amount of CO_2 and other greenhouses gases in the atmosphere was growing dramatically (McCarthy et al. 2001; Houghton 2001; Metz et al. 2001; Watson 2001). Recently, an independent assessment by the Berkeley Earth Surface Temperature group found that over the past 50 years the land surface warmed by 0.91 °C, a result that confirms the prior work by NASA, NOAA, and the U.K. Hadley Centre (Muller et al. 2013). The Berkeley group has also reviewed the question of the "heat island effect"—the possible exaggeration of the warming effect due to the location of weather stations in urban areas, which are warmer than rural ones because of buildings, concrete, automobiles, etc.—a potential source of error much emphasized by some contrarians (Wickham et al. 2013)—and finds that the observed warming cannot be explained away this way.

The Berkeley study received a good deal of media attention—arguably out of proportion to its scientific significance—because its spokesman, physicist Richard Muller, was previously a self-proclaimed skeptic, and because some of his funding came from the Koch Industries, a Fortune 500 company heavily involved in petroleum refining, oil and gas pipelines, and petrochemicals. (Both Koch brothers are political libertarians, opposed to environmental regulation: David Koch ran in 1980 for Vice President on the Libertarian party ticket, and Charles Koch is one of the founders of the Cato Institute, which has played a large role in US climate change denial; see Oreskes and Conway 2012.) But despite a flurry of media attention, Richard Muller's late-stage conversion had little political impact, and even less scientific, because the conclusions from the instrumental records that he first questioned but then affirmed have been amply corroborated by other, independent evidence from tree rings, ice cores, and coral reefs (IPCC, Alley et al. 2007). A paper in 2003 by a team lead by Jan Esper at the Swiss Federal Research Center, for example, had already demonstrated that tree rings can provide a reliable, long-term record of temperature variability, one which largely agrees with the instrumental records over the past 150 years (Esper et al. 2002).

Muller's reanalysis of existing temperature records raises the fundamental problem facing all inductive science: how many data are enough? If you have counted 10,000 white swans—or 100,000, or even 1,000,000—how do you know that a black swan isn't lurking around the corner? How do you know that the generalization you made from your observations is correct? After all, other generalizations could also be consistent with your observations.

The logical limitations of the inductive view of science have led some to argue that the core of scientific method is testing theories through logical deductions. *Deduction* is drawing logical inferences from a set of premises—the stock-in-trade of Sherlock Holmes. In science, deduction is generally presumed to work as part of what has come to be known as the *hypothetico-deductive model*—the model you will find in most textbooks that claim to teach the scientific method (sometimes also called the *deductive-nomological* model, referring to the idea that ultimately science seeks to develop not just hypotheses, but laws, from which conclusions may be deduced).

In this view, scientists develop hypotheses and then test them. Every hypothesis has logical consequences—deductions—and one can try to determine, primarily through experiment and observation, whether the deductions are correct. If they are, they support the hypothesis. If they are not, then the hypothesis must be revised or rejected. It's often considered especially good if the prediction is something that would otherwise be quite unexpected, because that would suggest that it didn't just happen by chance.

The most famous example of successful deduction in the history of science is the case of Ignaz Semmelweis, who in the 1840s deduced the importance of handwashing to prevent the spread of infection (Gillispie 1975; Hempel 1965). Semmelweis had noticed that many women were dying of fever after giving birth at his Viennese hospital. Surprisingly, women who had their infants on the way to the hospital—seemingly under more adverse conditions—rarely died of fever. Nor did women who gave birth at another hospital clinic where they were attended by midwives. Not surprisingly, Semmelweis was troubled by this pattern, which seemed to suggest that it was more dangerous to give birth when attended by a doctor than by a midwife, and more dangerous to give birth in a hospital than in a horse-drawn carriage.

In 1847, a friend of Semmelweis, Jakob Kolletschka, cut his finger while doing an autopsy and soon died. Autopsy revealed a pathology very similar to the women who had died after childbirth; something in the cadaver had apparently caused his death. Semmelweis knew that many of the doctors at his clinic routinely went directly from conducting autopsies to attending births, but midwives did not perform autopsies. So he hypothesized that the doctors were carrying cadaveric material on their hands, which was infecting the women (and killed his friend). He deduced that if physicians washed their hands before attending the women, then the infection rate would decline. They did so, and the infection rate did decline, demonstrating the power of the hypothetico-deductive method.

How does climate science stand up to this standard? Have climate scientists made predictions that have come true? Absolutely. The most obvious is the fact of global warming itself. Scientific concern over the effects of increased atmospheric CO_2 is based on physics—the fact that CO_2 is a greenhouse gas, something that has been known since the mid-nineteenth century. In the early twentieth century, Swedish chemist Svante Arrhenius predicted that increasing CO_2 from the burning of fossil fuels would lead to global warming, and by midcentury, a number of other scientists, including G. S. Callendar, Roger Revelle, and Hans Suess, concluded that the effect might soon be quite noticeable, leading to sea level rise and other global changes (Fleming 1998; Weart 2008). In 1965, Revelle and his colleagues wrote, "By the year 2000, the increase in atmospheric CO_2 … may be sufficient to produce measurable and perhaps marked change in climate, and will almost certainly cause significant changes in the temperature and other properties of the stratosphere" (Revelle 1965, 9). This prediction has come true (McCarthy et al. 2001; Houghton et al. 2001; Metz et al. 2001; Watson 2001).

Another prediction fits the category of something unusual that you might not even think of without the relevant theory. In 1980, climatologist Suki Manabe predicted that the effects of global warming would be strongest first in the polar regions. *Polar amplification* was not an induction from observations but a deduction from theoretical principles: the concept of ice-albedo feedback. The reflectivity of a material is called its *albedo*. Ice has a high albedo, reflecting sunlight into space much more effectively than grass, dirt, or water. One reason polar regions are as cold as they are is that snow and ice are very effective in reflecting solar radiation back into space. But if the snow starts to melt and bare ground (or water) is exposed, this reflective effect diminishes. Less ice means less reflection, which means more solar heat is absorbed, leading to yet more melting in a feedback loop. So once warming begins, its effects accelerate; Manabe and his colleagues thus predicted that warming would be more pronounced in polar regions than in temperate ones. The Arctic Climate Impact Assessment concluded in 2004 that this prediction had come true (Manabe and Stouffer 1980, 1994; Holland and Bitz 2003; Arctic Council 2004).

Falsification

Ignaz Semmelweis is among the famous figures in the history of science because his work in the 1840s foreshadows the germ theory of disease and the saving of millions of human lives. His story is a great one, told and retold many times. But the story has a twist because Semmelweis was right for the wrong reason. Cadaveric matter was *not* the cause of the infections: germs were. In later years, this would be demonstrated by James Lister, Robert Koch, and Louis Pasteur, who realized that handwashing was effective not because it removed the cadaveric material, but because it removed the germs associated with that material.

The story illustrates a fundamental flaw with the hypothetico-deductive model—the fallacy of affirming the consequent. If I make a prediction and it comes true, I may assume that my theory is correct. But this would be a mistake, for the accuracy of my deduction does not prove that my hypothesis was correct; my prediction may have come true for other reasons, as indeed Semmelweis' did. The other reasons may be related to the hypothesis—germs *were* associated with cadaveric matter—but in other cases the connection may be entirely coincidental. I can convince myself that I have proved my theory right, but this would be self-deception.

This realization led the twentieth-century philosopher Karl Popper to suggest that you can never prove a theory true. Any affirmation of a hypothesis through deduction runs to the risk of the fallacy of affirming the consequent. However, if the prediction does not come true, then you do know that there is something wrong with your hypothesis. Thus Popper emphasized that while we cannot prove a theory true, we can prove it false. Thus, scientific theories must be "falsifiable"—able to be shown, through experiment or observation—that they are false, and the scientific method is not to prove theories, but to show them to be false, a view known as *falsificationism* (Popper 1959).

How does climate science hold up to this modification? Can climate models be refuted? Falsification is a bit of a problem for models—not just climate models—because many models are built to forecast the future and the results will not be known for some time. By the time we find out whether the long-term predictions of a model are right or wrong, that knowledge won't be of much use. So while model predictions might be falsifiable in principle, many are not actually falsifiable in practice.

For this reason, many models are tested by seeing if they can accurately reproduce past events—what is sometimes called *retrodiction*. In principle, retrodiction should be a rigorous test: a climate model that fails to reproduce past temperature records is obviously faulty, and could be considered falsified. In reality, it doesn't work quite that way.

Climate models are complex, and they involve many variables—some that are well measured and others that are not. If a model does not reproduce past data very well, most modelers assume that one or more of the model parameters are not quite right, and they make adjustments in an attempt to obtain a better fit. This is generally referred to as *model calibration,* and many modelers consider it an essential part of the process of building a good model. But calibration can make models refutation-proof: the model doesn't get rejected; it gets revised. Given the complexity of climate models, there are myriad ways a model can be revised to ensure that it successfully retrodicts past climate change. Thus, in practice, the idea of falsification is not of great use in judging climate models.

Recently, however, one modeler has put his model to the test by making a genuine prediction of the future. When the Philippine volcano Mt. Pinatubo erupted in 1991, millions of tons of sulfur dioxide, ash, and dust were thrown into the atmosphere. NASA climate modeler James Hansen realized that these materials were likely to cause a global cooling effect, and that it was possible to use the NASA-GISS climate model to predict what that cooling would be. The model had been built to simulate long-term global warming, not short-term global cooling, but still, if the physics of the model were correct, he reasoned, it ought to be able to make this prediction. Hansen and his team ran the model, and forecast a short-term cooling effect of about 0.5 degree, that would briefly overwhelm the general warming trend from greenhouse gases (Hansen et al. 1992). That prediction came true (Kerr 1993).

This is still only one test, however, and if model results were the only basis for current scientific understanding, there would be grounds for some healthy skepticism. Models are therefore best viewed as heuristic devices: a means to explore what-if scenarios. This is, indeed, how most modelers use them: to answer questions like "If we double the amount of CO_2 in the atmosphere, what is the most likely outcome?"

One way in which modelers address the fact that a model can't be proved right or wrong is to make lots of different models that explore diverse possible outcomes—what modelers call *ensembles*. An example of this is <climateprediction.net>, a Web-based mass-participation experiment that enlists members of the public to run climate models on their home computers to explore the range of likely and possible climate outcomes under a variety of plausible conditions.

Over 90,000 participants from over 140 countries have produced tens of thousands of runs of a general circulation model produced by the Hadley Centre for Climate Prediction and Research. Figure 2.2 presents some initial results, published in the journal *Nature* in 2005, for a steady-state model in which atmospheric CO_2 is doubled relative to preindustrial levels and the model earth is allowed to adjust.

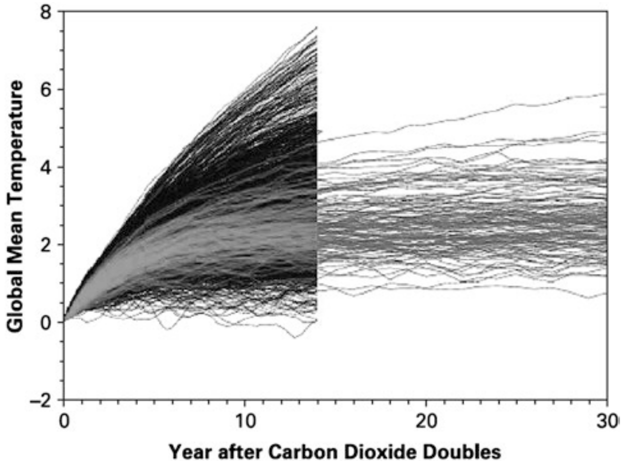

Fig. 2.2 Changes in global mean surface temperature after carbon dioxide values in the atmosphere are doubled. The *black lines* show the results of 2579 fifteen-year simulations by members of the general public using their own personal computers. The *gray lines* show comparable results from 127 thirty-year simulations completed by Hadley Centre scientists on the Met Office's supercomputer (<www.metoffive.gov.uk>). Figure prepared by Ben Sanderson with help from the <climateprediction.net> project team (Source: Reproduced by permission from http://www.climateprediction.net/science/results_cop10.phpi)

The results in black are the climateprediction.net's mass-participation runs; the results in gray come from runs made by professional climate scientists at the Hadley Centre on a supercomputer (Stainforth et al. 2005).

What does an ensemble like this show? For one thing, no matter how many times you run the model, you almost always get the same qualitative result: the earth will warm. The unanswered question is how much and how fast—in other words, tempo and mode.

The models vary quite a bit in their tempo and mode, but nearly all fall within a temperature range of 1–7 °C (2–14 °F) within 15 years after the earth's atmosphere reaches a doubling of atmospheric CO_2. Moreover, most of the runs are still warming at that point. The model runs were stopped at year 15 for practicality, but most of them had not yet reached equilibrium: model temperatures were still rising. Look again at Fig. 2.2. If the general-public model runs had been allowed to continue out to 30 years, as the Hadley Centre scientists' model runs do, many of them would apparently have reached still higher temperatures, perhaps as high as 12 °C!

How soon will our atmosphere reach a CO_2 level of twice the preindustrial level? The answer depends largely on how much CO_2 we humans put into the atmosphere—a parameter that cannot be predicted by a climate model. Note also that in these models CO_2 does not continue to rise: it is fixed at twice preindustrial levels. Nearly all experts now believe that even if major steps are taken soon to reduce the global production of greenhouse gases, atmospheric CO_2 levels will go well above that level. If CO_2 triples or quadruples, then the expected temperature increase will also increase. No one can say precisely when earth's temperature will increase by any specific value, but the models indicate that it almost surely *will* increase. With scant exceptions, the models show the earth warming, and some of them show the earth warming very quickly and very much.

Is it possible that *all* these model runs are wrong? Yes, because they are variations on a theme. If the basic model conceptualization were wrong in some way, then all the models runs could be wrong, too. Perhaps there is a negative feedback loop that we have not yet recognized. Perhaps the oceans can absorb more CO_2 than we think, or we have missed some other carbon sink (Smith 2002). This is one reason that continued scientific investigation is warranted. But note that Svante Arrhenius and Guy Callendar predicted global warming before anyone ever built a global circulation model (or even had a digital computer). You do not need to have a computer model to predict global warming, and you do not need to have a computer model to know that Earth is, currently, warming.

If climate science stands with or without climate models, then is there any information that would show that climate science is wrong? Yes. Scientists might discover a mistake in their basic physical understanding that showed they had misconceptualized the whole issue. They could discover that they had overestimated the significance of CO_2 and underestimated the significance of some other parameter. But if such mistakes are found, there is no guarantee that correcting them will lead to a more optimistic scenario. It could well be the case that scientists discover neglected factors that show that the problem is worse than we'd supposed. (Indeed, some scientists now think this is the case: that we have underestimated the cooling or "masking" effect of sulfate aerosols, and therefore the impact of greenhouse gases will be worse if and when China, for example, cleans up its air pollution problems.)

Moreover, there is another way to think about this issue. Contrarians have put inordinate amounts of effort into trying to find something that is wrong with climate science, and despite all this effort, they have come up empty-handed. Year after year, the evidence that global warming is real and serious has only strengthened.[15] Perhaps that is the strongest argument of all. Contrarians have repeatedly tried to falsify the consensus position, and they have repeatedly failed.

Consilience of Evidence

Most philosophers and historians of science agree that there is no ironclad means to prove a scientific theory. But if science does not provide proof, then what is the purpose of induction, hypothesis testing, and falsification? Most would answer that, in various ways, these activities provide warrant for our views. Do they?

An older view, which has come back into fashion of late, is that scientists look for consilience of evidence. *Consilience* means "coming together," and the term is generally credited to the English philosopher William Whewell, who defined it as the process by which sets of data—independently derived—coincided and came to be understood as explicable by the same theoretical account (Gillispie 1981; Wilson 2000). The idea is not so different from what happens in a legal case. To prove a defendant guilty beyond a reasonable doubt, a prosecutor must present a variety of evidence that holds together in a consistent story. The defense, in contrast, might need to show only that some element of the story is at odds with another to sow reasonable doubt in the minds of the jurors. In other words, scientists are more like lawyers than they might like to admit. They look for independent lines of evidence that hold together.

Do climate scientists have a consilience of evidence? Again the answer is yes. Instrumental records, tree rings, ice cores, borehole data, and coral reefs all point to the same conclusion: things are getting warmer overall. Keith Briffa and Timothy Osborn of the Climate Research Unit of the

University of East Anglia compared Esper's tree-ring analysis with six other reconstructions of global temperature between the years 1000 and 2000 (Briffa and Osborn 2002). All seven analyses agree: temperatures increased dramatically in the late twentieth century relative to the entire record of the previous millennium. Temperatures vary naturally, of course, but the absolute magnitude of global temperatures in the late twentieth century was higher than *any* known temperatures in the previous 1000 years, and many different lines of evidence point in this direction.

Inference to the Best Explanation

The various problems in trying to develop an account of how and why scientific knowledge is reliable have led some philosophers to conclude that the purpose of science is not proof, but explanation. Not just any explanation will do, however; the best explanation is the one that is consistent with the evidence (e.g., Lipton 1991). Certainly, it is possible that a malicious or mischievous deity placed fossils throughout the geological record to trick us into believing organic evolution—perhaps to test our faith?—but to a scientist this is not the best explanation because it invokes supernatural effects, and the supernatural is beyond the scope of scientific explanation. (It might not be the best explanation to a theologian, either, if that theologian was committed to heavenly benevolence.) Similarly, I might try to explain the drift of the continents through the theory of the expanding earth—as some scientists did in the 1950s—but this would not be the best explanation because it fails to explain why the earth has conspicuous zones of compression as well as tension. The philosopher of science Peter Lipton has put it this way: every set of facts has a diversity of possible explanations, but "we cannot infer something simply because it is a possible explanation. It must somehow be the best of competing explanations" (Lipton 2004, 56). (Isaac Newton, in the *Principia Mathematica*, argued that our explanations must invoke causes that we know actually exist—so-called *vera causa*. We might hypothesize that Martians hunted dinosaurs to extinction, thereby explaining their demise, but this would not be an inference to the best explanation, because we have no evidence that Martians exist, but invoking a meteorite can be, because large meteorites do.)

Best is a term of judgment, so it doesn't entirely solve our problem, but it gets us thinking about what it means for a scientific explanation to be the best available—or even just a good one. It also invites us to ask the question, "Best for what purpose?" For philosophers, *best* generally means that an explanation is consistent with all the available evidence (not just selected portions of it), that the explanation is consistent with other known laws of nature and other bodies of accepted evidence (and not in conflict with them), and that the explanation does not invoke supernatural events or causes that by definition cannot be refuted. In other words, *best* can be judged in terms of the various criterion invoked by *all* the models of science discussed above: Is there an inductive basis? Does the theory pass deductive tests? Do the various elements of the theory fit with each other and with other established scientific information? And is the explanation potentially refutable and not invoking unknown, inexplicable, or supernatural causes?

Contrarians have tried to suggest that the climate effects we are experiencing are simply natural variability. Climate does vary, so this is a *possible* explanation. No one denies that. But is it the *best* explanation for what is happening now? Most climate scientists would say that it's not the best explanation. In fact, it's not even a good explanation—because it is inconsistent with much of what we know.

Should we believe that the global increase in atmospheric CO_2 has had a negligible effect even though basic physics tells us it should be otherwise? Should we believe that the correlation between increased CO_2 and increased temperature is just a peculiar coincidence? If there were no theoretical reason to relate them, and if Arrhenius, Callendar, Suess, and Revelle had not predicted that all this would all happen, then one might well conclude that rising CO_2 and rising temperature were merely coincidental. But we have many reasons to believe that there is a causal connection and no good reason to believe that it is a coincidence. Indeed, the only reason we might think otherwise is to avoid committing to action: if this is just a natural cycle in which humans have played no role, then global warming might go away on its own in due course, and we would not have to do spend money or be otherwise inconvenienced by trying to remedy the problem.

2.4 Conclusion

To deny that global warming is real is to deny that humans have become geological agents, changing the most basic physical processes of the earth, and therefore to deny that we bear responsibility for adverse changes that are taking place around us. For centuries, scientists thought that earth processes were so large and powerful that nothing we could do would change them. This was a basic tenet of geological science: that human chronologies were insignificant compared with the vastness of geological time; that human activities were insignificant compared with the force of geological processes. And once they were. But no more. There are now so many of us cutting down so many trees and burning so many billions of tons of fossil fuels that we have become geological agents. We have changed the chemistry of our atmosphere, causing sea level to rise, ice to melt, and climate to change. There is no reason to think otherwise. And, in my view, there is, at this point in history, no excuse for not taking action to prevent the very significant losses that are likely to ensue—indeed, losses that are already becoming evident—if we sit around denying the reality that science has made clear.

Notes

1. Contrast this with the results of the Intergovernmental Panel on Climate Change's *Third* and *Fourth Assessment Reports*, which state unequivocally that average global temperatures have risen (Houghton et al. 2001; Alley et al. 2007).
2. http://royalsociety.org/uploadedFiles/Royal_Society_Content/News_and_Issues/Science_Issues/Climate_change/climate_facts_and_fictions.pdf
3. http://www.science.org.au/policy/climatechange-g8+5.pdf
4. In recent years, climate-change deniers have increasingly turned to non-scientific literature as a way to promulgate views that are rejected by most scientists (see, for example, Deming 2005). http://www.skepticalscience.com/global-warming-scientific-consensus-intermediate.htm

5. An e-mail inquiry to the Thomson Scientific Customer Technical Help Desk produced this reply: "We index the following number of papers in Science Citation Index—2004, 1,057,061 papers; 2003, 1,111,398 papers."
6. The analysis begins in 1993 because that is the first year for which the database consistently published abstracts. Some abstracts initially compiled were deleted from our analysis because the authors of those papers had put "global climate change" in their key words, but their papers were not actually on the subject.
7. This is consistent with the analysis of historian Spencer Weart, who concluded that scientists achieved consensus in 1995 (see Weart 2008).
8. In e-mails that I received after publishing my essay in *Science* (Oreskes 2004), this paper was frequently invoked. It did appear in the sample.
9. According to *Time* magazine, in 2006 a Gallup poll reported that "64 percent of Americans think scientists disagree with one another about global warming" (Americans see a climate problem 2006).
10. Objectivity certainly can be compromised when scientists address charged issues. This is not an abstract concern. It has been demonstrated that scientists who accept research funds from the tobacco industry are much more likely to publish research results that deny or downplay the hazards of smoking than those who get their funds from the National Institutes of Health, the American Cancer Society, or other nonprofit agencies (Bero 2003). On the other hand, there is a large difference between accepting funds from a patron with a clearly vested interest in a particular epistemic outcome and simply trying one's best to communicate the results of one's research clearly and in plain English.
11. Some petroleum companies, such as BP and Shell, have largely refrained from participating in misinformation campaigns (see Browne 1997). Browne began his 1997 lecture by focusing on what he accepted as "two stark facts. The concentration of carbon dioxide in the atmosphere is rising, and the temperature of the Earth's surface is increasing." On the other hand, after an initial flurry of attention caused by Lord Browne's public statements, BP continued to develop its petroleum resources and only to put modest efforts into developing renewables and carbon sequestration technologies. For an analysis of diverse corporate responses, see Van den Hove et al. (2002).
12. For an analysis of one ad, "Weather and Climate," see Environmental Defense (2005). An interesting development in 2003 was that Institutional

Shareholders Services advised ExxonMobil shareholders to ask the company to explain its stance on climate-change issues and to divulge financial risks that could be associated with it. For further information, see https://www.nytimes.com/2017/05/31/business/energy-environment/exxon-shareholders-climate-change.html?mcubz=1.

13. These efforts to generate an aura of uncertainty and disagreement have had an effect. This issue has been studied in detail by academic researchers (see, for example, Boykoff and Boykoff 2004).
14. *Reliable* is a term of judgment. By *reliable basis for action,* I mean that it will not lead us far astray in pursuing our goals, or if it does lead us astray, at least we will be able to look back and say honestly that we did the best we could given what we knew at the time.
15. This is evident when the three IPCC assessments—1990, 1995, 2001—are compared (Houghton et al. 1990, 2001; Bruce et al. 1996; Watson et al. 1996; Metz et al. 2001; Watson 2001; see also Weart 2008).

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